Geologic History of Salt Beds and Related Strata in the Upper Part of the Madison Group (Mississippian), Williston Basin, Montana and North Dakota

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Geologic History of Salt Beds and Related Strata in the Upper Part of the Madison Group (Mississippian), Williston Basin, Montana and North Dakota

By William J. Sando

U.S. GEOLOGICAL SURVEY BULLETIN 2112

Paleogeographic evolution of an ancient salt lake based on biostratigraphic analysis of Mississippian rocks in Montana and North Dakota

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CONTENTS

FIGURES

TABLES

Geologic History of Salt Beds and Related Strata in the Upper Part of the Madison Group (Mississippian), Williston Basin, Montana and North Dakota

By William J. Sando

ABSTRACT

During the latter part of Mississippian time, the Williston Basin of eastern Montana and North Dakota was part of an almost circular area of more rapidly subsiding crust on a broad, relatively stable cratonic platform. The Mississippian stratigraphic record on the platform consists of two continuous depositional sequences separated by a major hiatus, except in the center of the Williston Basin, where a thick deposit of halite at the top of the lower depositional sequence (Madison Group) is overlain conformably by basal, transgressive, terrigenous sediments of the upper depositional sequence (Big Snowy Group).

The upper part of the lower depositional sequence, represented by the Mission Canyon Limestone and Charles Formation, consists mainly of shallowing-upward, regressive shelf-carbonate and evaporite sediments deposited during the middle and late Osagean and early Meramecian. Intermittent deposition of marine anhydrite was common on most of the shelf during this time, but intermittent deposition of marine halite was confined to the central part of the Williston Basin later in the early Meramecian. The sea began a westward retreat from the Cordilleran platform in the late Osagean and left most of the platform exposed to subaerial erosion during the middle Meramecian, except for a vestigial landlocked salt lake at the center of the basin. A marine transgression, which originated in the Antler foreland basin west of the platform, swept eastward across the platform in middle Meramecian to Chesterian time, depositing mainly terrigenous sediments on the eroded surface of the Madison Group. The landlocked salt lake at the center of the basin was covered and extinguished by the basal deposits (Kibbey Formation) of this transgression.

A thorough review of previous research on Mississippian depositional sequences of the Williston Basin evaluates and reconciles seemingly contradictory evidence pertaining to the origin of the salt deposits and to the age relationships of associated strata. Lithic marker horizons, used widely as synchronous planes in chronostratigraphy in the subsurface, are shown to be regionally diachronous with respect to biozone boundaries, but they are considered suitable for most exploration work within the basin. Changes in relative sea level in the study area are probably the result of an interplay of eustacy and tectonism. Regionally variable changes in climate had an important effect on shaping the character of the sediments.

INTRODUCTION

The Mission Canyon Limestone and equivalent formations of the Madison Group comprise a thick, regressive sequence of shallow-water shelf carbonate and evaporitic rocks of Mississippian (middle Osagean–early Meramecian) age that occupies a large area of the northern Rocky Mountains and Great Plains (Sando, 1976). The Mission Canyon sequence is overlain in most places by the Big Snowy Group or Amsden Formation, which includes transgressive, mostly terrigenous rocks that range from Late Mississippian (middle Meramecian) to Middle Pennsylvanian in age (Sando and others, 1975).

During the latter part of Mississippian time, the Williston Basin of eastern Montana and North Dakota was part of an almost circular area of more rapidly subsiding crust (interior sag basin of Kingston and others, 1983, p. 2177–2178) on a broad, relatively stable cratonic platform (Cordilleran platform). In the subsurface of the Williston Basin (fig. 1), most geologists recognize a sequence of dolomite and evaporite beds called the Charles Formation at the top of the Madison Group and regard the contact between the Madison and the overlying Big Snowy as conformable and transitional, even though this contact represents a karst event of considerable duration in surface exposures of the Madison in the areas surrounding the Williston Basin to the south and west (Sando, 1988). The absence of karst features in the subsurface and the presence of a thick, unleached halite sequence at the top of the Madison in the center of the Williston Basin seems to support a transition between the two stratigraphic groups.

Discovery of fossils no younger than early Meramecian near the top of the Madison Group in cores from wells near the center of the Williston Basin (Sando, 1978; Sando and

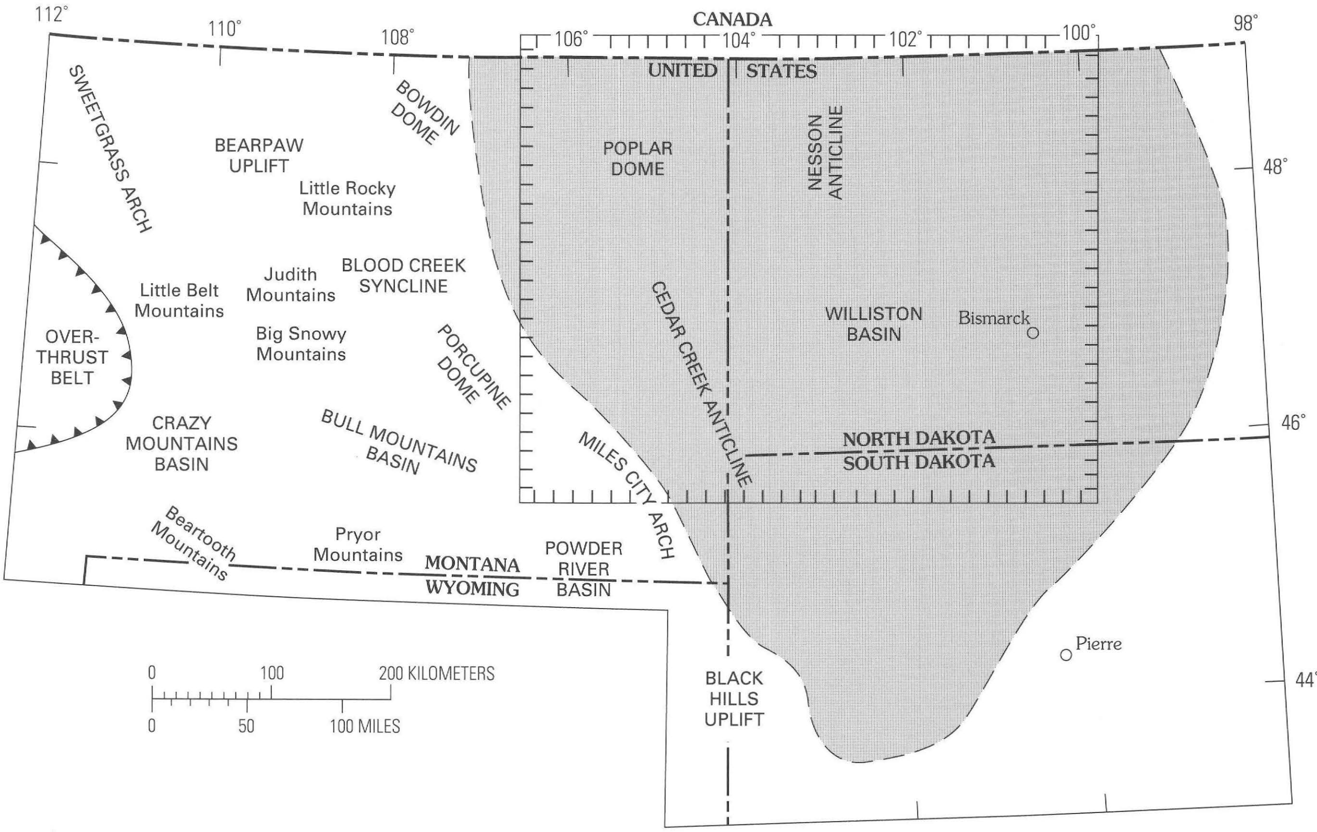


Figure 1. Location of Williston Basin (shaded) and other structural and geographic features in Montana and adjacent States. Hachured lines outline area of figure 12. Modified from Peterson (1984, fig. 3).

Mamet, 1981) is seemingly incompatible with the traditional subsurface interpretation of the age and geologic history of the top of the Madison. This paleontologic evidence suggests that a hiatus representing middle to late Meramecian time is present between the top of the Madison and the overlying Kibbey Formation, which is generally thought to be of Chesterian age in the Williston Basin (Sando, 1978). This interpretation does not explain, however, how marine salt deposits could be preserved beneath the top of the Madison if the central Williston Basin area had been exposed to subaerial erosion similar to the surrounding areas of Madison rocks.

This report presents a new interpretation of the depositional history of the upper part of the Madison Group, and of the origin of the Madison salt, that reconciles apparently contradictory evidence concerning the nature of the top of the Madison in the Williston Basin. The new interpretation was incorporated in paleogeographic maps by Sando (1989a, b, 1992) without discussion. The present report also examines some basic questions regarding the recognition of disconformities and time planes in the Williston Basin subsurface.

Acknowledgments.—I am indebted to S.B. Anderson (North Dakota Geological Survey, retired) for lithostratigraphic data on some North Dakota wells. I am also grateful to my U.S. Geological Survey colleagues J.T. Dutro, Jr., T.W. Henry, J.A. Peterson, and B.R. Wardlaw for their helpful reviews of the manuscript.

DEVELOPMENT OF CURRENT CONCEPTS

A review of the evolution of stratigraphic concepts is useful for understanding current interpretations of the top of the Madison Group and of the origin of the Madison salt deposits. After a brief synopsis of the early history of Madison and Big Snowy nomenclature, the following discussion is focused on the classification, age, and geologic history of the upper part of the Madison and of the lower part of the Big Snowy in the Williston Basin subsurface. Although the present study deals mainly with data from Montana and North Dakota, studies in South Dakota, Saskatchewan, and Manitoba are included in the historical summary because they affected development of the stratigraphic classification in Montana and North Dakota.

LITHOSTRATIGRAPHIC CLASSIFICATION

EARLY HISTORY IN OUTCROP AREA

Current stratigraphic concepts and nomenclature originated in studies of Carboniferous rocks in the mountains of southwest and central Montana made at the end of the 19th century and in the early years of the 20th century (fig. 2). Subdivisions of Peale's (1893) Madison Formation by Weed

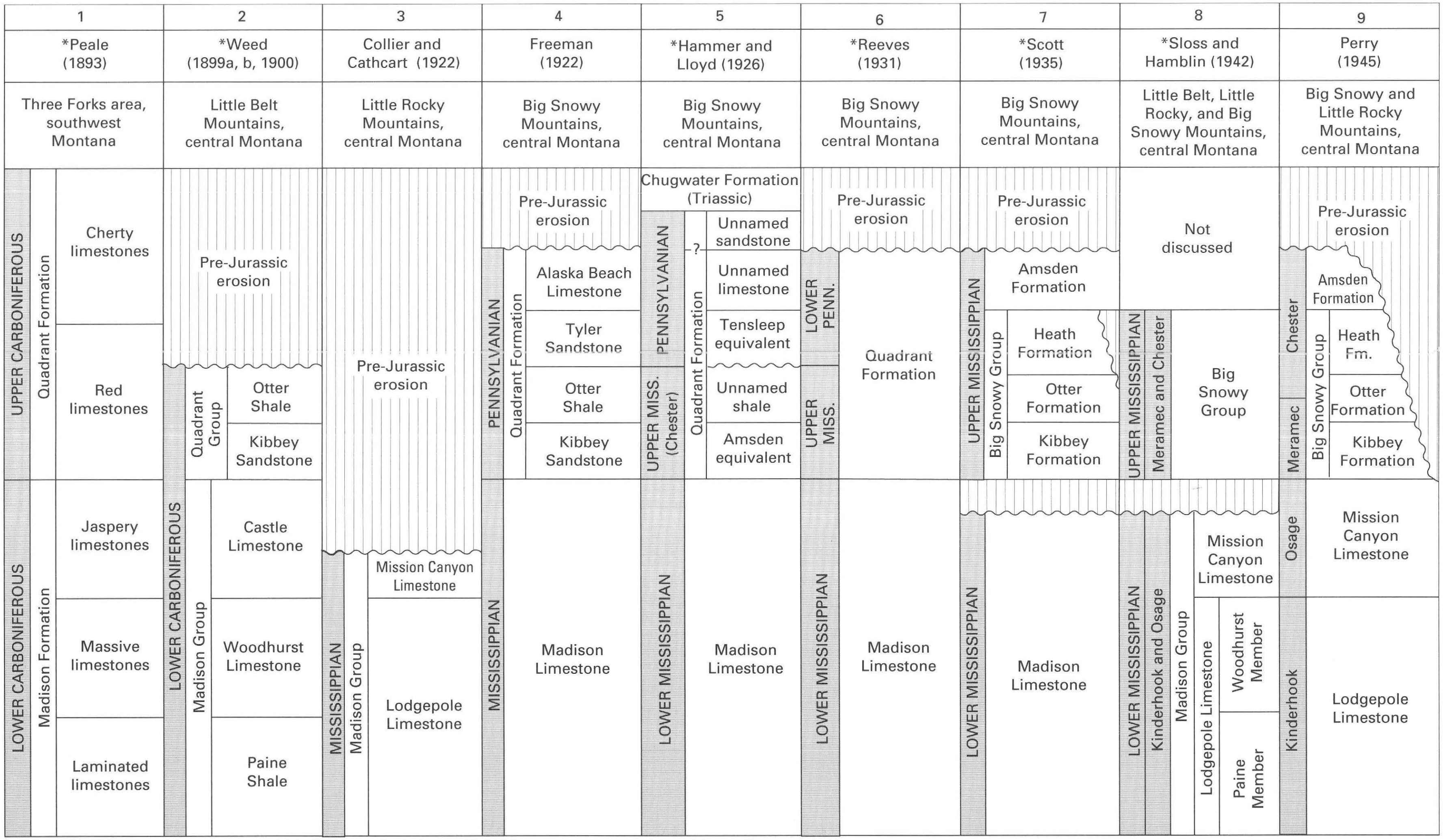


Figure 2. Evolution of lithostratigraphic classification and chronostratigraphy of Carboniferous rocks in central and southwestern Montana outcrop area prior to intensive deep drilling in Williston Basin. Chronostratigraphic units are shaded; vertical line pattern denotes hiatus; horizontal lines denote formation contacts (straight where conformable; wavy where disconformable or unconformable). Stratigraphic units are arranged in each column according to chronostratigraphy assigned by author(s) cited. Asterisk (*) marks reference in which fossils are described or discussed.

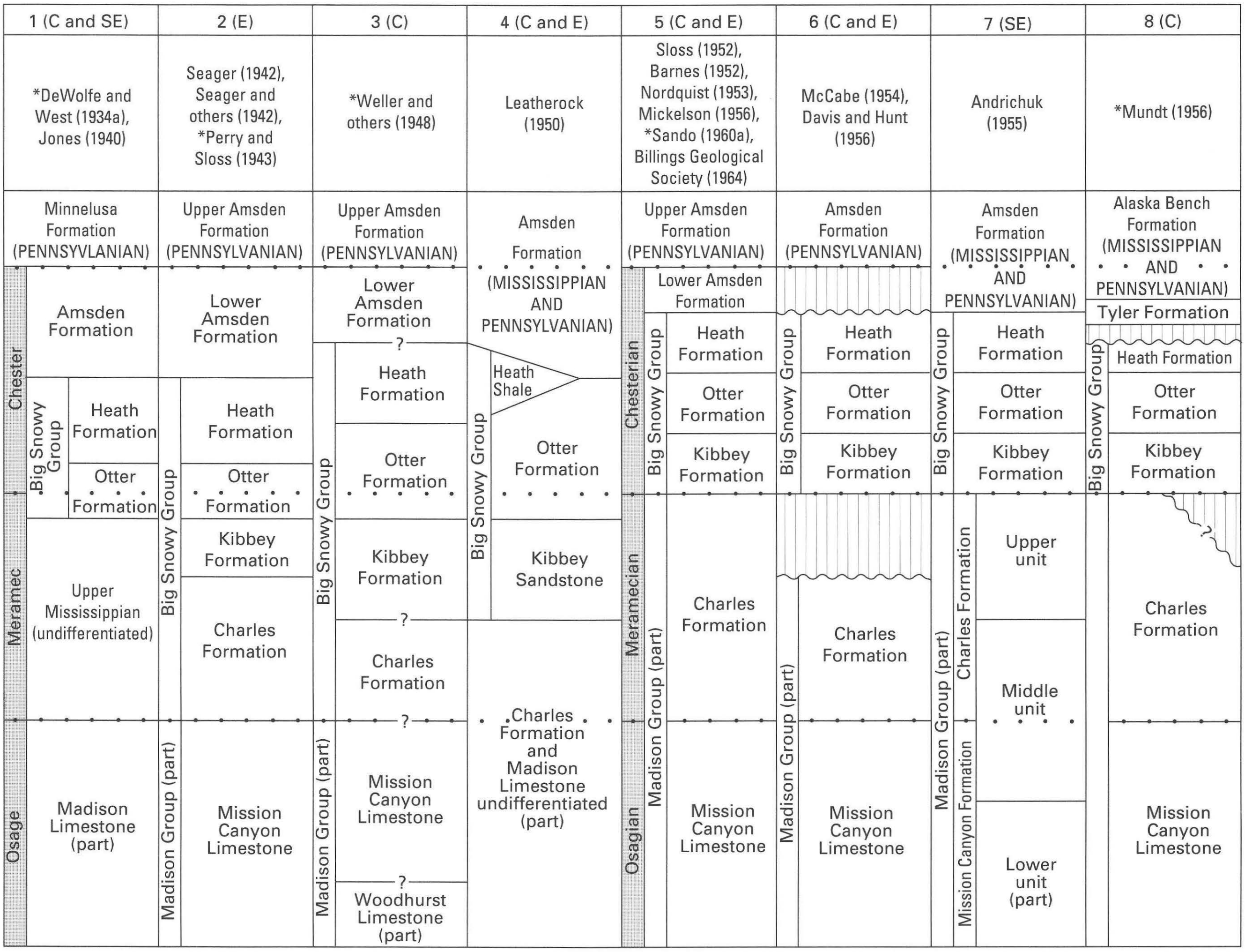
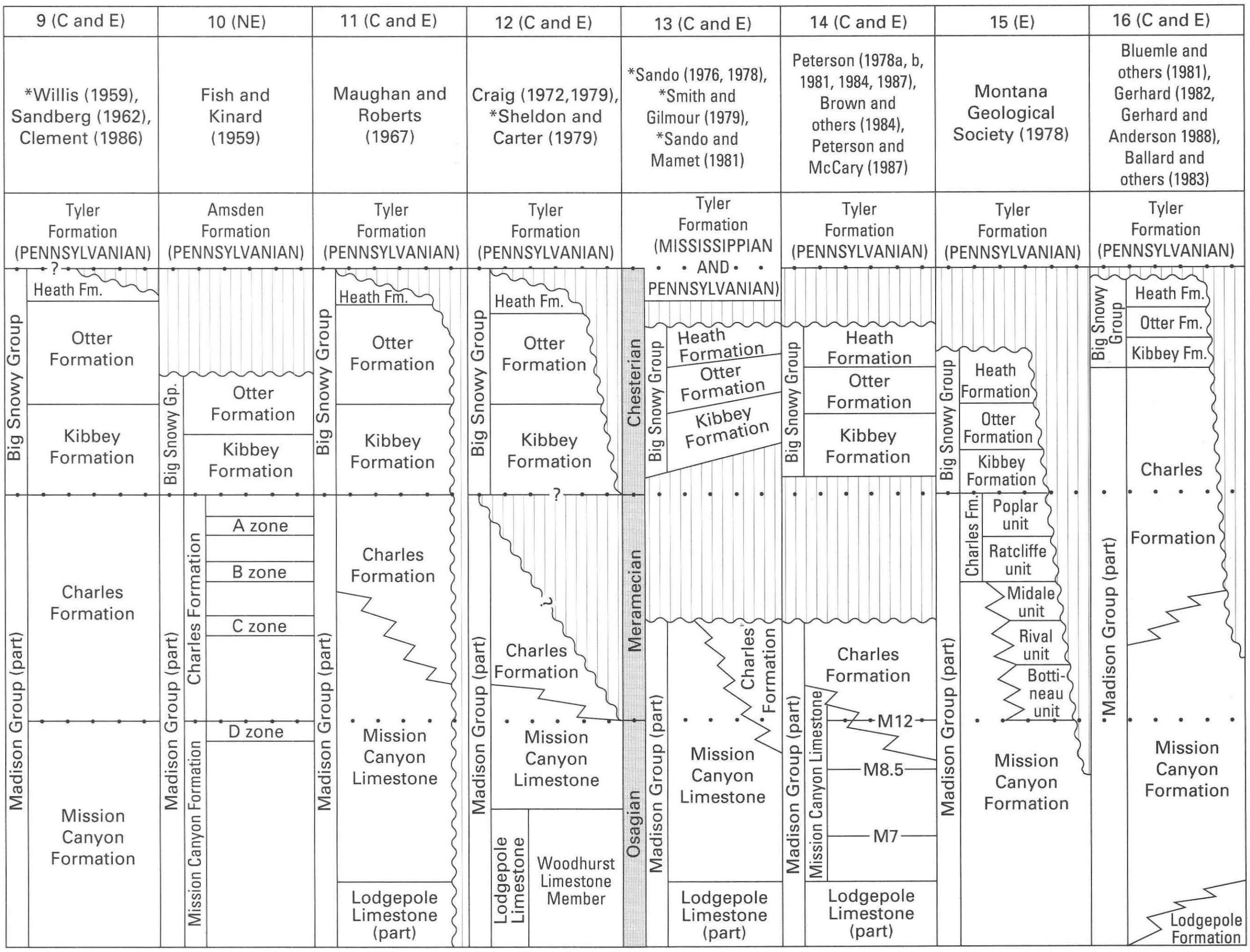


Figure 3 (above and facing page). Evolution of lithostratigraphic classification and chronostratigraphy of Osagean through Chesterian rocks and overlying formations in subsurface of Montana. Chronostratigraphic correlations in each column are those of the author(s) of that column or were determined by lithostratigraphic correlations to other columns. Mississippian provincial series are shaded. Base of diagram marks base of Osagean; other provincial series boundaries are marked by dots. Vertical line pattern denotes hiatus. Solid lines denote formation contacts (straight where conformable; wavy where disconformable or unconformable). Dashed lines denote boundaries of marker beds or marker-bed intervals. Asterisk (*) marks reference in which fossils are described or discussed.

(1899a, b, 1900) and Collier and Cathcart (1922) led ultimately to the classification of Sloss and Hamblin (1942), which served as a basis for all subsequent work on the Madison in Montana and North Dakota. The original Early Carboniferous assignment of the Madison was changed to Early Mississippian, and Kinderhookian and Osagean age equivalents were later recognized in it. The overlying Big Snowy Group (Scott, 1935) and its component formations evolved from subdivisions of Peale's (1893) Quadrant Formation by Weed (1899a, b, 1900), Hammer and Lloyd (1926), and Reeves (1931). The lower part of the Quadrant, originally thought to be of Late Carboniferous (Pennsylvanian) age, was reclassified as Late Mississippian. A regional disconformity was recognized at the top of the Madison, which was previously thought to be conformable with the overlying beds.

SUBSURFACE HISTORY

When petroleum companies first drilled deep test wells in 1935–1940 in the Williston Basin of eastern Montana, western North Dakota, and northeastern South Dakota, they encountered severe difficulties in correlating the subsurface Mississippian sequence with stratigraphic sequences exposed in the mountains of central Montana and western South Dakota, the closest areas of Mississippian outcrop (figs. 3–5). The first deep wells were drilled in the Porcupine dome and Cedar Creek anticline of southeastern Montana (fig. 1), where a thick, predominantly terrigenous sequence bearing Upper Mississippian fossils was found overlying Lower Mississippian carbonate rocks (fig. 3, col. 1). The subsurface Upper Mississippian rocks could not be correlated



into the Black Hills section in northeastern Wyoming and northwestern South Dakota, where the Pahasapa Limestone (Lower Mississippian, Madison equivalent) was overlain disconformably by the Minnelusa Formation (Pennsylvanian). Hence, the subsurface section was compared to sections in central Montana, where Scott (1935) (fig. 2, col. 7) had recently established the Upper Mississippian Big Snowy Group, which included the Kibbey, Otter, and Heath Formations, resting disconformably on the Lower Mississippian Madison Limestone. Scott also recognized the Amsden Formation (Upper Mississippian), whose type section was in the Bighorn Mountains of northern Wyoming, resting conformably and disconformably on the Big Snowy Group.

Another correlation problem arose when a deep test well drilled in 1937–1938 on the Nesson anticline in northwestern North Dakota revealed a thick sequence of limestone, dolomite, anhydrite, and halite between the Big Snowy Group and typical Madison Limestone (Kline, 1942, see also fig. 4, cols. 1, 2 of current report). This evaporitic sequence was also encountered in wells drilled in southeastern Montana (Mosby dome, Cedar Creek anticline) (fig. 3, col. 2), where Seager (1942) named it the Charles Formation, included in the Big Snowy Group. Stratigraphic limits of the Charles in its type well were defined by Perry and Sloss (1943, p. 1301, fig. 3) and redefined by Nordquist (1953, p. 79). Because the Charles Formation was not recognized in the outcrop area of Mississippian rocks in Montana, Wyoming, and South Dakota, it was thought to fill the erosional gap between the Madison and Big Snowy of outcrop. Hence, the Williston Basin sequence, unlike that of the outcrop area, was thought to represent continuous sedimentation through the Mississippian. These early lithostratigraphic concepts formed the basis for most later work on the Mississippian sequence, parts of which became major producers of petroleum, in the Williston Basin.

Perry and Sloss (1943) (fig. 3, col. 2; fig. 4, col. 2) presented a synthesis of the Mississippian stratigraphy of Montana and North Dakota and established lithologic criteria for recognizing the contact between the Madison and the Charles, which was causing some difficulty in the subsurface because of a gradation from normal marine limestone (Madison) into a carbonate and evaporite sequence (Charles). Lithogenetic similarity of the Charles Formation to the underlying Mission

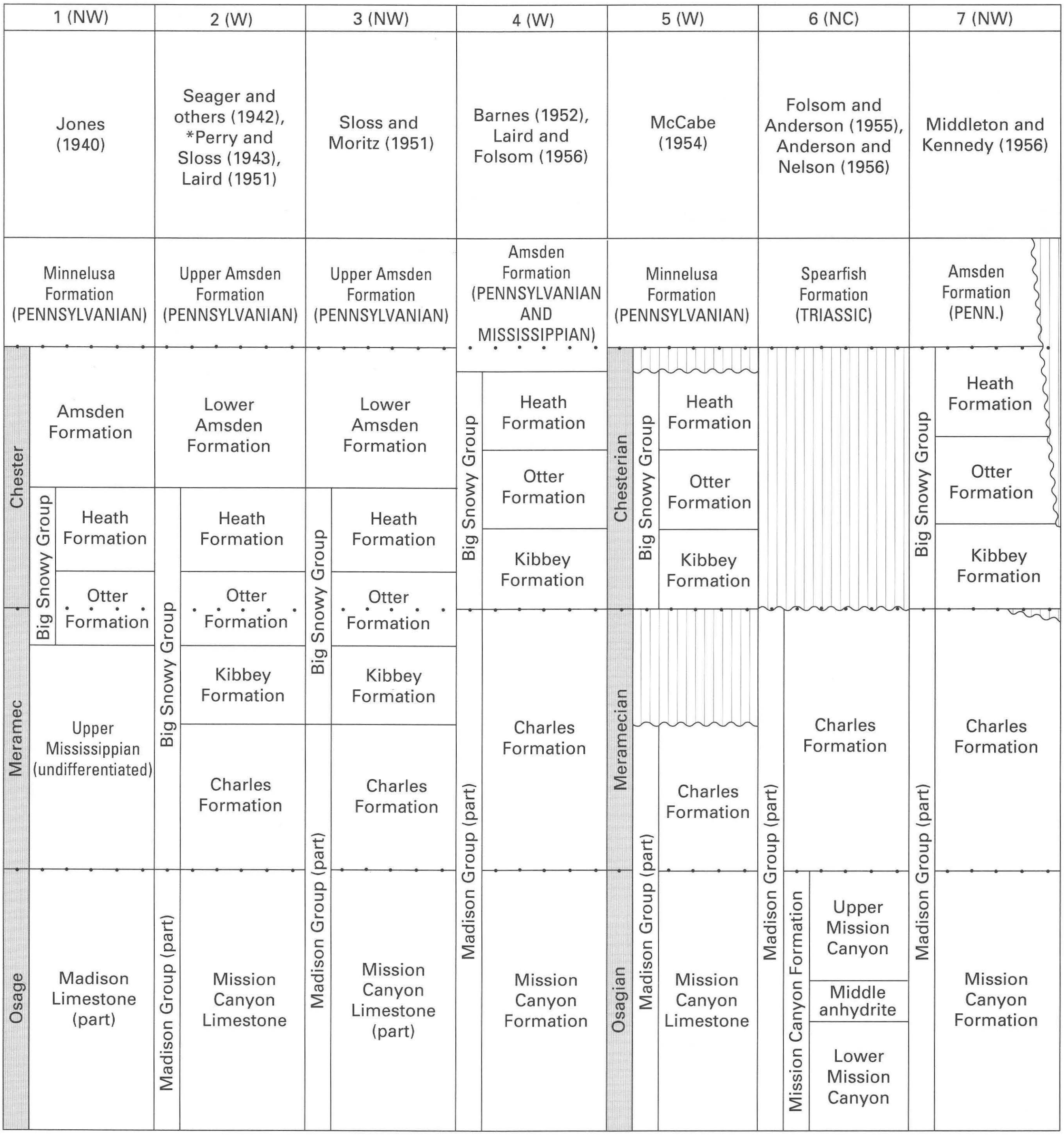
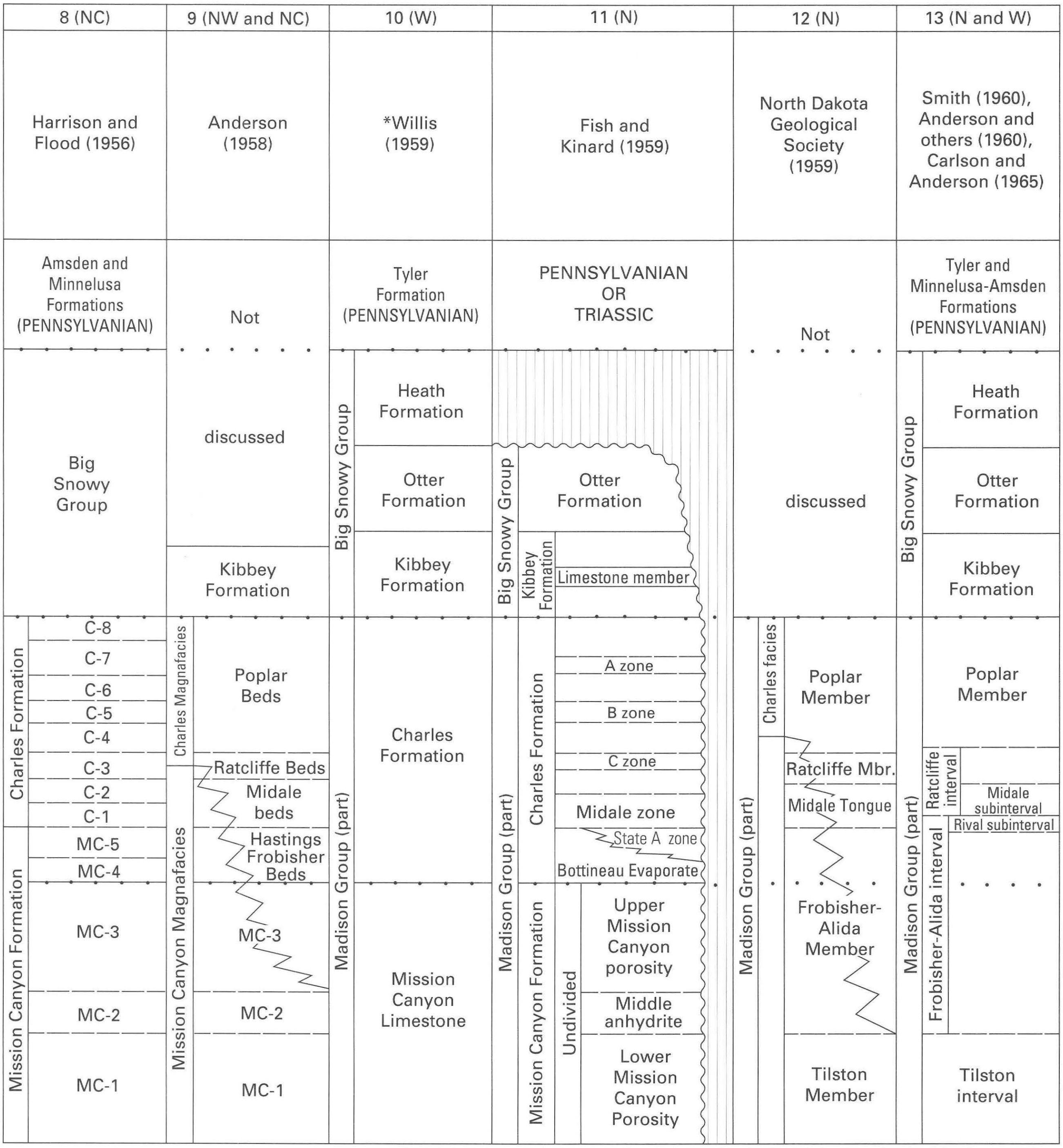
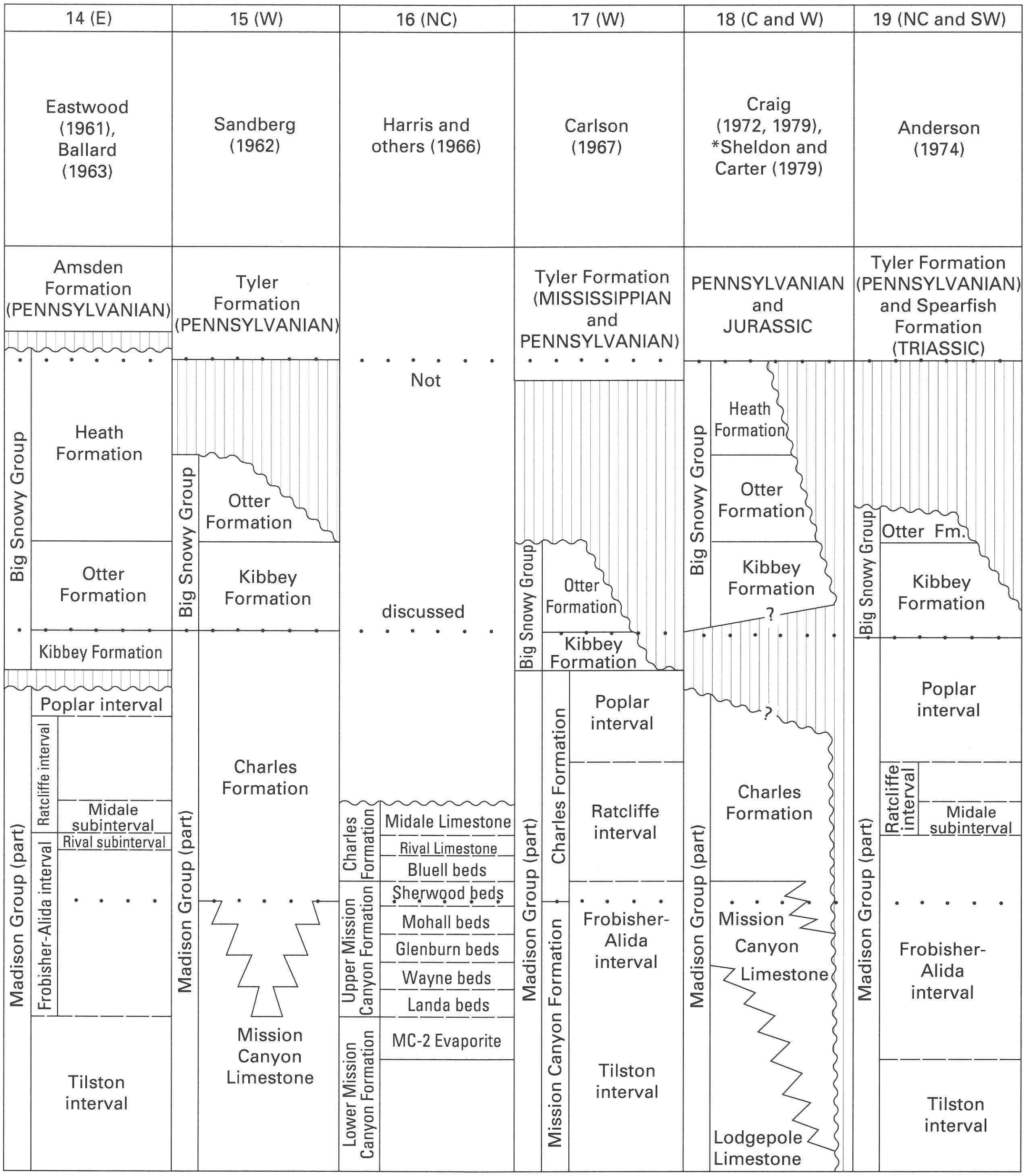
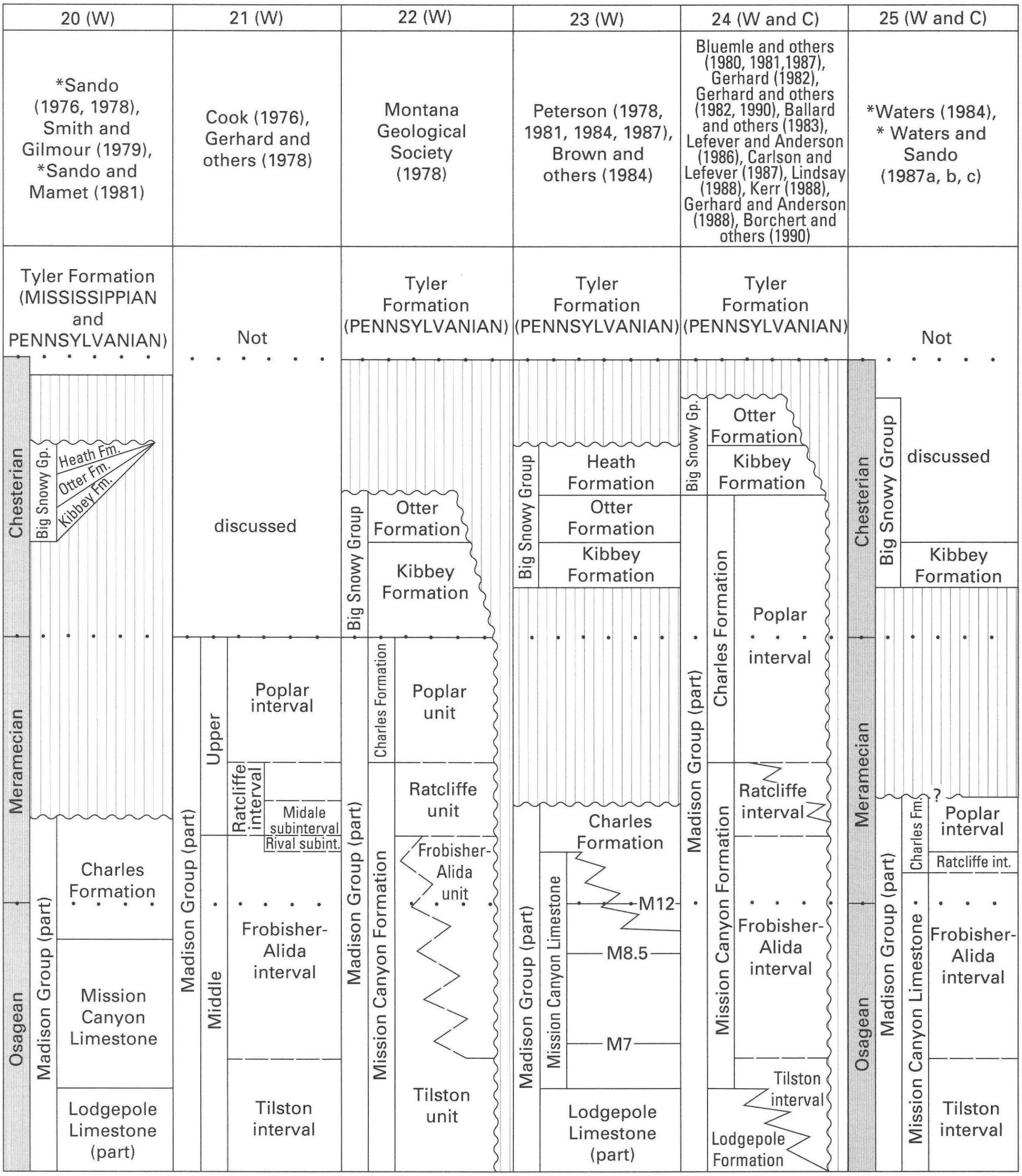


Figure 4. Evolution of lithostratigraphic classification and chronostratigraphy of Osagean through Chesterian rocks and overlying formations in subsurface of North Dakota. Chronostratigraphic correlations in each column are those of the author(s) of that column or were determined by lithostratigraphic correlations to other columns. Mississippian provincial series are shaded. Base of diagram marks base of Osagean; other provincial series boundaries are marked by dots. Solid lines denote formation contacts (straight where conformable; wavy where disconformable or unconformable). Dashed lines denote boundaries of marker beds or marker-bed intervals. Asterisk (*) marks reference in which fossils were described or discussed.


8 (NC)
Harrison and Flood (1956)
Amsden and Minnelusa Formations (PENNSYLVANIAN)
Big Snowy Group
Charles Formation
C-8
C-7
C-6
C-5
C-4
C-3
C-2
C-1
Mission Canyon Formation
MC-5
MC-4
MC-3
MC-2
MC-1
9 (NW and NC)
Anderson (1958)
Not
discussed
Kibbey Formation
Charles Magnafacies
Poplar Beds
Ratcliffe Beds
Midale beds
Hastings Frobisher Beds
Mission Canyon Magnafacies
MC-3
MC-2
MC-1
10 (W)
*Willis (1959)
Tyler Formation (PENNSYLVANIAN)
Big Snowy Group
Heath Formation
Otter Formation
Kibbey Formation
Madison Group (part)
Charles Formation
Mission Canyon Limestone
11 (N)
Fish and Kinard (1959)
PENNSYLVANIAN OR TRIASSIC
Big Snowy Group
Otter Formation
Kibbey Formation
Limestone member
Madison Group (part)
Charles Formation
A zone
B zone
C zone
Midale zone
State A zone
Bottineau Evaporate
Mission Canyon Formation
Undivided
Upper Mission Canyon porosity
Middle anhydrite
Lower Mission Canyon Porosity
12 (N)
North Dakota Geological Society (1959)
Not
discussed
Madison Group (part)
Charles facies
Poplar Member
Ratcliffe Mbr.
Midale Tongue
Frobisher-Alida Member
Tilston Member
13 (N and W)
Smith (1960), Anderson and others (1960), Carlson and Anderson (1965)
Tyler and Minnelusa-Amsden Formations (PENNSYLVANIAN)
Big Snowy Group
Heath Formation
Otter Formation
Kibbey Formation
Madison Group (part)
Poplar Member
Ratcliffe interval
Midale subinterval
Rival subinterval
Frobisher-Alida interval
Tilston interval


14 (E)
15 (W)
16 (NC)
17 (W)
18 (C and W)
19 (NC and SW)
Eastwood (1961), Ballard (1963)
Sandberg (1962)
Harris and others (1966)
Carlson (1967)
Craig (1972, 1979), *Sheldon and Carter (1979)
Anderson (1974)
Amsden Formation (PENNSYLVANIAN)
Tyler Formation (PENNSYLVANIAN)
Tyler Formation (MISSISSIPPIAN and PENNSYLVANIAN)
PENNSYLVANIAN and JURASSIC
Tyler Formation (PENNSYLVANIAN) and Spearfish Formation (TRIASSIC)
Not discussed
Big Snowy Group
Heath Formation
Otter Formation
Kibbey Formation
Otter Fm.
Madison Group (part)
Poplar interval
Ratcliffe interval
Midale subinterval
Rival subinterval
Frobisher-Alida interval
Tilston interval
Charles Formation
Mission Canyon Limestone
Charles Formation
Midale Limestone
Rival Limestone
Bluell beds
Upper Mission Canyon Formation
Sherwood beds
Mohall beds
Glenburn beds
Wayne beds
Landa beds
Lower Mission Canyon Formation
MC-2 Evaporite
Mission Canyon Formation
Lodgepole Limestone
?


20 (W)
21 (W)
22 (W)
23 (W)
24 (W and C)
25 (W and C)
*Sando (1976, 1978), Smith and Gilmour (1979), *Sando and Mamet (1981)
Cook (1976), Gerhard and others (1978)
Montana Geological Society (1978)
Peterson (1978, 1981, 1984, 1987), Brown and others (1984)
Bluemle and others (1980, 1981,1987), Gerhard (1982), Gerhard and others (1982, 1990), Ballard and others (1983), Lefever and Anderson (1986), Carlson and Lefever (1987), Lindsay (1988), Kerr (1988), Gerhard and Anderson (1988), Borchert and others (1990)
*Waters (1984), * Waters and Sando (1987a, b, c)
Tyler Formation (MISSISSIPPIAN and PENNSYLVANIAN)
Not
Tyler Formation (PENNSYLVANIAN)
Tyler Formation (PENNSYLVANIAN)
Tyler Formation (PENNSYLVANIAN)
Not
Chesterian
Big Snowy Gp.
Heath Fm.
Otter Fm.
Kibbey Fm.
discussed
Big Snowy Group
Otter Formation
Kibbey Formation
Big Snowy Group
Heath Formation
Otter Formation
Kibbey Formation
Big Snowy Gp.
Otter Formation
Kibbey Formation
Chesterian
Big Snowy Group
discussed
Kibbey Formation
Meramecian
Madison Group (part)
Charles Formation
Upper
Poplar interval
Ratcliffe interval
Midale subinterval
Rival subint.
Madison Group (part)
Charles Formation
Poplar unit
Ratcliffe unit
Frobisher-Alida unit
Madison Group (part)
Charles Formation
Poplar interval
Ratcliffe interval
Meramecian
?
Charles Fm.
Poplar interval
Ratcliffe int.
Osagean
Madison Group (part)
Mission Canyon Limestone
Lodgepole Limestone (part)
Middle
Frobisher-Alida interval
Tilston interval
Mission Canyon Formation
Tilston unit
Madison Group (part)
Mission Canyon Limestone
Charles Formation
M12
M8.5
M7
Lodgepole Limestone (part)
Mission Canyon Formation
Frobisher-Alida interval
Tilston interval
Lodgepole Formation
Osagean
Madison Group (part)
Mission Canyon Limestone
Frobisher-Alida interval
Tilston interval

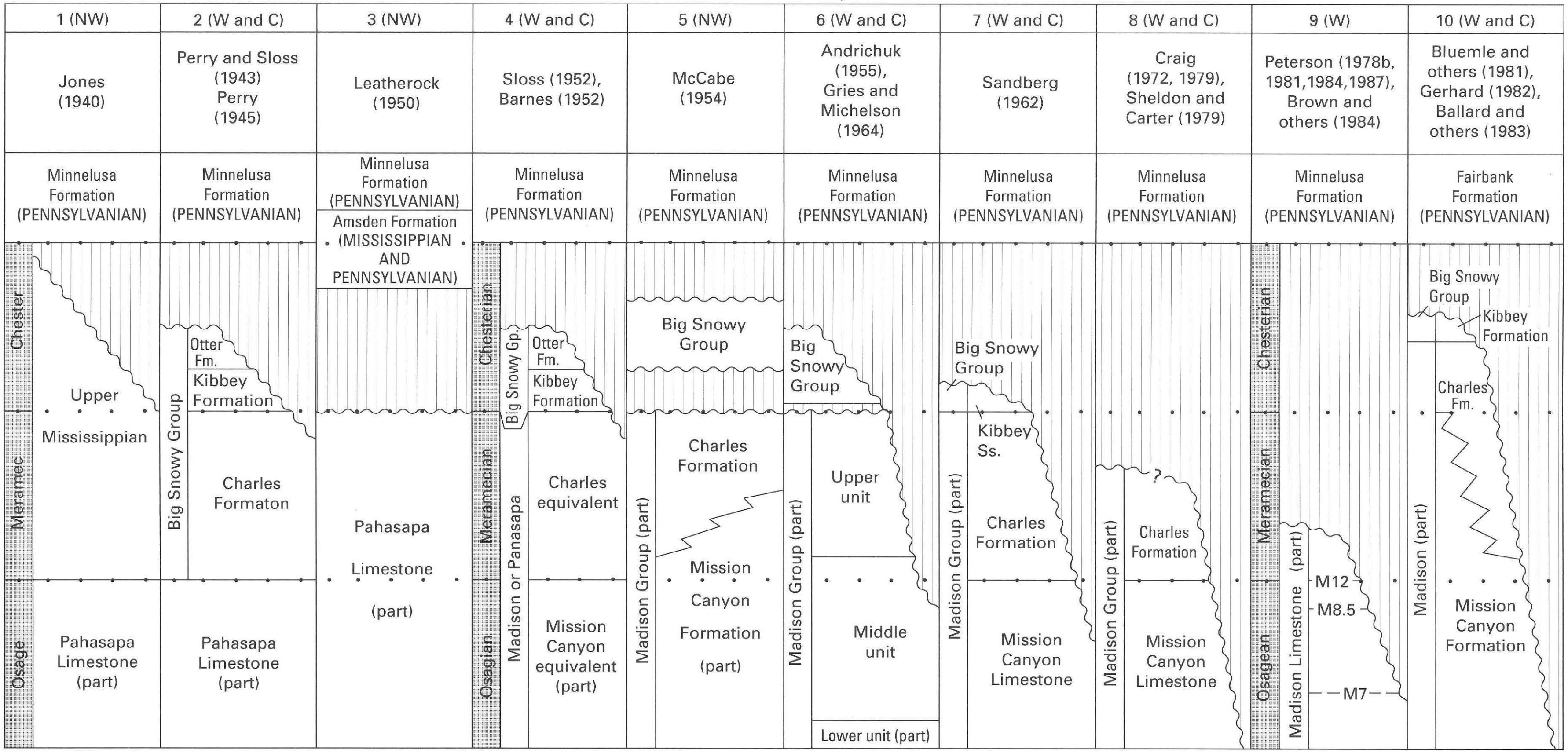


Figure 5. Evolution of lithostratigraphic classification and chronostratigraphy of Osagean through Chesterian rocks and overlying formations in subsurface of South Dakota. Chronostratigraphic correlations in each column are those of the author(s) of that column or were determined by lithostratigraphic correlations to other columns. Mississippian provincial series are shaded. Base of diagram marks base of Osagean; other provincial series boundaries are marked by dots. Vertical line pattern denotes hiatus. Solid lines denote formation contacts (straight where conformable; wavy where disconformable or unconformable). Dashed lines denote boundaries of marker beds or marker-bed intervals. Asterisk (*) marks reference in which fossils are described or discussed.

Canyon Formation led to the removal of the Charles from the Big Snowy Group and its recognition as the uppermost formation of the Madison Group in the subsurface (see fig. 3, cols. 4, 5; fig. 4, col. 4; fig. 5, col. 4). The classification of Perry and Sloss was used in Montana and North Dakota well into the 1950's (see fig. 3, cols. 3–9; fig. 4, cols. 3–7).

As more successful Madison wells were drilled in northeast Montana and northwest North Dakota and across the international boundary in adjacent Saskatchewan (fig. 6) and Manitoba (fig. 7), the need for a finer stratigraphic classification increased, particularly in the Mission Canyon and Charles Formations where most of the producing zones were found. Generally, the base of the Charles was placed at the base of the lowest evaporite encountered in the sequence, but geologists working in oil fields began to use local lithic marker horizons based on prominent, stratigraphically consistent deflections on mechanical, gamma ray-neutron, and gamma ray-sonic logs caused by thin layers of clay, silt, and sand (Cumming and others, 1959) to correlate adjacent well sections (fig. 3, col. 10; fig. 4, col. 8; fig. 6, col. 4; fig. 7, col. 1). As correlations became more dependent on lithic marker beds, the stratigraphic inconsistency of the Mission Canyon–Charles boundary became more apparent, and these traditional rock units were regarded as time-transgressive facies (Porter, 1955) (fig. 3, col. 10; fig. 4, col. 9; fig. 6, col. 5; fig. 7, col. 2). A system of named, but informal, lithic-marker-defined intervals was established by the Saskatchewan Geological Society (1956) (fig. 6, col. 6) and the North Dakota Geological Society (1959) (fig. 6, col. 7; fig. 4, col. 12) for correlations across the international boundary during the late 1950's, and this system was adopted by the North Dakota Geological Survey in the early 1960's (fig. 4, col. 13). Geologists working in Montana continued using the traditional Mission Canyon and Charles concepts but recognized the boundary between them as time-transgressive, until late in the 1970's, when the Montana Geological Society (1978) adopted the Saskatchewan and North Dakota system of named lithic-marker-defined units (fig. 3, col. 15; fig. 4, col. 22).

The system of named lithic-marker-defined intervals, with various minor modifications, prevailed into the 1960's and 1990's in Saskatchewan (fig. 6, col. 13), Manitoba (fig. 7, col. 4), and North Dakota (fig. 4, col. 24), whereas the marker-bed classification was not used generally in Montana (fig. 3, col. 16) and South Dakota (fig. 5, col. 10). J.A. Peterson (U.S. Geological Survey) presented a synthesis of subsurface Madison lithostratigraphy based on marker horizons without named intervals in Montana (fig. 4, col. 23), South Dakota (fig. 5, col. 9), and North Dakota (fig. 4, col. 23) in the 1980's.

The current lithostratigraphic classification and correlation of rock units between wells by means of physical log deflections has served the petroleum industry extremely well in the Williston Basin of the United States and Canada. By 1990, Saskatchewan had produced 1 billion barrels of oil (BBO), followed by North Dakota (840 million barrels of oil (MBO)), Montana (622 MBO), Manitoba (166 MBO), and South Dakota (16.5 MBO), for a grand total of more than 2.5 BBO mainly from Mississippian reservoirs (Gerhard and others, 1990, p. 507). Despite this excellent record of success in oil-finding, currently popular interpretations of the temporal relationships of the upper part of the Madison Group to coeval sedimentary rocks outside the Williston Basin are controversial, and this controversy about temporal relationships has a major effect on interpretations of the regional depositional history of the Mississippian System in the Western Interior region.

CHRONOSTRATIGRAPHY

Parts of the Mission Canyon Limestone and of the Big Snowy Group contain moderately rich marine invertebrate faunas in the mountains of central and southwest Montana, where the subsurface lithostratigraphic classification originated (fig. 2). Hence, much of the rock sequence included in these original lithostratigraphic units is well suited for determination of geologic age and correlation by traditional paleontologic methods. The Charles Formation, known certainly only in the subsurface, is less fossiliferous because it represents a restricted sedimentary facies characterized mostly by dolomite, anhydrite, and salt.

In recent years, the distribution of corals, foraminifers, and conodonts has been used extensively to zone and correlate Mississippian rocks in the Western Interior region (Sando, 1985) (fig. 8). In the following discussion, MFZ refers to foraminiferal zones of B.L. Mamet (*in* Mamet and Skipp, 1970a, b) and CZ refers to composite biozones of Sando (1985).

The precise position of the Osagean-Meramecian boundary in the Western Interior region is controversial, owing to differences of opinion regarding the ranges of foraminifers and conodonts in the type area of the Mississippian System (compare Mamet and Skipp, 1970a, b, with Brenckle and others, 1974, 1982). In this report, the Osagean-Meramecian boundary is placed between MFZ 9=CZ 11 and MFZ 10=CZ 12, a horizon that is well established on corals and foraminifers throughout the Western Interior region of the United States and Canada (Sando and Bamber, 1985).

MISSION CANYON LIMESTONE

Early studies of fossils from the Madison Limestone by C.D. Walcott (*in* Peale, 1893, p. 34–39), Charles Schuchert (*in* Weed, 1900, p. 293), and G.H. Girty (*in* Reeves (1931, p. 144) resulted in an age assignment of Early Carboniferous or Mississippian for the formation or group in southwest and central Montana. Sloss and Hamblin (1942, p. 311, 313) discussed the meager faunal studies available for dating the

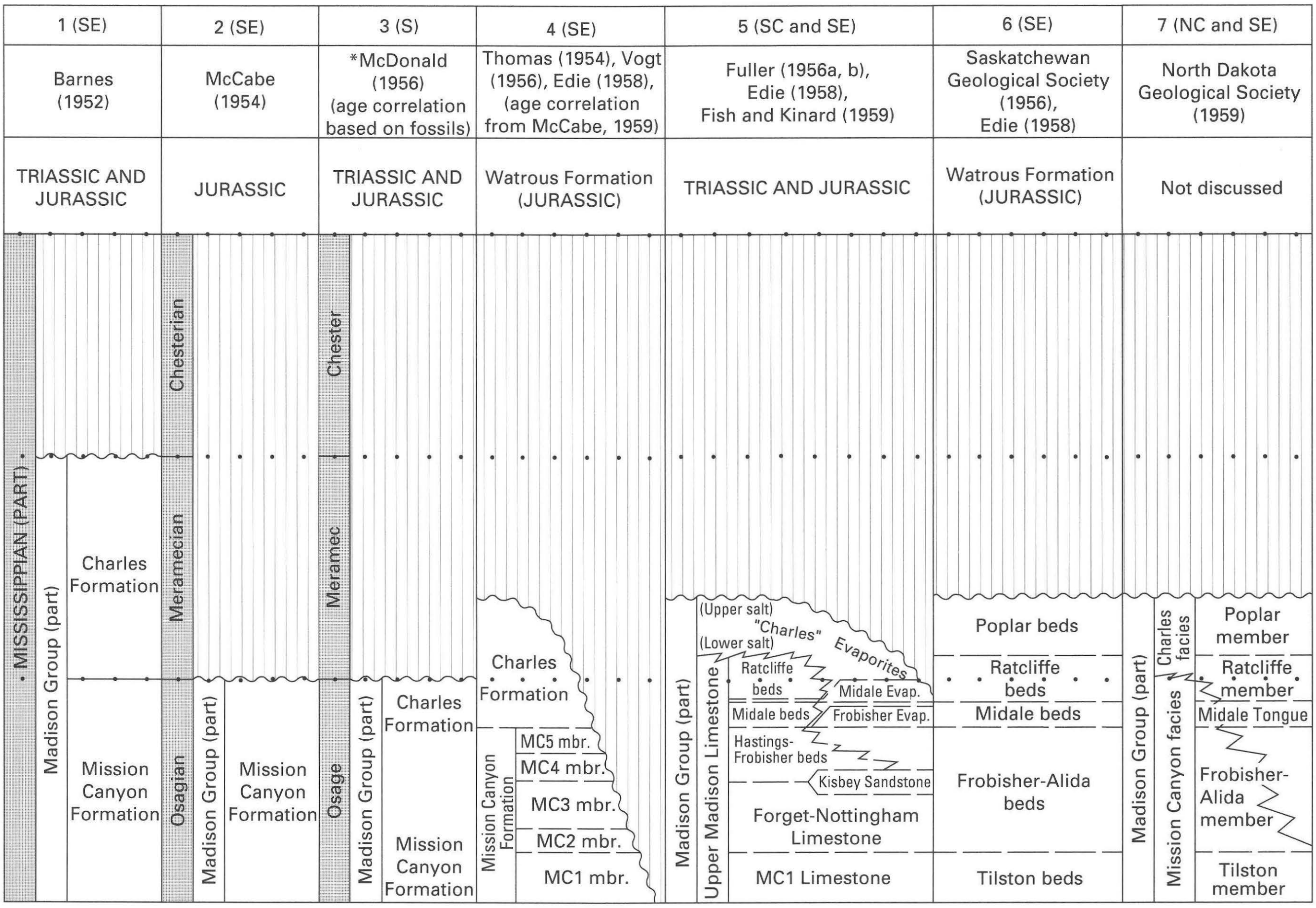
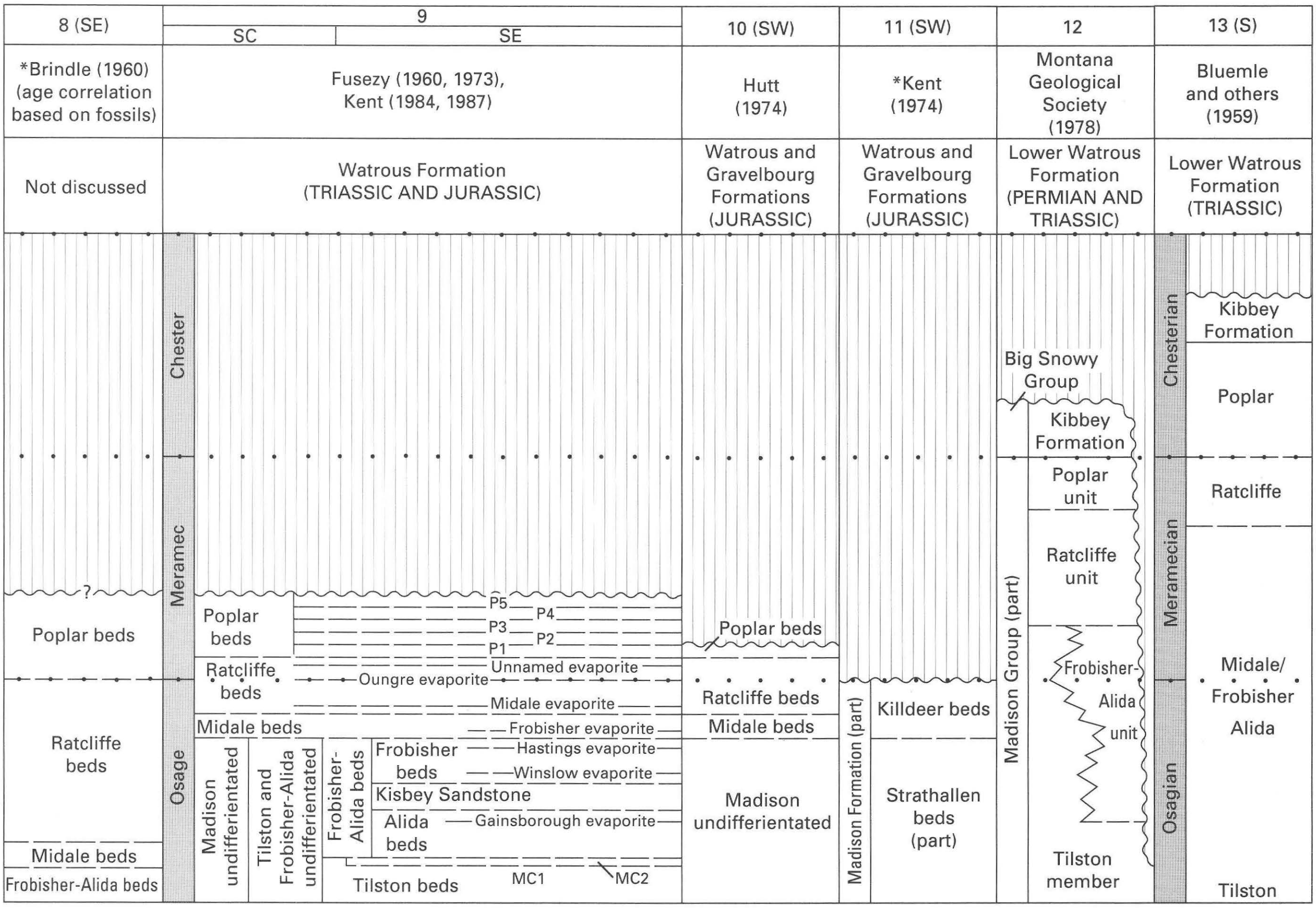


Figure 6 (above and facing page). Evolution of lithostratigraphic classification and chronostratigraphy of Osagean through Chesterian rocks and overlying formations in subsurface of Saskatchewan. Chronostratigraphic correlations in each column are those of the author(s) of that column or were determined by lithostratigraphic correlations to other columns. Mississippian provincial series are shaded. Base of diagram marks base of Osagean; other provincial series boundaries are marked by dots. Vertical line pattern denotes hiatus. Solid lines denote formtion contacts (straight where conformable; wavy where disconformable or unconformable). Dashed lines denote boundaries of marker beds or marker-bed intervals. Asterisk (*) marks reference in which fossils are described or discussed.

Madison and concluded that the group included both "Kinderhook" and "Osage" equivalents, but they did not date the Mission Canyon Limestone specifically, and they left open the possibility that beds of Late Mississippian age might be present in its upper part. Perry (1945, correlation chart) showed the age of the Mission Canyon Limestone as "Osage," overlying beds of "Kinderhook" age in the Lodgepole Limestone in central Montana, but he did not discuss the basis for these age assignments. James Steele Williams (*in* Weller and others, 1948, chart 5, cols. 39, 40, p. 139) showed the Mission Canyon Limestone as Osagean and the underlying Lodgepole Limestone as Kinderhookian and Osagean, but he did not discuss the faunal evidence for these age assignments. Williams (*in* Weller and others, 1948, p. 138–139) noted that, although many paleontologists had studied collections of fossils from the Madison, no consensus had been reached on detailed correlations with the Mississippi Valley section. Fossils from the Madison in two well cores in eastern Montana were not diagnostic for detailed correlation (A.H. Sutton *in* DeWolfe and West, 1939a, p. 472, 473). Peter Harker (*in* MacDonald, 1956, p. 27) studied marine invertebrates from well cores in the Mission Canyon of Saskatchewan and suggested that the fauna had "a Kinderhook and Osage aspect," but he was unable to make positive specific identifications of the fossils. These tentative age assignments based on limited faunal data formed the basis for the Osagean age assigned to the Mission Canyon Limestone in the subsurface of the Williston Basin by most geologists into the early 1950's (figs. 3–7).

Detailed biostratigraphic studies of corals, brachiopods, foraminifers, and conodonts from the Madison Group in central and southwest Montana beginning in the 1960's (Sando, 1960a, 1976; Sando and Dutro, 1960, 1974; Sando and others, 1969; Gutschick and others, 1980; Sando and Bamber, 1984, 1985) provide a sound basis for determining an Osagean (MFZ 8–9=CZ 10–11) and early Meramecian age



(MFZ 10–11=CZ 12–13) for the Mission Canyon Limestone of outcrop area. Studies of corals, brachiopods, and foraminifers from well cores in eastern Montana (Sando, 1960b, 1978; Sando and Mamet, 1981), southern Saskatchewan (MacDonald, 1956; Brindle, 1960; Kent, 1974), and western and central North Dakota (Sando, 1978; Sando and Mamet, 1981; Waters, 1984; Waters and Sando, 1987a–c) indicate that the subsurface Mission Canyon has approximately the same age range as it does in the outcrop area (fig. 3, cols. 5, 13; fig. 6, cols. 3, 8; fig. 4, col. 20). These paleontologic constraints on the age of the Mission Canyon Limestone were accepted in recent subsurface studies by members of the U.S. Geological Survey in Montana (fig. 3. col. 14) and North Dakota (fig. 4, col. 23) but were ignored by other geologists in Montana (fig. 3, cols. 15, 16), North Dakota (fig. 4, cols. 21, 22, 24), and Saskatchewan (fig. 6, cols. 12, 13), who extended the age of the Mission Canyon into younger Meramecian without explanation of the basis for their age determinations.

KIBBEY FORMATION

The Kibbey Formation is mainly red-weathering quartz sandstone, siltstone, and shale that disconformably overlie the Mission Canyon Limestone and form the basal unit of the Big Snowy Group in the mountains of southwest and central Montana (fig. 2). The Kibbey was traced into the subsurface of eastern Montana (fig. 3), western North Dakota (fig. 4), and western South Dakota (fig. 5), where most geologists believe that it rests conformably on the Charles Formation and where it includes a medial limestone and anhydrite unit (Ray Member of Rawson, 1968, 1969).

Fossils are very rare in the Kibbey Formation. Easton (1962, p. 11) reported fragmentary, unidentifiable brachiopods and ostracodes in strata questionably referred to the formation at Durfee Creek in central Montana, and Rawson (1968, p. 45; 1969, p. 167) recorded unidentified fragments of brachiopods, crinoids, and ostracodes from the Ray Member in the subsurface. Maughan (1984, p. 183) noted that B. Skipp identified "late Meramecian fossils in southwest Montana" from the Kibbey, but he gave no details of the occurrence. B.R. Wardlaw (*in* Sando and others, 1985, p. 7) reported middle or upper Meramecian (CZ 15–19) conodonts in the lower part of the formation at Bell Canyon in the Tendoy Mountains, extreme southwestern Montana, where the Kibbey rests conformably on the McKenzie Canyon Formation (lower Meramecian, MFZ 12=CZ 14). These conodonts, which consist of a few specimens of *Hindeodus penescitulus* in sample W82–135, 41 ft (12.5 m) above the

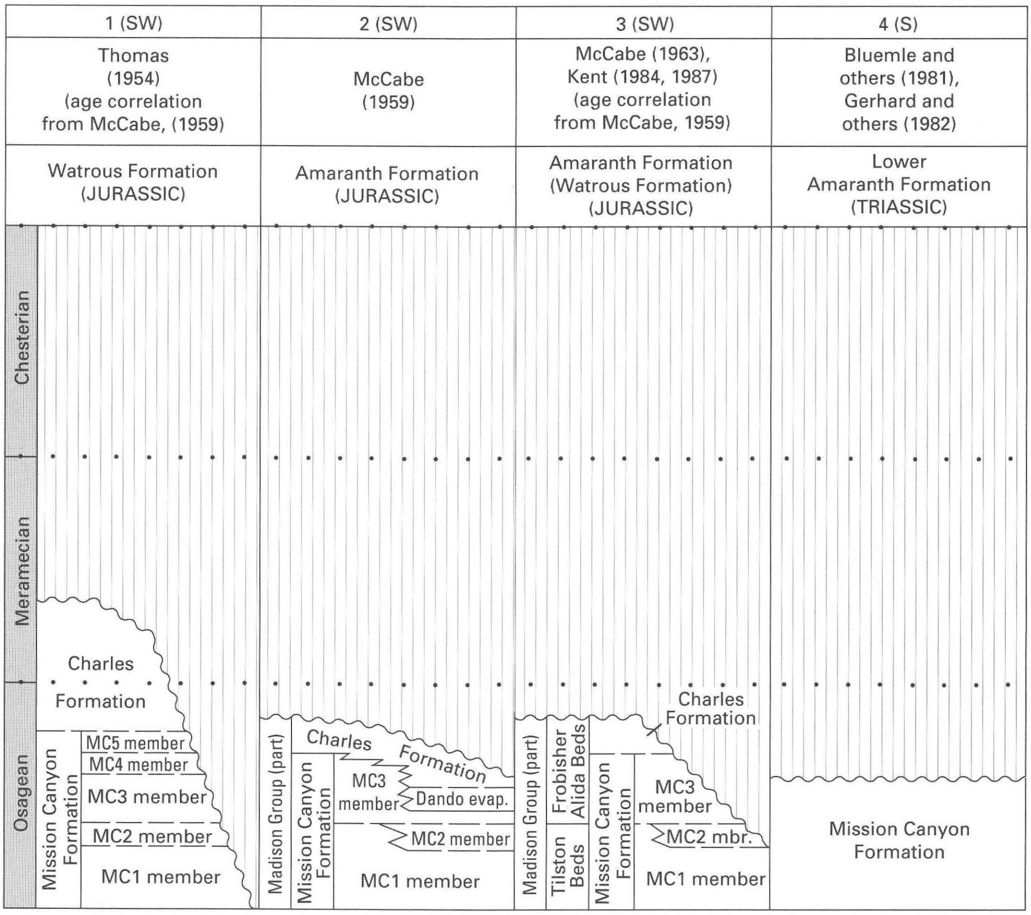


Figure 7. Evolution of lithostratigraphic classification and chronostratigraphy of Osagean through Chesterian rocks and overlying formations in subsurface of Manitoba. Chronostratigraphic correlations in each column are those of the author(s) of that column or were determined by lithostratigraphic correlations to other columns. Mississippian provincial series are shaded. Base of diagram marks base of Osagean; other provincial series boundaries are marked by dots. Vertical line pattern denotes hiatus. Solid lines denote formation contacts (straight where conformable; wavy where disconformable or unconformable). Dashed lines denote boundaries of marker beds or marker-bed intervals. Asterisk (*) marks reference in which fossils were described or discussed.

base of the Kibbey (B.R. Wardlaw, oral commun., 1993), were incorporated in Wardlaw's (1985) transgressive models for the Upper Mississippian and Lower Pennsylvanian rocks of Montana and Wyoming.

Most geologists dated the Kibbey in the subsurface as late Meramecian or early Chesterian by bracketing the formation between the presumed Meramecian or Chesterian Otter Formation overlying the Kibbey and the presumed Meramecian Charles Formation beneath it (figs. 3–5). This dating depended on variable interpretations of the age of the fossils in the Otter Formation and variable interpretations of the age of the Charles Formation made without paleontologic evidence. Some of this dating involved circular reasoning because the age of the Kibbey was also used as a constraint on the age of the Charles Formation. Interpretations of the Kibbey as early Chesterian by members of the U.S. Geological Survey (fig. 3, col. 14; fig. 4, col. 23) and by other geologists as middle or late Chesterian (fig. 3, col. 16; fig. 4, col. 24; fig. 5, col. 10) are the latest published opinions on the age of the formation in the Williston Basin subsurface.

Ostracodes from the uppermost beds of the Otter Formation were regarded by Scott (1942, p. 153) as "most similar to middle and upper Chester faunas." Conodonts from the type Otter Formation at Belt Creek (Gilmour, 1989, p. 32) indicate that the Meramecian-Chesterian (CZ 19/20) boundary is in the lower half of the Otter and that the Kibbey

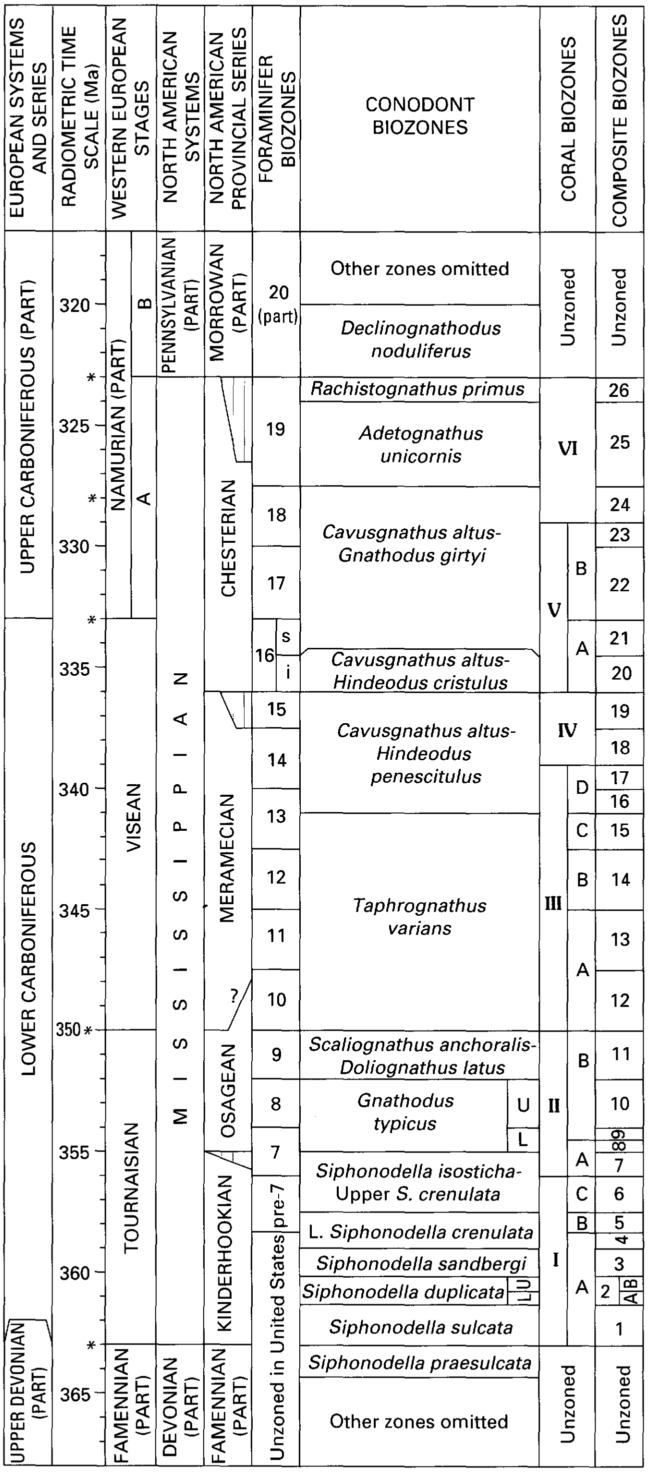


Figure 8. Radiometrically calibrated Western Interior Mississippian biozonations. Modified from Sando (1985, fig. 3). Asterisks in radiometric scale mark radiometric check points from Harland and others (1990). Vertical lines in series column denote hiatus. See Sando (1985) for sources of biozonations.

Formation is no younger than late Meramecian (CZ 19) in central Montana (table 1). The youngest paleontologically dated strata in the underlying Mission Canyon Limestone in central Montana are of early Meramecian age (MFZ 10=CZ 12, Monarch–U.S. 60 section, Sando and Dutro, 1974, pl. 1, col. 2). Hence, the *possible* age range of the Kibbey in its type area in central Montana, based solely on paleontologic constraints, is early Meramecian (MFZ 10=CZ 12) to latest Meramecian (MFZ 15=CZ 19).

Determination of the precise age of the Kibbey in central Montana requires accounting for the amount of time represented by the hiatus between the Kibbey and the underlying Mission Canyon Limestone. Data on the karst event that produced the hiatus in Wyoming and Montana indicate that deposition of the Madison Limestone or Group continued into latest early Meramecian time (MFZ 12=CZ 14) and was followed by retreat of the sea from the Cordilleran shelf to the Antler foreland basin to the west (Sando, 1988).

A Late Mississippian transgressive model based on bio- and lithostratigraphy (Sando and others, 1975, p. A54–A66) depicts the Kibbey Formation as the basal phase of a transgressive lobe that moved eastward across the Cordilleran platform in Montana slightly earlier than another transgressive lobe represented by the Amsden Formation in Wyoming. In Wyoming the transgression continued into the Pennsylvanian, whereas in Montana the transgression was more rapid and was terminated by uplift and erosion during latest Chesterian (MFZ 19=CZ 25–26) time. Recent conodont dating of the Kibbey Formation in southwestern Montana and of the lower part of the Otter Formation in central Montana (Wardlaw, 1985, *in* Gilmour, 1989) suggests that transgression of the Kibbey across Montana was even more rapid than postulated by Sando and others (1975). Eastward projection of the base of the Kibbey based on the new evidence suggests that the formation is probably of early Chesterian (CZ 20–21) age at its eastern limit in the subsurface of North Dakota.

CHARLES FORMATION

No fossils were reported from the Charles Formation when it was first described from a well core in southeastern Montana (Seager, 1942), although some of the fossils listed earlier by Sutton (*in* DeWolfe and West, 1939a, p. 472–475) from cores in the Baker-Glendive anticline near the eastern boundary of the State probably were from the sequence later referred to the formation. MacDonald (1956, p. 30) was unable to identify fossils found in cores of the Charles Formation in Saskatchewan. Fossils, mostly brachiopods, from cores of the Charles Formation in Montana were considered by J. Steele Williams, J.E. Smedley, and Mackenzie Gordon,

Table 1. Conodont faunules (in ascending order) from approximate type section of the Otter Formation at Belt Creek in sec. 11, T. 17 N., R. 6 E., Little Belt Mountains, Cascade County, central Montana.

[Identified by B. R. Wardlaw (written commun., 1993) in collections made by Gilmour (1989). See also Easton (1962, p. 114, pl. 14) for measured section. Conodont and composite zones are shown in figure 8. USGS numbers (–PC) refer to the Late Paleozoic Locality file of U.S. Geological Survey at National Center, Reston, Va.]

USGS collection number (–PC)	Feet (meters) above base of Gilmour section	Feet (meters) above base of Otter Formation	Conodont assemblage	Conodont zone	Composite zone
30003	14.4 (4.4)	56.4 (17.1)	*Hindeodus spiculus?*	*Cavusgnathus altus–Hindeodus penescitulus*	19
30004	19.5 (5.9)	61.5 (18.6)	*Cavusgnathus altus, Hindeodus scitulus, H. spiculus*	*Cavusgnathus altus–Hindeodus cristulus*	20
30005	24.3 (7.4)	66.3 (20.1)	*Cavusgnathus altus, Hindeodus cristulus*	*Cavusgnathus altus–Hindeodus cristulus*	20
30006	25.5 (7.7)	67.5 (20.5)	*Cavusgnathus altus, Hindeodus* sp.	*Cavusgnathus altus Hindeodus cristulus*	20
30007	34.0 (10.3)	76.0 (23.0)	*Cavusgnathus altus, Hindeodus cristulus, H. spiculus*	*Cavusgnathus altus–Hindeodus cristulus*	20

Jr., as very similar to or identical with fossils in the Mission Canyon Limestone (Lower Mississippian) of outcrop (Gardner, 1959, p. 332).

Early dating of the Charles as encompassing all of Meramecian time (fig. 3, cols. 2–11; fig. 4, cols. 2–4, 6–17; fig. 5, cols. 2, 4, 5, 7) was based on the premise that the formation represents continuous sedimentation from the top of the Mission Canyon Limestone (Osagean) to the base of the Kibbey Formation (Chesterian), thus filling the time gap postulated between these formations in the outcrop area. Restriction of the Charles to the subsurface Williston Basin was thought to indicate that this basin was a depositional feature in which sedimentation was continuous through Mississippian time, in contrast to the surrounding outcrop area in which uplift and erosion of the basin margin had interrupted deposition between Mission Canyon and Kibbey times. These paleotectonic and depositional concepts were maintained into recent years by many Williston Basin geologists (fig. 3, cols. 15, 16; fig. 4, cols. 21, 22, 24; fig. 5, col. 10; fig. 6, cols. 12, 13). Early dissent from the prevailing view was registered by W.S. McCabe (1954) and Davis and Hunt (1956) (fig. 3, col. 6; fig. 4; col. 5; fig. 5, col. 5), who postulated an unconformity between the Charles and the Kibbey in the subsurface. Geologists working in Saskatchewan and Manitoba were mostly relieved of the problem of the Charles-Kibbey boundary because pre-Mesozoic erosion removed the critical part of the Mississippian sequence except for a narrow area adjacent to the international boundary (figs. 6, 7).

Brindle (1960) listed and illustrated a large marine invertebrate fauna consisting mostly of brachiopods and corals from cores of the Frobisher-Alida, Midale, Ratcliffe, and Poplar beds, which constituted the "Charles facies" and part of the "Mission Canyon facies" in southeastern Saskatchewan. He concluded that the three older lithic-marker-bed units are of Osagean age and that the Poplar beds are of early Meramecian age. Brindle's (1960, p. 12) work demonstrates the partial time-equivalence of the Mission Canyon and Charles "facies." Although his collections of lower Meramecian fossils from the Poplar came from only two wells and did not extend to the top of the unit, they cast some doubt on the conventional interpretation of the Charles Formation as spanning the Meramecian in the area south of the international boundary.

Sando (1960b) described and illustrated a moderately large coral fauna from three well cores of the Madison Group in northeastern Montana, including one core in which the corals were in limestone beds interbedded with anhydrite and anhydritic carbonate at several levels in the Charles Formation, the highest of which was only about 50 ft (15 m) below the top of the formation. No specific statement on the age of the Charles was made in this paper because Sando's studies of Western Interior corals had just begun, and he did not collect data that led to his coral zonation until after the paper was submitted for publication.

In a later paper on seven well cores of the Madison Group in northeastern Montana and northwestern North Dakota, including the three cores previously studied, Sando (1978) found lower Meramecian (CZ 12–13) corals ranging from about 300 ft (92 m) below the top of the Mission Canyon Limestone to about 50 ft (15 m) below the top of the Charles Formation. Sando (1978, p. 236, 237) concluded that the top of the Charles in the subsurface can be no younger than early Meramecian and that its contact with the overlying Kibbey Formation must be a disconformity, just as it is in the outcrop area. Stratigraphic variation of the base of the Charles with respect to a coral zone boundary confirmed the diachronous nature of that lithologic boundary based on the first appearance of evaporite in the sequence.

Study of foraminifers and algae by Mamet (*in* Sando and Mamet, 1981) in coral samples from four of the well cores discussed by Sando (1978) confirmed the conclusions of the earlier study. Impoverishment of the foraminifer faunas and increased abundance and diversity of the algae were interpreted as results of the restricted depositional environments of the Mission Canyon and Charles Formation near the center of the Williston Basin. Samples from the Charles Formation indicated a possible biozone range of MFZ 10=CZ 12 to MFZ 12=CZ 14, which confirmed the early Meramecian age previously based on corals.

Waters (1984) and Waters and Sando (1987a–c) recognized four coral zonules ranging from Osagean to early Meramecian in age on the basis of a large coral fauna recovered from 29 well cores of the Mission Canyon Limestone (Tilston and Frobisher-Alida intervals) and Charles Formation (lower half of Ratcliffe interval) in western North Dakota. Although no corals were recovered from the Poplar interval, the Charles Formation was regarded as probably entirely of early Meramecian age, and a disconformity was thought to mark the top of the Charles.

LITHIC MARKER HORIZONS VERSUS BIOZONE BOUNDARIES AS TIME PLANES

Widespread thin beds of siltstone, sandstone, shale, anhydrite, and dolomite that cause sharp deflections on gamma-ray logs have been used as datum planes for stratigraphic correlations of well sections of the Madison Group since the early days of petroleum exploration in the Williston Basin, particularly the northern part (figs. 4, 6, 7). On the basis of radioactivity log studies, Thomas (1954, p. 70) used "persistent silt zones terminating limestone depositional cycles" to divide the Mission Canyon Limestone of Saskatchewan into five "members." Terrigenous beds were used most commonly in subsequent work on the lithic markers.

The premise that terrigenous marker horizons are approximately synchronous time planes was suggested by Porter (1955, p. 127, 128), who used the markers to demonstrate the diachroneity of the conventional boundary between the Mission Canyon Limestone (shelf carbonate sequence) and the Charles Formation (evaporitic sequence) in Manitoba and Saskatchewan. Porter (1955, p. 128) thought that the markers represent "times of epeirogenic fluctuations" within the cyclic carbonate and evaporite sequence. A similar interpretation was advanced by Harrison and Flood (1956), who modified Thomas' (1954) marker-bed system and extended it into North Dakota. Harrison and Flood (1956, p. 39) regarded the markers as breaks in sedimentation that resulted from minor tectonic movements, but they noted that the markers are not uniformly developed across the entire basin owing to the "steepness of the depth profile." Fuller (1956a, b) showed that some terrigenous marker beds mark the tops of transgressive-regressive carbonate-evaporite cycles, and he illustrated plant remains from a marker bed in the Mission Canyon Limestone of Saskatchewan. Although Fuller (1956a, p. 27) noted that the validity of lithic marker horizons as time planes "can be proved only by paleontology," he thought that the great areal extent of the marker beds was evidence of synchroneity.

Cumming and others (1959) summarized the theoretical basis for regarding the terrigenous marker horizons as approximately synchronous surfaces, based mostly on previous work, and introduced the term "non-sequential beds" for the terrigenous layers. They regarded the carbonate and evaporite intervals bounded by the terrigenous marker layers as informal para-time-rock units called "beds" and suggested that the marker beds represent introductions of terrigenous sediment resulting from rhythmic diastrophic pulses that terminated periods of widespread stillstand of normal shelf-carbonate sedimentation. The terrigenous materials in the marker beds were regarded as "accumulated sweepings of an exposed strand" or "no more than fossilized collections of beach combings" (Cumming and others, 1959, p. 730). Hence, although the marker beds are not synchronous because of their inherently transgressive character, their bounding surfaces were thought to be time-parallel and to be useful for chronostratigraphy. The conclusions of Cumming and others (1959) were accepted in most later lithostratigraphic studies of the Madison Group in the northern part of the Williston Basin.

Relatively few paleontologic tests of the validity of the marker horizons for chronostratigraphy have been published, and the published tests are seemingly contradictory. Brindle (1960, p. 12) found that species of brachiopods and corals "showed little or no tendency to "follow" the westwardly rising [carbonate and evaporite] facies" and that different faunal assemblages are generally restricted to intervals bounded by the marker beds in the Mission Canyon Limestone of Saskatchewan. He concluded that the paleontologic evidence did not contradict the validity of units bounded by lithic marker beds as para-time-rock units. On the other hand, Sando (1978, p. 234) and Sheldon and Carter (1979, p. 252, fig. 54) noted a significant angular difference between paleontologically determined Mississippian series boundaries and lithic marker horizons in a stratigraphic profile of the Madison Group from central Montana to southeastern Saskatchewan.

Waters (1984, p. 75, 105–108; Waters and Sando, 1987a, p. 198) observed that, although coral abundance and diversity are affected by water depth and salinity, coral zonules can be traced through several different depositional environments in the Mission Canyon Limestone of western North Dakota. Waters noted close parallelism between coral zonule boundaries and lithic marker horizons in three stratigraphic profiles from the margins to the center of the Williston Basin. He also pointed out that coral zonule boundaries can be traced into the center of the basin where the Bottineau, Tilston, and Frobisher-Alida interval boundaries are difficult to determine using lithic marker beds. Waters concluded that the marker-bed horizons are essentially time parallel.

Peterson (1978a, b, 1984, 1987) recognized four lithic marker horizons within the Madison Group of Montana, North Dakota, South Dakota, and Wyoming, two of which were correlated with standard lithic marker horizons recognized by other geologists in the Mission Canyon Limestone of North Dakota. Peterson (1987, p. 177) suggested eolian derivation, distribution during low sea level, and reworking by subsequent marine transgression during rising sea level for the origin of the terrigenous marker beds. He plotted coral zone boundaries from Sando (1978) on two well sections from northeastern Montana in a stratigraphic profile that shows the marker horizons (Peterson, 1987, fig. 7). Using these data and other information provided him by Sando, Peterson (1987, p. 178) concluded that two of his marker horizons were close to Mississippian series boundaries established on coral zones by Sando (1978). This exercise, although based on limited data, provided a tentative linkage between chronostratigraphy based on paleontology and the lithic marker bed system over a wide area of the Williston Basin subsurface.

MADISON-KIBBEY CONTACT

The contact between the Kibbey Formation and the underlying Mission Canyon Limestone (outcrop) or the Charles Formation (subsurface) has been interpreted, on the basis of physical relationships of the strata immediately below and above the contact, as disconformable or unconformable by some geologists and as conformable and transitional by others. Detailed observations of the relationships of these strata are made difficult by generally poor exposures in the outcrop area and by the lack of continuous cores through the contact in the subsurface. Most geologists working in the outcrop area favored a disconformity or unconformity, whereas majority opinion favored a conformable contact in the subsurface. These contradictory opinions have been influenced by different concepts of the regional geologic history of the upper part of the Mississippian sequence based on other evidence.

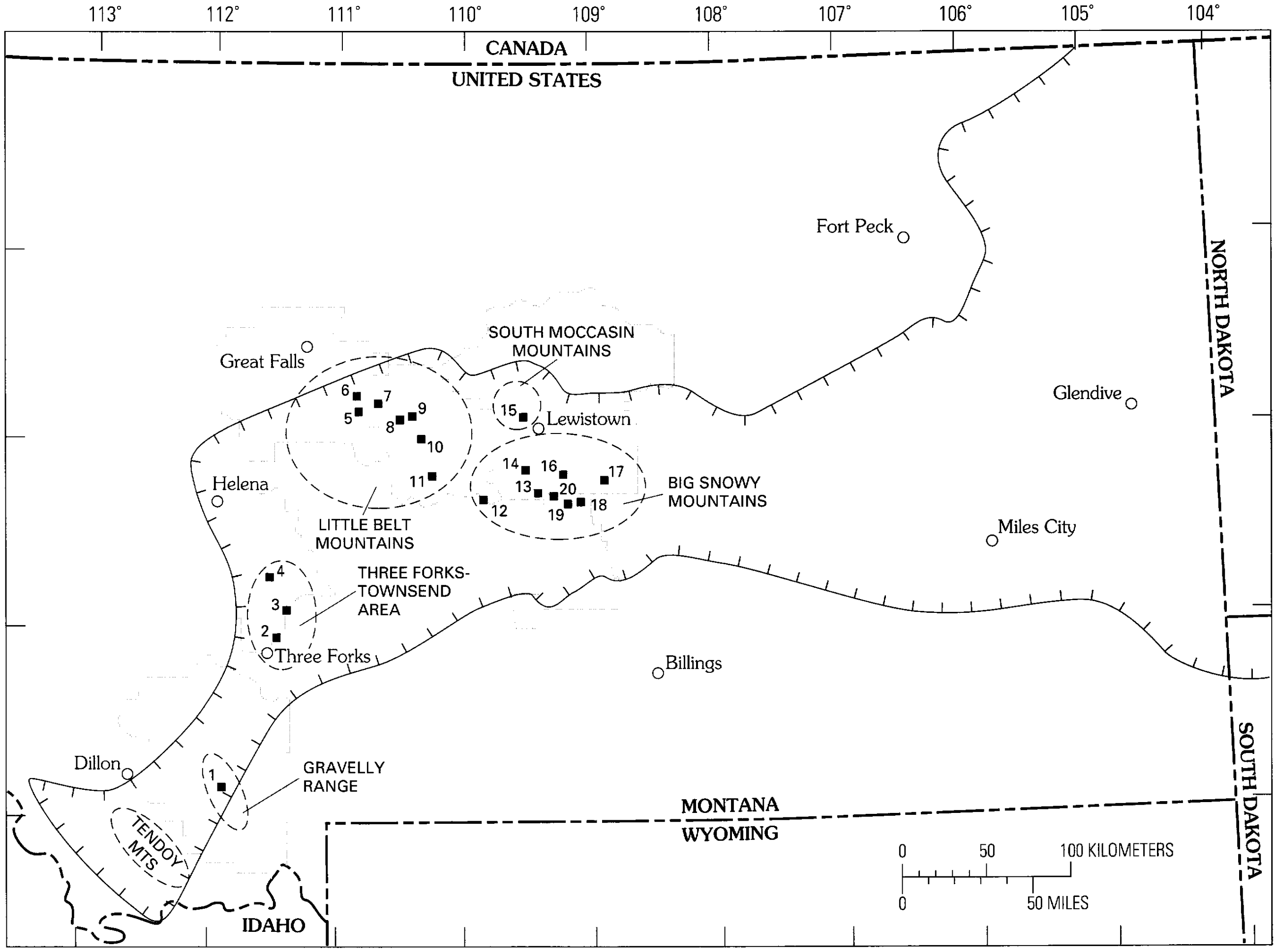
OUTCROP AREA

Most early investigators of the Madison and overlying rocks in central and southwestern Montana concluded that these sequences are conformable and that sedimentation was continuous across the boundary between them (Peale, 1893; Weed, 1899a, b; Freeman, 1922; Reeves, 1931), but they did not describe the contact or give reasons for their conclusions. Their ideas were probably biased by the opinions of paleontologists, who regarded the fossils from these rocks as representing a continuous biostratigraphic succession.

Scott (1935) concluded that the contact is a disconformable erosion surface, based on his observations of silicification and glazing of the top of the Madison, contact relief of 4–6 ft (1.2–1.8 m), and the presence of solution cavities, filled by sediments of the Kibbey, below the top of the Madison at many localities in southwestern and central Montana. Sloss and Hamblin (1942) used similar criteria to assert that the top of the Madison was an erosion surface throughout the area of its outcrop. Perry and Sloss (1942), Gardner and others (1946), and Walton (1946) described channels and filled solution cavities in the Madison in central Montana. Sando and Dutro (1960) measured relief of 30 ft (9 m) and 200 ft (60 m) in sinkholes in the top of the Madison beneath the Kibbey in southwestern Montana.

Similar observations of post-Madison, pre-Kibbey karst features in the outcrop area were recorded by Sloss (1950, 1952), Norton (1956), Miller (1959), Robinson (1963), and Sando and Dutro (1974). The Madison-Kibbey contact was also regarded as a disconformity or unconformity in the outcrop area, without detailed description, by Gardner and others (1945), Perry (1945), Leatherock (1950), Sloss and Moritz (1951), Gardner (1959), Easton (1962), Craig (1972), Sando and others (1975), Sando (1976, 1988, 1989a, b, 1992), Smith and Gilmour (1979), Wardlaw (1985), and Gilmour (1989). The distribution of specific locations at which physical evidence of disconformity has been reported is shown in figure 9. The only exception to the rule known to me is in the Tendoy Mountains in extreme southwestern Montana (fig. 9), where the Kibbey conformably overlies a Mississippian sabkha deposit represented by the McKenzie Canyon Formation of the Tendoy Group (Sando and others, 1985).

Maughan and Roberts (1967, p. B5) and Roberts (1979, p. 238) acknowledged published records of an unconformity in central and southwestern Montana, but they regarded the unconformity as of merely local significance. Their statement (Maughan and Roberts, 1967, p. B5) that the unconformity is confined to the "margin of deposition" is not verified by the distribution of locations at which this feature has been reported (fig. 9), which suggests instead that post-Madison, pre-Kibbey erosion characterized all the area of Kibbey deposition in central and southwestern Montana. Maughan (1984, p. 183) also minimized the significance of the hiatus between the Madison and the Kibbey by asserting that "karst development and some of the solution features are related to postdepositional collapse and flowage of the unconsolidated Big Snowy sediments into solution caverns in the Madison." These attempts to minimize or discredit evidence of a regional intra-Mississippian erosional event in the outcrop area are related to a pervasive belief by Maughan that the Mississippian-Pennsylvanian boundary is marked by an unconformity everywhere in North America and that the erosional event that produced this feature is the only significant erosional event recorded in the Carboniferous of North America. This concept, which stems from Chamberlin and Salisbury (1906)(see Maughan and Roberts, 1967, p. B20), has not been confirmed by modern biostratigraphic studies in the northern Cordilleran region (Dutro and others, 1984).



LOCATION INFORMATION

1. Baldy Mountain, secs. 26 and 27, T. 7 S., R. 3 W., Madison County (Sando and Dutro, 1960)
2. Eustis, secs. 7 and 8, T. 2 N., R. 2 E., Broadwater County (Gardner and others, 1946)
3. Lombard, sec. 7, T. 4 N., R. 3 E., Broadwater County (Sando and Dutro, 1960)
4. Townsend, sec. 7, T. 6 N., R. 1 E., Broadwater County (Scott, 1935)
5. Monarch-US 89, sec. 22, T. 16 N., R. 7 E., Cascade County (Perry and Sloss, 1942; Sando and Dutro, 1974)
6. Riceville-Belt Creek, secs. 24–26, T. 16 N., R. 6 E., Cascade County (Walton, 1946; Norton, 1956)
7. Kibbey School, sec. 8, T. 16 N., R. 8 E., Judith Basin County (Norton, 1956)
8. Peterson Gulch-Lone Tree Gulch, sec. 35, T. 16 N., R. 9 E., Judith Basin County (Norton, 1956)
9. Lone Tree Dome, sec. 20, T. 16 N., R. 10 E., Judith Basin County (Norton, 1956)
10. Running Wolf Creek, sec. 31, T. 15 N., R. 11 E., Judith Basin County (Norton, 1956)
11. Judith River, sec. 25, T., 13 N., R. 11 E., Judith Basin County (Norton, 1956)
12. Oka Creek, sec. 21, T. 11 N., R. 15 E., Judith Basin County (Norton, 1956)
13. Big Careless Creek, sec. 12, T. 11 N., R. 18 E., Fergus County (Norton, 1956)
14. Potter Creek Dome, sec. 8, T. 13 N., R. 21 E., Fergus County (Norton, 1956)
15. South Moccasin Mountains, sec. 11, T. 16 N., R. 17 E., Fergus County (Miller, 1959)
16. Beacon Hill, sec. 6, T. 12 N., R. 20 E., Fergus County (Gardner, 1959)
17. Durfee Creek Dome, sec. 13. T. 12 N., R. 22 E., Fergus County (Gardner and others, 1946; Gardner, 1959)
18. Stonehouse Ranch, sec. 32, T. 11 N., R. 21 E., Golden Valley County (Gardner, 1959)
19. State Road 25, sec. 25, T. 11 N., R. 20 E., Golden Valley County (Gardner, 1959)
20. Swimming Woman Canyon, sec. 16, T. 11 N., R. 19 E., Golden Valley County (Sloss and Hamblin, 1942)

Figure 9. Locations in central and southwestern Montana at which a disconformity was reported at the Madison-Kibbey contact. Hachured line marks erosional zero edge of Kibbey Formation; hachures are on side where Kibbey is present. Modified from Maughan and Roberts (1967, pl. 3).

SUBSURFACE

Most reports on the Charles or Kibbey Formations in the subsurface portrayed the boundary between the formations as conformable on graphic stratigraphic sections or made statements implying conformity, but they did not describe detailed physical relations at the contact (Dewolfe and West, 1939b; Jones, 1940; Seager and others, 1942; Sloss and Hamblin, 1942; Hadley and others, 1945; Perry, 1945; Walton, 1946; Sloss, 1952; Barnes, 1952; Folsom and Anderson, 1955; Fish and Kinard, 1959; Willis, 1959; Sando, 1960b; Easton, 1962; Sandberg, 1962; Carlson and Anderson, 1965; Carlson, 1967; Rawson, 1968; Craig, 1972; Cook, 1976; Bluemle and others, 1980, 1981, 1987; Gerhard, 1982; Gerhard and others, 1982, 1990; Ballard and others, 1983; Gerhard and Anderson, 1988; Kerr, 1988). In other reports, the terms "transitional" or "gradational" have been used to characterize contact relations, without detailed description (Perry and Sloss, 1943; Gardner and others, 1945; Hadley, 1950; Leatherock, 1950; Nordquist, 1953; Gardner, 1959). Maughan and Roberts (1967, p. B5, pl. 2, profile D–D') described the Charles-Kibbey contact as conformable throughout the subsurface of Montana and interpreted lithic changes at the contact in several wells in northeastern Montana as evidence of local intertonguing of the two formations.

The early literature on the Williston Basin includes a few reports that presented evidence for an unconformity at the Charles-Kibbey contact. Allen (1939, p. 1247) regarded variations in "thickness, lateral extent, and composition" of dolomite beds beneath the Kibbey Formation in eastern Montana as evidence of unconformity at the contact with the underlying "Madison." McCabe (1954) recognized an unconformity between the Charles and the Kibbey throughout the Williston Basin; he believed that axes of thinning shown by an isopachous map of the Madison Group were the results of erosion associated with pre-Kibbey folding. Although Middleton and Kennedy (1956, p. 56–57) believed that the Kibbey rests conformably on the Charles Formation over most of the Nesson anticline in northwestern North Dakota, they noted that absence of the uppermost salt beneath the Kibbey at the margins of the Williston Basin suggested "an unconformable relationship." Davis and Hunt (1956, fig. 2) showed the Charles-Kibbey contact as unconformable in a preliminary correlation chart for the northern part of the Cedar Creek anticline in eastern Montana but did not discuss the nature of the boundary. Mickelson (1956, p. 70, 71) recognized an unconformity between the Charles and the Kibbey in the subsurface of central Montana but gave no evidence for his conclusion. The North Dakota Geological Society (1959, p. 2) stated that the top of the "Charles facies" is "generally unconformable with overlying beds" in the Williston Basin. Ballard (1963, p. 26) stated that the Poplar interval (uppermost part of Madison Group) "is unconformably overlain by the Kibbey and Otter Formations" in eastern North Dakota, and he noted a breccia between the Poplar and the Kibbey in one well. Like McCabe (1954), Ballard attributed some thinning of the Poplar to pre-Kibbey erosion.

Arguments by Sando (Sando and others, 1975; 1976; 1978; Sando and Mamet, 1981) favoring a disconformity between the Charles and Kibbey Formations in the Williston Basin subsurface were based mainly on age relations established by biostratigraphy and lacked presentation of physical evidence at the contact. Sando (1978, p. 236) pointed out, however, that the presence of lower Meramecian corals only 50 ft (15 m) below the top of the Charles Formation in the Shell Pine well in northeast Montana contradicts Maughan and Roberts' (1967, pl. 2, profile D–D', well 50) postulated intertonguing of the Charles and Kibbey in that section. Sando's interpretation of the contact as a regional disconformity was followed by Peterson (1978a, b, 1984, 1987, 1988), Sheldon and Carter (1979), Smith and Gilmour (1979), Waters (1984), Brown and others (1984), Waters and Sando (1987a–c), and Peterson and McCary (1987) without significant discussion of physical relations of beds at the contact.

SALT BEDS IN THE MADISON GROUP

Bedded salt deposits were first recorded in the Madison Group by Kline (1942, p. 373, 374) in a part of the sequence referred to the Charles Formation by Seager and others (1942, p. 1420) in the Kamp 1 well on the Nesson anticline in northwestern North Dakota. Individual salt beds or the collective salt interval (commonly referred to as "Madison salt" or "Charles salt") have been noted, described, or discussed in many subsequent reports on the central area of the Williston Basin in northeastern Montana and western North Dakota (Perry and Sloss, 1943; Nordquist, 1953; McCabe, 1954; Folsom and Anderson, 1955; Beekly, 1956; Harrison and Flood, 1956; Laird and Folsom, 1956; Middleton and Kennedy, 1956; Anderson and Nelson, 1956; Anderson and Hansen, 1957; Kohanowski, 1957; Anderson, 1958, 1964; Fish and Kinard, 1959; Great Northern Railway Company, 1959; Sando, 1960b, 1976; Sandberg, 1962, 1973; Billings Geological Society, 1964; Carlson and Anderson, 1965; Carlson, 1967; Maughan and Roberts, 1967; Cook, 1976; Peterson, 1978b, 1984; Sheldon and Carter, 1979; Smith and Gilmour, 1979; Bluemle and others, 1980; Orchard, 1987), in southern Saskatchewan (Thomas, 1954; Fuller, 1956a, b; Brindle, 1960; Fuzesy, 1960), and in general summaries of Williston Basin Madison stratigraphy (Barnes, 1952; Sloss, 1952, 1953, 1956; North Dakota Geological Society, 1959; Pierce and Rich, 1962; Sando, 1976, 1989a, b, 1992; Gerhard, 1982; Gerhard and others, 1982, 1990; Brown and others, 1984; Peterson, 1987, 1988; Peterson and McCary, 1987; Gerhard and Anderson, 1988; Kerr, 1988; Borchert and others, 1990).

In this report, the informal term "Madison salt" is used for the entire salt-bearing sequence in the Madison Group. The informal term "top Madison salt" is used for the uppermost salt bed in the salt-bearing sequence.

STRATIGRAPHIC AND GEOGRAPHIC DISTRIBUTION

Early paleogeographic maps of the Charles Formation in Montana, North Dakota, South Dakota, and southern Canada by Perry and Sloss (1943, fig. 7B) and Sloss (1953, fig. 4) do not distinguish distribution of halite from that of anhydrite. Nordquist (1953, p. 79) noted that "a massive salt bed is present at the top of the Charles over an extensive area" in northeastern Montana and that the top of the salt made a good marker for separating the Charles and Kibbey Formations (see also North Dakota Geological Society, 1959, p. 2). He distinguished as many as eight salt beds in the Charles on his stratigraphic profile for northeastern Montana (Nordquist, 1953, fig. 5).

Nordquist (1953, p. 80) suggested that thinning of the Charles Formation on the East Poplar anticline may be due to subaerial erosion on islands in the Charles sea, but he also observed that the absence of the salt in the Poplar area may have resulted from leaching rather than nondeposition. Beekly (1956, fig. 4) presented a map showing thickness variation of the "Charles salt" (Madison salt of this report) in the Poplar area, but he did not explain the reason for the variation. Brown and others (1984, p. B17) noted that the thickness of the Charles Formation in the area of salt deposition may have been affected by postdepositional dissolution of halite. Orchard (1987) presented evidence that the absence of salt beds on the Poplar dome was the result of Tertiary dissolution.

Fuller (1956a, p. 36, fig. 2) described two "salt beds" in the "Charles evaporites" between the top of the Ratcliffe beds and the pre-Mesozoic unconformity in south-central Saskatchewan, but he pointed out that these "salt beds" are mostly anhydrite and mudstone containing molds of halite crystals. These "upper and lower" salt beds in the Poplar interval of Saskatchewan were also noted by Brindle (1960, p. 13, fig. 2) and by Fuzesy (1960, p. 39).

Anderson and Hansen (1957) distinguished six separate salt beds, labeled A to F in descending order, interbedded with anhydrite, limestone, and dolomite in the Charles Formation of North Dakota and a seventh salt bed (bed X) near the base of the Charles in a small area east of the main body of Mississippian salt deposits. They indicated that beds A to F are also present in northeastern Montana and that beds D and F extend into Canada. Isopach maps showing the distribution of each salt bed in North Dakota were presented. Beds A–X comprise the "Madison salt," and bed A is the "top Madison salt" of this report.

Six salt beds were reported in the Charles Formation or Poplar interval in the northern part of the Williston Basin in Montana and North Dakota by Anderson (1958, fig. 2), Fish and Kinard (1959, pl. IV), Sandberg (1962, p. 60–62), Pierce and Rich (1962, p. 57), and Cook (1976), but as many as seven or nine salt beds were reported by Kohanowski (1957, p. 77) and Great Northern Railway Company (1959, appendix I), respectively. Sandberg (1962) and Pierce and Rich (1962) followed the classification of Anderson and Hansen (1957), but they placed the X salt in the upper part of the Mission Canyon Limestone.

Most of the information on the distribution of salt beds in the Madison Group is based on radioactivity log studies because of the great expense of coring the salt and the difficulties encountered in recovering good cuttings and cores of such soluble material. Kohanowski's (1957, p. 74) study of the petrography and chemistry of core samples of the Charles salt in northwestern North Dakota led him to conclude that "electric logs portray an idea of continuous salt horizons, while in reality there are numerous disconnected but overlapping lenses." He also found evidence of much paragenetic alteration of original halite, and he noted that alteration becomes more advanced as thickness of salt lenses increases. Study of cores from three wells on the Nesson anticline in northwestern North Dakota by Great Northern Railway Company (1959, appendixes F–H) revealed many beds of ankerite, anhydrite, and green shale 1–4 in. (2.5–10 cm) thick within the salt deposits.

Total isopach maps of the Madison salt were presented by Great Northern Railway Company (1959, appendix A), Pierce and Rich (1962, fig. 21), Sandberg (1962, fig. 16; 1973, fig. 26), Cook, 1976, pl. 3), and Sheldon and Carter (1979, fig. 66). The area of Madison salt distribution was also shown by Peterson (1984, fig. 11, pl. 3; 1987, fig. 20; 1988, figs. 8, 9), Peterson and McCary (1987, figs. 15, 24), and Kerr (1988, fig. 21). Isopach maps of the top Madison salt (A salt of Anderson and Hansen, 1957) were presented by Anderson and Hansen (1957, fig. 4), Great Northern Railway Company (1959, appendix B), and Anderson (1964, fig. 4). These distribution data for the salt deposits of the Charles Formation indicate that a depocenter was located in northwestern North Dakota, that the salt beds thin toward the margin of the area of salt deposition, and that the area of salt deposition expanded, then contracted during Charles time.

ORIGIN

Early explanations of the origin of the Charles evaporite sequence, including the salt, postulated an increase in salinity owing to restriction of the last phases of the Madison sea in the central and deeper part of a depositional basin in Montana and North Dakota (Sloss and Hamblin, 1942, p. 325; Perry and Sloss, 1943, p. 1301; Hadley, 1950, p. 46; Nordquist, 1953; Sloss, 1953, 1956; Thomas, 1954). Perry and Sloss's (1943, fig. 7B) paleogeographic map of the Charles Formation shows the formation separated from coeval rocks in the geosyncline to the west by an intervening area exposed to subaerial erosion, although they postulated intermittent marine connections to account for the alternation of anhydrite and limestone in the Williston Basin. Most theories on the origin of the salt deposits postulate a marine environment for all the salt beds.

In his general theory of the origin of ancient evaporite deposits, Sloss (1953, p. 151–153, 156–158, table 1) classified the Charles Formation as a tectonically silled intrabasinal evaporite sequence and showed marine connections between the western geosyncline and the Williston Basin on his paleogeographic map of Charles time (Sloss, 1953, fig. 4). This apparent westward extension of the Charles sea, seemingly inconsistent with evidence of erosion in the area between the Williston Basin and the western geosyncline during pre-Kibbey time, may have been influenced by Nordquist's (1953, fig. 8) recognition of the Charles Formation in the subsurface across northern Montana. Sloss's (1953, p. 156–158; 1958, p. 11) intrabasin model for the Charles evaporites postulates separation of a rapidly subsiding basin of deposition from a surrounding open-circulation shelf by a tectonically stable submarine sill, increased salinity in the restricted area caused by excess evaporation of surface waters in an arid climate, and gravity flow of the denser, highly saline brines into the deeper central part of the basin. Sloss's (1953) theory of evaporite deposition was followed by most later writers on the origin of Mississippian salt in the Williston Basin (Thomas, 1954, p. 72; Landes, 1960, p. 56; Sandberg, 1962, p. 63, 64; 1973, p. 149; Billings Geological Society, 1964, p. 107).

Sandberg (1962, p. 63, 64; 1973, p. 149) suggested that the ancestral Cedar Creek anticline may have been a restricting shoal area during deposition of the Charles salt beds (beds A–F of Anderson and Hansen, 1957). He postulated a sabkha or salt-marsh origin for the salt at the top of the Mission Canyon Limestone (bed X of Anderson and Hansen, 1957) because of its location near the eastern shoreline of the Mississippian sediments. Smith and Gilmour (1979, p. X19) attributed the origin of evaporite beds in the Charles Formation of northeastern Montana to sabkhas and salt pans developed during Late Mississippian regression.

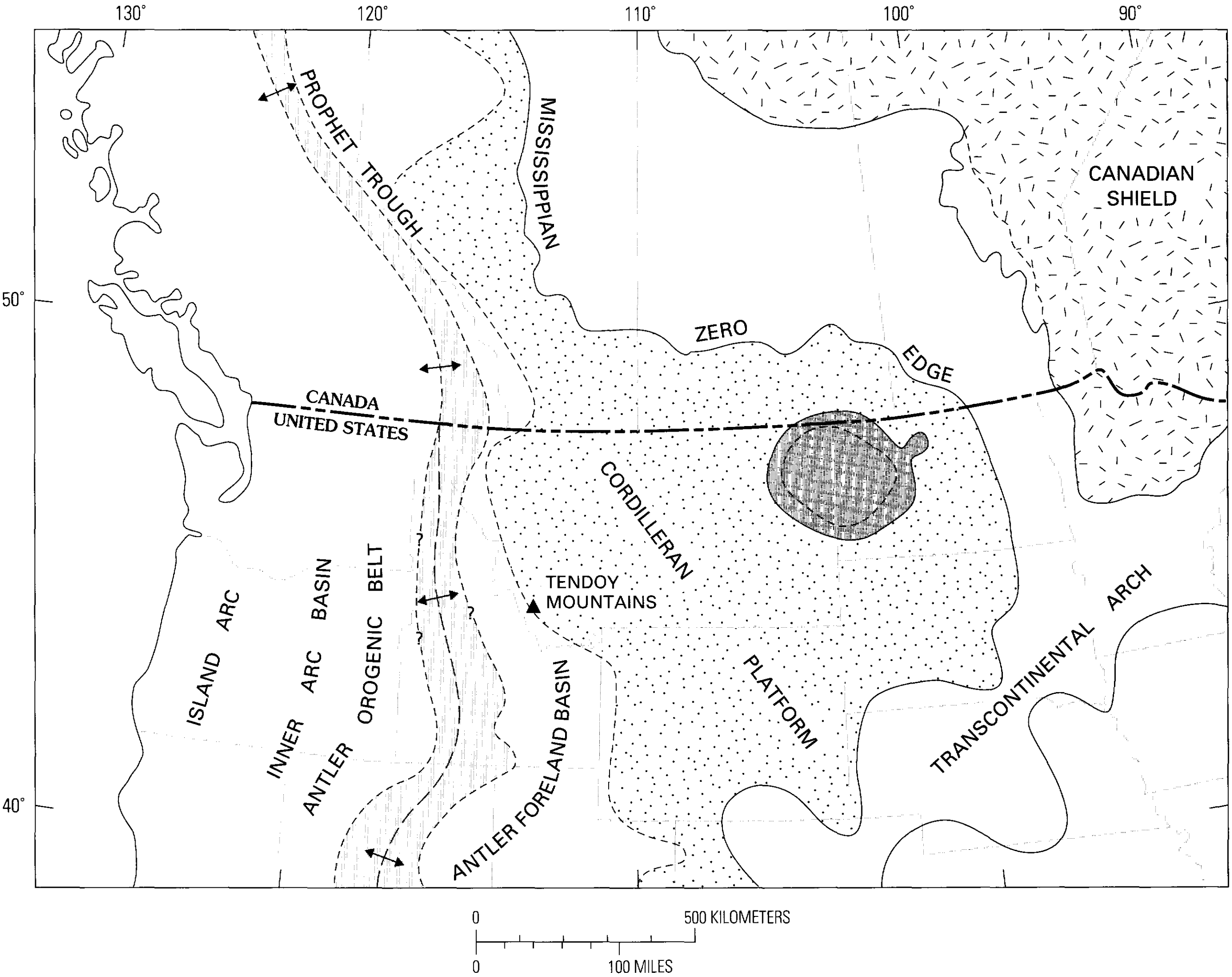
Sando (1976, fig. 6) noted that the area of late Osagean and early Meramecian evaporite deposition was much larger than indicated by previous writers because of the presence of evaporite-solution breccias in western Montana and parts of Wyoming. He invoked the evaporite model of Adams and Rhodes (1960), originally proposed for the Permian of the southwestern United States, to explain the distribution of anhydrite, salt, and dolomite in the Mississippian of the northern Rocky Mountain region (Sando, 1976, p. 333–335). In this model, an evaporite lagoon formed on a broad shelf when restriction of circulation on the shelf by sediment buildup at the shelf margin caused a salinity increase within the lagoon. Shoreward increase in salinity resulted in a shoreward progression of less soluble to more soluble evaporite deposits. Application of the model to the Mississippian of the Williston Basin places emphasis on this basin as a part of the huge Cordilleran shelf and not as a separate depositional system, as has been implied in most subsurface studies. Sando (1988, 1989a, b, 1992) modified this model to include a continental salt lake as the final phase of the shallowing-upward sedimentary progression represented by the Madison Group in the Williston Basin.

INTERPRETIVE SUMMARY OF PREVIOUS WORK

Despite a distinguished record of research into the history of Mississippian sedimentation in the Williston Basin and successful exploitation of its petroleum resources, some troublesome inconsistencies in interpretation of the geologic history remain to be resolved. Review of previous work evokes the following observations.

1. Many subsurface stratigraphers, particularly those working in the heart of the basin in North Dakota, have paid little or no attention to biostratigraphic evidence, from the outcrop area to the west and even from the subsurface of the basin itself, that contradicts ages and regional chronostratigraphic correlations assigned by them to Mississippian rocks. Although biostratigraphy seems to confirm the validity of lithic marker beds as approximate time planes within the basin, apparent divergence of some biostratigraphic and lithic marker horizons between stratigraphic sections in the basin and those in outcrop areas to the west presents a problem for regional interpretation of geologic history. Time-tested traditional biostratigraphic methods are still the most reliable means for regional chronostratigraphy. Recent work by Peterson (1987, p. 187) suggests that some lithic marker horizons are close to biostratigraphic horizons traced into the subsurface from outcrop sections where fossils are obtained and studied relatively easily. Some coral zonules have been shown to extend into the heart of the Williston Basin, where lithic marker horizons are absent or poorly developed (Waters and Sando, 1987a, p. 199). Regional stratigraphic syntheses and future development of petroleum resources within the Williston Basin would benefit by consideration of all available evidence by geologists working in the basin.

2. Biostratigraphic studies (Brindle, 1960; Sando, 1960a, 1978; Sando and Mamet, 1981; Waters, 1984; Waters and Sando, 1987 a–c) show that strata in the upper part of the subsurface Madison Group outside of the area of salt deposition and beneath the Madison salt at the center of the Williston Basin are the same age (early Meramecian, MFZ 11–12=CZ 13–14) as strata at the top of the Madison in the outcrop area of central Montana, where a disconformable relationship with the overlying Kibbey Formation (early Chesterian) is well established on physical evidence. The age of the Madison salt remains to be determined unequivocably because the salt has not yielded fossils; however, the only biostratigraphic evidence of post-early Meramecian, pre-early Chesterian strata known from the Cordilleran platform west of the Williston Basin is in the Mississippian sequence at the western edge of the platform in the Tendoy Mountains of extreme southwestern Montana (Sando and others, 1985) (fig. 10), where a shoreline is defined by a sabkha facies in the McKenzie Canyon Formation. Although shelf-carbonate strata of the Madison Group and equivalent formations



EXPLANATION

Madison salt (central Williston Basin)—Area of top Madison salt bounded by dashed line

Mississippian rocks (Antler foreland basin and Prophet trough)

Area where paleontologically dated post-early Meramecian, pre-Chesterian rocks are absent (Cordilleran platform)

Pre-Mississippian Paleozoic rocks (Transcontinental arch and border of Canadian shield)

Pre-Mississippian rocks (Antler orogen)

Precambrian rocks (Canadian shield)

Figure 10. Paleotectonic map of part of western North America showing isolation of Madison salt area from marine areas during post-early Meramecian, pre-Chesterian time. Modified from Sando and others (1990, fig. 1).

extend northward from Montana and North Dakota into Canada and southward into Wyoming and South Dakota, no evidence exists for marine connections between the Williston Basin and the Antler foreland basin to the west through these areas during middle and late Meramecian time. After initial flooding of the Cordilleran platform during Kinderhookian time, major transgressions and regressions of the Madison sea proceeded across the platform in an essentially east-west direction perpendicular to shorelines that trended northeast-southwest (Sando, 1976). Hence, no marine source was accessible to the center of the Williston Basin between early middle Meramecian (MFZ 13=CZ 15) evacuation of the shelf and Chesterian transgression (fig. 10).

3. Although a few writers noted physical evidence of disconformity or unconformity near the center of the Williston Basin, most writers described the contact between the Madison Group and the overlying Kibbey Formation as gradational and transitional in that area. Moreover, the top Madison salt is apparently continuous over most of the central part of the basin and shows little or no evidence of pre-Kibbey dissolution (with the possible exception of the Poplar dome area). Thus, these two lines of physical evidence remain as apparent contradictions to the geologic history derived from biostratigraphy.

NEW INTERPRETATION OF CRITICAL EVIDENCE

The preceding historical summary suggests that the controversy about the age and stratigraphic relations of the upper part of the Madison Group in the Williston Basin is not the result of a lack of information but rather is a conflict in interpretations of existing lithic and paleontologic data. Resolution of this conflict requires explanation of all available evidence.

CONTACT BETWEEN MADISON SALT AND KIBBEY FORMATION

TRUNCATION OF BEDS IN THE SALT SEQUENCE BELOW THE TOP MADISON SALT

Careful examination of some published stratigraphic profiles across the margins of the Madison salt basin reveals geometric evidence of erosional truncation of carbonate and evaporite beds in the upper part of the Charles Formation beneath the Kibbey Formation outside the area of the top Madison salt. Such truncation is particularly evident in the detailed profiles of Cook (1976, pls. 5–9) in western North Dakota, which are reinterpreted in figure 11. Carbonate and evaporite beds beneath the top Madison salt were shown by Cook as pinching out before reaching the top of the Charles Formation between control points, requiring convergence to explain angular differences in attitudes of these beds from attitudes of beds beneath them. A simpler explanation, consonant with prevailing dips, extends these beds to the truncated top of the Charles Formation (figs. 11*B, C, E, F*). Truncation of beds at the top of the Charles is also clearly shown, without revision, by Anderson's (1958, fig. 11*B*) profile in western North Dakota (fig. 11*C*).

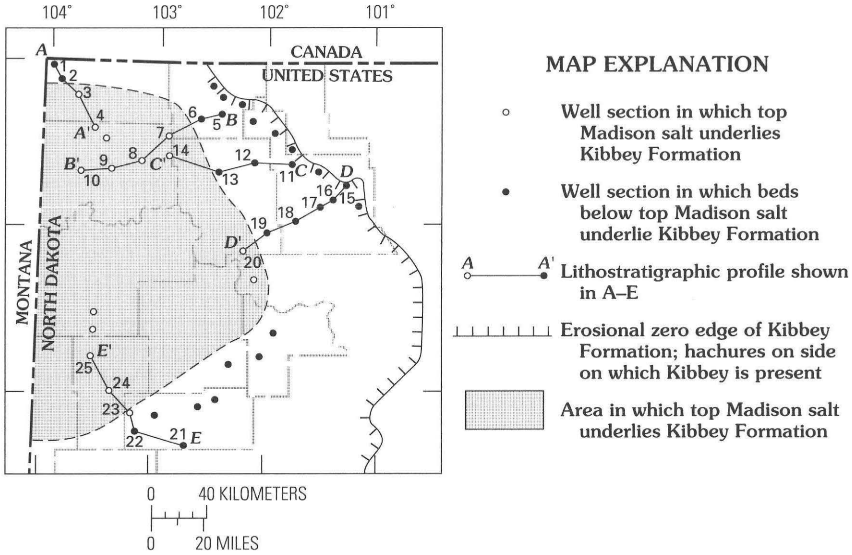
Other evidence of truncation of individual beds in the upper part of the Charles can be seen in Leatherock's (1950) profile A–A' (sections 1–10) in southeastern Montana and in her profile B–B' (sections 11–16) in northwestern South Dakota. Peterson (1984, pl. 5) showed variations in thickness of his M–12 to Mc interval that are suggestive of truncation in his profile B–B' (sections M–Y–5 to M–GF–5) in southeastern Montana and in his (1984, pl. 4) profile A–A' (sections M–Y–5 to ND–ML–2) in northeastern Montana and northwestern North Dakota.

BIOSTRATIGRAPHIC EVIDENCE

Corals and foraminifers representative of lower Meramecian CZ 12, CZ 13, and probably CZ 14 were recovered from the upper part of the Charles Formation beneath the Kibbey Formation in two wells just outside the area of the Madison salt in Montana (well numbers 1 and 3 in figs. 12–14, table 2). Within the salt basin, the youngest corals recovered represent lower Meramecian CZ 12, and these fossils are restricted to the lower part of the Charles Formation beneath the oldest salt bed (figs. 13, 14, table 2); this is due to adverse environmental conditions within the salt basin. The CZ 12/CZ 13 boundary was projected through the unfossiliferous sequence by assuming approximate parallelism with lithic marker horizons within the salt basin.

These biostratigraphic data, together with the evidence for truncation at the top of the Charles, indicate that the salt sequence below the top Madison salt is a lateral equivalent of the surrounding marine shelf carbonate and evaporite sequence and that it is no younger than early Meramecian (CZ 14).

Figure 11 (adjacent and following pages). Lithostratigraphic profiles across margin of top Madison salt basin showing erosional truncation of beds at top of Madison Group beneath Kibbey Formation in North Dakota. See Cook (1976) and Anderson (1958) for detailed locations of well sections. Index map modified from Cook (1976, pl. 9). *A*, Profile modified from Cook (1976, pl. 5): 1, NDGS 4193; 2, NDGS 3441; 3, NDGS 2721; 4, NDGS 984. *B*, Profile modified from Cook (1976, pl. 6): 5, NDGS 2892; 6, NDGS 3596; 7, NDGS 3979; 8, NDGS 3363; 9, NDGS 3406; 10, NDGS 3235. *C*, Profile modified from Anderson (1958, fig. 2}: 11, S.G. Harrison, J.H. Anderson et al 1; 12, Hunt Oil Co., L.C. Anderson 1; 13, Hunt Oil Co., Horne 1; 14, Amerada Petroleum Co., H.O. Bakken 1. *D*, Profile modified from Cook (1976, pl. 8): 15, NDGS 2929; 16, NDGS 2930; 17, NDGS 4153; 18, NDGS 2051; 19, NDGS 2779; 20, NDGS 4386. *E*, Profile modified from Cook (1976, pl. 9): 21, NDGS 4198; 22, NDGS 1536; 23, NDGS 2117; 24, NDGS 4833; 25, NDGS 4455.


104°
103°
102°
101°
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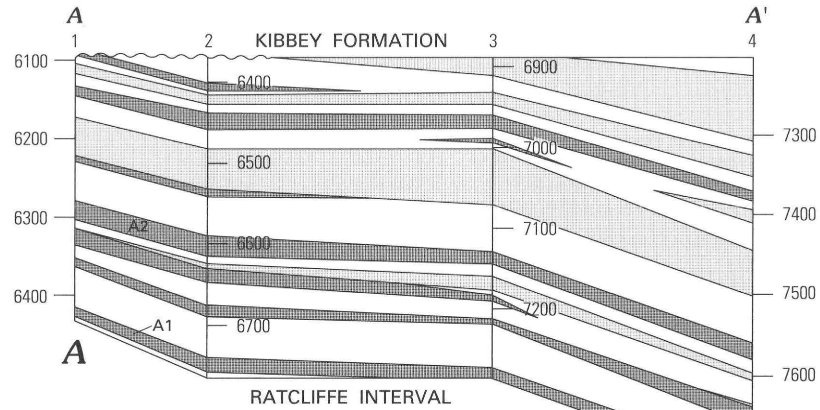
CANADA
UNITED STATES
MONTANA
NORTH DAKOTA
A
A'
B
B'
C
C'
D
D'
E
E'
0 40 KILOMETERS
0 20 MILES
MAP EXPLANATION
Well section in which top Madison salt underlies Kibbey Formation
Well section in which beds below top Madison salt underlie Kibbey Formation
Lithostratigraphic profile shown in A–E
Erosional zero edge of Kibbey Formation; hachures on side on which Kibbey is present
Area in which top Madison salt underlies Kibbey Formation


A
A'
1
2
3
4
KIBBEY FORMATION
6100
6200
6300
6400
6400
6500
6600
6700
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7200
7300
7400
7500
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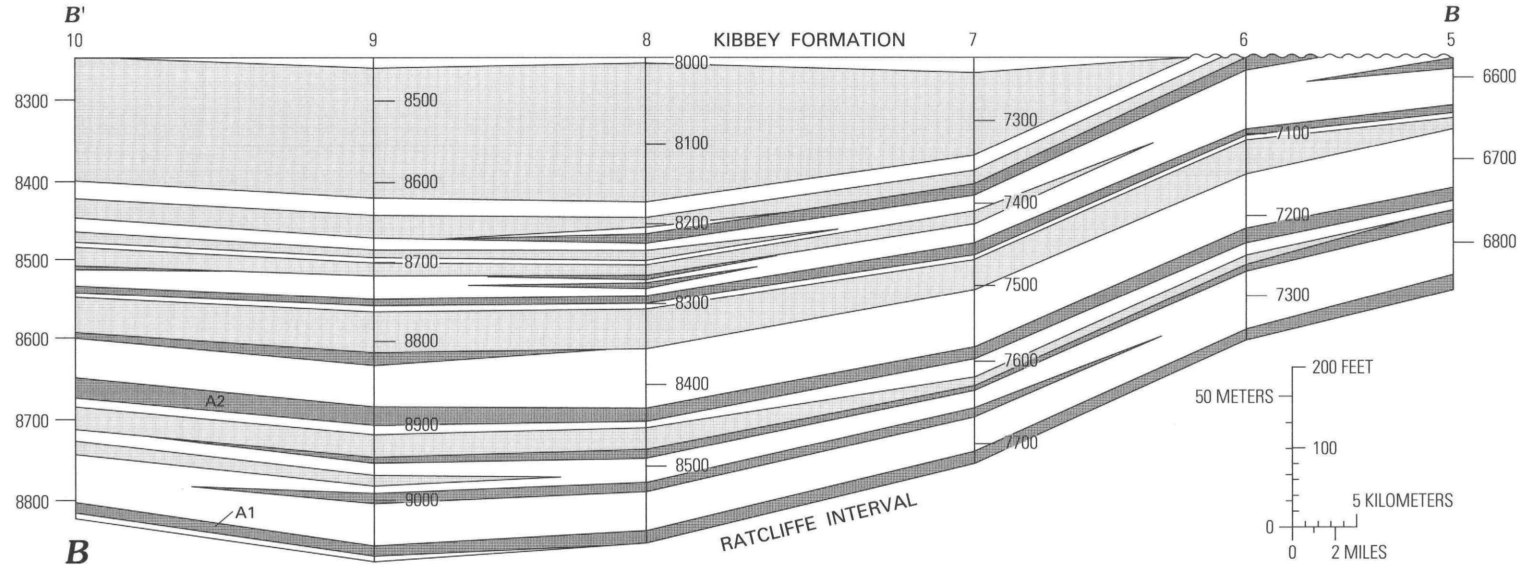
7700
A2
A1
RATCLIFFE INTERVAL
A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KIBBEY FORMATION
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7300
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RATCLIFFE INTERVAL
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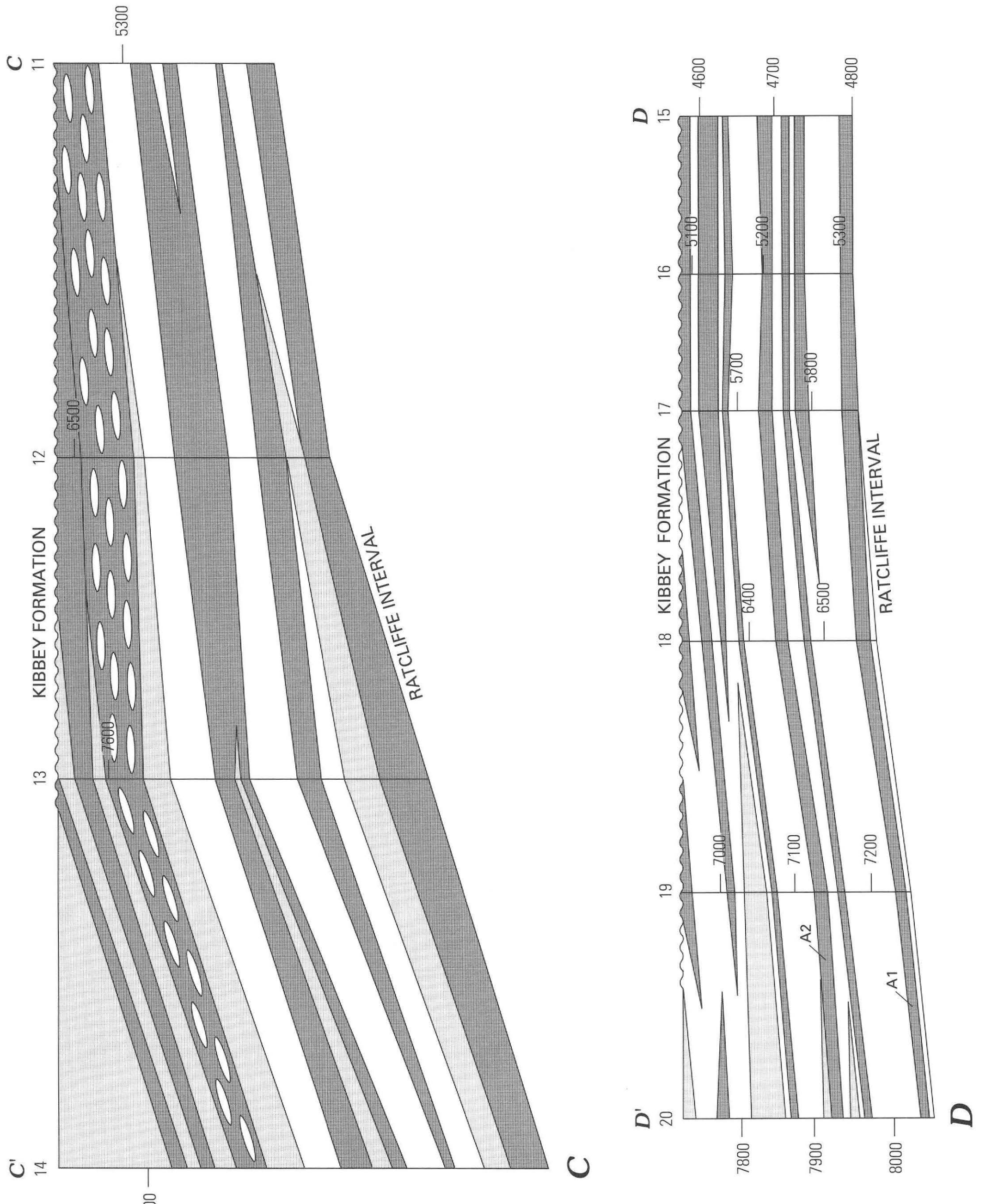
B


C
11
5300
12
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KIBBEY FORMATION
RATCLIFFE INTERVAL
C'
14
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D
15
4600
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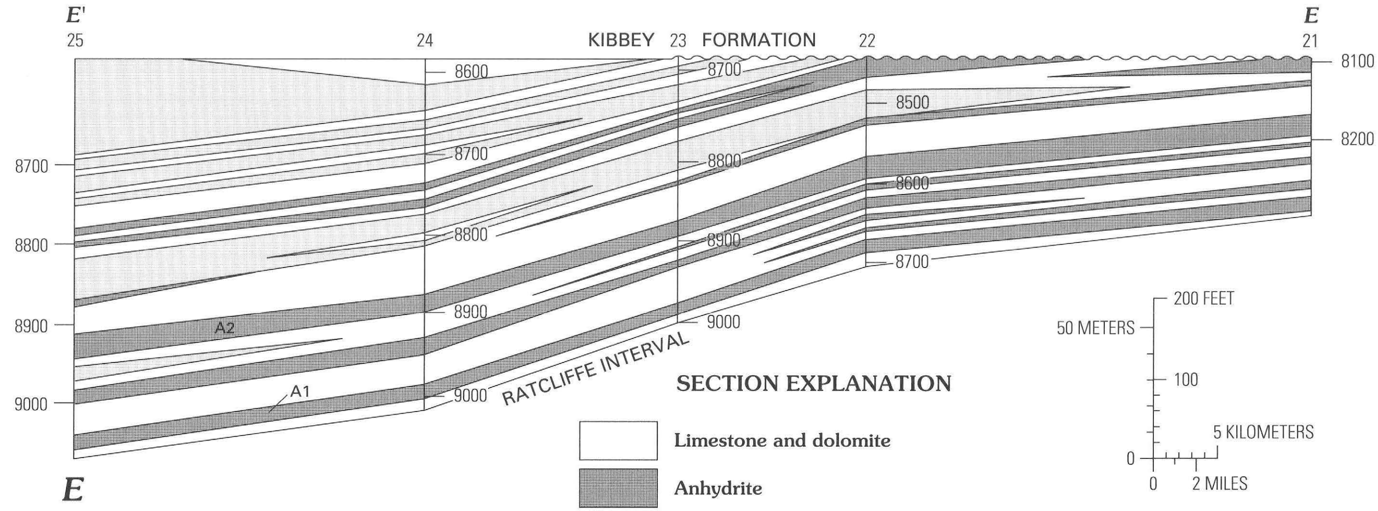
4800
16
5100
5200
5300
17
5700
5800
18
6400
6500
KIBBEY FORMATION
RATCLIFFE INTERVAL
19
7000
7100
7200
A2
A1
D'
20
7800
7900
8000
D



SECTION EXPLANATION

Limestone and dolomite

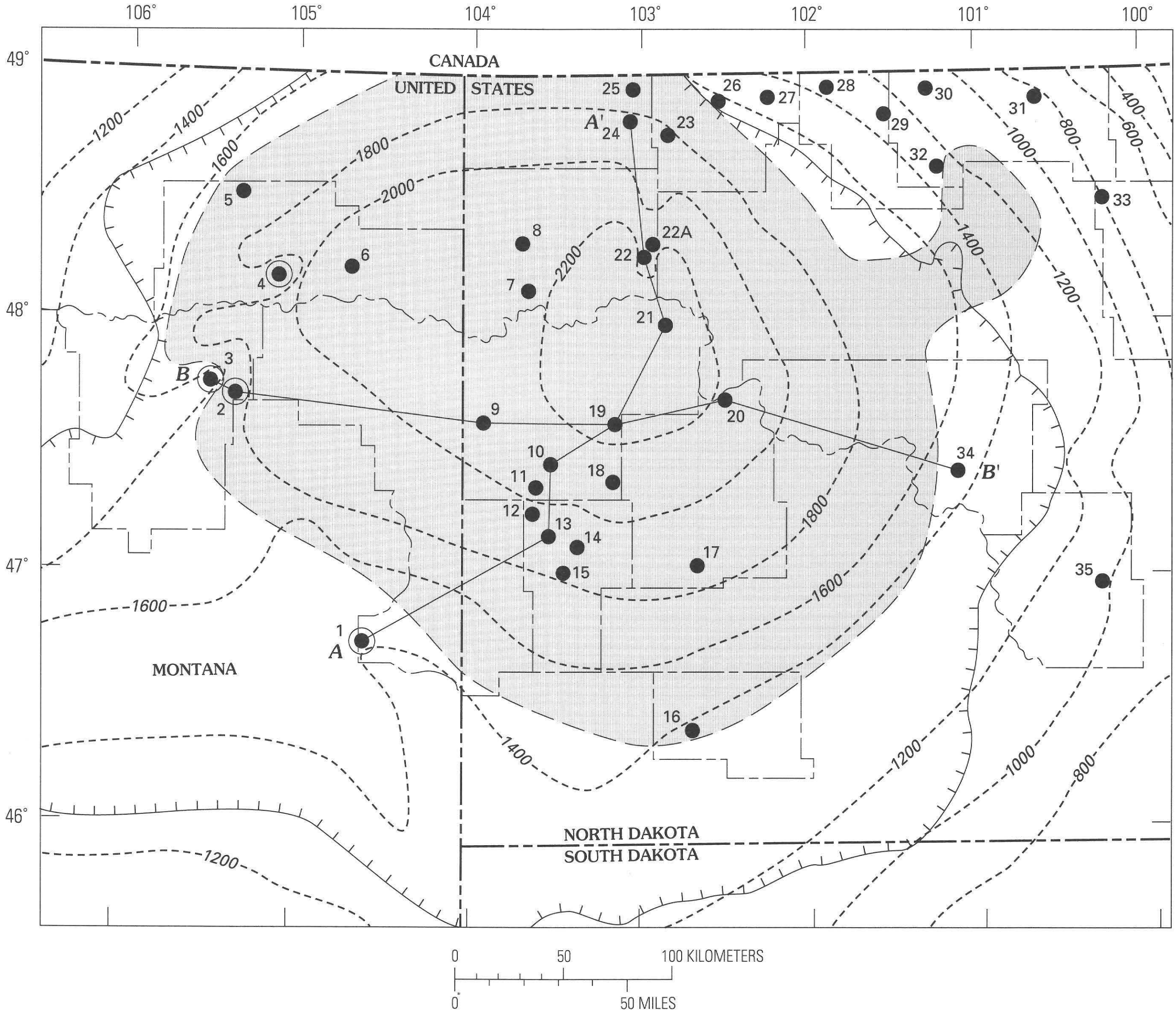
Anhydrite

Halite

A1, A2 **Key beds of Cook (1976)**

Postulated angular unconformity

8200 **Feet below top of Poplar interval**—Datum is top of Poplar interval



EXPLANATION

- Well section from which corals were collected
- Well section from which corals, foraminifers, and algae were collected
- --1600-- **Total Madison Group isopach line**—Contour interval 200 feet
- **Erosional zero edge of Kibbey Formation**—Hachures on side on which Kibbey is present
- **Area in which salt beds are present in Charles Formation and Mission Canyon Limestone**—Limits approximate

Figure 12. Locations of well sections of Charles Formation and Mission Canyon Limestone in Montana and North Dakota from which corals, foraminifers, and algae were collected. Area of Madison salt and total Madison Group isopachs from Sandberg (1962, fig. 15). Erosional zero edge of Kibbey Formation from Maughan and Roberts (1967, pl. 3), Rawson (1968, fig. 4), and Anderson (1974). See figure 1 for location of map area with respect to limits of Williston Basin. See figures 13 and 14 for stratigraphic profiles *A–A'* and *B–B'* across area of Madison salt and table 2 for locations and sources of data for well sections.

RELATION OF TOP MADISON SALT TO BEDS ABOVE AND BELOW

The top Madison salt is readily distinguished from other salt beds in the Madison salt sequence by its stratigraphic position at the top of the sequence and its greater thickness (almost a third of the total thickness of the Madison salt)(figs. 13, 14). It has a slightly smaller areal extent than several older salt beds that define the maximum limits of the salt basin. A bed of limestone or anhydrite separates it locally from the overlying Kibbey Formation. No fossils have been recovered from the top Madison salt or from the overlying limestone. Although most geologists described the contact between the salt and the overlying Kibbey Formation as conformable and transitional (see p. 20), contact relations are difficult to determine because of dissolution and caving of the salt and the paucity of cores at the contact.

ORIGIN OF MADISON SALT SEQUENCE

Continuity of marine carbonate strata no younger than CZ 14 that are complexly interbedded with continuous and discontinuous anhydrite and salt beds suggests that the evaporite sequence in the Charles Formation beneath the top Madison salt represents restricted, mostly marine sedimentation in the Madison salt basin during early Meramecian time. The intrabasinal model of Sloss (1953) (see p. 21 of current report) is a reasonable explanation for this part of the Charles Formation. The discontinuous nature of many of the salt and anhydrite beds in the marine evaporite sequence (figs. 13, 14) suggests a complex of smaller, deeper areas of high salinity that shifted geographically within the basin during much of the time represented by the sequence.

The stratigraphic position of the top Madison salt above beds dated paleontologically as no younger than early Meramecian (CZ 14) and beneath beds probably no younger than early Chesterian (CZ 21) (see p. 13–17) suggests an age range of middle Meramecian possibly into early Chesterian for this highest salt. Assuming that published interpretations of the contact between this salt and the Kibbey Formation are valid, the top Madison salt represents a central area of continuous sedimentation from early Meramecian into early Chesterian time within the area of the older marine salt basin. In view of the evidence for truncation of older marine salt beds at the basin margins and the absence of evidence of marine connections of the salt basin during middle Meramecian to early Chesterian time, the top Madison salt probably represents a landlocked remnant of the epeiric sea that was becoming shallower throughout Madison time. This ancient salt lake was gradually overrun by the transgressing Kibbey sea during Chesterian time. The prevalence of an arid climate may explain the absence of solution features in the carbonate bedrock beneath the karst plain in the central part of the Williston Basin.

BIOZONE BOUNDARIES VERSUS LITHIC MARKER HORIZONS IN REGIONAL CHRONOSTRATIGRAPHY

A critical analysis of the depositional history represented by the upper part of the Madison Group in the Williston Basin must first consider the accuracy of methods used for establishing a chronostratigraphic framework for this lithostratigraphic sequence. Basic questions are:

1. How reliable are the lithic marker horizons that have been used extensively as planes of synchroneity in Williston Basin Madison stratigraphy?
2. Are biozone boundaries more reliable planes of synchroneity than lithic marker horizons?
3. Are the lithic time planes parallel to the paleontologic time planes?

Previous work provides seemingly contradictory answers to these basic questions (see p. 17–18). Brindle (1960) and Waters (1984; Waters and Sando, 1987a) concluded that the lithic marker horizons parallel faunal zone boundaries and that the lithic markers are reliable time planes, whereas Sando (1978) and Sando and Dutro (*in* Sheldon and Carter, 1979) noted a significant angular difference between the two measures of synchroneity.

Stratigraphic profiles replotted from Sheldon and Carter (1979) and Waters and Sando (1987a) reveal remarkably consistent angular differences of 3°–4° between lithic marker horizons and paleontologic boundaries in directions approximately parallel with inferred sedimentary progradation directions (perpendicular to paleoshorelines) across the Cordilleran shelf in Montana and North Dakota (figs. 15–17). These profiles show that the top of the Tilston interval and the top of the Frobisher-Alida interval climb stratigraphically with respect to the Osagean-Meramecian paleontologic boundary westward and southwestward (that is, in directions seaward from the Mississippian shoreline). The only exception is in profile *C–C'* (figs. 15, 17), probably due to poor selection of the lithic marker horizon in well 1 near the center of the salt basin, where Waters (Waters and Sando, 1987a, p. 198, 199) noted that the boundaries of lithic marker intervals are difficult to identify.

The angular differences between lithic markers and paleontologic markers in the directions of progradation can cause significant differences in the stratigraphic positions of time planes based on the markers. Over short distances within North Dakota (fig. 17, profiles *A–C* and *B–B'*), the angular differences result in stratigraphic discrepancies of approximately 75–80 ft (23–24 m), whereas, from central Montana to southeastern Saskatchewan (fig. 16, profile *A–E*), the stratigraphic discrepancy is approximately 300 ft (92 m). In a profile perpendicular to progradation (fig. 15, profile *A–B*), the angular difference is zero and there is no stratigraphic discrepancy.

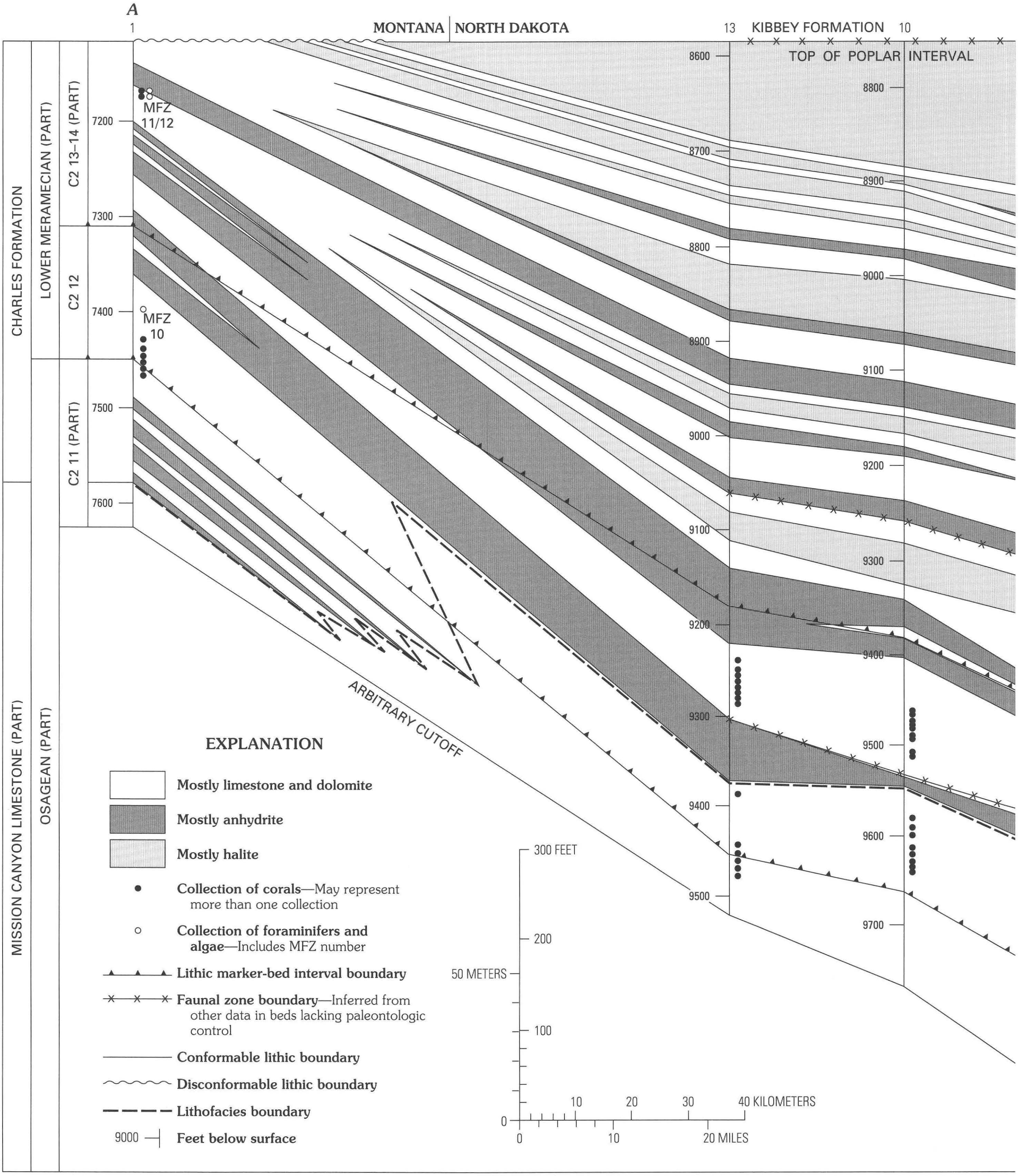
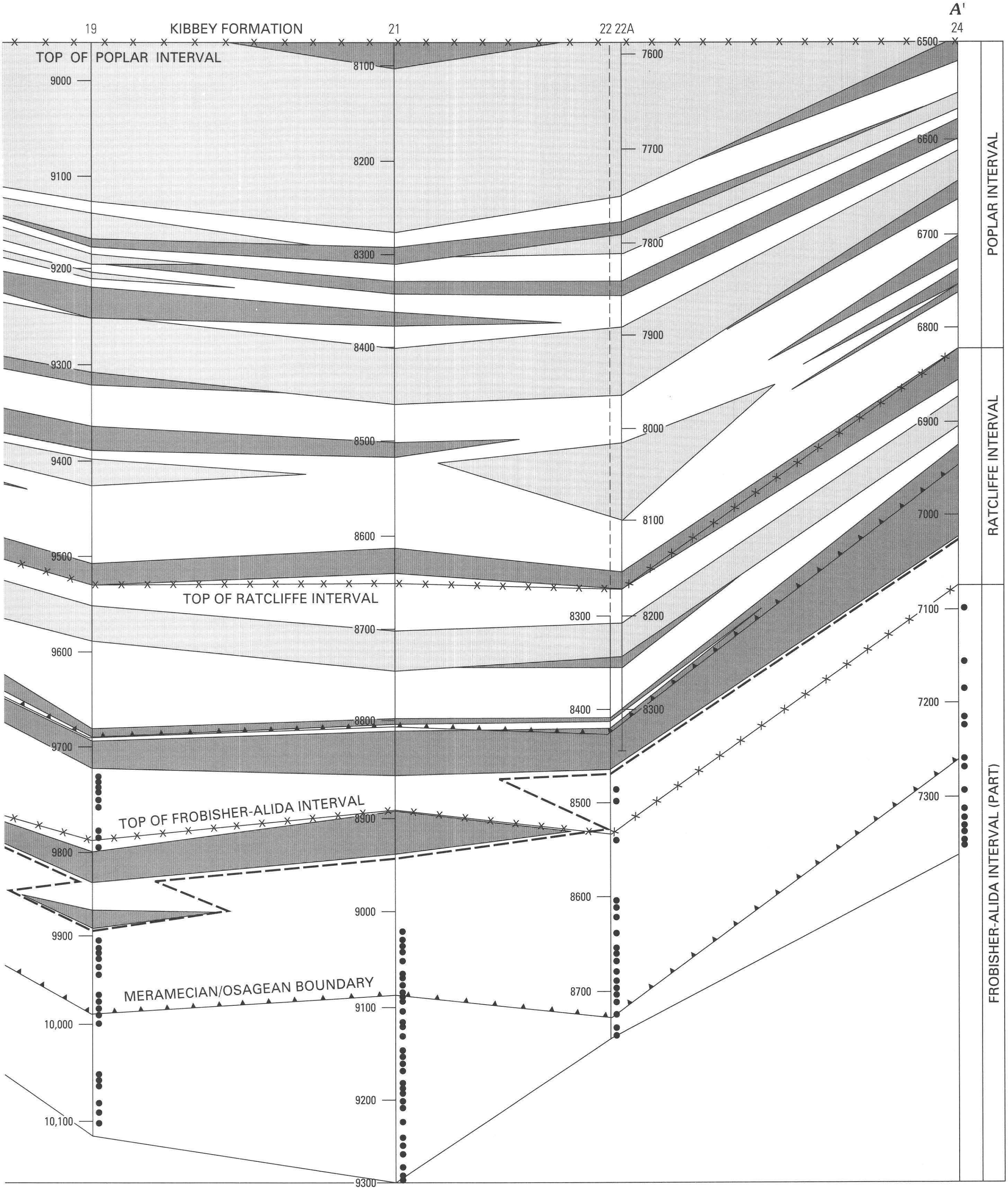


Figure 13 (above and facing page). Approximately south to north lithostratigraphic profile of Charles Formation and uppermost Mission Canyon Limestone across Madison salt basin in Montana and North Dakota. Datum is top of Charles Formation. See figure 12 and table 2 for data on well sections.


A'
19
KIBBEY FORMATION
21
22 22A
24
TOP OF POPLAR INTERVAL
TOP OF RATCLIFFE INTERVAL
TOP OF FROBISHER-ALIDA INTERVAL
MERAMECIAN/OSAGEAN BOUNDARY
POPLAR INTERVAL
RATCLIFFE INTERVAL
FROBISHER-ALIDA INTERVAL (PART)
9000
9100
9200
9300
9400
9500
9600
9700
9800
9900
10,000
10,100
8100
8200
8300
8400
8500
8600
8700
8800
8900
9000
9100
9200
9300
7600
7700
7800
7900
8000
8100
8200
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7000
7100
7200
7300

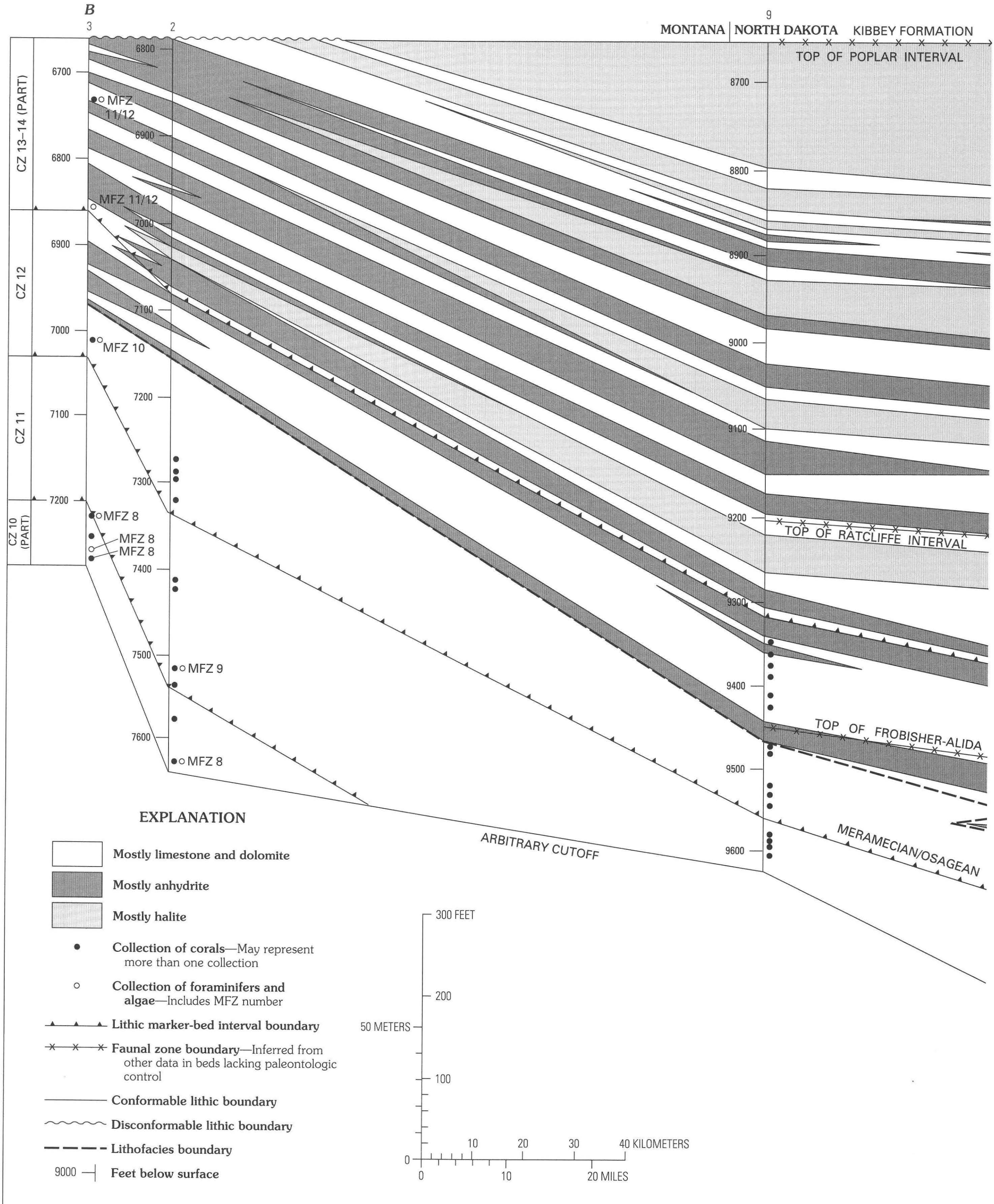


Figure 14 (above and facing page). Approximately east to west lithostratigraphic profile of Charles Formation and uppermost Mission Canyon Limestone across Madison salt basin in Montana and North Dakota. Datum is top of Charles Formation. See figure 12 and table 2 for data on well sections.

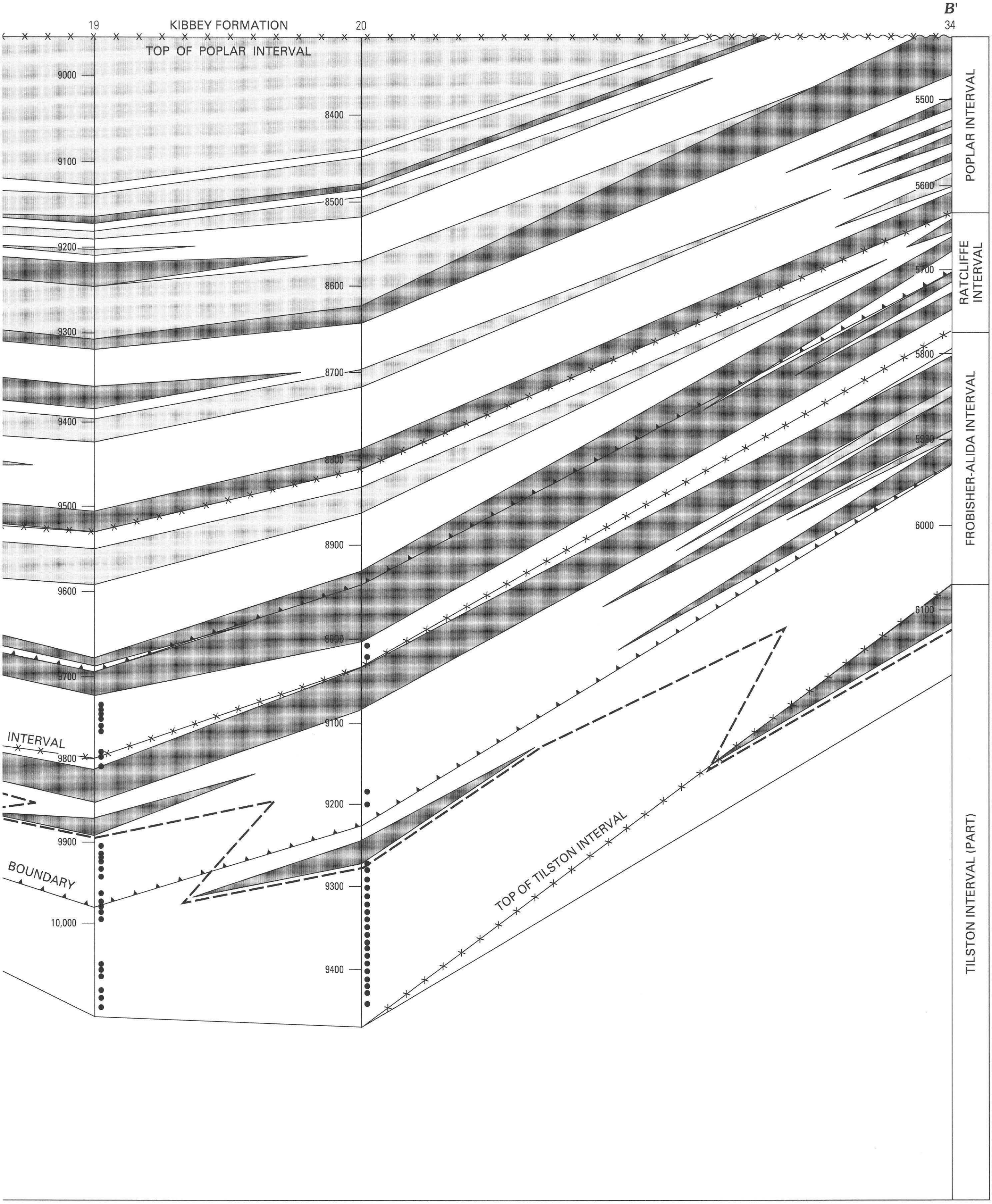

B'
19
KIBBEY FORMATION
20
34
TOP OF POPLAR INTERVAL
9000
8400
5500
9100
8500
5600
9200
8600
5700
9300
8700
5800
9400
8800
5900
9500
8900
6000
9600
9000
6100
9700
9100
9800
9200
9900
9300
10,000
9400
INTERVAL
BOUNDARY
TOP OF TILSTON INTERVAL
POPLAR INTERVAL
RATCLIFFE INTERVAL
FROBISHER-ALIDA INTERVAL
TILSTON INTERVAL (PART)

Table 2. Locations and sources of data for well sections shown in figure 12.

[Asterisk (*) denotes well section in stratigraphic profiles in figures 13 and 14. NDGS numbers refer to Wilson M. Laird Core and Sample Library of the North Dakota Geological Survey, Grand Forks, N. Dak. Amstrat refers to well logs of American Stratigraphic Company, Denver, Colo.]

Well No.	Well name	Location	Sources of data: Lithology	Sources of data: Paleontology
		MONTANA		
1*	Shell Oil Co., Pine Unit 1	SW¼SW¼NE¼ sec. 30, T. 12 N., R. 57 E., Wibaux Co.	Amstrat log M–705	Sando (1960b, pl. 13; 1978, pl. 1), Sando and Mamet (1981, fig. 2).
2*	Shell Oil Co., Richey area Northern Pacific Railroad 1	SW¼NW¼NW¼ sec. 19, T. 23 N., R. 50 E., Dawson Co.	Amstrat log M–2425	Sando (1960b, pl. 13; 1978, pl. 1), Sando and Mamet (1981, fig. 2).
3*	Hodge, Smith, and Hodge Co., Eggebrecht 1	Center SW¼SE¼ sec. 3, T. 23 N., R. 49 E., McCone Co.	Amstrat log B–220	Sando (1978, pl. 1), Sando and Mamet (1981, fig. 2).
4	C. H. Murphy Co., East Poplar Unit 1	Center SW¼NE½ sec. 2, T. 28 N., R. 51 E., Roosevelt Co.	Amstrat log B–29	Sando (1960b, pl. 13; 1978, pl. 1), Sando and Mamet (1981, fig. 2).
5	California Co., Grimm 1	Center NE¼SE¼ sec. 13, T. 32 N., R. 49 E., Roosevelt Co.	Amstrat log B–260	Sando (1978, pl. 1), Sando and Mamet (1981, fig. 2).
6	Socony Vacuum Oil Co. (Mobil Producing Co.), Damm F–33–23–P	NW¼SE¼ sec. 23, T. 29 N., R. 54 E., Roosevelt Co.	Amstrat log B–430R	Sando (1978, pl. 1), Sando and Mamet (1981, fig. 2).
7	Texas Co., Donahue 1	Center SW¼NE¼ sec. 23, T. 154 N., R. 100 W., Williams Co.	Amstrat log M–760	Sando (1978, pl. 1), Sando and Mamet (1981, fig. 2).
		NORTH DAKOTA		
8	Sun Oil Co., State Lease 1 (NDGS 3235)	NW¼NW¼ sec. 16, T. 156 N., R. 101 W., Williams Co.	Waters (1984, pl. 2), Waters and Sando (1987a, fig. 8), Cook (1976, pl. 6)	Waters (1984, pl. 2), Waters and Sando (1987a, fig. 8).
9*	Shell Oil Co., Shell USA 42–28–43 (NDGS 7207)	SE¼NE¼ sec. 28, T. 148 N., R. 104 W., McKenzie Co.	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7), S.B Anderson (written commun., 1993)	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7).
10*	Texaco Oil Co., Govt. Mary Pace 1 (NDGS 2667)	SW¼NW¼ sec. 14, T. 146 N., R. 101 W., McKenzie Co.	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7), Cook (1976, pl. 9)	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7).
11	Tiger Oil Co., Roughrider Federal 3–32 (NDGS 5258)	SW¼NE¼ sec. 32, T. 145 N., R. 101 W., McKenzie Co.	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7)	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7).
12	Shell Oil Co., Northern Pacific Railway Co., Govt. 44–14 (NDGS 4419)	SE¼SE¼ sec. 14, T. 144 N., R. 102 W., Billings Co.	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7)	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7).
13*	Shell Oil Co., Govt. 41x–18 (NDGS 4455)	NE¼NE¼ sec. 18, T. 143 N., R. 101 W., Billings Co.	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7), Cook (1976, pl. 9)	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7).
14	W. H. Hunt Trust Estate, Rodakowski 1 (NDGS 7104)	SE¼SW¼ sec. 3, T. 142 N., R. 100 W., Billings Co.	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7)	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7).
15	Tenneco Oil Co., David USA 1–35 (NDGS 7446)	SE¼NE¼ sec. 35, T. 142 N., R. 101 W., Billings Co.	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7)	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7).
16	Socony Vacuum Oil Co., Jacobs 1–F–14–24–P (NDGS 511)	SW¼SW¼ sec. 24, T. 134 N., R. 96 W., Hettinger Co.	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7), Cook (1976, pl. 9)	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7).
17	Socony Vacuum Oil Co., Dvorak F–32–6–P (NDGS 505)	SE¼NE¼ sec. 6, T. 141 N., R. 94 W., Dunn Co.	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7), Cook (1976, pl. 9)	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7).

Table 2. Locations and sources of data for well sections shown in figure 12.
[Asterisk (*) denotes well section in stratigraphic profiles in figures 13 and 14. NDGS numbers refer to Wilson M. Laird Core and Sample Library of the North Dakota Geological Survey, Grand Forks, N. Dak. Amstrat refers to well logs of American Stratigraphic Company, Denver, Colo.]

Well No.	Well name	Location	Sources of data: Lithology	Sources of data: Paleontology
		NORTH DAKOTA—Continued		
18	Gulf Energy and Minerals Co., Lind 2–13–2–D (NDGS 6230)	SW¼NE¼ sec. 13, T. 145 N., R. 98 W., McKenzie Co.	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7), Cook (1976, pl. 9)	Waters (1984, pl. 1), Waters and Sando (1987a, fig. 7).
19*	California Oil Co., Rough Creek Unit 1 (NDGS 527)	NW¼NE¼ sec. 13, T. 148 N., R. 98 W., McKenzie Co.	Waters (1984, pl. 2), Waters and Sando (1987a, fig. 8), S.B. Anderson (written commun., 1993)	Waters (1984, pl. 2), Waters and Sando (1987a, fig. 8).
20*	Mobil Oil Co., Kennedy F–32–24–P (NDGS 607)	SW¼NE¼ sec. 24, T. 149 N., R. 93 W., Dunn Co.	Waters (1984, pl. 2), Waters and Sando (1987a, fig. 8), S.B. Anderson (written commun., 1993)	Waters (1984, pl. 2), Waters and Sando (1987a, fig. 8).
21*	Amerada Petroleum Corp., Brenna–Lacey Unit 1 (1 Antelope Unit A) (NDGS 1350)	NE¼NE¼ sec. 1, T. 152 N., R. 95 W., McKenzie Co.	Waters (1984, pl. 2), Waters and Sando (1987a, fig. 8)	Waters (1984, pl. 2), Waters and Sando (1987a, fig. 8).
22*, 22*A	Amerada Petroleum Corp., Jens Kvam 4 (NDGS 480), and Amerada Petroleum Corp., 9 Unit A	NE¼SW¼ sec. 29 and SE¼SW¼ sec. 16, T. 156 N., R. 95 W., Williams Co.	Waters (1984, pl. 2), Waters and Sando (1987a, fig. 8), Carlson (1967, pl. 5)	Waters (1984, pl. 2), Waters and Sando (1987a, fig. 8).
23	Pan American Petroleum Corp., Calma Dove 1 (NDGS 3510)	SW¼NW¼ sec. 12, T. 161 N., R. 94 W., Burke Co.	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9)	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9).
24*	Phillips Petroleum Co., Braathen 1 (NDGS 1024)	NE¼NW¼ sec. 29, T. 162 N., R. 95 W., Divide Co.	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9), Anderson (1958, fig. 3)	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9).
25	Cardinal Petroleum Co., Orrin Lien 1–3417 (NDGS 4692)	SW¼SE¼ sec. 17, T. 163 N., R. 95 W., Divide Co.	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9)	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9).
26	Sun Oil Co., A. Bloom 3 (NDGS 2630)	NE¼SE¼ sec. 3, T. 162 N., R. 92 W., Burke Co.	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9)	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9).
27	U.S. Smelting, Refining, & Mining Co., Radenz "A" 1 (NDGS 3932)	SW¼NW¼ sec. 29, T. 163 N., R. 89 W., Burke Co.	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9)	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9).
28	Kissinger Petroleum Corp., Knutson 14–1 (NDGS 5551)	SE¼SW¼ sec. 1, T. 163 N., R. 87 W., Renville Co.	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9)	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9).
29	Chandler and Associates, Inc., Crooks 15–25 (NDGS 5247)	SW¼SE¼ sec. 25, T. 162 N., R. 84 W., Renville Co.	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9)	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9).
30	Chandler and Associates, Inc., Halloff 1 (NDGS 3944)	NE¼SW¼ sec. 21, T. 163 N., R. 82 W., Bottineau Co.	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9)	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9).
31	Lion Oil Co., Einar Madsen 1 (NDGS 939)	SE¼NW¼ sec. 27, T. 163 N., R. 77 W., Bottineau Co.	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9)	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9).
32	California Oil Co., Blanche Thompson 1 (NDGS 38)	SW¼SE¼ sec. 31, T. 160 N., R. 81 W., Bottineau Co.	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9)	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9).
33	Phillips Petroleum Co., Olivia Saude 1 (NDGS 274)	NW¼SE¼ sec. 19, T. 158 N., R. 74 W., Pierce Co.	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9)	Waters (1984, pl. 3), Waters and Sando (1987a, fig. 9).
34*	Herman Hansen Oil Syndicate, Samuelson 1 (NDGS 1516)	SE¼SW¼ sec. 32, T. 146 N., R. 82 W., McLean County	Waters (1984, pl. 2), Waters and Sando (1987a, fig. 8), S.B. Anderson (written commun., 1993)	Waters (1984, pl. 2), Waters and Sando (1987a, fig. 8).
35	Tom F. Marsh Co., Clark 1 (NDGS 6254)	NW¼SW¼ sec. 10, T. 140 N., R. 76 W., Burleigh Co.	Waters (1984, pl. 2), Waters and Sando (1987a, fig. 8), S.B. Anderson (written commun., 1993)	Waters (1984, pl. 2), Waters and Sando (1987a, fig. 8).

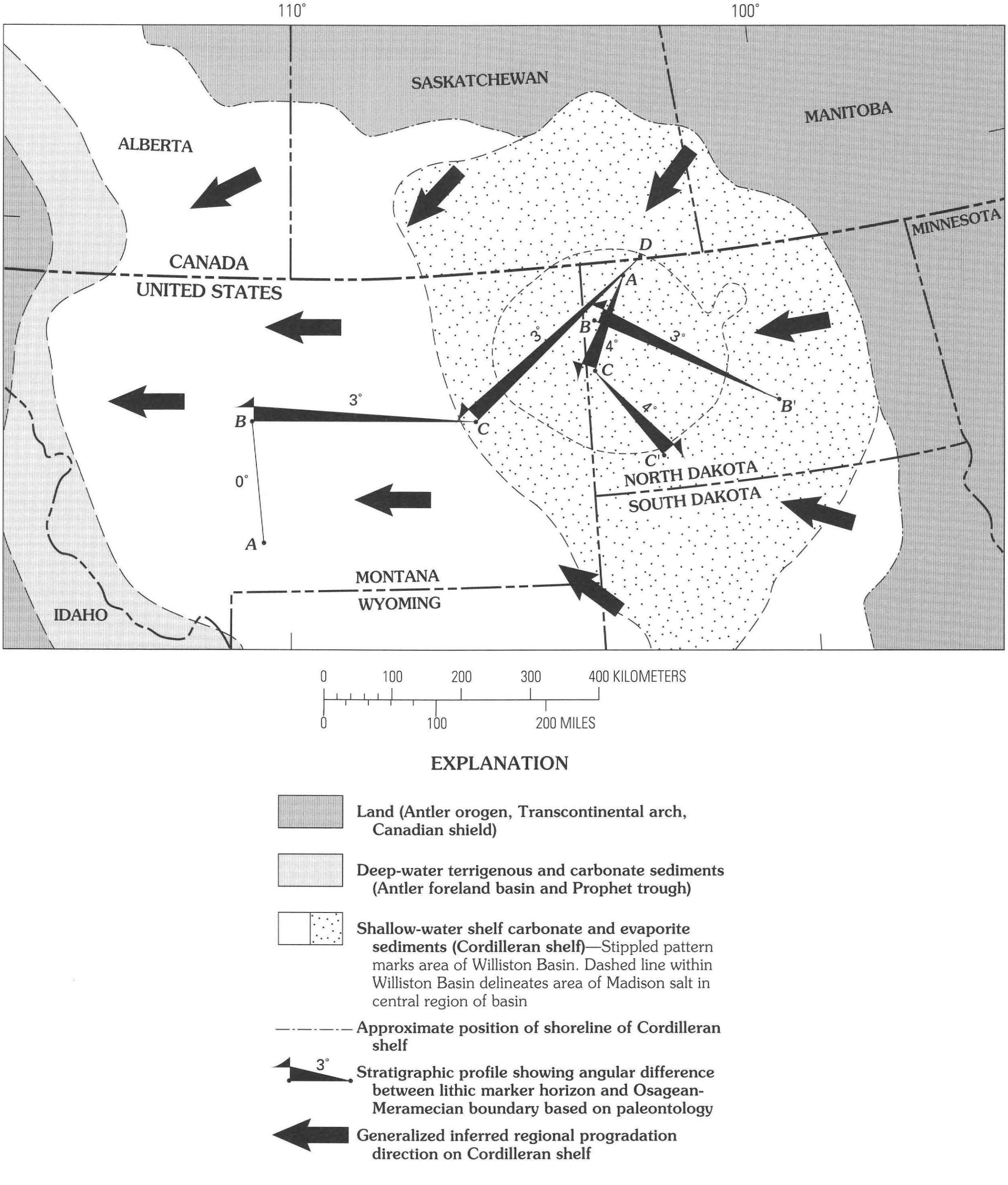


Figure 15. Generalized paleogeographic map of Williston Basin and adjacent areas during latest Osagean and earliest Meramecian (CZ 11–12) time showing component progradation directions and magnitudes as measured by angular differences between key lithic marker horizons and paleontologically determined Osagean-Meramecian boundary in profiles shown in figures 13, 14, and 16. Outline of Williston Basin modified from Peterson (1984, fig. 3) and Kent (1984, fig. 2).

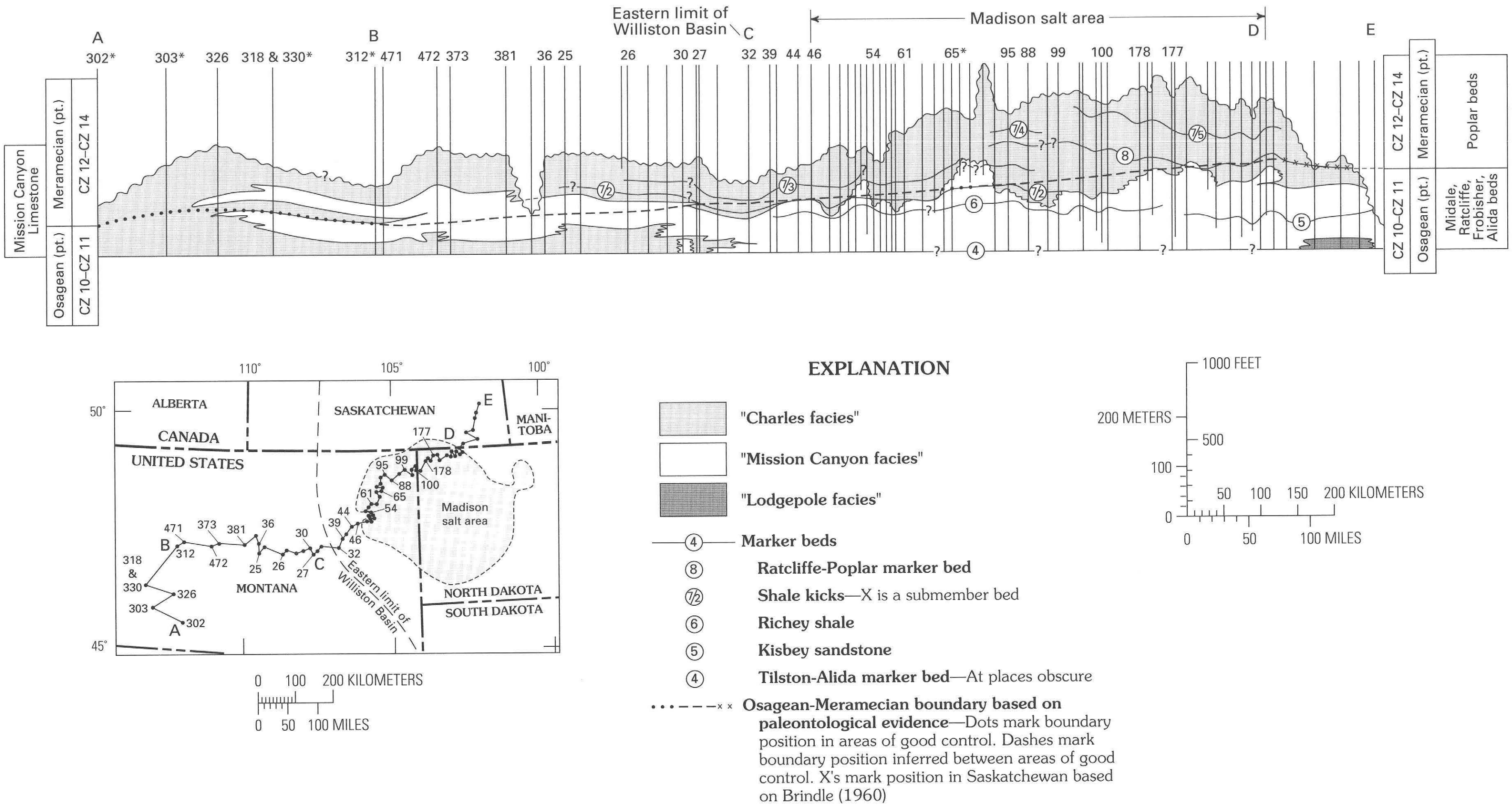


Figure 16. Stratigraphic profile from Madison outcrop area into Williston Basin showing relation between lithic marker beds and Osagean-Meramecian boundary as determined biostratigraphically. Datum is Tilston-Alida marker bed. Replotted from Sheldon and Carter (1979, fig. 54). See Sheldon and Carter (1979, table 4) for locations of control sections.

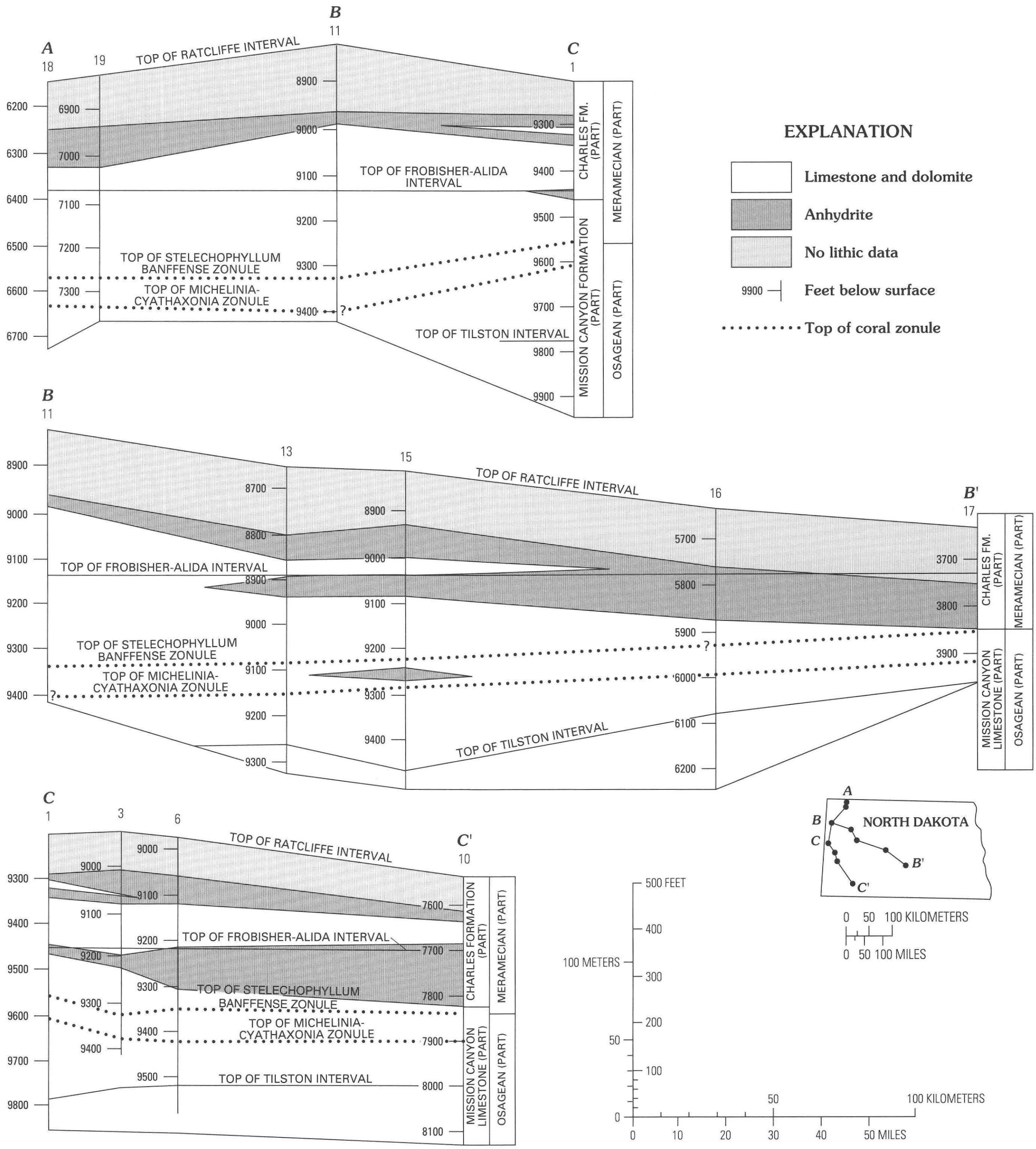


Figure 17. Stratigraphic profiles in western North Dakota showing relations between lithic marker beds, lithofacies, and coral zonule tops from margins to center of Williston Basin. Datum is top of Frobisher-Alida interval. Replotted from Waters and Sando (1987a, figs. 7–9). See Waters and Sando (1987a, table 1) for locations of control sections.

EVALUATION OF CHRONOSTRATIGRAPHIC METHODS

The lithic marker beds of the Madison Group have been interpreted as terrigenous interruptions that terminate periods of widespread stillstand in a cyclic carbonate-evaporite sequence (see p. 17). Although neither the stillstands nor the pulses of terrigenous sediment that follow them are theoretically instantaneous over the broad expanse of the Cordilleran shelf, the lithic marker horizons are clearly more reliable measures of synchroneity than conventional lithic datum planes used to define formations. The widespread distribution of the lithic markers and their ease of recognition on radioactivity logs (except for the central area of the Madison salt basin) have made these markers excellent practical tools for approximate chronostratigraphy in the subsurface of the Williston Basin.

Biozone boundaries recognized in the Madison Group are based on abrupt evolutionary changes in assemblages of benthic marine organisms. Similar to the lithic marker horizons, these interruptions in the marine evolutionary continuum were not theoretically instantaneous over the entire shelf because the organisms were restricted to the bottom environment of a shallow sea that shifted seaward and shoreward many times during Madison time. Net seaward progradation of the shallow-water carbonate sediment forced benthic organisms to migrate seaward along with the sediment; hence the seaward occurrences of these organisms are inevitably progressively younger than their occurrences closer to shore.

The fact that the lithic marker horizons climb stratigraphically with respect to faunal zone boundaries in directions perpendicular to the shoreline suggests that the terrigenous pulses represented by the lithic marker beds prograded seaward at a slower rate than that of migrations of the organisms. Stillstands, some marked by surfaces of subaerial exposure, could not have affected the entire expanse of the huge Cordilleran shelf instantaneously because the assemblages of benthic organisms immediately above the stillstands are indistinguishable from the assemblages below them, indicating that the organisms did not migrate to some distant area off the shelf. If such migrations had occurred, the character of succeeding organic assemblages would have changed dramatically because none of the shallow-water genera are known in coeval deep-water areas west of the Cordilleran shelf.

I conclude that the biozone boundaries are closer approximations to absolute synchroneity than are the lithic marker horizons. The time differences between the two time measures are not greatly significant for exploration stratigraphy within the subsurface of the Williston Basin, but the differences can be quite significant in regional chronostratigraphic correlations between the outcrop area and the subsurface of the Williston Basin.

SUMMARY OF REGIONAL DEPOSITIONAL HISTORY

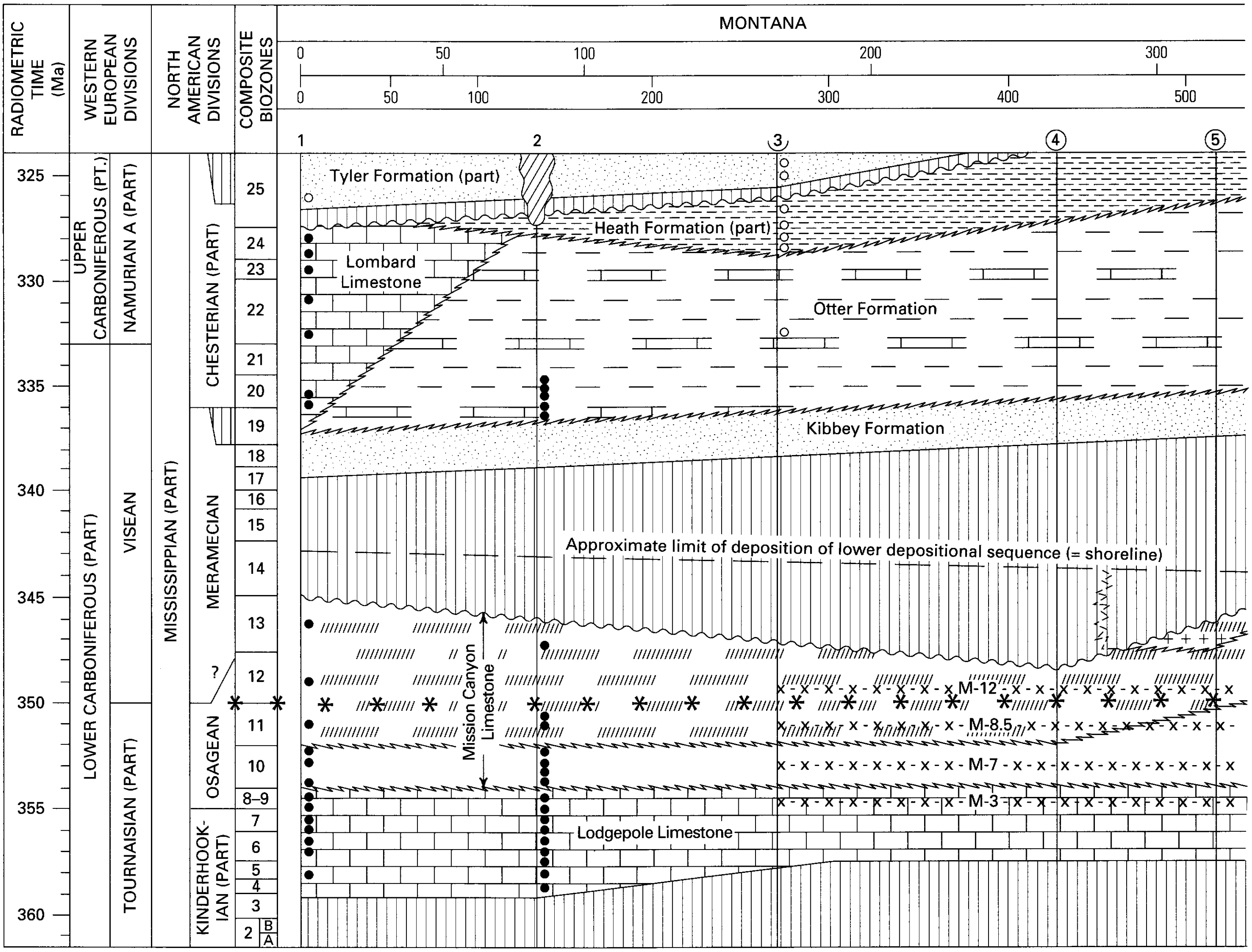
REGIONAL CHRONOSTRATIGRAPHIC LITHOFACIES PROFILE

A chronostratigraphic lithofacies profile of the Madison and Big Snowy Groups from central Montana to eastern North Dakota (fig. 18, table 3) places the Madison salt in a regional framework of Mississippian depositional history and forms the principal basis for analyzing the history of the salt. This profile shows two depositional sequences separated by a major hiatus, except in the center of the Williston Basin, where the top Madison salt is present.

The upper part of the lower depositional sequence consists mainly of shallowing-upward, regressive, shelf carbonate and evaporite sediments of the Mission Canyon Limestone and Charles Formation deposited during the Osagean and Meramecian (CZ 10 to CZ 14). Intermittent marine anhydrite sedimentation was common on most of the shelf during the middle and late Osagean and early Meramecian (CZ 10 to CZ 14), but intermittent marine halite deposition was confined to the central area of the basin during later early Meramecian time (CZ 13 to CZ 14). Although marine sedimentation on the shelf surrounding the Williston Basin continued into CZ 14, as it did in the basin, preservation of younger (CZ 13 and CZ 14) strata in the basin indicates that these strata were protected from the erosion that removed more of the stratigraphic record during middle and late Meramecian (CZ 15 through CZ 19) from areas surrounding the basin. Sinking of the crust beneath the Williston Basin evidently was the principal factor in preserving the stratigraphic record, but an arid climate that curtailed solution during emergence probably also contributed to the preservation of carbonate and evaporite strata. The top Madison salt, deposited in a landlocked lake, represents the final phase in the drying up of the Madison sea.

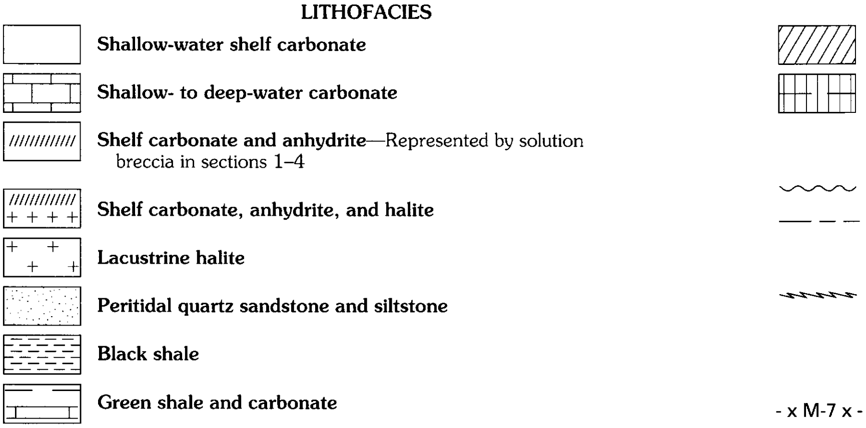
Diachroneity of boundaries between lithofacies in the lower depositional sequence is evident from the margins of the Williston Basin toward its center owing to slow progradation of carbonate sediments. West of the basin, the lithofacies boundaries appear to be synchronous because progradation was too rapid to be detected by the biozonation.

The upper depositional sequence consists mainly of deepening-upward, transgressive, terrigenous sediments of the Big Snowy Group deposited on the eroded surface of the Madison Group during late Meramecian (CZ 17 through CZ 19) and Chesterian (CZ 20 through CZ 26) time. Sediments of the Kibbey Formation, basal phase of the transgression, swept eastward across the Madison karst plain, invaded the salt lake, and gradually extinguished halite deposition in the early Chesterian (CZ 20).



EXPLANATION

LITHOFACIES



Shallow-water shelf carbonate

Shallow- to deep-water carbonate

Shelf carbonate and anhydrite—Represented by solution breccia in sections 1–4

Shelf carbonate, anhydrite, and halite

Lacustrine halite

Peritidal quartz sandstone and siltstone

Black shale

Green shale and carbonate

HIATUS

Sedimentary record removed by post-Carboniferous erosion

Sedimentary record removed by intra-Carboniferous erosion—Restored limit of deposition shown by dashed line

SEDIMENTARY BOUNDARIES

Unconformity

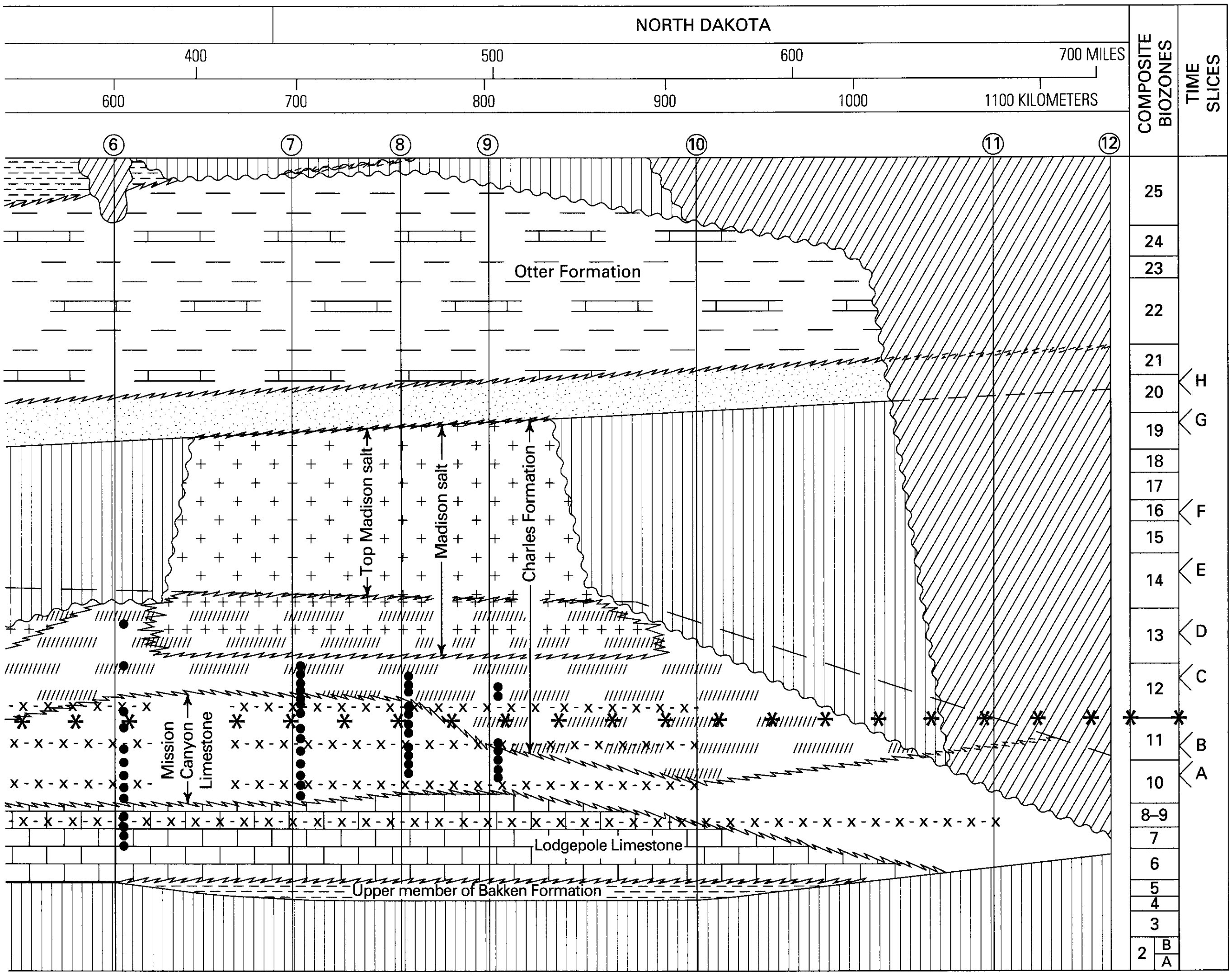
Beginning of deposition on unconformable surface—Dashed where inferred in areas in which sedimentary record was removed by erosion

Transitional or interfingering lithofacies boundary—Dashed where inferred in areas in which sedimentary record was removed by erosion

LITHOCHRONOLOGIC CONTROL

- x M-7 x - Time plane based on marker bed of Peterson (1984)

Figure 18. Chronostratigraphic lithofacies profile of Madison and Big Snowy Groups from central Montana to eastern North Dakota. See table 3 for locations and references for control sections. Time-slice positions A–H at right margin of diagram refer to paleogeographic maps in figure 19. Vertical lines in column for North American divisions denote hiatus.



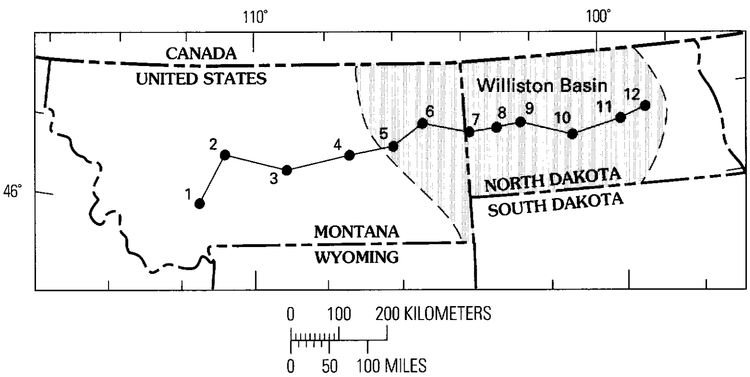
BIOCHRONOLOGIC CONTROL

- ● Collections of fossils critical for composite zone determination
- ○ Collections of other fossils used for biostratigraphic correlation
- * * Osagean-Meramecian boundary based on fossils and used as datum for profile

STRATIGRAPHIC SECTIONS
(see table 3 for locations and references)

- 1 Outcrop section
- ④ Subsurface section
- ◡3◡ Composite of outcrop and subsurface sections

INDEX MAP



REGIONAL PALEOGEOGRAPHIC MAPS

Regional paleogeographic maps (fig. 19) for selected sequential time slices through the chronostratigraphic lithofacies profile (pl. 4) are also useful for visualizing Mississippian depositional history in the study area. These maps were prepared by using the profile as the main determinant and augmenting data in the profile with data from other control points in Montana, North Dakota, South Dakota, and Wyoming from Sando and Bamber (1985) and Peterson (1984). Maps published by Sando and others (1975) and Sando (1988, 1989a) served as general guides.

SHORELINES

Movements of the shoreline during deposition of the Mission Canyon Limestone and Charles Formation shown on the maps are an improvement over the static shorelines shown on previous maps. These movements were revealed by projection of the maximum limit of deposition of the lower depositional sequence on the profile to the erosional zero edge of the Madison Group in North Dakota. This projection is based on the time constraints imposed by biostratigraphic dating of the youngest Madison strata and earliest Big Snowy strata and chronostratigraphic projection of these constraints eastward through the Williston Basin to a line slightly east of the erosional zero edge of the Madison. The time plane of maximum deposition inclines downward toward the erosional zero edge because withdrawal of the Madison sea was more rapid in the area adjacent to the shoreline than at the center of the Williston Basin, where subsidence of the sea floor proceeded at a faster rate. Successive shoreline positions shown on the maps are locations where the time-slice planes intersect the time plane of maximum deposition.

TIME SLICE A (CZ 10, MIDDLE OSAGEAN)

Middle Osagean time (CZ 10) was characterized by deposition of carbonate sediments in shallow marine water (depths probably 50 m or less) over most of the Cordilleran shelf except in a linear belt several hundred kilometers west of the shoreline, where anhydrite was deposited intermittently in many small, very shallow areas of restricted circulation within the complex of shelf carbonate environments. The evaporite belt may have originated on a slightly higher area of the sea floor. The climate was arid.

TIME SLICE B (CZ 11, LATE OSAGEAN)

By late Osagean time (CZ 11), the shoreline had moved westward more than 100 km as the sea retreated. The area of intermittent anhydrite deposition within the carbonate complex had expanded to cover most of the Cordilleran shelf except for areas of freer circulation in slightly deeper water in a belt adjacent to the shoreline and in the center of the Williston Basin.

TIME SLICE C (CZ 12, EARLIEST MERAMECIAN)

Earliest Meramecian time (CZ 12) was characterized by continued westward movement of the shoreline and expansion of the area of restricted circulation that resulted in anhydrite deposition within the shelf carbonate complex. The entire Cordilleran shelf in the study area was characterized by a complex of very shallow, restricted environments.

TIME SLICE D (CZ 13, EARLY MERAMECIAN)

Slightly later in early Meramecian time (CZ 13), marine halite was deposited intermittently in the center and slightly southwest of the center of the Williston Basin. The two discrete areas of halite deposition shown on the paleogeographic map may have been connected, and the absence of salt in the intervening Poplar dome area may be due to removal of salt by later solution in that area. The shoreline had moved slightly west of its position in time slice C, and the eastern edge of the area of halite deposition was less than 100 km from the shore. Intermittent halite deposition took place in more restricted marine areas, probably in somewhat deeper water, according to the model of Sloss (1953)(see p. 21).

The area of the X salt of Anderson and Hansen (1957) and Anderson (1964) is not shown on the map for this time because this salt is not intersected by the time slice, and the salt is not shown on Peterson's (1984, pl. 4, ND–W–1 and ND–ML–2) graphic sections used to construct the chronostratigraphic lithofacies profile (fig. 18). The X salt was thought to be "near the base of the Charles Formation" by Anderson and Hansen (1957) or in the upper part of the Mission Canyon Limestone by Sandberg (1962, p. 60, fig. 5). This salt was originally shown by Anderson and Hansen (1957, fig. 10) as occupying a small area in Bottineau, Renville, Ward, and McHenry Counties, North Dakota, but it was extended southward into McLean, Mercer, and Oliver Counties by Anderson (1964, fig. 10). The X salt is probably a nearshore eastward extension of the marine carbonate, anhydrite, and halite lithofacies shown in figure 18.

TIME SLICE E (CZ 14, LATE EARLY MERAMECIAN)

During late early Meramecian time (CZ 14), the sea continued to retreat westward across the Cordilleran platform, and the shoreline moved westward into central Montana, leaving most of the platform exposed to subaerial erosion. Continued subsidence of the crust in the center of the Williston Basin produced a landlocked salt lake that contained the last vestige of the restricted shelf sea that had previously covered the platform.

Table 3. Locations and sources of data for stratigraphic sections shown in figure 18.

Section No.	Name	Location	Source
1	Logan–Lombard composite	Logan: sec. 25, T. 2 N., R. 2 E., Gallatin Co., Montana. Lombard: SW¼ sec. 7, T. 4 N., R. 3 E., Broadwater Co., Mont.	Logan: Sando and Dutro (1974, p. 4–8). Lombard: Wardlaw and Pecora (1985, p. B4–6), Sando (unpub. field notes).
2	Dry Fork–Monarch composite	Dry Fork: secs. 35 and 36. Monarch: secs. 22 and 27. Both in T. 16 N., R. 7 E., Cascade Co., Mont.	Dry Fork: Sando and Dutro (1974, p. 12–16). Monarch: Sando and Dutro (1974, p. 8–12).
3	Stonehouse Canyon–Shell 21–19 NP well composite	Stonehouse Canyon: sec. 25, T. 11 N., R. 20 E., and sec. 29, T. 31 N., R. 21 E. Shell well: sec. 19, T. 9 N., R. 21 E. Both in Golden Valley Co., Mont.	Stonehouse Canyon: Easton(1962, p. 121–124), Sando and others (1975, pl. 10). Shell well: Peterson (1984, pl. 8, M–GV–1).
4	Ralph Lowe Sandquist 1 well	Sec. 28, T. 16 N., R. 36 E., Garfield Co., Mont.	Peterson (1984, pl. 5, M–GF–5).
5	Pan American NPRR well	Sec. 33, T. 17 N., R. 45 E., McCone Co., Mont.	Peterson (1984, pl. 4, M–MC–9).
6	Shell Richey NPRR 1 well–Hodge, Smith, and Hodge Eggebrecht 1 well composite	See entries 2 and 3 in table 2 for locations and data sources.	
7	Shell USA 42–28–43 well–J.H. Moore et al 1 Olson well composite	Shell well: see entry 9 in table 2 for location and data source. Moore well: sec. 18, T. 151 N., R. 103 W., McKenzie Co., N. Dak.	Moore well: Peterson (1984, pl. 4, ND–MK–18).
8	California Rough Creek Unit 1 well–Texas 1 Hovde well composite	California well: see entry 19 in table 2 for location and data source. Texas well: sec. 15, T. 154 N., R. 98 W., Williams Co., N. Dak.	Texas well: Peterson (1984, pl. 4, ND–WI–23).
9	Mobil Kennedy F–32–24P well–Hunt W. and D. Dunham well composite	Mobil well: see entry 20 in table 2 for location and data source. Hunt well: sec. 24, T. 155 N., R. 90 W., Mountrail Co., N. Dak.	Hunt well: Peterson (1984, pl. 4, ND–MO–7).
10	Herman Hansen Samuelson 1 well–Stanolind 1 McLean Co. well composite	Hansen well: see entry 34 in table 2 for location and data source. Stanolind well: sec. 28, T. 150 N., R. 80 W., McLean Co., N. Dak.	Stanolind well: Peterson (1984, pl. 4, ND–ML–2).
11	Calvert 1 Zwinger well	Sec. 8, T. 146 N., R. 68 W., Wells Co., N. Dak.	Peterson (1984, pl. 4, ND–WL–2).
12	Wetch et al 1 C. E. Blaskey well	Sec. 9, T. 148 N., R. 62 W., Eddy Co., N. Dak.	Peterson (1984, pl. 4, ND–ED–1).

TIME SLICE F (CZ 16, MIDDLE MERAMECIAN)

The entire Cordilleran platform in the study area was subaerially exposed during middle Meramecian time (CZ 16), forming a karst plain subjected to deep solution by groundwaters in areas outside the Williston Basin (Sando, 1988). The shoreline had retreated to extreme southwestern Montana, where the earliest phase of the Big Snowy–Amsden transgression had already begun (Sando, 1988, fig. 12.3.D). Deposition of halite continued in the landlocked lake at the center of the Williston Basin.

TIME SLICE G (CZ 19, LATE MERAMECIAN)

Late Meramecian time (CZ 19) was characterized by eastward transgression of the Big Snowy–Amsden sea across much of Montana and Wyoming (Sando, 1988, fig. 12.3.D). The initial phase of the transgression in the study area consisted of deposition of peritidal terrigenous sediments of the Kibbey Formation, which invaded and partly covered the eastern half of the salt lake at the center of the Williston Basin. A lobate area of lagoonal terrigenous and carbonate sediments of the Otter Formation that followed Kibbey deposition was present in central Montana.

TIME SLICE H (CZ 20, EARLIEST CHESTERIAN)

Earliest Chesterian time (CZ 20) is close to the culmination of the Big Snowy–Amsden transgression. The frontal lobe of the transgression, represented by the Kibbey Formation, completely covered the salt lake at the center of the Williston Basin. The lagoonal phase (Otter Formation) that followed Kibbey deposition occupied most of central and eastern Montana.

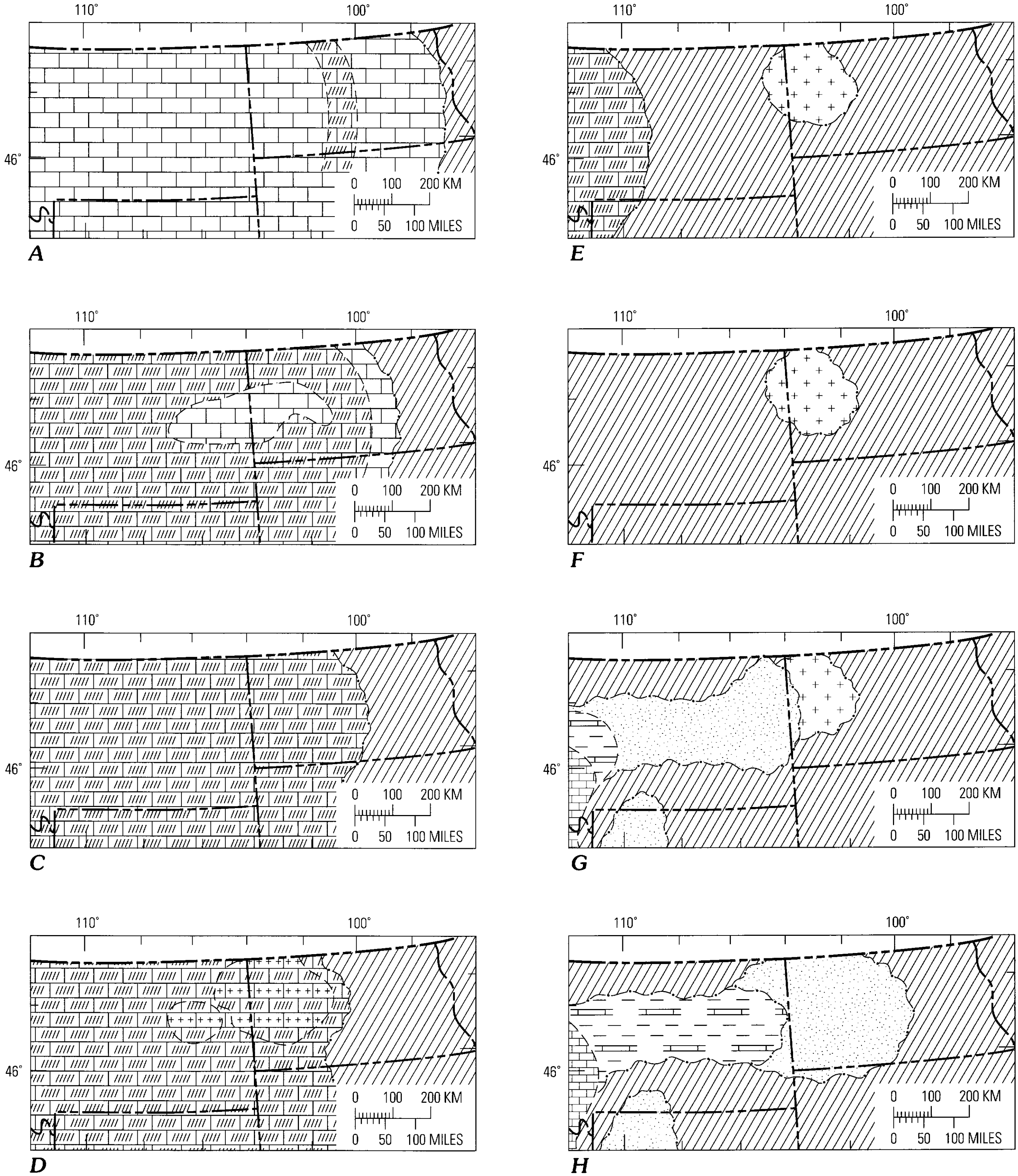
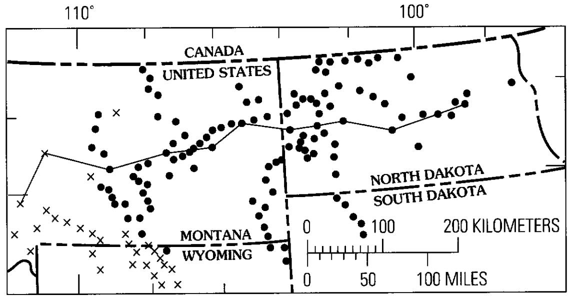


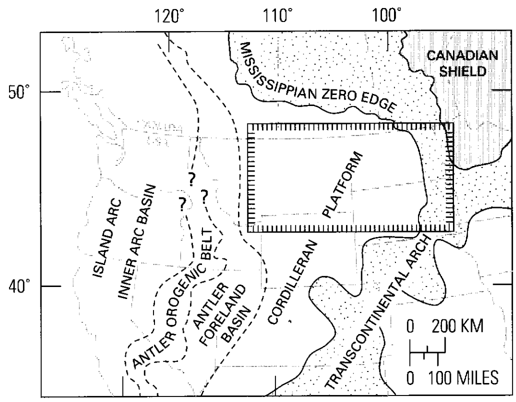
Figure 19. Sequential time-slice paleogeographic maps of the Mission Canyon Limestone and Charles Formation in Montana, North Dakota, and adjacent States. See figure 18 for chronostratigraphic positions of maps A–H. On index map x's mark locations of surface control sections and dots mark locations of subsurface control sections.

EXPLANATION

- Approximate shoreline inferred from stratigraphic geometry
- Approximate boundary between lithofacies
- Land
- Shelf carbonate
- Shelf carbonate and anhydrite
- Shelf carbonate, anhydrite, and halite
- Basinal carbonate
- Lacustrine halite
- Peritidal terrigenous silt and sand
- Lagoonal terrigenous mud and carbonate



INDEX MAP OF CONTROL POINTS



INDEX MAP

GENERAL CONCLUSIONS ABOUT GEOLOGIC MECHANISMS

The sequence of events inferred from lithic and biotic data in this report strongly suggests marked changes in relative sea level produced by more than one geologic mechanism. Moreover, other factors in addition to sea level were important in shaping the character of the sediments.

EUSTACY

Movements of the sea across the Cordilleran platform in the study area follow the general pattern of the eustacy curve described by Ross and Ross (1987, fig. 2) for the Osagean to Chesterian interval as defined in this report. Regression on the Cordilleran platform coincides with the Keokuk-Warsaw regression of Ross and Ross, the post-Madison, pre-Kibbey evacuation of the platform coincides with their post-Warsaw, pre-Salem lowstand, and the Big Snowy–Amsden transgression coincides with their Salem-Chester highstand. Ross and Ross (1987, fig. 2) also identified an exposed lowstand surface in their coastal onlap curve that coincides approximately with the post-Madison, pre-Kibbey hiatus. Biostratigraphic correlations between the study area and the type Mississippian, based mainly on foraminifers identified by B.L. Mamet, provide a general confirmation of the Ross and Ross sealevel curves; however, the eustacy curve and coastal onlap curves of Ross and Ross show several eustatic events not detected on the Cordilleran platform.

The stratigraphic sequence of the Cordilleran platform is a record of local events, some of which may have had global causes. Although the general pattern of eustacy appears to be confirmed, I cannot agree that all the events ascribed to eustacy by Ross and Ross are truly global.

TECTONISM

Evidence of vertical crustal movements is manifested by pulses of terrigenous sediment derived from the adjacent Transcontinental arch and by concentric sinking of the sea floor about the center of the Williston Basin.

The greatest influx of terrigenous sediment occurred during the Big Snowy–Amsden transgression, which suggests that sources of this sediment on the Transcontinental arch were subjected to uplift in that area at the same time that the Cordilleran platform was experiencing a highstand of the sea. A humid climate in the terrigenous source area may also have been a factor. Submergence of the southern part of the platform at the same time that the northern part was subaerially exposed (Sando, 1989a, fig. 3E–G) substantiates, however, the role of tectonism as a factor in controlling movements of the sea as well as shaping the character of the sediments.

Differential sinking of the sea floor in the Williston Basin was an important factor in the origin of the landlocked salt at the center of the basin. Sinking of the sea floor produced a topographic depression that, coupled with an arid climate, created conditions necessary for halite accumulation. The probable cause of sea-floor sinking was downward movement of the underlying crust.

CLIMATE

An arid climate was necessary for production of marine evaporite sediments that characterize parts of the Mission Canyon Limestone and most of the Charles Formation on most of the Cordilleran platform. However, the existence of an extensive river system and deep solution effects in the carbonate bedrock of the karst plain in the area surrounding the Williston Basin (Sando, 1988) are evidence of a humid climate in that part of the platform and on the Transcontinental arch. Moreover, the presence of a salt lake on the emergent platform in the Williston Basin, indicating aridity in that area, shows that the two contrasting climate regimes were operating in different parts of the platform at the same time. These coeval climatic indications suggest a complex regional climatic picture.

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