The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States— Montana

By DONALD L. SMITH *and* ERNEST H. GILMOUR

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Historical review and summary of areal, stratigraphic, structural, and economic geology of Mississippian and Pennsylvanian rocks in Colorado

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THE MISSISSIPPIAN AND PENNSYLVANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES—MONTANA

By DONALD L. SMITH[1] and ERNEST H. GILMOUR[2]

ABSTRACT

Carboniferous strata underlie all but the northwestern corner of Montana and are well exposed on the flanks of Tertiary uplifts throughout the State. The Carboniferous rock package attains a maximum thickness of 1,000 m along the Big Snowy trough, an east-trending paleostructural feature in central Montana; it thins to 300 m and 450 m in northern and southern Montana, respectively, on the flanks of the trough.

The contact of the Carboniferous rocks with underlying strata is unconformable, the rocks beneath the unconformity ranging in age from Ordovician to latest Devonian and generally increasing in age toward the southern part of the State. The contact of Carboniferous strata with overlying rocks is also unconformable, the overlying strata ranging from Permian and Triassic at the Montana-Wyoming border to Middle Jurassic in the northern part of the State.

Carboniferous rocks of Montana are divided into four lithologic units, each deposited under a different set of tectonic and environmental conditions. These units are the Madison Group, the Big Snowy Group, the Amsden Group, and the Quadrant Formation. In the Carboniferous section in Montana, a general upward decrease in clean limestone and an increase in both fine and coarse detrital components reflects the increasing epeirogenic-orogenic tempo of the later Carboniferous.

Major groups of Carboniferous strata were named or recognized in the late 1800's; since then, detailed studies have refined the stratigraphic nomenclature to its present complexity. The Madison Group of Kinderhookian, Osagean, and Meramecian age consists of the Lodgepole, Mission Canyon, and Charles Formations, in ascending order. The Lodgepole is divided into the Cottonwood Canyon, Paine, and Woodhurst Members. The Big Snowy Group is Chesterian in age and incorporates the Kibbey, Otter, and Heath Formations. The Amsden Group is latest Mississippian (Springerian), Morrowan, and Atokan(?) in age and includes three formations—the Tyler, Alaska Bench, and Devils Pocket. The Tyler is divided into the unnamed lower member and the Cameron Creek Member. The Desmoinesian-age Quadrant Formation is the fourth package, completing the Carboniferous section in Montana.

Carboniferous strata in Montana were deposited predominantly on the western edge of the North American craton, but in the extreme western part of the State, Carboniferous sediments accumulated in the Cordilleran miogeosyncline. During the latest Devonian and earliest Mississippian, the craton was divided into four shallow marine basins, all separated by low-lying arches that, through the erosion of rocks as old as Cambrian, provided a source of fine-grained sediment. Throughout the remainder of Madison and Big Snowy deposition, the Montana part of the craton was characterized by stable shelves to the north and south, separated by the elongate Big Snowy trough that extended from the Cordilleran miogeosyncline on the west to the Williston basin in the extreme northeastern corner of the State. During deposition of the Amsden Group, uplift in northern Montana on the site of the former northern stable shelf provided clastic sediment to the Big Snowy trough, which continued to subside. Deposition of the Quadrant Formation brought the Carboniferous to a close; the coarse clastic sediments were provided from large western uplifts as well as from the eastern craton.

Deposition of Carboniferous rocks began with a complex interplay of sea-level change and epeirogenic warping of the craton. In shallow basins between low-lying arches, black shale and siltstone of the late Devonian Bakken, Exshaw, and Englewood Formations and the Sappington Member of the Three Forks Formation were deposited. This latest Devonian transgression was short-lived and the sea partly regressed from Montana as epeirogenic movements continued to block out arches and basins on the Montana craton, providing coarser clastic sediment to the intervening basins. The earliest Mississippian transgression from the Cordilleran miogeosyncline is recorded in the black shale and siltstone of the Cottonwood Canyon Member of the Lodgepole Formation and the upper black shale of the Bakken Formation. The environments in which these fine-grained clastic rocks accumulated quickly gave way to higher energy environments in which the bioclastic facies at the base of the Paine Member of the Lodgepole Formation were deposited.

After the deposition of the bioclastic facies of the Paine Member, the rate of transgression and/or subsidence of the Big Snowy trough outstripped the rate of carbonate sediment production, creating a deeper water environment in central Montana while shallow-water carbonate sediments contemporaneously accumulated on the stable shelves to the north and south. A decrease in the rate of sea-level rise and/or rate of subsidence of the Big Snowy trough and concomitant increased production of carbonate sediment led to the progradation of high-energy, shallow-water carbonate sediments from the north and south into the Big Snowy

[1] Department of Earth Sciences, Montana State University, Bozeman, Mont. 59717.

[2] Department of Geology, Eastern Washington State University, Cheney, Wash. 99004.

trough, leading to deposition of the cyclic neritic deposits of the Woodhurst Member of the Lodgepole Formation.

The Mission Canyon Limestone was deposited under similar but more stable conditions than was the Woodhurst Member of the Lodgepole Limestone. The limestone of the Mission Canyon records shallow-water high-energy conditions that eventually gave rise to restricted environments in which extensive evaporite deposits accumulated, creating the evaporite-solution-breccia couplets of the surface and subsurface of Montana. The Charles Formation is probably the evaporite-rich subsurface equivalent of the upper brecciated part of the Mission Canyon Limestone. After deposition of the Mission Canyon-Charles evaporites, the Madison sea retreated to the Cordilleran miogeosyncline from the craton, and the ensuing exposure and erosion produced a karst surface of regional extent.

In Chesterian time, the Big Snowy sea transgressed across this surface, beginning in southwestern Montana and proceeding across the Big Snowy trough to the Williston basin. At the leading edge of this sea, the Kibbey Sandstone was deposited in beach and nearshore environments. Synchronously, in deeper, quieter water eastward of the coarse clastic zone, shale and limestone of the Otter Formation were deposited. In the deep and quiet water of the trough axis, dark shale and limestone of the Heath Formation accumulated. After deposition of the Big Snowy Group, the sea withdrew from most of the Big Snowy trough, creating an unconformity between Big Snowy strata and overlying deposits.

During the next major transgressive phase of the Carboniferous, strata of the Amsden Group were deposited. The Tyler Formation was deposited in either stagnant marine or nonmarine environments in central and eastern Montana along the axis of the Big Snowy trough. A marine limestone tongue, the Bear Gulch Limestone Member, near the top of the Tyler in central Montana, bears a marine fauna identified as latest Mississippian. Thus, the Mississippian-Pennsylvanian systemic boundary appears to be within the Tyler Formation rather than at the unconformity at the Big Snowy-Tyler contact.

After deposition of the Tyler Formation, limestone, dolomite, and mudstone of the Alaska Bench Formation accumulated in the Big Snowy trough in marine environments that ranged from supratidal to subtidal.

Dolomite, limestone, sandstone, and shale of the Devils Pocket Formation were deposited unconformably over the top of the Alaska Bench Formation in the Big Snowy trough. These sediments, like those of the underlying Alaska Bench Formation, were deposited in shallow marine environments.

After deposition of the Amsden Group in Montana, the Quadrant Formation accumulated in Desmoinesian time. The contact with the underlying Devils Pocket is gradational. The Quadrant Formation is probably of shallow marine origin. Uplifts to the west and the craton to the east provided abundant quartz sand.

INTRODUCTION

Carboniferous rocks of Montana have been the subject of man's curiosity and exploitation from approximately 2,000 years before the present, when stone-age miners quarried Mississippian chert from bluffs overlooking the Madison River in southwestern Montana (Davis, 1976), to the last several decades, when Carboniferous strata have produced petroleum, water, and aggregate and have provided abundant intellectual stimulus and challenge to students of Mississippian and Pennsylvanian rocks. Geologic investigation of Carboniferous strata from Peale's (1893) early work to the present has revealed a complex and detailed geologic history of transgressions and regressions, depositional environments, and epeirogenic activity; however, in the process of providing answers, this investigation has supplied a great number of unanswered questions. As a consequence, this paper is a compilation of work on diverse topics by many geologists having diverse backgrounds and orientations and should be read accordingly. The manuscript is a joint effort: Smith is responsible for the Mississippian parts; Gilmour, for the Pennsylvanian. We have made little attempt to resolve current stratigraphic, paleontologic, and sedimentologic conflicts and have chosen to present both arguments where two interpretations exist.

Carboniferous strata underlie all of Montana except the northwest corner, where they have been removed by Tertiary erosion (fig. 1). They are well exposed in the Cenozoic uplifts of central Montana, in the overthrust belt of western Montana, around large Laramide intrusive bodies, and on the flanks of basement block uplifts. In these exposures, the Madison Group forms a series of strong cliffs and ridges above the relatively nonresistant Devonian Three Forks Formation, the Big Snowy and Amsden Groups form a swale with low ridges, and the Quadrant Formation crops out in a series of cliffs and ridges.

Carboniferous rocks attain a maximum thickness of 1,000 m in an east-trending belt in central Montana, thinning to less than 300 m to the north and 450 m to the south. These thickness trends reflect cratonic paleotectonic elements that controlled Carboniferous sediment accumulation as well as Carboniferous and post-Carboniferous erosional events.

The contact of the Carboniferous rocks with the underlying rocks is generally unconformable, the age of the rocks under the unconformity generally increasing southward into Wyoming. However, in central and eastern Montana, the time value of this unconformity increases along the Bearpaw and Cedar Creek anticlines and the central Montana uplift, reflecting the positive nature of these structures during latest Devonian and earliest Mississippian

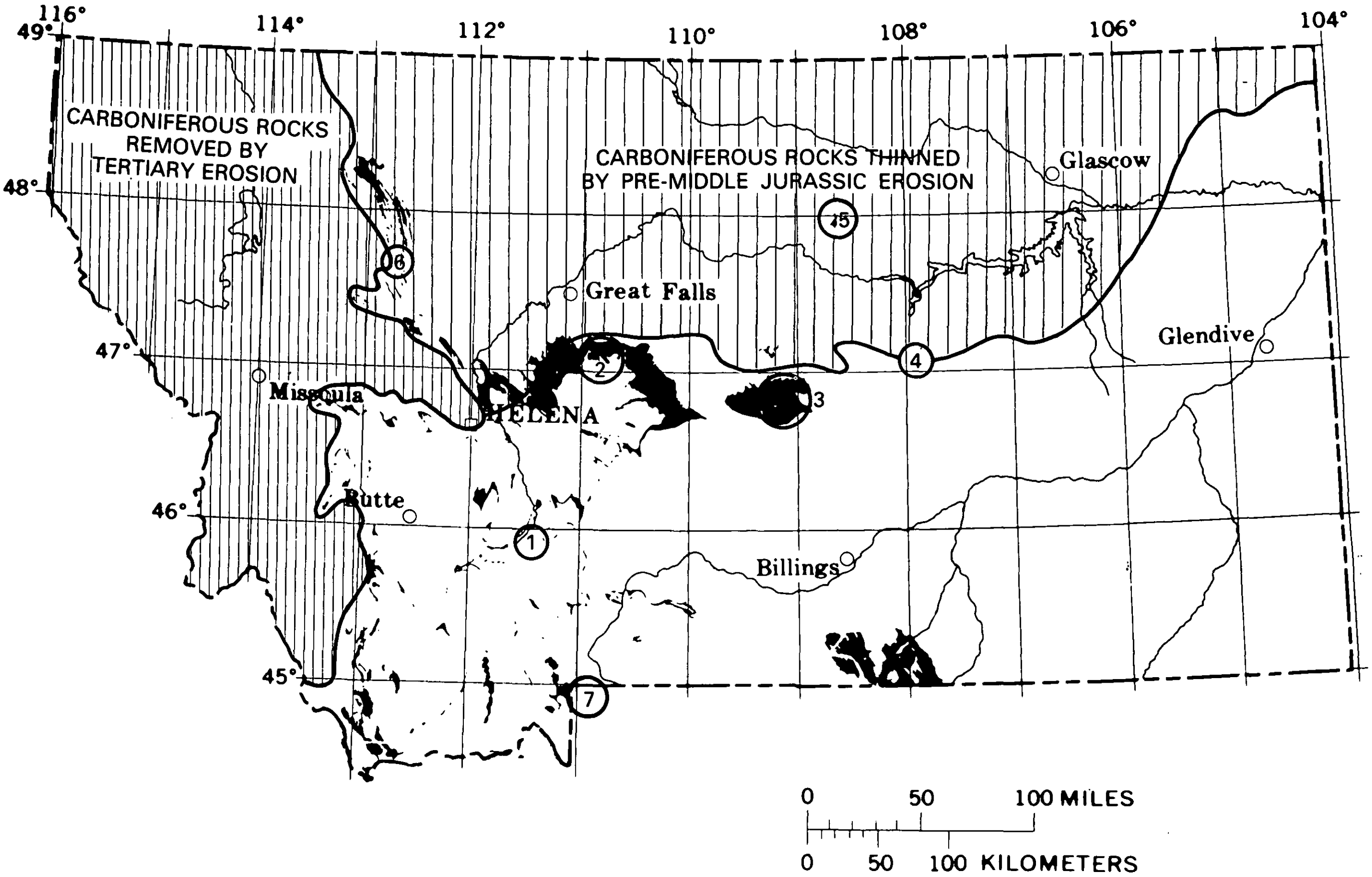


FIGURE 1.—Index map of major exposures of Carboniferous rocks in Montana, showing areas modified by pre-Jurassic and Tertiary erosion. Numbers refer to Carboniferous type and reference sections. (1) Logan-Three Forks area-type section of the Madison Group. (2) Northern Little Belt Mountains-type sections of the Paine and Woodhurst Members of the Lodgepole Limestone and reference section for the Mission Canyon Limestone. (3) Big Snowy Mountains-type sections of the Kibbey, Otter, and Heath Formations of the Big Snowy Group, the Bear Gulch, Cameron Creek, and Stonehouse Canyon Members of the Tyler Formation, and the Devils Pocket and Alaska Bench Formations. (4) Arro Oil and Refining Company and California Company No. 4 well-type well of the Charles Formation. (5) Little Rocky Mountains-type sections of the Lodgepole and Mission Canyon Formations. (6) Sawtooth Range-type sections of Allan Mountain Limestone, Castle Reef Dolomite, and Sun River Dolomite. (7) Quadrant Mountain, Gallatin Range, Wyoming-type section of the Quadrant Formation. (Map modified from Ross, Andrews, and Witkind, 1955, and Sando, 1976).

time. This deformation may be related to the Antler orogeny in the Cordilleran geosyncline to the west.

The contact of Carboniferous rocks with overlying strata is also unconformable and reflects the tectono-sedimentary history of the area from the beginning of the Permian through the Middle Jurassic. Beneath this unconformity, rocks as old as Osagean are unconformably overlain by the Middle Jurassic Ellis Group in northern Montana, whereas, to the south, Permo-Triassic rocks truncate the Middle and Upper Pennsylvanian Quadrant Formation. This erosional interval produced a northern zero edge on the Big Snowy, Amsden, and Quadrant Formations and significantly thinned the upper part of the Madison Group. This truncation suggests late Paleozoic-early Mesozoic uplift along the "Milk River uplift" of Maughan and Roberts (1967).

Carboniferous strata of Montana consist of four depositional packages of rock, each deposited under unique paleotectonic conditions. These are the dominantly carbonate Madison Group, the clastic and carbonate Big Snowy and Amsden Groups, and the clastic Quadrant Formation. The upward increase in detrital components in these Carboniferous units reflects increasing epeirogenic tempo on the craton and the influence of the Antler orogeny in the Cordilleran geosyncline to the west.

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomenclature used here conforms with the current usage of the Montana Bureau of Mines and Geology.

HISTORY OF NOMENCLATURE

Carboniferous nomenclature in Montana has evolved from Peale's (1893) naming of the Madison limestone and overlying Quadrant Formation to the present Madison, Big Snowy, and Amsden Groups and the Quadrant Formation. The history of this evolution has been reviewed and clarified for the Madison Group by Sando and Dutro (1974) and has been discussed for the Big Snowy and Amsden Groups and the Quadrant Formation by Maughan and Roberts (1967). The following discussion has been derived from original sources, with the guidance of these papers. Important developmental stages are charted in figure 2.

MADISON GROUP NOMENCLATURE

Madison Group nomenclature was initially derived from the Three Forks area of southwestern Montana, but formation names were soon added from the Little Belt Mountains and, decades later, from the Little Rocky Mountains, the subsurface of central Montana, and outcrops in northwest Montana (fig. 1).

Prominent lower Carboniferous outcrops in the Three Forks area were given the name Madison Limestone by Peale (1893). In this area, these rocks are sandwiched between the Devonian Three Forks Formation and the upper Carboniferous Quadrant Formation. Although Peale did not designate a type section, and there has been much subsequent debate about whether the type section is along the Madison River or in the Madison Range, Sloss and Hamblin (1942) proposed and Sando and Dutro (1974) have concurred that the type section is along the Madison River at Logan (fig. 1). In this area, Peale (1893) divided the Madison into the Laminated limestones, the Massive limestones, and the Jaspery limestones, in ascending order. Several years later, Weed (1899, 1900) recognized three similar lithologic units in the Little Belt Mountains, which he termed Paine Shale, Woodhurst Limestone, and Castle Limestone. However, here, as in the Three Forks area, type sections were not designated, and Sando and Dutro (1974) proposed type sections for the Paine and Woodhurst and a reference section for the Mission Canyon Formation (Jaspery limestones) in the northern Little Belt Mountains (fig. 1).

Collier and Cathcart (1922) identified similar Madison rocks in the Little Rocky Mountains (fig. 1) and applied the local physiographic names Lodgepole and Mission Canyon to formations within the Madison that they recognized as a formal group (fig. 2). However, the threefold division of Peale (1893) and Weed (1899) is recognizable in the Little Rocky Mountains, and the Lodgepole also contains the lower two of the three stratigraphic units (Sando and Dutro, 1974).

In their synthesis of Madison nomenclature, Sloss and Hamblin (1942) gathered these lower Carboniferous names into a single classification scheme (fig. 2) that included Weed's (1899) Paine Shale and Woodhurst Limestone as members of Collier and Cathcart's (1922) Lodgepole Formation and that equated Peale's (1983) Jaspery limestones, Weed's (1899) Castle Limestone, and Collier and Cathcart's (1922) Mission Canyon Limestone, retaining the last name as a second formation at the top of the Madison group.

The name Charles was proposed by Seager (1942) for an interbedded sequence of limestone, dolomite, and evaporite above the Madison and below the Kibbey Formation in the subsurface of central Montana (fig. 1). Seager designated the Charles Formation as the basal unit of the Big Snowy Group, but a decade later, Sloss (1952) suggested that the Charles should be considered the uppermost unit of the Madison Group (fig. 2). Seager (1942) designated a type well for the Charles, for which a graphic log was prepared by Perry and Sloss (1943). The Charles is presently in a state of stratigraphic limbo, as indicated by Balster (1971, p. 220):

> There is some doubt that the Charles Formation persists to the outcrop. Stratigraphers disagree: some believe that the breccia zones in the uppermost part of the Mississippian represent the Charles with evaporites removed by selective solution; others believe that the Charles is restricted to the subsurface. Obviously, more study is necessary.

Sando and Dutro (1974) suggested that until a definitive study is conducted, the Charles should be considered the equivalent of the upper part of the Mission Canyon and that the use of the name should be restricted to the subsurface of the Williston basin.

The name Little Chief Canyon Member was proposed by Knechtel, Smedley, and Ross (1954) for a thin black shale at the base of the Lodgepole Limestone at its type section in the Little Rocky Mountains. This black shale is in a similar stratigraphic position in many parts of the State and is variously included in the Bakken Formation and the Cottonwood Canyon Member of the Lodgepole Formation (Sandberg and Klapper, 1967; Macqueen and Sandberg, 1970). The name Cottonwood Canyon Member was proposed by Sandberg and Klapper (1967) from exposures of black shale and siltstone at the base of the Madison Formation in the northern Big Horn Mountains of Wyoming, and Sando and Dutro (1974) recommended the use of this term and the abandonment of the name Little Chief Canyon Member.

The names Silvertip Conglomerate, Saypo Limestone, Dean Lake Chert, Rooney Chert, and Monitor Mountain Limestone were all proposed by Deiss (1933) for five members of the Madison Limestone in northwestern Montana. Later, Deiss (1941, 1943) included these members in the Hannan Limestone, replacing the term Madison. Since that time, these terms have been only locally used, and the Montana Geological Society (Balster, 1971) recommended that "more current terminology" be applied to these rocks.

Additional Madison terms for northwestern Montana (figs. 1, 2) were proposed by Mudge, Sando, and Dutro (1962, p. 2004) because "... formational boundaries recognized in the type locality cannot be consistently followed in this area." These names are Allan Mountain Limestone and Castle Reef Dolomite, which are chronologically and lithologically similar to the Lodgepole Limestone and Mission Canyon Limestone, respectively (Mudge, 1972). The Allan Mountain Limestone is divided into three unnamed members, and the Castle Reef Dolomite is composed of an unnamed lower member and the overlying Sun River Dolomite (Mudge, Sando, and Dutro, 1962; Mudge, 1972). The Montana Geological Society (Balster, 1971) suggested that the names Allan Mountain and Castle Reef should be abandoned in favor of the more widely used names Lodgepole and Mission Canyon.

BIG SNOWY GROUP NOMENCLATURE

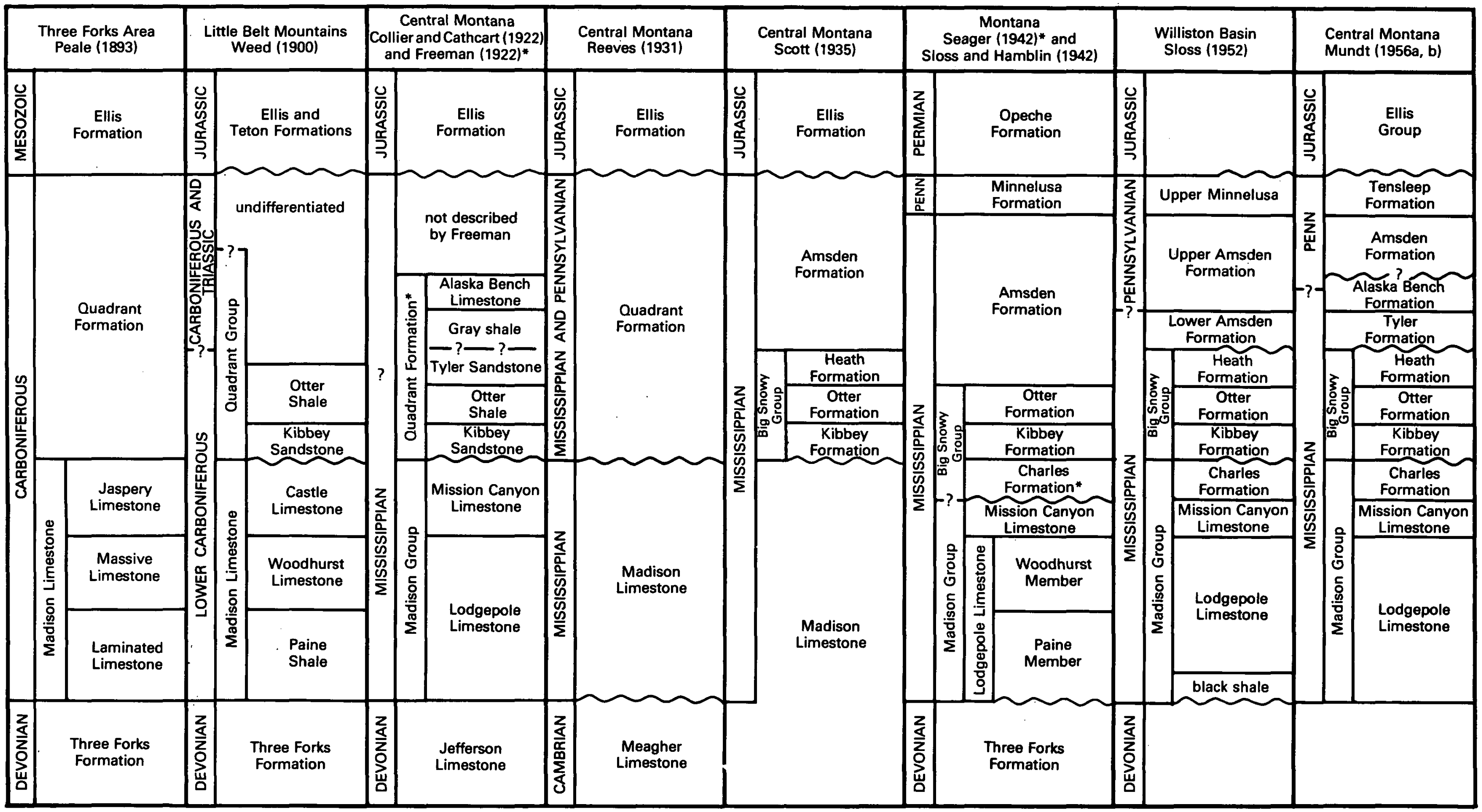
The Big Snowy Group was named by Scott (1935) from exposures in the Little Belt and Big Snowy mountains of central Montana (fig. 1). In the northern Little Belt Mountains, he included the Kibbey and Otter Formations that were previously described as part of the Quadrant Group by Weed (1899, 1900). The third formation of the Big Snowy Group—the Heath—is absent in the Kibbey and Otter type area, but is present in the eastern Little Belt Mountains and in the Big Snowy Mountains, where it was described by Scott (1935). With few exceptions, Scott's (1935) terminology has been used in subsequent syntheses; the marked exception was Gardner (1959), who expanded the Big Snowy Group to include rocks that Scott (1935) and subsequent investigators included in the Amsden Group (fig. 2).

AMSDEN GROUP NOMENCLATURE

Originally, rocks now considered part of the Amsden Group were included in the Quadrant Formation as used by Peale (1893), Weed (1896), Freeman (1922), and Reeves (1931). Freeman (1922) divided the Quadrant Formation into the Kibbey Sandstone, Otter Shale, Tyler Sandstone, and Alaska Bench Limestone (fig. 2).

Scott (1935) established the Big Snowy Group, which included the Kibbey Sandstone, the Otter Shale, and the overlying Heath Shale. Rocks above the Heath Shale were placed in the Amsden Formation, named by Darton (1904) for similar rocks exposed in northern Bighorn Mountains, Wyoming. Mundt (1956a) referred to sandstone and shale beds between the Heath Shale and the overlying limestone as the Tyler Formation and the overlying limestone as the Alaska Bench Formation (fig. 2). Rocks overlying the Alaska Bench Limestone were called the Amsden Formation by Mundt (1956a). Gardner (1959) and Easton (1962) placed the contact between the Heath Shale and the overlying sandstone and red beds at the lithologic break between the black shale and red beds. Gardner named this sandstone and red-bed sequence the Cameron Creek Formation and used the Alaska Bench Formation for the overlying limestone. He substituted the name Devils Pocket Formation for the overlying dolomite and sandstone referred to as Amsden Formation in earlier studies. Willis (1959) used the Tyler Formation to include the lower dark shale interstratified with sandstone above the black shale of the Heath Formation, which he called the lower member. The red shale and interbedded limestone sequence above the lower member was named the Cameron Creek Member. The carbonate rocks were grouped into the Amsden Formation (restricted) and divided into two members: the Alaska Bench Member and the dolomite member. Rocks above the dolomite member were referred to as the Tensleep Sandstone.

Easton (1962) and Gilmour (1967, 1969) used essentially the nomenclature suggested by Gardner. Gilmour (1969, p. 181) used Tyler Sandstone and Bear Gulch Limestone as member designations for parts of the Cameron Creek Formation.



Three Forks Area
Peale (1893)
MESOZOIC
Ellis Formation
CARBONIFEROUS
Quadrant Formation
Madison Limestone
Jaspery Limestone
Massive Limestone
Laminated Limestone
DEVONIAN
Three Forks Formation
Little Belt Mountains
Weed (1900)
JURASSIC
Ellis and Teton Formations
CARBONIFEROUS AND TRIASSIC
undifferentiated
Quadrant Group
Otter Shale
Kibbey Sandstone
LOWER CARBONIFEROUS
Madison Limestone
Castle Limestone
Woodhurst Limestone
Paine Shale
DEVONIAN
Three Forks Formation
Central Montana
Collier and Cathcart (1922) and Freeman (1922)*
JURASSIC
Ellis Formation
not described by Freeman
Quadrant Formation*
Alaska Bench Limestone
Gray shale
Tyler Sandstone
Otter Shale
Kibbey Sandstone
MISSISSIPPIAN
Madison Group
Mission Canyon Limestone
Lodgepole Limestone
DEVONIAN
Jefferson Limestone
Central Montana
Reeves (1931)
JURASSIC
Ellis Formation
MISSISSIPPIAN AND PENNSYLVANIAN
Quadrant Formation
MISSISSIPPIAN
Madison Limestone
CAMBRIAN
Meagher Limestone
Central Montana
Scott (1935)
JURASSIC
Ellis Formation
Amsden Formation
MISSISSIPPIAN
Big Snowy Group
Heath Formation
Otter Formation
Kibbey Formation
Madison Limestone
Montana
Seager (1942)* and Sloss and Hamblin (1942)
PERMIAN
Opeche Formation
PENN
Minnelusa Formation
Amsden Formation
MISSISSIPPIAN
Big Snowy Group
Otter Formation
Kibbey Formation
Charles Formation*
Mission Canyon Limestone
Madison Group
Lodgepole Limestone
Woodhurst Member
Paine Member
DEVONIAN
Three Forks Formation
Williston Basin
Sloss (1952)
JURASSIC
PENNSYLVANIAN
Upper Minnelusa
Upper Amsden Formation
Lower Amsden Formation
MISSISSIPPIAN
Big Snowy Group
Heath Formation
Otter Formation
Kibbey Formation
Madison Group
Charles Formation
Mission Canyon Limestone
Lodgepole Limestone
black shale
DEVONIAN
Central Montana
Mundt (1956a, b)
JURASSIC
Ellis Group
PENN
Tensleep Formation
Amsden Formation
Alaska Bench Formation
Tyler Formation
MISSISSIPPIAN
Big Snowy Group
Heath Formation
Otter Formation
Kibbey Formation
Madison Group
Charles Formation
Mission Canyon Limestone
Lodgepole Limestone

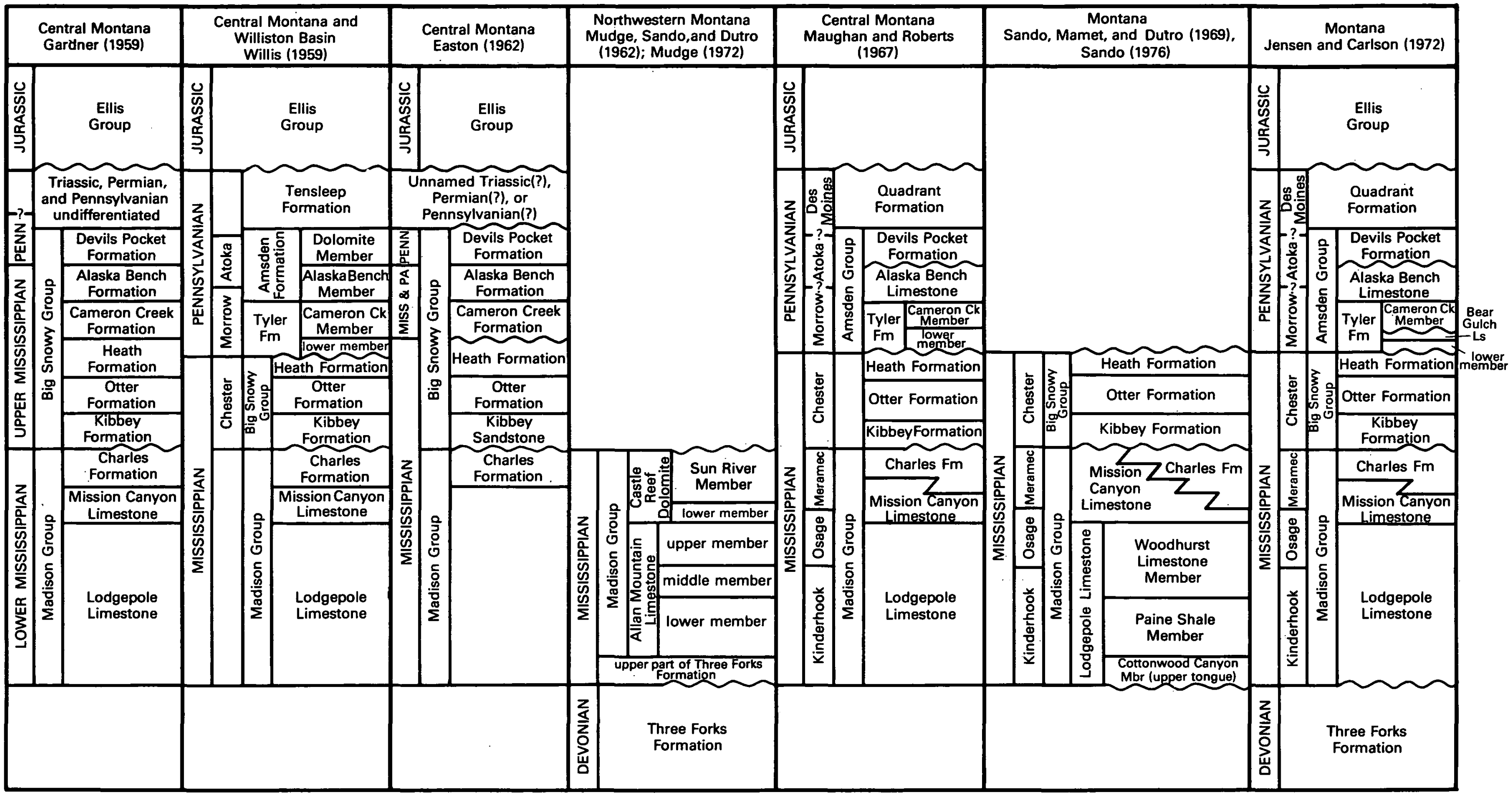


FIGURE 2.—History of Carboniferous nomenclature in Montana, 1893–1976. (Compiled from original sources with guidance from Maughan and Roberts, 1967, and Sando and Dutro, 1974.)

Maughan and Roberts (1967) and Maughan (1975) included all the rocks above the Heath Formation and below the uppermost sandstone beds (Quadrant Formation) as the Amsden Group, consisting of the Tyler Formation, Alaska Bench Limestone, and Devils Pocket Limestone. The Tyler Formation was divided into the Stonehouse Canyon Member and the overlying Cameron Creek Member. These units are overlain by the Alaska Bench Limestone, which, in turn, is overlain unconformably by the Devils Pocket Limestone. Maughan and Roberts (1967, p. B19) also recommended that this nomenclature be used in the subsurface throughout eastern Montana to the State boundary where the Minnelusa Formation is used in North Dakota, South Dakota, and eastern Wyoming. They also suggested that the strata found in southwestern Montana and western Wyoming, approximately equivalent to the Amsden Group in central Montana, be referred to as the Amsden Formation.

For this report, the nomenclature suggested by Maughan and Roberts (1967) is used. However, the use of formations and members should be based strictly on lithology and not on questionable unconformities in black-shale sequences, or between partially dolomitized limestones and totally dolomitized limestones.

QUADRANT FORMATION NOMENCLATURE

The Quadrant Formation was named by Peale (1893). Weed (1896) designated the type locality as Quadrant Mountain in the Gallatin Range, Wyoming (fig. 1), which included 32 m of limestone and shale now referred to as the Amsden Formation. Maughan and Roberts (1967, p. B6) used the name Quadrant Formation for the quartzite or sandstone sequence overlying the Devils Pocket Formation in central Montana and the Amsden Formation in southwestern Montana. Mallory (1972) also used Quadrant "Sandstone" for the same rocks in his synthesis of the Pennsylvanian System. Other workers (Scott, 1935; Mundt, 1956a; and Willis, 1959) assigned these rocks to the Tensleep Formation, which was named by Darton (1904) from the lower canyon of Tensleep Creek in the Big Horn Mountains, north-central Wyoming.

The term Quadrant Formation is used in this report in accord with workers in the U.S. Geological Survey. However, the authors recognize the general use of Tensleep Sandstone by workers in the petroleum industry in central and southern Montana.

GEOLOGIC SETTING

REGIONAL PALEOTECTONIC SETTING

Carboniferous sedimentation patterns are closely tied to the latest Devonian and Carboniferous tectonic framework of the northern Rocky Mountains. In eastern and central Montana, this framework was dominated by the North American craton. Western Montana was the site of the Cordilleran miogeosyncline. Because most of the Carboniferous strata were removed from western Montana by Tertiary erosion, the Carboniferous history of the Cordilleran miogeosyncline is incompletely known there. However, Huh (1967) documented the craton-miogeosynclinal margin in extreme southwestern Montana and adjacent Idaho, where he recognized a "transition zone" between these two major tectonic elements. Other students of the northern Rockies Carboniferous place the craton-miogeosyncline boundary in the vicinity of Huh's craton-transition line (figs. 3, 4).

MISSISSIPPIAN PALEOTECTONIC ELEMENTS

During the latest Devonian and earliest Mississippian, the craton in Montana was the site of parts of four shallow marine basins (fig. 4), the Bakken and Exshaw basins in northern Montana and the Sappington-Cottonwood Canyon and Englewood basins in the southern part of the State. These basins were separated by linear uplifts that may have been a cratonic manifestation of the Antler orogeny. The largest of these positive features was the central Montana uplift, an anticline that separated the two northern basins from the two southern basins and that probably provided sediment to both sides from the weathering and erosion of Cambrian through Devonian strata. In eastern Montana, the Cedar Creek anticline was similarly active, and as much as 230 m of Cambrian through Devonian rocks was eroded along a high-angle fault on its western flank (Sandberg and Mapel, 1967).

This uppermost Devonian and lowermost Mississippian pattern of shallow cratonic basins and uplifts changed markedly in Early Mississippian time. East of the craton-miogeosyncline hingeline, the Mississippian cratonic setting of Montana featured three major tectonic elements: the Cordilleran platform (Sando, Gordon, and Dutro, 1975) in northern and southern Montana, the unstable shelf or Big Snowy trough in central Montana, and the Williston basin in easternmost Montana and adjacent western North Dakota (fig. 3). The Cordilleran platform is, in turn, divided into a northern Alberta shelf and

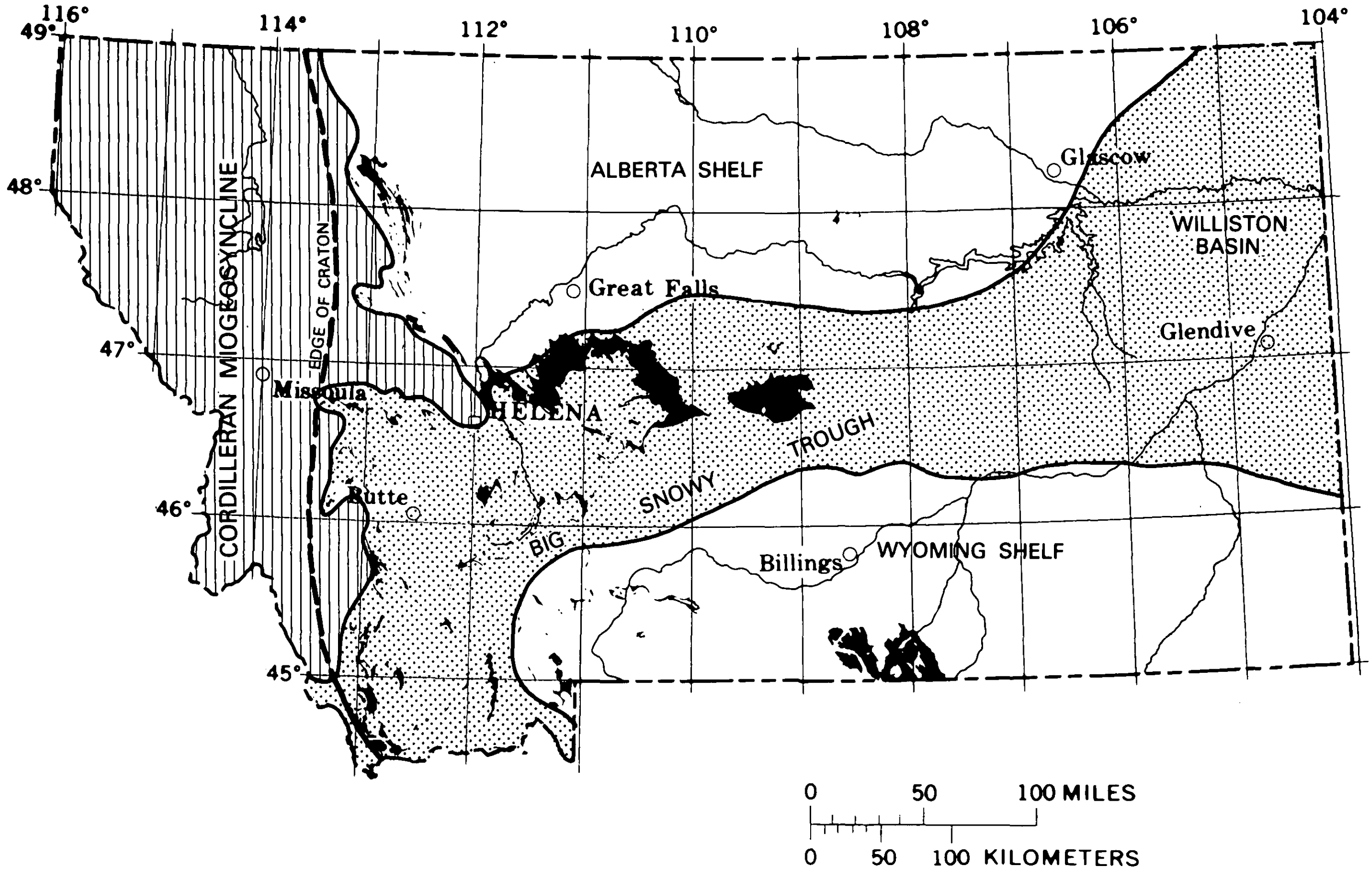


FIGURE 3.—Mississippian paleostructural features in Montana. The shelf-trough boundaries are drawn on Craig's 450-m isopach for the Mississippian. (Map modified from Sando, 1967; Rose, 1976; Sando, 1976; and Craig, 1972).

a southern Wyoming shelf, both having stable or relatively neutral Mississippian histories. These structural elements remained intact during deposition of the Madison Group but began to be modified at the onset of Big Snowy deposition (latest Meramecian-earliest Chesterian). During accumulation of the diverse rocks of the Big Snowy Group, the Big Snowy trough was inundated and the Wyoming shelf formed an east-trending peninsular feature—the southern Montana arch (Sando, 1976)—that separated the Wyoming basin to the south from the Big Snowy trough on the north. This uplift influenced sedimentation until the latest Chesterian when parts of the Big Snowy trough were uplifted, providing sediment to the Amsden Formation of the northward-expanding Wyoming basin (Sando, Gordon, and Dutro, 1975; Sando, 1976).

PENNSYLVANIAN PALEOTECTONIC ELEMENTS

At the beginning of Pennsylvanian time, the sea occupying the Big Snowy trough was severely restricted. Uplift to the north exposed land areas that provided much of the terrigenous sediment for the Tyler, Alaska Bench, and Devils Pocket Formations. The Big Snowy trough continued to subside through Morrowan and Atokan time, and deposition was more or less continuous in local areas. The Montana uplift (Sando, Gordon, and Dutro, 1975) produced a large island area in south-central and southeast Montana in late Morrowan time. During Atokan and Desmoinesian time, large uplifts in the west provided sand-sized clastic sediment for the Quadrant and equivalent formations.

STRATIGRAPHY

Carboniferous strata of Montana are divisible into four depositional packages, each representing a transgressive-regressive event. These packages are, in ascending order, the Madison Group, Big Snowy Group, Amsden Group, and Quadrant Formation. The time value of the hiatus separating these packages is variable, but, in general, is greater on the Cordilleran platform than in central Montana and the Williston basin.

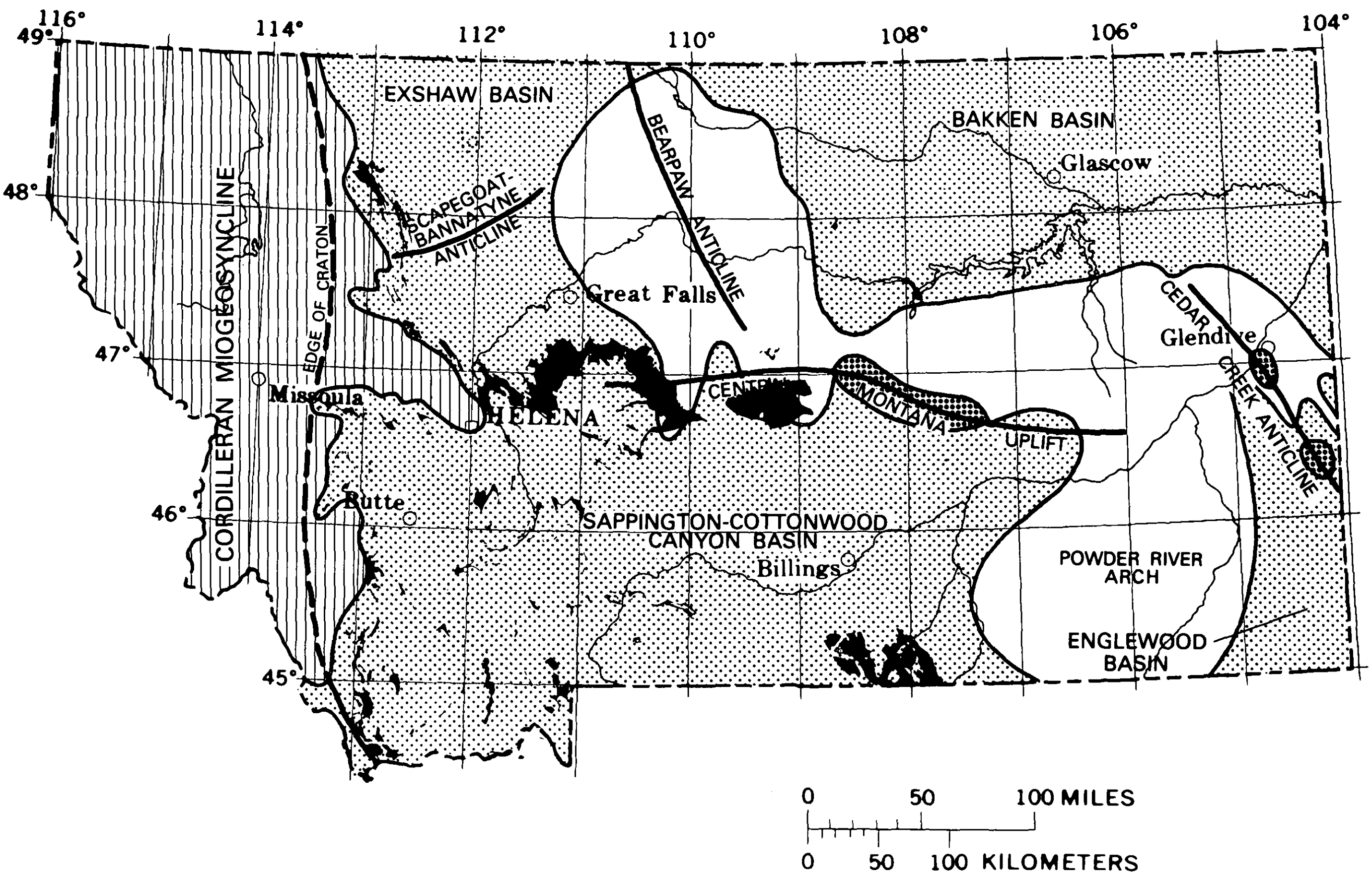


FIGURE 4.—Map of uppermost Devonian and lowermost Mississippian rocks and structural features. Light-shaded areas are basins in which rocks of the Bakken, Exshaw, and Englewood Formations and Cottonwood Canyon and Sappington Members accumulated. Unshaded areas in central and eastern Montana are uplifts that separated these basins. Dark-shaded areas along the axes of the central Montana uplift and the Cedar Creek anticline are areas where uppermost Devonian and lowermost Mississippian erosion cut down into Cambrian, Ordovician, and Silurian strata. (Map modified from Sandberg and Klapper, 1967; Sandberg and Mapel, 1967; and Baars, 1972).

UPPER DEVONIAN AND LOWER MISSISSIPPIAN STRATA

Black shale and dolomitic siltstone below and at the base of the Madison Group unconformably overlie earlier Devonian and other lower Paleozoic strata and record the complex history of the Devonian-Mississippian transition in Montana. Rocks included in this sequence are the Bakken and Exshaw Formations, the Sappington Member of the Three Forks Formation, and the Englewood Formation.

The Bakken Formation is restricted to the Bakken basin in northeastern Montana (fig. 4). Here, it attains a maximum thickness of 42 m in the North Dakota part of the Williston basin, and it thins from 21 m along the international boundary to zero on the northern flank of the central Montana uplift. The Bakken is composed of two black radioactive carbonaceous shale beds that sandwich a medial dolomitic siltstone and sandstone (Coleville Sandstone Member). To the west, the upper black shale has been removed by earliest Mississippian erosion on the Bearpaw anticline, and an arbitrary western limit has been drawn along this axis (Macqueen and Sandberg, 1970). Conodonts from the Bakken Formation indicate a Late Devonian age (lower and upper *to* V), and a spore flora indicates a position near the Devonian-Mississippian boundary (Macqueen and Sandberg, 1970). This boundary may be within the Coleville Sandstone Member (fig. 5).

In northwestern Montana, the Exshaw Formation is a southern extension of that formation from Alberta and, according to Macqueen and Sandberg (1970), represents a western continuation of the basal black shale and medial siltstone of the Bakken Formation (fig. 5). The Exshaw Formation is restricted to the Exshaw basin that is bounded on the east by the Bearpaw anticline, on the south by the Scapegoat-Bannatyne anticline, and on the west by the Cordilleran miogeosyncline (fig. 4). The formation attains its maximum thickness in Alberta and is only approximately 40 m thick at the international boundary. It thins southward onto the Scapegoat-Bannatyne anticline, where it is less than 6 m thick and where the siltstone was removed by erosion in early Mississippian time. The basal black carbonaceous shale is fissile and has at its base a thin phosphatic sandstone bed. This bed has been interpreted as a basal lag deposit, a product of the erosional interval represented by the Three Forks-Exshaw unconformity (Macqueen and Sandberg, 1970). The upper siltstone is calcareous, grading in places to a silty limestone. Its contact with the underlying black shale is gradational. South of the Scapegoat-Bannatyne anticline, the basal black shale of the Exshaw is equated with a similar shale at the base of the Sappington Member of the Three Forks Formation, and the medial Exshaw siltstone is considered to be equivalent to limestone, siltstone, and shale (units 2 through 5) of the Sappington Member (fig. 5). Conodonts collected from the Exshaw Formation north of the international boundary indicate a very late Devonian and early Mississippian age for the unit, the contact being somewhere within the black-shale unit (Macqueen and Sandberg, 1970).

The Sappington Member of the Three Forks Formation occupies the western end of the incipient Big Snowy trough, sandwiched between the Scapegoat-Bannatyne anticline and the Wyoming shelf (figs. 3, 4). It attains a maximum thickness of approximately 30 m in the center of the "Sappington basin" (Gutschick, McLane, and Rodriquez, 1976) and thins northward onto the Scapegoat-Bannatyne anticline and southward and eastward onto the Wyoming shelf. The Sappington Member was divided into five units by Sandberg (1962, 1965). These are: (1) a basal black carbonaceous shale, similar to the basal shale of the Exshaw, with which it is equated: (2) an alga-sponge biostromal limestone; (3) a lower siltstone; (4) a middle olive-gray shale; and (5) an upper calcareous siltstone, which is a cliff former and which is occasionally cross stratified and ripple marked. Analysis of conodont faunas and spore floras suggests that units 1 through 4 are all latest Devonian but that the upper part of unit 4 and all of unit 5 are earliest Mississippian (fig. 5).

The Cottonwood Canyon Member of the Lodgepole Formation occupies that part of the Cordilleran platform called the Wyoming basin. The member is in a linear belt from west-central Wyoming to the flanks of the Big Snowy uplift in central Montana (fig. 4). Along the axis of this belt, thicknesses are as great as 18 m, but the unit thins abruptly both east and west and is less than 3 m thick over half its extent (Sandberg and Klapper, 1967). In Montana, the Cottonwood Canyon Member unconformably overlies the Sappington and Trident Members of the Three Forks Formation and is overlain by and intertongues in its upper part with the Paine Member of Lodgepole Limestone. The Cottonwood Canyon Member is composed of two tongues (fig. 5), each of which is divisible into a western shale and siltstone facies and an eastern dolomitic facies (Sandberg and Klapper, 1967). The base of each tongue is characterized by a basal conglomeratic sandstone that contains phosphatic nodules, coprolites, conodonts, fish fossils, and glauconite grains. Sandberg and Klapper (1967) interpreted this rock as a lag deposit, the product of erosion and reworking during marine transgression. This basal lag deposit is similar in character and origin to those of the Sappington, Exshaw, and possibly the Bakken black-shale beds. The lower tongue of the Cottonwood Canyon Member is restricted for the most part to the Wyoming basin, bears latest Devonian conodonts, and intertongues with the basal beds of the Madison Formation. The upper tongue is more extensive than its lower counterpart, interfingers with the Madison Limestone, and is entirely of Mississippian age (fig. 5), according to Sandberg and Klapper's (1967) analysis of conodonts.

The Englewood Formation unconformably underlies the Madison-equivalent Pahasapa Limestone in the Black Hills and subsurface of southeastern Montana. Here, it accumulated in an embayment that extended from southeastern Wyoming to central North Dakota (Sandberg and Mapel, 1967). In Montana, the Englewood is 0 to 6 m thick and unconformably overlies the Devonian Three Forks and Jefferson Formations and the Ordovician Bighorn Dolomite (Baars, 1972). The Englewood is characterized by a basal shale that is overlain by silty dolomite, dolomitic limestone, and limestone containing beds of sandstone, shale, and siltstone. Conodont faunas from the Englewood were sampled and analyzed by Klapper and Furnish (1962), Sandberg (1963), and Klapper (1966) and determined to be of Late Devonian-Early Mississippian age.

A complex depositional history was proposed for these uppermost Devonian and lowermost Mississippian rocks by Sandberg and Klapper (1967), a history that features shallow marine basins isolated

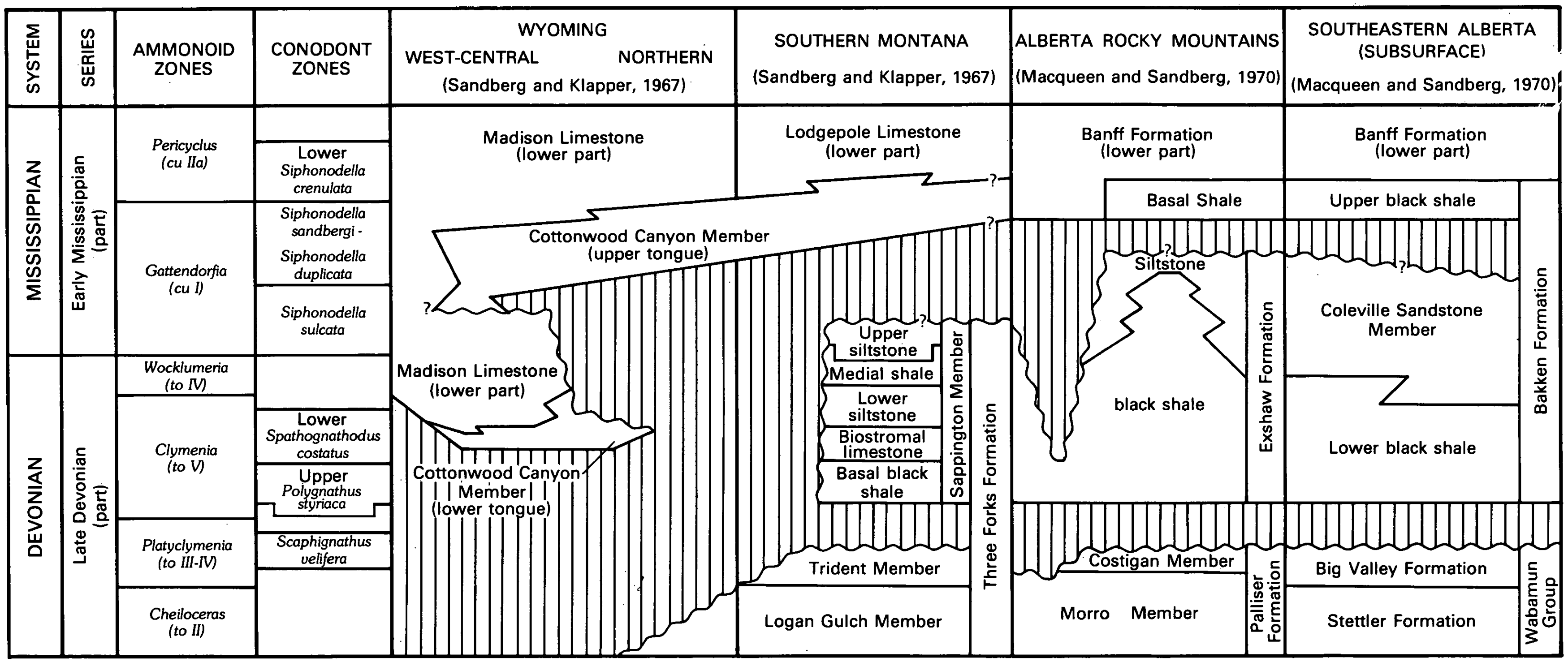


FIGURE 5.—Stratigraphic relationships of uppermost Devonian and lowermost Mississippian strata in northern Wyoming, southern Montana, and southern Alberta. (Modified from Sandberg and Klapper, 1967; Sandberg, 1965; Gutschick, Suttner, and Switek, 1962; and Macqueen and Sandberg, 1970).

by Antler orogeny-related cratonic uplifts and by minor transgressions and regressions.

In the latest Devonian (Lower *to* V), a marine transgression took place that inundated the shallow marine basins of the Montana craton (fig. 4). This transgression is recorded by the basal sandstone and black shale of the Sappington, Exshaw, and Bakken. The sandstone in each of these units represents lag accumulations on the weathered and eroded surface of the Three Forks Formation. Fine-grained clastic debris was probably derived from weathering and erosion of low-lying, basin-separating uplifts (fig. 4) and was deposited in shallow stagnant marine water.

Accompanying this brief transgression were more intense movements of the uppermost Devonian and lowermost Mississippian arches and uplifts, most notably the central Montana uplift and the Cedar Creek anticline (fig. 4). Erosion of these and other positive elements provided coarser sediment to the regressing latest Devonian sea, resulting in the accumulation of the medial siltstone of the Bakken Formation, the upper siltstone of the Exshaw, and units 2 through 5 (Sandberg, 1965) (units E through H of Gutschick, Suttner, and Switek, 1962) of the Sappington Member of the Three Forks Formation. These sediments accumulated in a variety of intertidal and subtidal depositional environments in the Bakken, Exshaw, and Sappington basins.

At the same time that the sea was regressing from the Montana basins and these coarser clastic rocks were accumulating there, the lower tongue of the Cottonwood Canyon Member of the Lodgepole Limestone was deposited in a shallow trangressive sea in the Cottonwood Canyon or Wyoming basin in western Wyoming. Here, deposition of the basal black shale and sandstone of the lower tongue took place in an environment similar to that of the earlier Montana basins. This stagnant marine environment gave way in time and space to less restricted environments in which the lower part of the Madison Limestone was deposited during latest Devonian time (Upper V and *to* IV). This initial transgression of the Madison sea was short lived, ending in a brief regression during earliest Mississippian time (Lower *cu* I). At approximately this same time, the sea may have regressed from the Sappington basin, but shallow seas continued to occupy the Exshaw and Bakken basins, and black shale and siltstone continued to accumulate there. However, prior to the invasion of the craton by the second and major advance of the Madison sea, these shallow seas regressed from all the Montana basins, with the exception of the western part of the Sappington basin (Sandberg and Klapper, 1967), producing the interregional unconformity shown in figure 5.

The second advance of the Madison sea was not restricted to isolated basins and embayments as was the first transgression, but was an eastward transgression along the entire length of the Cordilleran miogeosyncline (Sandberg and Klapper, 1967). During this relatively rapid transgression, the basal lag sandstone and black shale of the upper tongue of the Cottonwood Canyon Member accumulated in shallow stagnant environments, as did the contemporaneous upper black shale of the Bakken Formation (fig. 5). As transgression continued, these stagnant conditions gave way to the more agitated and oxygenated environments in which the shale and siltstone facies and dolomite facies of the upper tongue of the Cottonwood Canyon Member were deposited in intertidal and shallow subtidal environments. As the transgressing Madison sea rapidly engulfed and effectively mantled sources of detrital sediment, the bioclastic facies at the base of the Paine Member of the Lodgepole Limestone was deposited in a series of shoals. This coarse-grained, glauconitic, bioclastic limestone spread rapidly eastward across the stable and unstable shelves of Montana in response to the rapid expansion of the shallow detritus-free Madison sea.

MADISON GROUP

Excellent syntheses of sedimentation, stratigraphy, paleontology, and depositional history of the Madison Group in Montana and adjacent areas have been published by Craig (1972), Sando (1976), Rose (1976), and Gutschick, McLane, and Rodriguez (1976), and comprehensive lists of references are found in these papers.

The Madison Limestone covers all of Montana except for the centers of Tertiary uplifts and the northwestern part of the State, where it was removed by Tertiary erosion. It is a blanket of limestone and dolomite that reaches maximum thicknesses of 550 to 660 m in the Big Snowy trough and Williston basin, respectively, 600 m in the miogeosyncline of extreme southwestern Montana, and that ranges in thickness from 200 to 450 m on the Wyoming and Alberta shelves (fig. 6). The northward thinning is due to pre-Jurassic erosion; the southward thinning is primarily depositional, although original thicknesses may have been modified here by the formation of a late Mississippian karst across much of the area (Henbest, 1958; Roberts, 1966; Sando, 1974).

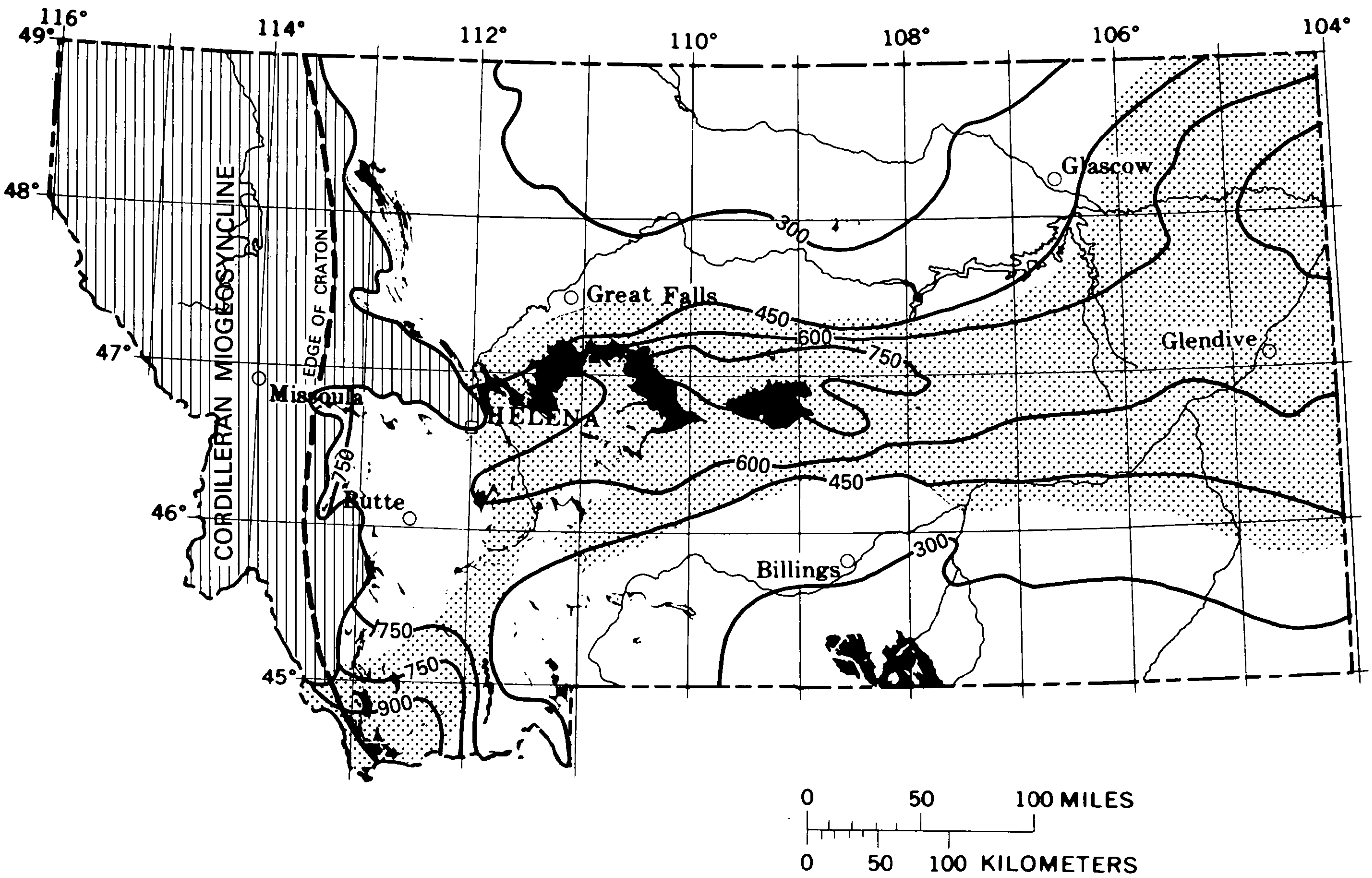


FIGURE 6.—Total thickness of Mississippian rocks in Montana. Light-shaded area indicates extent of Big Snowy Group. Isopach values are given in meters, and isopachs are modified from those of Sando (1976) and McMannis (1965).

In Montana, the Madison Group is composed of the Lodgepole, Mission Canyon, and Charles Formations. The Lodgepole is divided into the Cottonwood Canyon, Paine, and Woodhurst Members. These rocks are products of the first major transgression of the Madison sea onto the North American craton in Montana. The Lodgepole records (1) the initial rapid inundation of the Montana stable and unstable shelves, beginning with the accumulation of shallow-water sediments of the Cottonwood Canyon Member; (2) accumulation of deeper water deposits in the Big Snowy trough and expansion of the Madison sea on the Cordilleran platform as transgression continued; and (3) progradation of shallow-water carbonate sediment from the stable shelves across the Big Snowy trough, bringing to a close the deeper water phase of Lodgepole deposition. The Mission Canyon and Charles Formations accumulated as the Madison sea began to retreat prior to the late Mississippian emergence of the craton.

The biostratigraphic studies of conodonts, foraminifers, and corals and brachiopods summarized by Sando, Mamet, and Dutro (1969) indicate that the Lodgepole is Kinderhookian and early Osagean and that the Mission Canyon and Charles are late Osagean and early Meramecian.

LODGEPOLE LIMESTONE

The Lodgepole Limestone is a slightly lenticular deposit 240 m thick in the Big Snowy trough and Williston basin; it thins northward to 170 m in the Little Rocky Mountains on the Alberta shelf and southward to 130 to 150 m in the Beartooth Mountains on the Wyoming shelf. In the miogeosyncline of extreme southwestern Montana, the Lodgepole is more than 300 m thick. Lodgepole strata unconformably overlie Upper Devonian rocks throughout most of Montana, except along the central Montana uplift and the Cedar Creek anticline, where they overlie rocks as old as Cambrian and Ordovician (fig. 4).

Throughout most of Montana, the Lodgepole Limestone is divided into two members, the Paine and the Woodhurst. However, in southwestern Montana, a third member is present where the upper tongue of the Cottonwood Canyon Member intertongues with and is overlain by the widespread bioclastic and glauconitic limestone at the base of the Paine Member. A similar stratigraphic configuration exists in north-central and northeastern Montana, where the upper black shale of the Bakken Formation unconformably overlies the medial Bakken siltstone but conformably underlies the Lodgepole Limestone (fig. 5). In northwestern Montana, temporal and lithologically equivalent strata are called the Allan Mountain Limestone, which is divided into three unnamed members (fig. 2).

The Paine Member of the Lodgepole Limestone is most extensive and thickest in the Big Snowy trough in central Montana, where it is 75 to 90 m thick. From this slight thickening along the axis of the trough, the Paine Member thins north and south onto the Alberta and Wyoming shelves. On the Wyoming shelf, the Paine Member thins to 45 m before it becomes indistinguishable by intertonguing with the lower dolomite member of the Madison Formation (Sando, 1972).

At the base of the Paine Member, Upper Devonian strata or the siltstone of the Cottonwood Canyon Member are overlain by a widespread but discontinuous sheet of light-gray bioclastic and glauconitic limestone 0 to 17 m thick. Rocks of this unit are both micritic and sparry and are composed of coarse fragments of crinoids, brachiopods, bryozoans, and corals. This basal unit is abruptly overlain by 30 to 70 m of uniformly thin-bedded dark argillaceous lime mudstone and calcareous shale. Alternation of these rocks produced the distinctive rhythmic outcrop pattern of the Paine Member. These dark lime mudstone beds are characterized by a sparse fauna of crinoids, corals, bryozoans, brachiopods, and spicules of unknown origin, in addition to the trace fossils *Cosmoraphe* and *Scalarituba* (Gutschick, McLane, and Rodriguez, 1976). Large "interformational truncation surfaces" and smaller scale soft-sediment deformation features are also found in this dark lime mudstone (Wilson, 1969; Smith, 1977).

The dark lime mudstone of the Paine Member enclosed lime mud bioherms in the Bridger Range and the Big Snowy Mountains, as well as in several other localities in central Montana and along the Cedar Creek anticline. These are "Waulsortian" bioherms, comparable with those of similar age in North America and Europe (Cotter, 1965, 1966; Stone, 1972). The cores of these bioherms are characterized by alternating bioclast-rich and bioclast-poor layers, inclined at as much as 35° to the enclosing dark lime mudstone bedding and traceable vertically for as much as 50 m. Fossil components of these layers are more diverse than those of the enclosing dark lime mudstone and include crinoids, fenestrate bryozoans, brachiopods, coelenterates, and mollusks (Merriam, 1958). Between bioherm cores is a flank facies, composed of large crinoid fragments in a lime-mud matrix.

The upper few meters of the Paine Member is gradational from dark lime mudstone to thicker bedded, lighter colored, pellet and bioclastic limestone beds. The top of the member is placed ". . . at the base of the lowest crinoidal limestone bed, which marks the beginning of cyclical alternation of crinoidal limestone (commonly oolitic) and shaly, predominantly fine grained limestone characteristic of the Woodhurst Member" (Sando and Dutro, 1974, p. 4).

The Woodhurst Member of the Lodgepole Limestone is easily distinguished from the underlying Paine Member by its distinctive outcrops of medium to thick resistant beds that are cyclically interspersed with recessive units of thinner beds. This member is more widespread than the Paine Member and occurs not only in central Montana but also on the Cordilleran platform in southern and northern Montana. The Woodhurst Member is nearly 180 m thick in the Big Snowy trough in central Montana, thinning to less than 90 m to the north and south on the Alberta and Wyoming shelves.

Woodhurst lithologies are arranged in cyclic packages, each package consisting of a thin-bedded, fine-grained, nonresistant lower part that is capped by more thickly bedded, coarser grained bioclastic and oolitic limestone beds that form distinctive resistant ledges. Definition of these cycles has varied, from the 28 described by Laudon and Severson (1953) in the Bridger Range to the 5 to 8 described by Wilson (1969) and Smith (1972) from central Montana. A typical Woodhurst cycle begins with a mixed oolite and bioclastic lime grainstone interval that commonly overlies an undulating surface on top of the capping bed of the previous cycle. Overlying this initial unit are thin beds of pellet and bioclastic grainstone and packstone beds. Bioclastic components in these beds include crinoid fragments, dasyclad algae, fragments of bryozoans, and endothyrid foraminifers. These beds grade upward into more bioclast-rich, cross-stratified lime grainstone beds which are capped by resistant thick-bedded oolitic and bioclastic grainstone beds that complete the cycle. This capping bed is composed of crinoid-cored oolites and abundant crinoid debris and is characterized by trough cross-stratification and ripple-drift cross-lamination (Jenks, 1972).

The contact of the Woodhurst Member is conformable with the overlying Mission Canyon Formation and is generally placed at the base of the first massive cliff-forming limestone bed above the base of the Madison Group. According to Sando and Dutro (1974, p. 4), ". . . the top of the Woodhurst is placed at the top of the highest shaly, thin-bedded, predominantly fine grained limestone beneath the thicker crinoidal beds of the Mission Canyon."

According to Sando, Mamet, and Dutro (1969), the Lodgepole Limestone includes two foraminiferal zones and part of a third, four coral-brachiopod megafaunal zones (fig. 7), and, at its base, three conodont zones (fig. 5). The Cottonwood Canyon Member contains conodonts of the early Kinderhookian *Siphonodella sandbergi–S. duplicata* Zone and is included in the Cordilleran megafaunal pre-A Zone and global foraminiferal pre-7 Zone. The Paine Member is also included in the pre-7 Zone but is characterized by Kinderhookian Zone A corals and brachiopods and by conodonts of the *Siphonodella crenulata* Zone (Sandberg and Klapper, 1967). The Woodhurst Member includes the latest Kinderhookian-early Osagean megafaunal C_1 Zone and foraminiferal zone 7 and the lower part of zone 8 (fig. 7).

The depositional history of all or part of the Lodgepole Formation has been reviewed by Sando (1976); Gutschick, McLane, and Rodriguez (1976); Rose (1976); Rodriguez and Gutschick (1970); Sandberg and Klapper (1967); and Smith (1972, 1977).

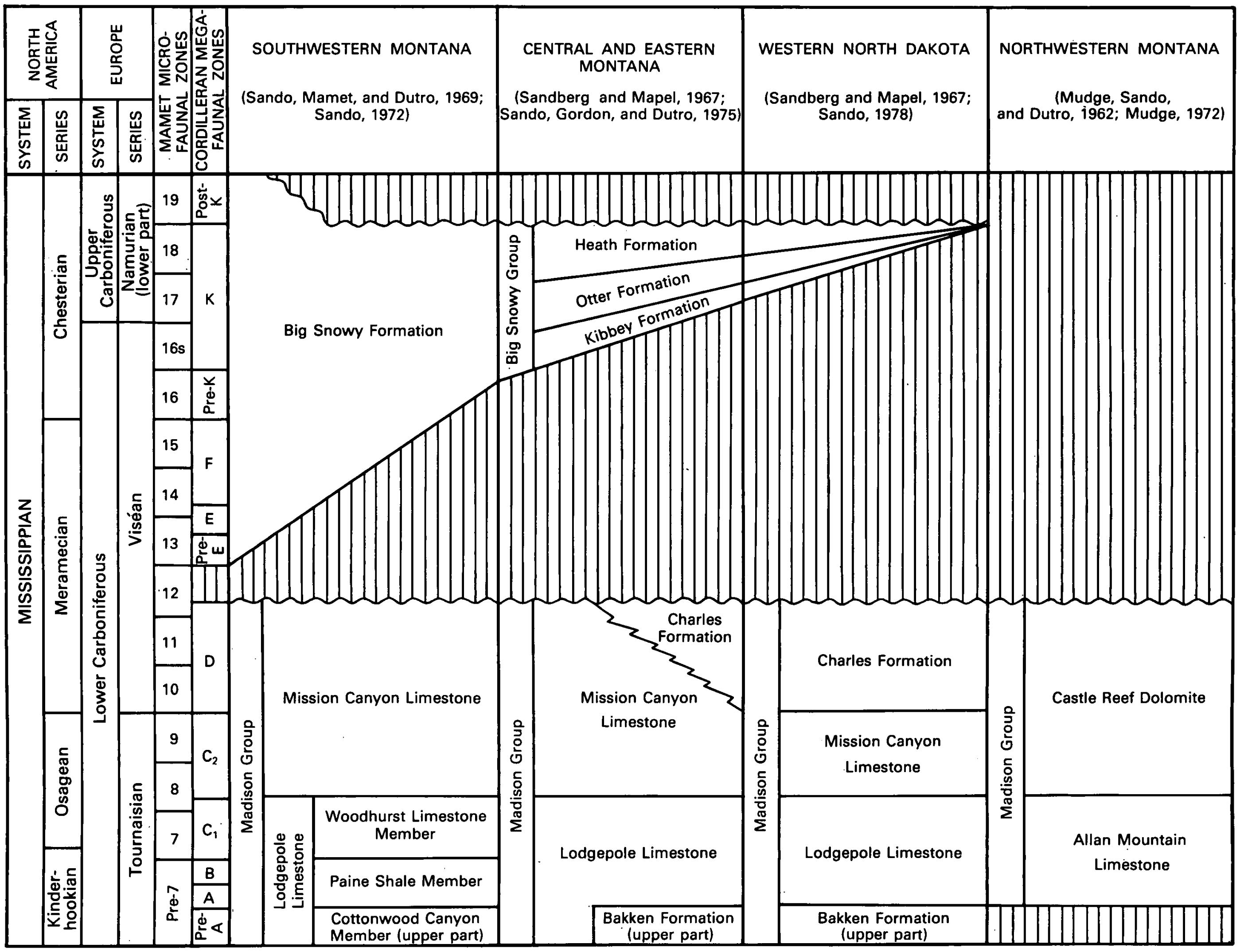


FIGURE 7.—Nomenclature, faunal zones, and temporal relationships of Mississippian rock units in Montana and adjacent areas. Vertical lines indicate hiatus. (Modified from Sando, 1976).

Lodgepole strata record the initial incursion of the Madison sea from the Cordilleran miogeosyncline onto the craton in Montana. This transgression began in latest Devonian time and resulted in the accumulation of the Cottonwood Canyon Member in southwestern Montana and the upper black shale of the Bakken Formation in the northeastern corner of the State. These rocks were deposited over an irregular erosion surface in shallow basins between latest Devonian-earliest Mississippian tectonic elements. Rocks of the Cottonwood Canyon Member occur in two facies tracts—an eastern dolomitic shale and siltstone facies deposited in shallow-water marine environments at the rapidly advancing margin of the Madison sea, and a western siltstone and shale facies that accumulated in slightly deeper offshore marine environments (Sandberg and Klapper, 1967; Rodriguez and Gutschick, 1970). Clastic sediments for these facies were probably provided by low-lying uplifts adjacent to this shallow basin.

Continued rapid transgression in the late Kinderhookian resulted in the deposition in shallow agitated water of the widespread bioclastic and glauconitic limestone at the base of the Paine Member as low-lying terrigenous sediment sources were progressively inundated and effectively mantled. Sedimentation apparently kept pace with the combined effects of downwarping of the incipient Big Snowy trough and rising sea level.

As rapid transgression of the late Kinderhookian Madison sea continued to its latest Kinderhookian maximum, downwarping of the Big Snowy trough and (or) rise of sea level exceeded rates of carbonate and terrigenous sediment influx, resulting in deeper water environments there. Along the slope of this trough, lime-mud bioherms were raised by the combined activities of crinoids and bryozoans from the shallow sea floor into shallower water.

At this same time, shallow-water carbonate sediments were deposited on the Wyoming shelf (Sando, 1972). However, between the Big Snowy trough and the Wyoming shelf, there was no abrupt break-in-slope and attendant marginal carbonate buildups.

During the early Osagean, regression of the Madison sea began and subsidence of the Big Snowy trough diminished. In the trough, deeper water conditions that prevailed during deposition of the Paine Member gave way to shallower depositional environments, resulting in the cessation of bioherm growth and an increase in the bioclastic content of the limestones that overlie the dark rhythmic lime mudstone beds. On the Wyoming shelf, and probably on the Alberta shelf, carbonate production and accumulation exceeded subsidence, resulting in northward and southward progradation of oolitic and bioclastic shoals of the Woodhurst Member across the Big Snowy trough.

Widespread intertidal and subtidal environments prevailed throughout Montana during the first half of Osage time, and bioclastic and oolitic shoal and finer grained intershoal carbonate sediments accumulated. Alternate high- and low-energy shallow-water lithotopes migrated across the State in response to minor transgressions and regressions (Sando, 1976) or to some combination of eustatic change, varying rates of carbonate production, and differential subsidence (Smith, 1977). The migration of these shoal and intershoal lithotopes produced the cycles that characterize the Woodhurst Member.

MISSION CANYON LIMESTONE

The Mission Canyon Limestone is a prominent cliff- and ridge-forming limestone above the less resistant Lodgepole Limestone and below the recessive Big Snowy and Amsden Groups. The formation is present throughout the State, except where it has been removed by Tertiary erosion. However, the original thickness and lithologic distribution is masked by Triassic and Early Jurassic erosional thinning in the northern part of Montana.

The Mission Canyon Limestone conformably overlies the Lodgepole Limestone and is, in turn, overlain by various upper Paleozoic and Mesozoic strata. In the Big Snowy trough, the Mission Canyon is unconformably overlain by the Big Snowy Group. However, to the north, it is unconformably overlain by the Jurassic Sawtooth and Nesson Formations. South of the Big Snowy trough, the Mission Canyon is unconformably overlain by the Pennsylvanian Amsden Formation, the contact marked by a regional karst surface (Roberts, 1966; Sando, 1974).

The Mission Canyon Limestone is thickest in the Big Snowy trough and Williston basin (300 m), thinning northward because of Triassic and early Jurassic erosion and southward because of deposition. This lenticular geometry reflects the relative negative and positive aspects of these paleotectonic elements both during and after deposition of the Mission Canyon Limestone.

The Mission Canyon Limestone is characterized by less detrital sediment than is the underlying Lodgepole; it is composed of massive beds of limestone and dolomite, the percentage of dolomite in the formation generally increasing southward onto the Wyoming shelf (Andrichuk, 1955). Interbedded with these carbonate rocks in the upper part of the formation are beds of gypsum or anhydrite in the subsurface that are manifest in surface sections as solution breccia zones (Roberts, 1966). Evaporite beds are more abundant in the Big Snowy trough and Williston basin than they are on the northern and southern shelves (Craig, 1972).

On the shelf in southern Montana, Sando (1972) delineated three members of the Mission Canyon: the lower limestone member, the cliffy limestone member, and the Bull Ridge Member, in ascending order. The lower limestone member ranges from 85 to 100 m in thickness and is the time-stratigraphic equivalent of the cherty dolomite member of Wyoming (Sando, 1972). The base of this member consists to 15 to 30 m of cross-stratified, oolitic, and crinoidal limestone. This basal unit is overlain by interbedded limestone and dolomite, and the top of the member is placed at the base of a widespread evaporite solution breccia. The cliffy limestone member includes this 7.5 to 15-m-thick breccia at its base. This breccia bed appears in most sections of southwestern Montana and is the "lower solution zone" of Sando (1972). Above this breccia, the cliffy limestone member consists of 55 to 70 m of cliff-forming oolitic and bioclastic limestone and dolomitized limestone. The Bull Ridge Member is 3 to 36 m thick, and its base is characterized by an evaporite solution breccia or brecciated dolomitic siltstone and shale interval 3 to 7.5 m thick, the "upper solution zone" of Sando (1972). Above this breccia, the member consists of cherty bioclastic limestone. Brecciation in the Bull Ridge Member is common; red sand, clay, and silt from Pennsylvanian erosion and deposition fill cavities and sinkholes (Sando, 1972).

Although these three members have not been extended out of the Beartooth Mountains area, the lower breccia zone has been extended to the type section at Logan, as well as to the Monarch section in the Big Snowy Mountains (Sando and Dutro, 1974). The upper breccia zone has been correlated only through the Beartooth Mountains. Because it is roughly coincident with the Osagean-Meramecian boundary, it is a good correlation horizon (Sando, 1972). However, in both the Logan and Monarch sections, this breccia may be absent because of nondeposition and is absent in the type section of the Mission Canyon because of pre-Jurassic erosion.

In its type area in the Little Rocky Mountains, the Mission Canyon section was abbreviated by pre-Jurassic erosion, and the 90 m of section there is considered to be the time-equivalent of the lower two-thirds of the lower limestone member in the Beartooth Mountains (Sando and Dutro, 1974, pl. 1). In the Little Rockies, the Mission Canyon consists of medium- to coarse-grained crinoidal limestone in beds reaching a maximum thickness of 1.5 m. These coarse-grained beds are interbedded with finer grained limestone. Both limestone types contain lentils and nodules of chert that may constitute as much as 20 percent of the section.

In northwestern Montana, Mudge, Sando, and Dutro (1962) and Mudge (1972) used the term Castle Reef Dolomite for time-stratigraphic equivalents of the Mission Canyon Limestone. This unit was divided into a lower member and the Sun River Member. The lower member is 116 to 156 m of thick-bedded, fine to coarsely crystalline dolomite and limestone. Many of the coarsely crystalline limestone beds are crinoidal and are cross stratified. The Sun River Member ranges from 76 to 100 m in thickness and correlates with the upper part of the Mission Canyon in the Three Forks area (Mudge, 1972). It contains thin to thick beds of very fine to medium crystalline dolomite interbedded with thick lenses of dolomitized crinoidal limestone. The upper part of the Sun River Dolomite contains sandstone lenses that are interpreted as Jurassic cave fillings, but the karst surface that is so extensive over the southern part of the State is absent here (Mudge, 1972).

The Charles Formation has been the subject of controversy since Seager (1942, p. 863) applied the name to a "series of interbedded limestones, dolomite, anhydrite, and some shales" in a well in central Montana (fig. 1). Sloss (1952, p. 67) described the Charles of the Williston basin as "three major evaporite cycles which include normal fossiliferous limestones, sugary dolomites, dense dolomites, and anhydrite in upward succession." The base of the Charles is usually picked at the base of the lowest evaporite; the top is the unconformable contact with the Kibbey Formation of the Big Snowy Group. Attempts have been made to identify the Charles Formation in outcrops of central Montana but "it is defined on criteria that are difficult to use with precision in outcrop areas" (Sando and Dutro, 1974, p. 2). Until definitive stratigraphic work has refined knowledge of the relationship between the Charles and the Mission Canyon, the Charles is probably best considered as the subsurface lithic and temporal equivalent of the upper part of the Mission Canyon Formation (Sloss, 1952), and the use of the term should be restricted to the subsurface of the Williston basin (Sando and Dutro, 1974).

The Mission Canyon Limestone and its equivalents include three and part of two more foraminiferal zones and two coral-brachiopod megafaunal zones (fig. 7). Both biostratigraphic schemes give the formation a middle Osagean to early Meramecian age (Sando, Mamet, and Dutro, 1969).

The depositional history of the Mission Canyon Limestone and its equivalents was summarized by Andrichuk (1955) and recently by Rose (1976) and Sando (1976). These summaries suggested that Mission Canyon carbonate and evaporite strata record the regression of the Madison sea from the craton in Montana. As shallowing and exposure progressed, the shelves became the sites of sabkhas and salt pans in which evaporites were deposited; dolomitizaton of intertidal and subtidal limestone took place at the same time. Progressive shallowing of the Madison sea also restricted circulation, which led to the accumulation of thick evaporite beds in the Big Snowy trough and Williston basin. Periodic freshening of the sea by normal marine water, related to transgressive pulses of the major regression or to differential sedimentation and epeirogenic warping, probably accounted for the carbonate-evaporite cycles that characterize both basins and shelves.

After its early Meramecian restricted phase, the Madison sea withdrew from most of the craton in Montana, exposing the upper part of the Mission Canyon and its equivalents to subaerial weathering and subsequent karst formation prior to the later Meramecian and earliest Chesterian transgression of the Big Snowy sea.

BIG SNOWY GROUP

The lithology, stratigraphy, and paleontology of the Big Snowy Group have been described by Scott (1935), Walton (1946), Mundt (1956a, b), Willis (1959), Easton (1962), Maughan and Roberts (1967), Harris (1972), Craig (1972), Jensen and Carlson (1972), and Sando, Gordon, and Dutro (1975). The least known but probably the most detailed of these studies is that of Harris (1972), who measured 58 Big Snowy sections in central Montana and who also used existing subsurface data in his synthesis. Much of the following is from Harris' unpublished work.

The Big Snowy Group is restricted to the Big Snowy trough in central Montana, the Williston basin in eastern Montana, and an extension of the Big Snowy trough in southwestern Montana (fig. 6). In central Montana, the Big Snowy trough was bordered on the north by the "Milk River uplift" of Maughan and Roberts (1967) and on the south by the southern Montana arch (Sando, 1976). The group is thickest (360 m) along the axis of the Big Snowy trough; it thins abruptly north and south away from the trough axis. To the north, this thinning is due, in part, to pre-Jurassic erosion (Maughan and Roberts, 1967). South of the trough, the thinning is due to a combination of depositional thinning and latest Chesterian erosion (Sando, Gordon, and Dutro, 1975; Sando, 1976).

In the Big Snowy trough of central Montana and the Williston basin, the Big Snowy Group consists of three formations—the Kibbey Sandstone and the Otter and Heath Formations, in ascending order (fig. 7). However, in southwestern Montana, where these members have not been formally delineated, the Big Snowy has formational rank. Rocks of the Big Snowy Group are interpreted as products of the second major Mississippian transgression in Montana. The Kibbey is the basal transgressive unit, deposited at the eastward-advancing margin of the Big Snowy sea; the Otter consists of shale and limestone, deposited just offshore from the Kibbey; and the Heath is an accumulation of dark limestone and shale along the axis of the Big Snowy trough (Sando, Gordon, and Dutro, 1975). These formations are a classic diachronous transgressive sequence (fig. 7), older in southwestern Montana (latest Meramecian), progressively younger eastward in the Big Snowy trough of central Montana (earliest Chesterian), and youngest in the Williston basin of eastern Montana (middle Chesterian) (Sando, 1976).

KIBBEY SANDSTONE

The contact of the Kibbey Sandstone with the underlying Madison Group is reported to be conformable in eastern Montana and in the center of the Big Snowy trough in central Montana (Maughan and Roberts, 1967; Harris, 1972), where it is said to intertongue with or conformably overlie the Charles Formation or its Madison Group equivalent. However, these same workers stated that the Big Snowy Group rests unconformably on Madison strata in southwestern Montana, as well as in the southern part of the Big Snowy trough in central Montana. These interpretations suggest that during the regressive phase of the latest early Meramecian, the Madison sea regressed from the central and western parts of the Big Snowy trough; it remained as an isolated marine body in the more negative eastern parts of the trough and Williston basin, producing the Madison-Big Snowy unconformity in western and central Montana and the conformable and intertonguing relationships between these groups in the eastern trough and Williston basin.

Counter to this view is the concept that the Madison sea retreated from the Big Snowy trough and the Williston basin, as well as from the surrounding shelf areas during the latest early Meramecian (Sando, Gordon, and Dutro, 1975; Sando, 1976), producing a major disconformity between the Madison and Big Snowy Groups. In support of this concept, Sando (1978) identified megafaunal zone D corals 15 to 20 m below the top of the Charles Formation in the subsurface of the Williston basin. Additional faunal evidence bearing on this problem was provided by Scott (1945) and Easton (1962), who indicated that faunas from the Otter Formation are Chesterian. Inasmuch as the age of the intervening Kibbey Formation has not been definitely established by fossil evidence, at least three and possibly four megafaunal zones are absent at the Madison-Big Snowy contact. The absence of these fossil zones, the classic transgressive stratigraphic and sedimentologic sequence of the Big Snowy Group, the paleogeographic problem presented by an isolated marine body in a cratonic basin, and similar stratigraphic relationships of the Darwin Sandstone in Wyoming, all strongly suggest the presence of an interregional disconformity between the Madison and Big Snowy Groups.

The Kibbey Formation is thickest along the northern edge of the Big Snowy trough (76 m), thinning abruptly to the north and south. In southwestern Montana, the Kibbey equivalent is 45 m thick. Where the formation is thickest and most extensive in central and eastern Montana, Harris (1972) delineated three informal members. The lower member is 0 to 30 m thick and consists of red shale containing beds and lenses of green shale, sandstone, and gypsum. The middle member is 1.5 to 12 m thick and occurs only in the middle and eastern parts of the Big Snowy trough. In the central Montana part of the trough, this member is composed of dolomite containing thick gypsum beds. However, in the eastern part of the trough, this dolomite grades into oolitic and fragmental limestone (Rawson, 1968). The upper member of the Kibbey consists of fine-grained quartz sandstone and interbedded red and gray shale and lenses of dolomite. This member is 46 m thick in the axis of the Big Snowy trough, where shale is the predominant rock type. At the southern margin of the trough, sandstone is dominant.

The Kibbey Formation is interpreted as intertidal to subtidal deposits at the leading edge of the advancing Big Snowy sea. During deposition of the lower member, sand from the craton accumulated along high-energy shorelines at the same time as finer-grained detritus was deposited in intertidal and shallow subtidal environments. Thick beds of gypsum interbedded with these clastic rocks indicate that circulation of shallow marine water in the Big Snowy trough must have been spatially and temporally restricted, probably by a combination of the irregular topography of the eroded Madison surface, minor transgressive-regressive fluctuations of the Big Snowy sea, and gentle epeirogenic activity in the trough. Similar environmental controls and configurations prevailed during deposition of the middle member of the Kibbey, but the supply of coarse clastic debris from the craton had diminished and parts of the Big Snowy trough were less restricted, resulting in the accumulation of evaporite and dolomite in central and western Montana and oolitic and bioclastic limestone in the eastern Big Snowy trough and Williston basin. This facies pattern of rocks of hypersaline origin in the western part of the trough and normal marine limestone in the eastern part of the trough and the Williston basin presents a paleogeographic problem concerning the source of the water for this marine embayment. Rawson (1968) suggested that normal marine water fed into the Williston basin from a northwestern link with the Cordilleran miogeosyncline. An equally strong argument may be made for nonrestricted flow of normal marine water through the Big Snowy trough from the Cordilleran miogeosyncline on the west to the Williston basin on the east, peripheral shallow restricted embayments providing sites for evaporite accumulation at the margins of the trough. The upper member of the Kibbey records an influx of coarser clastic material from the Canadian shield (Ballard, 1964; Harris, 1972), sand that was deposited in high-energy intertidal shoreline environments near the margins of the Big Snowy trough. However, shale dominates this member in the central part of the trough, suggesting deeper quieter depositional conditions there.

Throughout most of Montana, the Kibbey grades into the Otter through 3 to 6 m of intertongued typical Kibbey sandstone beds and light-gray shale typical of the Otter. However, in parts of southwestern Montana, the Kibbey and Otter are unconformably overlain by the Tyler Formation equivalent (Sando, Gordon, and Dutro, 1975).

OTTER FORMATION

The Otter Formation or its equivalents occur throughout the Big Snowy trough, the Williston basin, and southwestern Montana (Sando, Gordon, and Dutro, 1975). Along the trough axis, the formation is 150 m thick, but it thins abruptly to a featheredge to the north and south. In central Montana, Harris (1972) divided the Otter into three informal and unnamed members. The lower member is 75 m thick along the trough axis and consists predominantly of gray and dark-gray shale and interbedded green and maroon shale, thin sandstone lenses and beds, dolomite, and thin beds of stromatolitic and oolitic limestone. Green shale and dolomite predominate along the southern margin of the trough, and dark-gray shale and limestone are dominant in the trough axis. The middle member of the Otter is 35 m thick in the Big Snowy trough and is predominantly oolitic, pelletal, bioclastic, stromatolitic, and micritic limestone containing minor beds of green to dark-gray shale, cherty dolomite, and gypsum. The darker rocks generally occupy the center of the trough; the green shale and dolomite are found at the southern trough margin. The upper member is 90 m of green shale containing lenses of variegated calcareous and siliceous shale and beds of chert-rich, stromatolitic, oolitic, and bioclastic limestone. These light-colored rocks dominate the upper member along the trough margins. The axial part of the trough is characterized by dark shale and interbedded limestone.

The carbonate-rich Otter Formation records a change from the coarse clastic deposits of the Kibbey Formation to more normal marine, more agitated, but sand-free depositional conditions. The lower member was deposited in intertidal and shallow subtidal environments, where fine-grained clastic sediment, ooliths, calcareous skeletal debris, and lime mud were synchronously deposited under variable environmental conditions. Concentration of green shale and dolomite along the southern trough margin suggests oxidizing and, possibly, supratidal environments there, close to the source of terrigenous clastic sediment. The predominant gray shale and limestone of the lower member suggest deposition in agitated and calm subtidal environments toward the trough axis. In the center of the Big Snowy trough, deeper water environments favored accumulation of dark shale.

The Otter-Heath contact is gradational through a 15- to 30-m sequence of interbedded black Heath-like shale and limestone and typical green shale of the Otter Formation. However, in parts of southwestern Montana, the Otter is unconformably overlain by the Tyler equivalent, and in the northern part of the Big Snowy trough, by the Tyler Formation, the Quadrant Formation, or the Ellis Group.

HEATH FORMATION

Along the axis of the Big Snowy trough, the Heath is 120 m thick, thinning abruptly toward the northern and southern trough margins. In southwestern Montana, the Heath is 45 m thick; dark-gray to black shale and limestone are dominant. The dark shale is fissile, petroliferous, and is the predominant Heath lithology in the middle of the Big Snowy trough. Heath limestone beds are massive, micritic, sparsely fossiliferous, and may have sparse chert nodules or beds and scattered quartz sand grains. Limestone is the dominant Heath lithology at the southern margin of the trough.

Heath shale accumulated in calm, oxygen-poor environments in the center of the Big Snowy trough. Depositional environments at the margins of the trough, however, were shallower, more agitated, and were conducive to the accumulation of lime mud and well-washed bioclastic debris, both containing admixtures of quartz sand from a cratonic source (Harris, 1972).

Relief of as much as 45 m on the unconformity between the Tyler and the Heath indicates that extensive erosion took place in the Big Snowy trough after deposition of the Heath. At the southern trough margin, as well as in southwestern Montana, the Tyler or its equivalent unconformably overlies Kibbey, Otter, and Heath equivalents (Sando, Gordon, and Dutro, 1975). At the northern margin of the Big Snowy trough, rocks of the Jurassic Ellis Group unconformably overlie and truncate all three formations of the Big Snowy Group (fig. 9).

AMSDEN GROUP

The Amsden Group as defined by Maughan and Roberts (1967) consists of three formations—the Tyler Formation, Alaska Bench Limestone, and Devils Pocket Formation (fig. 2). This terminology is used for central and eastern Montana. Maughan and Roberts (1967) arbitrarily used Amsden Group terminology eastward to the Montana-North Dakota border, at which point they used Minnelusa Formation. In southwestern Montana, strata approximately equivalent to the Amsden Group were referred to as the Amsden Formation (Maughan and Roberts, 1967).

The Amsden Group ranges from a featheredge to more than 270 m in thickness in central Montana (Mallory, 1972). More commonly, the group is about 150 m thick through the center of the Big Snowy

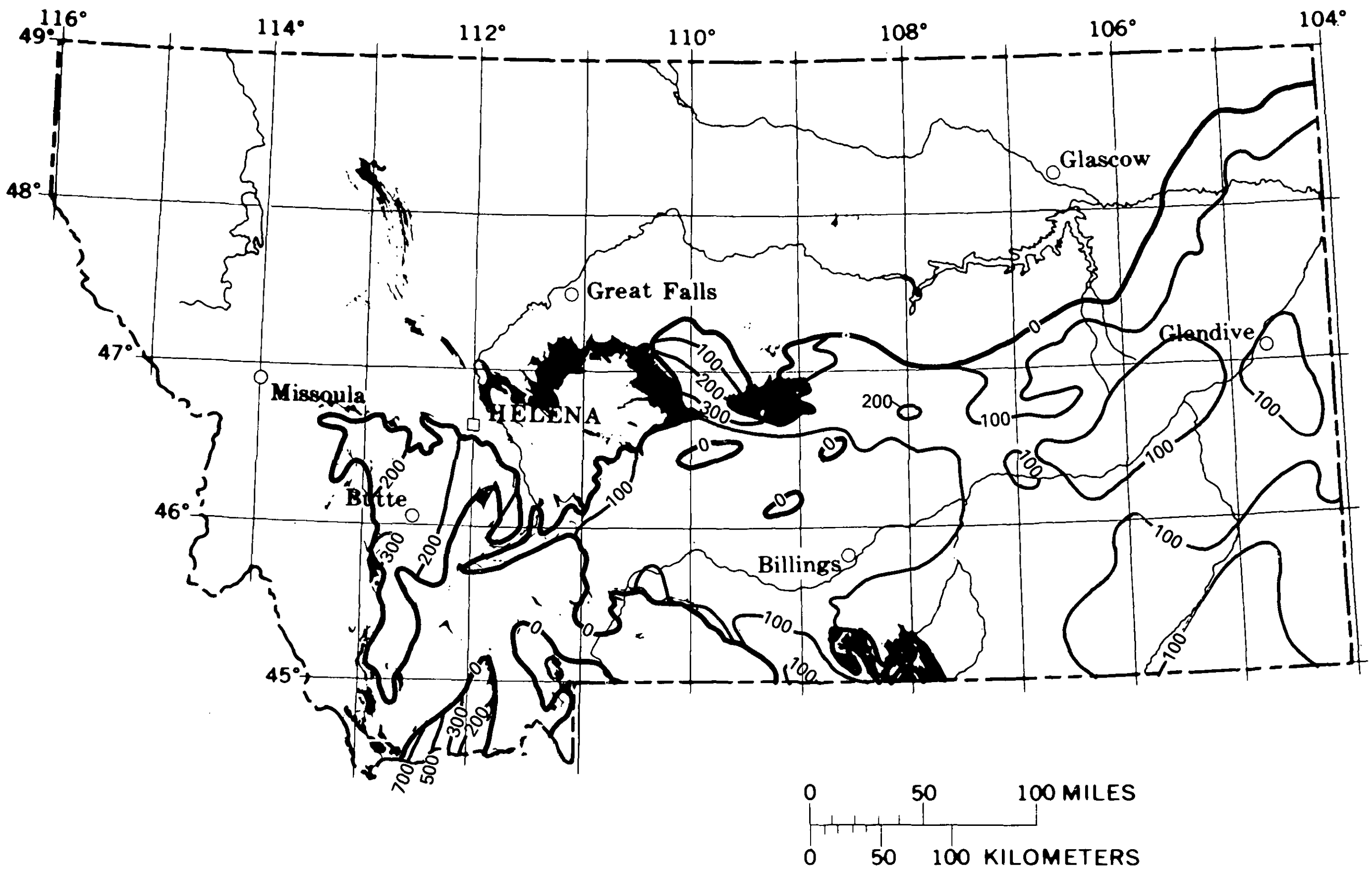


FIGURE 8.—Map of total thickness of the Pennsylvanian System (adapted from McKee and Crosby, 1975, pl. 11). Thicknesses include Stonehouse Canyon Member of the Tyler Formation, part of which may belong in the Mississippian System. Isopach thicknesses in meters.

trough. The group extends from southwestern Montana northeastward through the Big Snowy trough to the Montana-North Dakota border (fig. 8). Northward, pre-Jurassic erosion has truncated the group (Maughan and Roberts, 1967); southward, the group thins over the southern Montana arch, where it grades into the Ranchester Limestone Member of the Amsden Formation (Sando, Gordon, and Dutro, 1975). Lithologies present are sandstone, siltstone, shale, limestone, dolomite, sandy dolomite, and a few dolomite beds with chert nodules.

The Amsden Group grades upward from dark-gray shale and sandstone to red beds to interbedded limestone, shale, and dolomite to sandy dolomite and sandstone. This vertical relationship is similar to that described by Sando, Gordon, and Dutro (1975, p. A3–A7) for the Amsden Formation in Wyoming. Lateral gradations of rocks between and within formations have been reported by several workers (Gardner, 1959; Maughan and Roberts, 1967; Gilmour, 1969; Sando, Gordon, and Dutro 1975). Sando, Gordon, and Dutro (1975, p. A64) postulated an east-west facies relationship across Montana of a nearshore sand belt, an intermediate offshore lagoonal facies, and a central dolomitic carbonate-shale facies.

TYLER FORMATION

The lowest unit of the Amsden Group is the Tyler Formation, named by Freeman (1922) for exposures in the Big Snowy Mountains (fig. 1). The Tyler Formation was redefined by Maughan and Roberts (1967) as consisting of two members: a lower member called the Stonehouse Canyon Member and an upper member called the Cameron Creek Member. The two members were established "largely on color and partly on lithology" (Maughan and Roberts, 1967, p. B12).

In Easton's (1962) section at Stonehouse Canyon, designated as a reference section and reinterpreted by Maughan and Roberts (1967, p. B12), the Stonehouse Canyon Member consists of 31 m of covered black fissile shale and poorly exposed dark-greenish-gray to very dark brownish-gray shale. At the type section given by the authors, the member is 76 m thick and consists of buff to brown sandstone (21 m), black and dark-gray fissile shale (53 m), and light-gray to buff limestone (2 m). Both these sections were included in the Heath Formation by Easton (1962).

The Cameron Creek Formation was originally named by Gardner (1959) and was reduced in rank to member status by Willis (1959) and again by Maughan and Roberts (1967) (fig. 2). This unit comprises the varicolored shale, gray and brownish sandstone, and thin gray limestone above the sandstone and dark shale of the Stonehouse Canyon Member and below the Alaska Bench Limestone. The two members are lithologically similar, as pointed out by Maughan and Roberts (1967, p. B12): "The boundary between Stonehouse Canyon and Cameron Creek is difficult or impossible to pick consistently at the same stratigraphic position from place to place owing to the gradation and intertonguing of one into the other." At the west end of Alaska Bench (locally called "Beacon Hill"), the Cameron Creek Member is 25 m thick (Easton, 1962, p. 117) and at the Stonehouse Canyon section, it is 67 m thick (Easton, 1962, p. 123).

The extent of the Tyler Formation approximates the same area defined as the Big Snowy trough. It generally thins eastward towards the Cedar Creek anticline in eastern Montana but thickens again eastward into the Williston basin area after crossing the anticline. The formation also thins southward across the southern Montana arch toward Wyoming. Westward, the Tyler Formation or its equivalent extends into the Cordilleran miogeosyncline. Total thickness for the Tyler Formation ranges from a featheredge to more than 242 m near the Little Belt Mountains in central Montana. Generally, the formation is 30 to 90 m thick.

Vertically, the formation changes from dominantly sandstone and black shale at the base to sandstone and red beds in the middle to interbedded limestone and red shale at the top in central Montana. The percentage of sandstone in the lower part (Stonehouse Canyon Member) increases westward toward southwestern Montana; the percentage of limestone in the upper part (Cameron Creek Member) increases eastward toward the Williston basin (Mallory, 1972, p. 112).

Most of the fossils found in the Tyler Formation indicate an Early Pennsylvanian (Morrowan) age. Several detailed reports on the fauna and flora of the Tyler Formation have been published by Easton (1962), Maughan and Roberts (1967), Gordon (1975), and Sando, Gordon, and Dutro (1975). Easton (1962) interpreted the fauna in the Tyler Formation (Cameron Creek Formation of Easton) as Late Mississippian (Chesterian). Sando, Gordon, and Dutro (1975) listed three brachiopods from the Tyler Formation that are exclusively Mississippian in Wyoming and two species that are Mississippian and Pennsylvanian in Wyoming. Exclusively Mississippian are *Pugnoides quinqueplecis* Easton, *Anthracospirifer curvilateralis curvilateralis* (Easton), and *A.* cf. *A. occiduus* (Sadlick) form A. *Schizophoria depressa* Easton and *Eolissochonetes pseudoliratus* (Easton) are found in both Mississippian and Pennsylvanian rocks. Sando, Gordon, and Dutro (1975) also listed six species of brachiopods in the Tyler Formation that are exclusively Pennsylvanian. These include *Orthotetes* sp. A. Gordon, *Echinoconchus* sp. A. Gordon, *Antiquatonia* cf. *A. coloradoenis* (Girty), *Linoproductus eastoni* Gordon, *Composita ovata* Mather, and *Anthracospirifer occiduus* (Sadlick). *Petrocrania chesterenis* (Miller and Gurley) was collected near the top of the Stonehouse Canyon Member and is regarded as Chesterian, according to Gordon (Maughan and Roberts, 1967, p. B20). This brachiopod occurs with *Eolissochonetes pseudoliratus* (Easton), considered by Sando, Gordon, and Dutro (1975) as Mississippian and Pennsylvanian. This type of information tends to support the contention of Easton (1962, p. 25) ". . . that the fauna of the Big Snowy group [Easton included the Cameron Creek Formation in the Big Snowy Group] may prove to be particularly significant in subsequent attempts to recognize the Mississippian-Pennsylvanian boundary, because the fauna occurs in the critical interval and is replete with species."

Maughan and Roberts (1967, p. B12–B14) gave particular attention to the age of the Tyler Formation and concluded that the Tyler Formation above the regional unconformity with the Heath Formation is Morrowan. They reported Early Pennsylvanian plant spores from the upper part of the Stonehouse Canyon Member and extended this age assignment to the base of the Tyler. However, they (Maughan and Roberts, 1967, p. B21) also quoted R. H. Tschudy as saying that spores from the lower part of the Stonehouse Canyon Member "may be from a Pennsylvanian horizon not yet examined, or may represent a transitional flora between the Late Mississippian and the Early Pennsylvanian." Mallory (1972) also described the Tyler Formation as Morrowan in age.

The Cameron Creek Member contains several brachiopods that are restricted to Morrowan or younger rocks (Maughan and Roberts, 1967). These include *Linoproductus eastoni* Gordon, *Rugoclostus nivalis* Easton, and *"Marginifera" planocosta* Easton. Easton (1962, pl. 3) illustrated *Millerella* collected from the Cameron Creek Member. According to B. A. Skipp, this form "may be considered Pennsylvanian as much as they may be Mississippian forms" (Maughan and Roberts, 1967, p. B21).

From the foregoing discussion, it appears that the upper part of the Stonehouse Canyon Member and the Cameron Creek Member are Morrowan on the basis of the faunal evidence. However, the exact age of the lower part of the Stonehouse Canyon Member (upper part of Heath Formation of Easton, 1962), as redefined by Maughan and Roberts (1967), is still open to question, and additional work is needed.

Both marine and nonmarine environments of deposition have been proposed for the Tyler Formation in central and eastern Montana (Mundt, 1956b; Gardner, 1959; Willis, 1959; Foster, 1961; Ballard, 1964; Maughan and Roberts, 1967; Jensen and Carlson, 1972). The Stonehouse Canyon Member is believed to have been deposited on an erosional surface of the Mississippian Heath Formation (Beekly, 1955). The interbedded sandstone and dark-gray to black shale of the Stonehouse Canyon Member are lagoonal, deltaic, and estuarine deposits varying from marine to nonmarine (Beekley, 1955). Mundt (1956b) interpreted the dark gray and black shale in the lower Tyler as nonmarine and the erratic sands in the lower part of the formation as channel deposits. He believed that "a gradation upward from nonmarine to normal marine shale apparently coincides with the color change" from dark gray to reddish shades.

According to Gardner (1959, p. 337, 344), the Tyler Formation represents deposition in a shallow marine basin where currents of water, flowing seaward from tributary rivers, cut local channels across tidal flats and shallow parts of the sea. These channels were filled with sand, as well as debris torn from the sides and bottom of the channel. When changes in current velocity or positions of currents took place, typical marine sediments could be interbedded with channel deposits. Gardner (1959) presented evidence opposing a nonmarine interpretation of the paleontological data. Thus, Gardner supported an interpretation that both the Heath and the Tyler Formation are part of a continuous marine sequence.

THE BEAR GULCH LIMESTONE PROBLEM

Mundt (1956a, b) included a marine limestone tongue in the Tyler Formation that is locally present near the top of the formation. This limestone was shown in a diagrammatic correlation section (Mundt, 1956a, p. 1925). Mundt (1956c) also measured and described a section designated as "Bear Gulch composite section" that contained a detailed description of the Tyler Formation and the included limestone tongue. Willis (1959, p. 1953) referred to this limestone as the Bear Gulch limestone tongue for exposures along Bear Gulch Creek, south of Forest Grove. Other workers (Foster, 1956, p. 122; Norton, 1956, p. 58, 62; Todd, 1959) also made reference to this limestone tongue.

All the above workers placed the Bear Gulch limestone tongue in some part of the Tyler Formation and above the regional unconformity between the Heath and Tyler described by Maughan and Roberts (1967). Maughan and Roberts (1967, p. B11, fig. 5) also showed an extensive limestone tongue in the middle of the Tyler Formation that thins from north to south (fig. 9). However, they did not discuss the lithology, age, or extent of the limestone unit. Mundt (1956a, p. 1924) depicted a depositional model for the Tyler Formation showing sandstone deposited simultaneously with the Bear Gulch limestone tongue, both of which are above the regional unconformity between the Heath and Tyler.

On the basis of studies of conodonts and fish (W. G. Melton and J. R. Horner, written commun., 1978), the age of the Bear Gulch limestone tongue is believed to be Springeran (latest Mississippian). This age may be equivalent to that of foraminiferal zone 19, which was included in the Chesterian by Sando, Gordon, and Dutro (1975). Mackenzie Gordon, Jr. (written commun., 1978), in 1970 studied the cephalopod fauna of the Bear Gulch limestone tongue at the Allen Surprise quarry in Fergus County and concluded that because it contained *Epistroboceras, Tylonautilus,* and *Anthracoceras,* it was of late Chesterian (Late Mississippian) age. This information throws doubt on the interpretation that the unconformity between the Heath and the Stonehouse Canyon Member of the Tyler Formation represents the Mississippian-Pennsylvanian boundary. The position of the systemic boundary appears to be somewhere in the Stonehouse Canyon-Cameron Creek sequence (fig. 9).

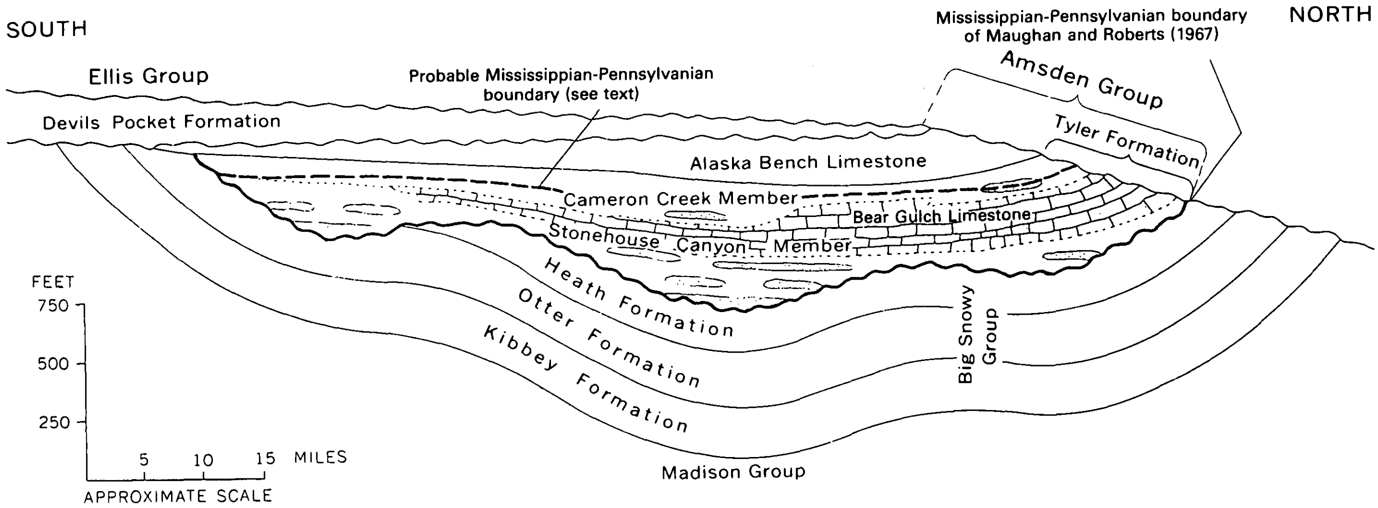


FIGURE 9.—Diagrammatic cross section of Big Snowy and Amsden Groups in central Montana. (Modified from Mundt, 1956a, and Maughan and Roberts, 1967.)

ALASKA BENCH LIMESTONE

Freeman (1922) was the first to apply the name Alaska Bench Limestone to the gray fossiliferous limestone that forms the sloping benches and hogbacks around the Big Snowy Mountains (fig. 1). Mundt (1956a), Gardner (1959), Easton (1962), Maughan and Roberts (1967), and Gilmour (1969) used the name as a formational designation. Only the limestone in the Big Snowy trough is called the Alaska Bench, although Willis (1959) stated that the lower limestone of the Minnelusa Formation in the Williston basin is probably equivalent to the Alaska Bench. Carbonate units at the same interval in southwestern Montana constitute the upper part of the Amsden Formation (Maughan and Roberts, 1967). In Wyoming and southern Montana, limestone of similar age belongs to the Ranchester Limestone Member of the Amsden Formation (Sando, Gordon, and Dutro, 1975).

The Alaska Bench Limestone thins northward toward the depositional edge of the Big Snowy trough (Gilmour, 1969). The formation is also truncated northward by pre-Jurassic erosion. This combination of depositional thinning and postdepositional erosion accounts for the northward thinning and truncation of the Alaska Bench. The formation is truncated southward, where it was probably eroded from the Montana uplift of Sando, Gordon, and Dutro (1975) during Atokan time.

Thickness of the formation varies considerably over short distances owing to nondeposition and periods of postdepositional erosion. Maximum thicknesses reported are 43 m at Durfee Creek Dome (Easton, 1962), 40 m at Beacon Hill (Gilmour, 1967), and 88 m at Judith Gap (Maughan and Roberts, 1967). The formation thins eastward toward the Williston basin, where it does not exceed 38 m.

Lithologically, the Alaska Bench consists of interbedded gray limestone, red mudstone, and dolomite. Limestone beds generally range from 0.3 m to 0.6 m in thickness, but beds as thick as 1.5 m do occur. Beds of red mudstone 0.3 to 1.5 m thick occur throughout the formation (Gilmour, 1967). Dolomite beds are also found throughout the Alaska Bench. Maughan and Roberts (1967) reported a greater proportion of carbonate in the lower 30 m of the Alaska Bench and equal amounts of carbonate and mudstone in the thicker sections (Judith Gap). In the North Fork of Flat Willow Creek, the Alaska Bench Limestone is 25 m thick and contains 33 percent mudstone (Gilmour, 1967, pl. 20). The lower 10 m of the Stonehouse Canyon section is 50 percent mudstone (Gilmour, 1967, pl. 3).

Contacts between the Alaska Bench Limestone and the underlying Cameron Creek Member of the Tyler Formation are gradational with interbedded gray limestone and red mudstone. Lateral intertonguing between these two lithologies was mentioned by Maughan and Roberts (1967) and discussed in detail by Gilmour (1967). Evidence for an unconformity between the Alaska Bench Limestone and the overlying Devils Pocket Formation was presented by Mundt (1956a) and further supported by Maughan and Roberts (1967, p. B15). However, the use of a limestone-dolomite contact between the two formations as the unconforimity is open to question because of secondary dolomitization downward into the Alaska Bench Limestone.

Fossils compose a large percentage of the limestone in the Alaska Bench Limestone. Occurrence of specific fossils or fossil debris depends on which microfacies is represented by a particular limestone bed (Gilmour, 1969). Ostracodes are particularly abundant, as they occur in most of the microfacies described, especially in the algal biolithites and ostracodal muds. Brachiopods, bryozoans, pelmatozoans, echinoids, opthalmid Foraminifera, gastropods, and millerellids are major components in the normal marine microfacies.

Six species of brachiopods were listed by Sando, Gordon, and Dutro (1975) as present in the Alaska Bench Limestone and exclusively Pennsylvanian in Wyoming. These species are: *Antiquatonia* cf. *A. coloradoensis* (Girty), *Linoproductus eastoni* Gordon, *Composita ovata* Mather, *Anthracospirifer occiduus* (Sadlick), *Orthotetes* sp. A. Gordon, and *Echinoconchus* sp. A. Gordon.

Scott (1945) reported fusulinids from the lower part of the Alaska Bench Limestone near Beacon Hill, identified as *Millerella marblensis* Thompson and *Millerella advena* Thompson. Easton (1962) identified *Dicromyocrinus granularis* Easton from the Alaska Bench.

Most paleontological evidence supports a Morrowan age for the Alaska Bench Limestone (Scott, 1945; Gilmour, 1967; Sando, Gordon, and Dutro, 1975), although some writers place the uppermost part of the Alaska Bench in the Atokan (Willis, 1959; Maughan and Roberts, 1967; Mallory, 1972; Maughan, 1975). The Alaska Bench is equivalent to the upper part of the Namurian Series and possibly extends upwards into the base of the Westphalian Series (Sando, Gordon, and Dutro, 1975).

The Alaska Bench Limestone was deposited in a shallow-water marine environment, resulting in a series of microfacies, described by Gilmour (1969). These microfacies represent rocks deposited in supratidal-intertidal, marginal subtidal marine, and normal subtidal marine environments. These microfacies were deposited as cyclic units and record the transgressive-regressive movements of the strandline of the Morrowan sea across central Montana. The strandline was oriented east-west, the sea floor gently sloping to the south. Maughan (1975) stated that an increase of terrigenous sediments in western Montana and the Dakotas suggests land areas west and east of central Montana. Because of the fine size of the material, he believed that the sedimentary source areas probably were moderately distant or low lying or both. Gilmour (1969) believed that these interbedded terrigenous sediments in central Montana were deposited in both marine and nonmarine environments concurrently with the various carbonate microfacies.

DEVILS POCKET FORMATION

Gardner (1959, p. 347–348) proposed the name Devils Pocket Formation for 43 m of cherty dolomite, limestone, red sandstone and shale, and chert breccia that overlies the Alaska Bench Limestone in Road Canyon, southeastern Big Snowy Mountains (fig. 1). According to Maughan and Roberts (1967, p. B15) similar rocks in the equivalent position extend throughout eastern and southern Montana and have been included previously within the Minnelusa Formation. Dolomite and sandstone of the Devils Pocket Formation intertongue with and grade into sandstone of the Quadrant Formation toward western Montana (Maughan, 1975, p. 286). The Devils Pocket overlaps older strata toward the south.

Thickness of the Devils Pocket Formation varies considerably because of pre-Middle Jurassic erosion, which removed much of the formation. A thickness of 67 m in southwestern Big Snowy Mountains is the most complete exposure of the formation. Gardner (1959, p. 348) listed thicknesses of 5.5, 11.5, and 21.5 m in central Montana. The formation thins eastward toward the Williston basin (Willis, 1959, fig. 12).

The Devils Pocket Formation consists of sandstone and siliceous dolomite and some dolomitic limestone and siltstone (Gardner, 1959, p. 338, 342–343). The formation changes from predominantly dolomite in the lower part to sandstone in the upper part. Mundt (1956a, p. 1931) presented evidence for an unconformity between the Devils Pocket and the underlying Alaska Bench Limestone. Maughan and Roberts (1967) and Mallory (1972) also supported this idea. Alternatively, Gardner (1959, p. 335) stated that the Devils Pocket rests conformably on the Alaska Bench Limetone and that lithologies are transitional from one formation to the other. In central Montana, the Devils Pocket Formation is overlain unconformably by Jurassic rocks of the Ellis Group. In eastern Montana, southern Montana, and western Montana, the carbonate rocks of the Devils Pocket grade upward into the sandstone or quartzite of the Quadrant Formation. Maughan and Roberts (1967, p. B16) reported an increase in sand westward until the Devils Pocket Formation cannot be separated from the overlying Quadrant Formation. They also stated that the dolomitic middle member of the Minnelusa Formation in eastern Montana grades laterally into the Quadrant of central Montana and the Tensleep of Wyoming and should be included in the Devils Pocket Formation.

Few fossils have been reported from the Devils Pocket Formation. Henbest (1954, p. 50, 51) and Easton (1962, p. 16–17) reported fusulinids from clasts and matrix of the breccia near the top of the formation. Included in their faunal lists are: *Climacammina* sp., *Endothyra* sp., *Bradyina* sp., *Tetrataxis* sp., *Millerella* sp., *Pseudostaffella* sp., *Profusulinella* sp., *Cornuspira* sp., *Spiroplectammina* sp., *Climacammina magna*? Roth and Skinner, 1930, *Derbyia* sp., and *Straparollus* (Euomphalus) sp. Both authors believed that the formation is Atokan because of the presence of *Profusulinella* sp. George Verville (oral commun. reported by Maughan, 1975) assigned a late Atokan age to the Devils Pocket Formation on the basis of fusulinid studies.

Dolomite and sandstone of the Devils Pocket Formation are believed to have been deposited in ". . . a marine environment of above normal salinity" (Maughan, 1975, p. 288). This assumption is based on the type of fossils described and a belief that the dolomite is either primary or penecontemporaneous. Easton (1962, p. 26) believed that the formation "represents warm, emergent conditions, which favored the deposition of interbedded red clastics and sandy calcareous deposits which altered penecontemporaneously or later to cherty dolomite." Some of the dolomite beds in the Devils Pocket Formation are very similar to those in the underlying Alaska Bench Formation described by Gilmour (1967) as dolomitized normal marine beds. Fossils listed in the Devils Pocket Formation indicate normal marine conditions (fusulinids and brachiopods). Present available evidence suggests that the Devils Pocket Formation was deposited in a marine environment of normal salinity.

A rising land area to the west or northwest is suggested by the great thickness of sandstone in western Montana, the rapid eastward thinning, and the overlap of sandstone over carbonate rocks eastward (Maughan, 1975, p. 287). Maughan believed that Ordovician sandstone was eroded and served as the principal source for the Pennsylvanian sand. He also suggested that the mudstone in the eastern part of the area was derived from land areas to the east or southeast.

QUADRANT FORMATION

The Quadrant Formation as used in this report refers to the quartzite or sandstone sequence that overlies the Devils Pocket Formation in central Montana and the Amsden Formation in southwestern Montana. The Quadrant grades eastward into dolomite and sandy dolomite that are included in the middle member of the Minnelusa Formation in eastern Montana.

The Quadrant ranges in thickness from zero in central Montana to more than 80 m at the northwest corner of Yellowstone Park (Williams, 1962). South and west it thickens markedly to more than 800 m near the Idaho-Montana State line (Sloss and Moritz, 1951, p. 2163). Sandstone and dolomitic sandstone referred to as Quadrant or Tensleep extends from the Williston basin southwestward to the Idaho-Mantana border and southward to the Wyoming-Montana border. Scott (1935) described the Quadrant "quartzite" as well-bedded, white to pink, fine- to medium-grained quartzite, containing thin beds of siliceous limestone. Gardner and others (1945) described the Quadrant as light-gray quartzitic sandstone with pink or yellowish-brown tints, composed of fine- to medium-grained, angular to subangular quartz grains. In southwestern Montana, the Quadrant is composed of sandstone and quartzite; sandy dolomite beds are found in the lower part of the formation. The percentage of dolomite increases towards central Montana, and dolomite is the dominant lithology in eastern Montana.

The contact between the Quadrant Formation and the underlying Devils Pocket Formation is gradational; the boundary is generally arbitrarily placed between the dominantly carbonate sequence and the overlying dominantly quartzite or sandstone sequence (Maughan and Roberts, 1967, p. B16). Near the Idaho-Montana border, Sloss and Moritz (1951) placed the base of the Quadrant at the base of the lowest massive sandstone bed, leaving several thin sandstone beds in the Amsden and some dolomite beds in the basal Quadrant.

The top of the Quadrant is marked by a major unconformity throughout most of Montana. Rocks overlying the unconformity range in age from Early Permian to Middle Jurassic and, locally, Cretaceous (Mallory, 1972, p. 122).

The age of the Quadrant Formation is Desmoinesian, on the basis of fusulinids (Thompson and Scott, 1941; Henbest, 1954, 1956). Henbest (1954, p. 52) listed the following fossils for the Tensleep (Quadrant Formation of this paper) in Montana: *Endothyra* sp., *Wedekindellina euthy-*

septa (Herbert), *Fusulina tregoensis* (?) Roth and Skinner, *Bradyina* sp., and *Fusulina* sp. Henbest believed that this fauna represents the lower half or two-thirds of the Desmoinesian.

Scott (1935) and Williams (1962) supported a marine origin for the Quadrant Formation in southern Montana and Wyoming. Mallory (1972, p. 122) and Maughan (1975, p. 288, 289) stated that during deposition of the Quadrant, the entire area was inundated by a shallow sea in which the circulation of marine water was restricted. The uplift to the west was the source of clastic materials in western Montana; an eastward source continued to supply fine clastic sediments to the east and southeast. Thin beds of chert and dolomite in the Quadrant contain the fusulinids described by Henbest (1954). As fusulinids are known only from normal marine environments, the conclusion is that at least some of the Quadrant Formation was deposited under such conditions.

PETROLEUM AND NATURAL GAS

MISSISSIPPIAN STRATA

Mississippian strata produce oil and gas from approximately 1,100 wells in 37 fields in Montana. Of these fields, 26 produce only oil, 2 produce only gas, and 9 produce both oil and gas (Montana Board of Oil and Gas Conservation, 1976).

Production figures for the 21 largest of these fields indicate average production depths of 1925 m, cumulative production through 1976 of 252,793,000 bbls of oil, and reserves of 58,457,000 bbls of oil. Total 1976 oil production from these wells was

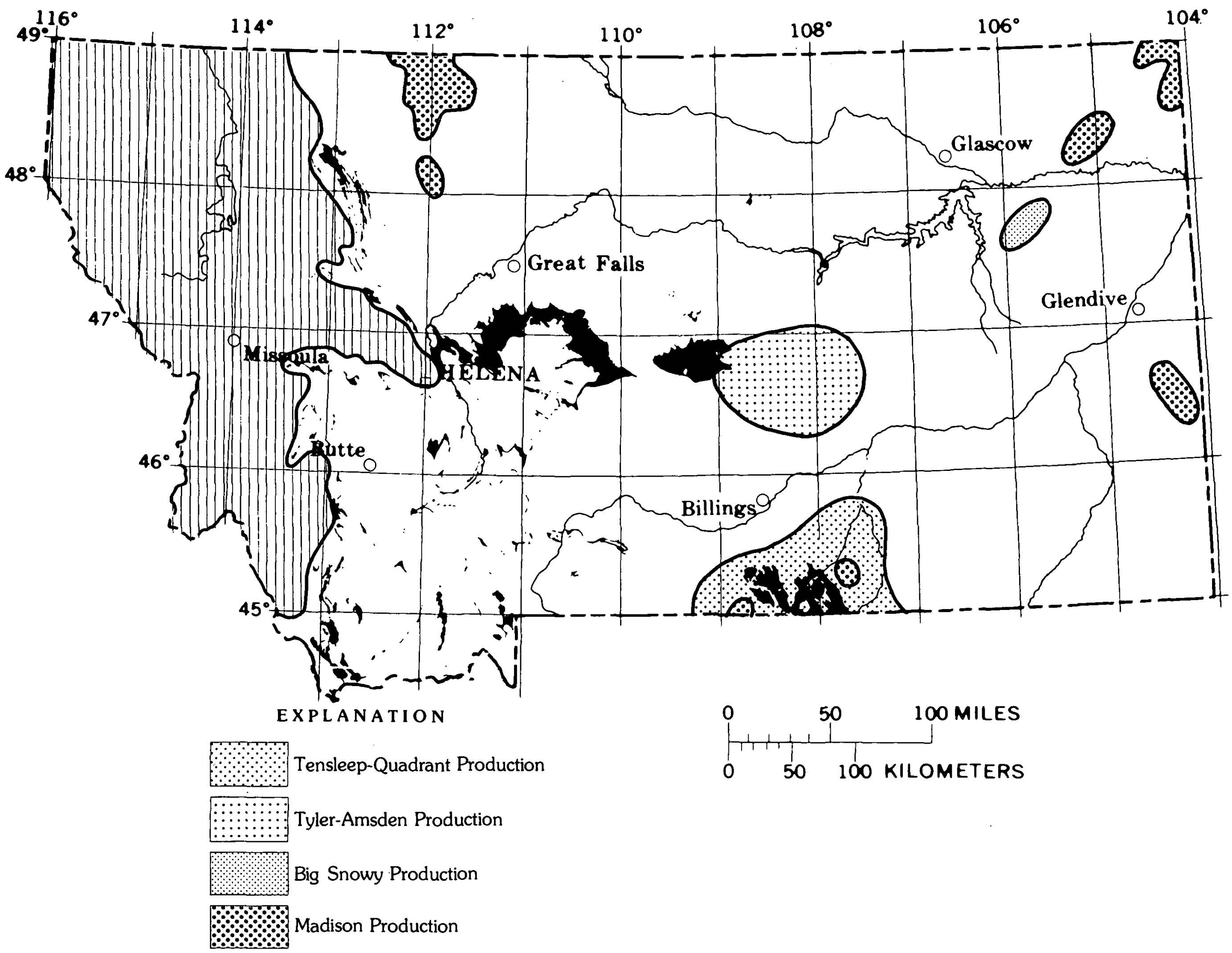


FIGURE 10.—Carboniferous oil and gas fields in Montana.

6,697,853 bbls. Total 1976 gas production from Mississippian wells was 524,282 MCF.

Of these 21 largest fields, 18 produce from Madison Group strata, primarily the upper Mission Canyon and Charles Formations, and 3 produce from Big Snowy Group rocks (Kibbey and Heath Formations).

Madison fields occur in front of the overthrust belt in northwestern Montana, along the northwestern margin of the Williston basin, on the Cedar Creek anticline on the southwestern margin of the Williston basin, and on the flanks of the Bighorn and Powder River (fig. 10). Big Snowy Group fields are centered on the Big Snowy trough, along Tertiary structures east of the Big Snowy Mountains.

PENNSYLVANIAN STRATA

Thirty-four fields produced oil from 305 wells in Pennsylvanian strata during 1976 (Montana Board of Oil and Gas Conservation, 1976). No fields produce only gas, but three fields produce both oil and gas (Elk Basin, Keg Coulee, and Sumatra). Approximate cumulative production from Pennsylvanian fields in Montana is 127,984,000 bbls. Known oil reserves in the 26 largest fields are 33,346,000 bbls. Sixty-two percent of the Pennsylvanian fields produce from the Tyler Formation. Tyler oil ranges from 28 to 34 gravity °API, having a mean value of 32 °API. The Amsden Formation accounts for 22 percent of the producing fields; the oil ranges from 19 to 30 gravity °API. Sixteen percent of the Pennsylvanian fields produce from the Tensleep Formation (Quadrant Formation); the oil ranges from 27 to 37 gravity °API.

Nearly all fields producing from the Tyler and Amsden Formations are in central Montana (fig. 10). Fields producing from the Tensleep (Quadrant) are in south-central Montana. Largest Pennsylvanian fields on the basis of past production are Elk Basin (Carbon County), Sumatra (Rosebud County), and Stensvad (Musselshell County). In 1976, Sumatra field produced 2,019,813 bbls of oil and 160,915 MCF of gas. Jim Coulee (Musselshell County) produced 489,808 bbls of oil, and Elk Basin produced 482,390 bbls of oil and 369,660 MCF of gas. In 1976, two new fields were found in the Tyler Formation and two extensions were made in Tyler producing fields.

The dark organic shale and limestone of the Heath Formation (Mississippian) and the black limestone of the Bear Gulch Limestone tongue (Mississippian?) are believed to be the source of oil for the Tyler Formation (Varland, 1956; Willis, 1969). Principal production is from sandstone in the Stonehouse Canyon Member of the Tyler. Traps are found in the crests or axes of domes or anticlines and on the flanks of anticlines (Jensen and Carlson, 1972).

REFERENCES CITED

Andrichuk, J. M., 1955, Mississippian Madison Group stratigraphy and sedimentation in Wyoming and southern Montana: Am. Assoc. Petroleum Geologists Bull., v. 39, no. 11, p. 2170–2210, 12 figs.

Baars, D. L., 1972, Devonian System, *in* Rocky Mountain Assoc. Geologists, Geologic atlas of the Rocky Mountain region: Denver, Colo., p. 90–99, 8 figs.

Ballard, W. W., 1964, Lower Tyler of central Montana, marine or non-marine?: Billings Geol. Soc. Spec. Paper, 20 p.

Balster, C. A., ed., 1971, Catalog of stratigraphic names for Montana: Montana Bur. Mines and Geology Spec. Pub. 54, 448 p.

Beekly, E. K., 1955, The Heath-Amsden boundary on the central Montana uplift at Big Wall field, *in* Am. Assoc. Petroleum Geologists, Rocky Mountain Sec., Geological Record, Feb. 1955: p. 111–120.

Collier, A. J., and Cathcart, S. H., 1922, Possibility of finding oil in laccolithic domes south of the Little Rocky Mountains, Montana: U.S. Geol. Survey Bull. 736–f, p. 171–178.

Cotter, Edward, 1965, Waulsortian-type carbonate banks in the Mississippian Lodgepole Formation of central Montana: Jour. Geology, v. 73, no. 6, p. 881–888, 4 figs.

——— 1966, Limestone diagenesis and dolomitization in Mississippian carbonate banks in Montana: Jour. Sed. Petrology, v. 36, no. 3, p. 764–774.

Craig, L. C., 1972, Mississippian System, *in* Rocky Mountain Assoc. Geologists, Geologic atlas of the Rocky Mountain region: Denver, Colo., p. 100–110, 8 figs.

Darton, N. H., 1904, Comparison of the stratigraphy of the Black Hills, Bighorn Mountains, and Rocky Mountain Front Range: Geol. Soc. America Bull., v. 15, p. 379–448, pls. 23–26.

Davis, L. C., 1976, Dating chert mining and processing activities at the Schmitt site in southwestern Montana [abs.]: Plains Anthropol. Conf., 34th, Minneapolis, Minn.

Deiss, C. F., 1933, Paleozoic formations of northwestern Montana: Montana Bur. Mines and Geology Mem. 6, 51 p., 3 pls.

——— 1941, Structure of central part of Sawtooth Range, Montana [abs.]: Geol. Soc. America Bull., v. 52, no. 12, pt. 2, p. 1896–1897.

——— 1943, Stratigraphy and structure of southwest Saypo quadrangle, Montana: Geol. Soc. America Bull., v. 54, no. 2, p. 205–262, 5 pls., 3 figs.

Easton, W. H., 1962, Carboniferous formations and faunas of central Montana: U.S. Geol. Survey Prof. Paper 348, 126 p.

Foster, D. I., 1956, N.W. Sumatra field, *in* Billings Geol. Soc., Guidebook, 7th Ann. Field Conf., Central Montana, Aug. 16–18, 1956: p. 116–123.

Foster, F. W., 1961, Tyler, sand trend becoming better known in Dakotas: World Oil, v. 152, no. 1, p. 89–93.

Freeman, O. W., 1922, Oil in the Quadrant formation in Montana: Eng. Mining Jour.-Press, v. 113, no. 19, p. 825–827.

Gardner, L. S., 1959, Revision of Big Snowy group in central Montana: Am. Assoc. Petroleum Geologists Bull., v. 43, no. 2, p. 329–349.

Gardner, L. S., Hendricks, T. A., Hadley, H. D., and Rogers, C. P., Jr., 1945, Mesozoic and Paleozoic in the mountains of south-central Montana, 1945: U.S. Geol. Survey Oil and Gas Inv. Prelim. Chart 18.

Gilmour, E. H., 1967, Carbonate petrology and paleontology of the Alaska Bench Formation, central Montana: Missoula, Univ. Montana, Ph.D. dissert., 152 p. (Abs. *in* Dissert. Abs., Sec. B, Sci. and Eng., v. 28, no. 5, p. 1992B, 1967.)

——— 1969, Carbonate petrology of the Alaska Bench Formation, central Montana, *in* Montana Geol. Soc., Guidebook, 20th Ann. Field Conf., 1969, p. 179–200.

Gordon, Mackenzie, Jr., 1975, Brachiopoda of the Amsden Formation (Mississippian and Pennsylvanian) of Wyoming: U.S. Geol. Survey Prof. Paper 848–D, 86 p., 13 pls.

Gutschick, R. C., McLane, Michael, and Rodriguez, Joaquin, 1976, Summary of Late Devonian-Early Mississippian biostratigraphic framework in western Montana—Tobacco Root Geol. Soc., Guidebook, 1976 Field Conf.: Montana Bur. Mines and Geology Spec. Pub. 73, p. 91–124, 17 figs.

Gutschick, R. C., Suttner, L. J., and Switek, M. J., 1962, Biostratigraphy of transitional Devonian-Mississippian Sappington Formation of southwest Montana, *in* Billings Geol. Soc., Guidebook, 13th Ann. Field Conf., 1962: p. 79–89.

Harris, W. L., 1972, Upper Mississippian and Pennsylvanian sediments of central Montana: Missoula, Mont., University of Montana, unpub. Ph.D. dissert., 252 p.

Henbest, L. G., 1954, Pennsylvanian Foraminifera in Amsden Formation and Tensleep Sandstone, Montana and Wyoming, *in* Billings Geol. Soc., Guidebook, 5th Ann. Field Conf., Pryor Mountains-Northern Bighorn Basin, Montana, 1954: p. 50–53.

——— 1956, Foraminifera and correlation of the Tensleep Sandstone of Pennsylvanian age in Wyoming, *in* Wyoming Geol. Assoc., Guidebook, 11th Ann. Field Conf., Jackson Hole, 1956: p. 58–63.

——— 1958, Significance of karst terrane and residuum in Upper Mississippian and Lower Pennsylvanian rocks, Rocky Mountain region, *in* Wyoming Geol. Assoc., Guidebook, 13th Ann. Field Conf., Powder River Basin, 1958: p. 36–38, 1 fig.

Huh, O. K., 1967, The Mississippian System across the Wasatch line, east-central Idaho, extreme southwestern Montana, *in* Centennial basin of southwest Montana—Montana Geol. Soc., Guidebook, 18th Ann. Field Conf., 1967: [Billings, Mont.], p. 31–62, 1 pl., 13 figs.

Jenks, Susan, 1972, Environment of deposition and diagenesis of the Lodgepole Formation (Mississippian), central Montana, *in* Montana Geol. Soc., Guidebook 21st Ann. Field Conf., Crazy Mountains basin, Sept. 1972: p. 19–27, 5 figs.

Jensen, F. S., and Carlson, K. P., 1972, The Tyler Formation in the subsurface, central Montana, *in* Rocky Mountain Assoc. Geologists, Geologic atlas of the Rocky Mountain region: Denver, Colo., p. 128–129.

Klapper, Gilbert, 1966, Upper Devonian and Lower Mississippian conodont zones in Montana, Wyoming, and South Dakota: Kansas Univ. Paleont. Contr., Paper 3, 43 p., 6 pls., 2 figs.

Klapper, Gilbert, and Furnish, W. M., 1962, Devonian-Mississippian Englewood Formation in the Black Hills, South Dakota: Am. Assoc. Petroleum Geologists Bull., v. 46, no. 11, p. 2071–2078, 1 fig.

Knechtel, M. M., Smedley, J. E., and Ross, R. J., Jr., 1954, Little Chief Canyon Member of Lodgepole Limestone of Early Mississippian age in Montana: Am. Assoc. Petroleum Geologists Bull., v. 38, no. 11, p. 2395–2400, 2 figs.

Laudon, L. R., and Severson, J. L., 1953, New crinoid fauna, Mississippian Lodgepole Formation, Montana: Jour. Paleontology, v. 27, no. 4, p. 505–536.

Macqueen, R. W., and Sandberg, C. A., 1970, Stratigraphy, age, and interregional correlation of the Exshaw Formation, Alberta Rocky Mountains: Bull. Canadian Petroleum Geology, v. 18, no. 1, p. 32–66.

Mallory, W. W., 1972, Regional synthesis of the Pennsylvanian System, *in* Rocky Mountain Assoc. Geologists, Geologic atlas of the Rocky Mountain region: Denver, Colo., p. 111–127.

Maughan, E. K., 1975, Montana, North Dakota, northeastern Wyoming, and northern South Dakota, *in* McKee, E. D., and Crosby, E. J., coordinators, Introduction and regional analyses of the Pennsylvanian System, Pt. 1 *of* Paleotectonic investigations of the Pennsylvanian System in the United States: U.S. Geol. Survey Prof. Paper 853, p. 277–293.

Maughan, E. K., and Roberts, A. E., 1967, Big Snowy and Amsden Groups and the Mississippian-Pennsylvanian boundary in Montana: U.S. Geol. Survey Prof. Paper 554–B, 27 p., 4 pls., 7 figs.

McKee, E. D., and Crosby, E. J., and others, 1975, Paleotectonic investigations of the Pennsylvanian System in the United States—Part III, Plates: U.S. Geol. Survey Prof. Paper 853, pt. 3, 60 pls. (See especially pls. 1–14.)

McMannis, W. J., 1965, Resumé of depositional and structural history of western Montana: Am. Assoc. Petroleum Geologists Bull., v. 49, no. 11, p. 1801–1823, 16 figs.

Merriam, R. W., 1958, A Madison bioherm, Big Snowy Mountains, Montana (M.S. thesis): Pullman, Wash., Washington State Univ., 87 p.

Montana Board of Oil and Gas Conservation, 1976, Annual review for the year 1976: Montana Dept. Nat. Resources and Conserv., v. 20, 31 p., 3 pls.

Mudge, M. R., 1972, Pre-Quaternary rocks in the Sun River Canyon area, northwestern Montana: U.S. Geol. Survey Prof. Paper 663–A, 142 p., 3 pls., 40 figs., 9 tables.

Mudge, M. R., Sando, W. J., and Dutro, J. T., Jr., 1962, Mississippian rocks of Sun River Canyon area, Sawtooth Range, Montana: Am. Assoc. Petroleum Geologists Bull., v. 46, no. 11, p. 2003–2018, 6 figs.

Mundt, P. A., 1956a, Heath-Amsden strata in central Montana: Am. Assoc. Petroleum Geologists Bull., v. 40, no. 8, p. 1915–1934.

——— 1956b, The Tyler and Alaska Bench formations [Montana], *in* Billings Geol. Soc., Guidebook, 7th Ann. Field Conf., Central Montana, Aug. 16–18, 1956: p. 46–51.

——— 1956c, Bear Gulch composite section, *in* Billings Geol. Soc., Guidebook, 7th Ann. Field Conf., central Montana, Aug. 16–18, 1956: p. 16.

Norton, G. H., 1956, Evidences of unconformity in rocks of Carboniferous age in central Montana, *in* Billings Geol. Soc., Guidebook, 7th Ann. Field Conf., central Montana, Aug. 16–18, 1956, p. 52–66.

Peale, A. C., 1893, The Paleozoic section in the vicinity of Three Forks, Montana: U.S. Geol. Survey Bull. 110, 56 p.

Perry, E. S., and Sloss, L. L., 1943, Big Snowy Group, lithology and correlation in the northern Great Plains: Am. Assoc. Petroleum Geologists Bull., v. 27, no. 10, p. 1287–1304.

Rawson, R. R., 1968, The "Kibbey Limestone" of the Williston basin and central Montana: Earth Sci. Bull. (Wyoming Geol. Assoc.), v. 1, no. 3, p. 35–47.

Reeves, Frank, 1931, Geology of the Big Snowy Mountains, Montana: U.S. Geol. Survey Prof. Paper 165–E, p. 135–149.

Roberts, A. E., 1966, Stratigraphy of Madison Group near Livingston, Montana, and discussion of karst and solution-breccia features: U.S. Geol. Survey Prof. Paper 526–B, 23 p., 10 figs.

Rodriguez, Joaquin, and Gutschick, R. C., 1970, Late Devonian-early Mississippian ichnofossils from western Montana and northern Utah, *in* Crimes, T. P., and Harper, J. C., eds., Trace fossils: Geol. Jour., Spec. Issue 3, p. 407–438, 10 pls., 6 figs.

Rose, P. R., 1976, Mississippian carbonate shelf margins, western United States: U.S. Geol. Survey Jour. Research, v. 4, no. 4, p. 449–466, 10 figs.

Ross, C. P., Andrews, D. A., and Witkind, I. J., compilers, 1955, Geologic map of Montana: Washington, D.C., U.S. Geol. Survey, 2 sheets, scale 1:500,000.

Sandberg, C. A., 1962, Stratigraphic section of type Three Forks and Jefferson Formations at Logan, Montana, *in* Billings Geol. Soc., Guidebook, 13th Ann. Field Conf., 1962: p. 47–50.

——— 1963, Dark shale unit of Devonian and Mississippian age in northern Wyoming and southern Montana: U.S. Geol. Survey Prof. Paper 475–C, p. C17–C20.

——— 1965, Nomenclature and correlation of lithologic subdivisions of the Jefferson and Three Forks Formations of southern Montana and northern Wyoming: U.S. Geol. Survey Bull. 1194–N, 18 p.

Sandberg, C. A., and Klapper, Gilbert, 1967, Stratigraphy, age, and paleotectonic significance of the Cottonwood Canyon Member of the Madison Limestone in Wyoming and Montana: U.S. Geol. Survey Bull. 1251–B, 70 p., 5 figs.

Sandberg, C. A., and Mapel, W. J., 1967, Devonian of the northern Rocky Mountains and Plains, *in* Oswald, D. H., ed., International symposium on the Devonian System, Calgary, Alberta, 1967, [Proc.], v. 1: Calgary, Alberta Soc. Petroleum Geologists, p. 843–877, 10 figs.

Sando, W. J., 1967, Mississippian depositional provinces in the northern Cordilleran region: U.S. Geol. Survey Prof. Paper 575–D, p. D29–D38, 3 figs.

——— 1972, Madison Group (Mississippian) and Amsden Formation (Mississippian and Pennsylvanian) in the Beartooth Mountains, northern Wyoming and southern Montana, *in* Montana Geol. Soc., Guidebook, 21st Ann. Field Conf., Sept. 1972: p. 57–63, 9 figs. 1 pl.

——— 1974, Ancient solution phenomena in the Madison Limestone (Mississippian) of north-central Wyoming: U.S. Geol. Survey Jour. Research, v. 2, no. 2, p. 133–141, 3 figs.

——— 1976, Mississippian history of the northern Rocky Mountains region: U.S. Geol. Survey Jour. Research, v. 4, no. 3, p. 317–338, 10 figs.

——— 1978, Coral zones and problems of Mississippian stratigraphy in the Williston basin: Montana Geol. Soc., Guidebook, 27th Ann. Field Conf., 1978.

Sando, W. J., and Dutro, J. T., Jr., 1974, Type sections of the Madison Group (Mississippian) and its subdivisions in Montana: U.S. Geol. Survey Prof. Paper 842, 22 p., 1 pl., 11 figs.

Sando, W. J., Gordon, Mackenzie, Jr., and Dutro, J. T., Jr., 1975, Stratigraphy and geologic history of the Amsden Formation (Mississippian and Pennsylvanian) of Wyoming: U.S. Geol. Survey Prof. Paper 848–A, 83 p., 11 pls., 22 figs.

Sando, W. J., Mamet, B. L., and Dutro, J. T., Jr., 1969, Carboniferous megafaunal and microfaunal zonation in the northern Cordillera of the United States: U.S. Geol. Survey Paper 613–E, 29 p., 7 figs.

Scott, H. W., 1935, Some Carboniferous stratigraphy in Montana and northwestern Wyoming: Jour. Geology, v. 43, no. 8, pt. 2, p. 1011–1032.

——— 1945, Age of the Amsden Formation [abs]: Geol. Soc. America Bull., v. 56, no. 12, pt. 2, p. 1195.

Seager, O. A., 1942, Test on Cedar Creek anticline, southeastern Montana: Am. Assoc. Petroleum Geologists Bull., v. 26, no. 5, p. 861–864.

Sloss, L. L., 1952, Introduction to the Mississippian of the Williston Basin, *in* Billings Geol. Soc., Guidebook, 3rd Ann. Field Conf., Sept. 1952: p. 65–69, 2 figs.

Sloss, L. L., and Hamblin, R. H., 1942, Stratigraphy and insoluble residues of Madison Group (Mississippian) of Montana: Am. Assoc. Petroleum Geologists Bull., v. 26, no. 3, p. 305–335, 11 figs.

Sloss, L. L., and Moritz, C. A., 1951, Paleozoic stratigraphy of southwestern Montana: Am. Assoc. Petroleum Geologists Bull., v. 35, no. 10, p. 2135–2169.

Smith, D. L., 1972, Depositional cycles of the Lodgepole Formation (Mississippian) in central Montana, *in* Montana Geol. Soc., Guidebook, 21st Ann. Field Conf., Sept. 1972: p. 29–35, 7 figs.

——— 1977, Transition from deep- to shallow-water carbonates, Paine Member, Lodgepole Formation, central Montana, *in* Enos, P., and Cook, H. E., Deep-water carbonate environments: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 25, p. 187–201.

Stone, R. A., 1972, Waulsortian-type bioherms (reefs) of Mississippian age, central Bridger Range, Montana, *in* Montana Geol. Soc., Guidebook, 21st Ann. Field Conf., Sept. 1972: p. 37–55, 23 figs.

Thompson, M. L., and Scott, H. W., 1941, Fusulinids from the type sections of the Lower Pennsylvanian Quadrant Formation: Jour. Paleontology, v. 15, no. 4, p. 349–353.

Todd, D. F., 1959, The lower Tyler of central Montana, *in* Billings Geol. Soc., Guidebook, 10th Ann. Field Conf., Aug. 1959: p. 69–74.

Varland, R. O., 1956, Big Wall field, *in* Billings Geol. Soc., Guidebook, 7th Ann. Field Conf., Aug. 1956: p. 113–115.

Walton, P. T., 1946, Ellis, Amsden, and Big Snowy group, Judith Basin, Montana: Am. Assoc. Petroleum Geologists Bull., v. 30, no. 8, pt. 1, p. 1294–1305.

Weed, W. H., 1896, Yellowstone National Park; sedimentary rocks: U.S. Geol. Survey Geol. Atlas, Folio 30, p. 4–5.

——— 1899, Description of the Fort Benton quadrangle [Montana]: U.S. Geol. Survey Geol. Atlas, Folio 55, 7 p.

——— 1900, Geology of the Little Belt Mountains, Montana: U.S. Geol. Survey Ann. Rept. 20, 1898–99, pt. 3, p. 257–461.

Williams, J. S., 1962, Pennsylvanian System in central and northern Rocky Mountains, *in* Branson, C. C., ed., Pennsylvanian System in the United States—A symposium: Tulsa, Okla., Am. Assoc. Petroleum Geologists, p. 159–187, 15 figs.

Willis, R. P., 1959, Upper Mississippian-Lower Pennsylvanian stratigraphy of central Montana and Williston Basin [North Dakota]: Am Assoc. Petroleum Geologists Bull., v. 43, no. 8, p. 1940–1966.

Wilson, J. L., 1969, Microfacies and sedimentary structures in "deeper water" lime mudstones, *in* Friedman, G. M., ed., Depositional environments in carbonate rocks—A symposium: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 14, p. 4–19.

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The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States

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ON THE COVER

Swamp-forest landscape at time of coal formation: lepidodendrons (left), sigillarias (in the center), calamites, and cordaites (right), in addition to tree ferns and other ferns. Near the base of the largest *Lepidodendron* (left) is a large dragonfly (70-cm wingspread). (Reproduced from frontispiece in Kukuk, Paul (1938), "Geologie des Niederrheinisch-Westfälischen Steinkohlengebietes" by permission of Springer-Verlag, New York, Inc.)

The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—

M. Iowa, by Matthew J. Avcin and Donald L. Koch
N. Missouri, by Thomas L. Thompson
O. Arkansas, by Boyd R. Haley, Ernest E. Glick, William M. Caplan, Drew F. Holbrook, and Charles G. Stone
P. Nebraska, by R. R. Burchett
Q. Kansas, by William J. Ebanks, Jr., Lawrence L. Brady, Philip H. Heckel, Howard G. O'Connor, George A. Sanderson, Ronald R. West, and Frank W. Wilson
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CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

H. William Menard, *Director*

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FOREWORD

The year 1979 is not only the Centennial of the U.S. Geological Survey—it is also the year for the quadrennial meeting of the International Congress on Carboniferous Stratigraphy and Geology, which meets in the United States for its ninth session. This session is the first time that the major international congress, first organized in 1927, has met outside Europe. For this reason it is particularly appropriate that the Carboniferous Congress closely consider the Mississippian and Pennsylvanian Systems; American usage of these terms does not conform with the more traditional European usage of the term "Carboniferous."

In the spring of 1976, shortly after accepting the invitation to meet in the United States, the Permanent Committee for the Congress requested that a summary of American Carboniferous geology be prepared. The Geological Survey had already prepared Professional Paper 853, "Paleotectonic Investigations of the Pennsylvanian System in the United States," and was preparing Professional Paper 1010, "Paleotectonic Investigations of the Mississippian System in the United States." These major works emphasize geologic structures and draw heavily on subsurface data. The Permanent Committee also hoped for a report that would emphasize surface outcrops and provide more information on historical development, economic products, and other matters not considered in detail in Professional Papers 853 and 1010.

Because the U.S. Geological Survey did not possess all the information necessary to prepare such a work, the Chief Geologist turned to the Association of American State Geologists. An enthusiastic agreement was reached that those States in which Mississippian or Pennsylvanian rocks are exposed would provide the requested summaries; each State Geologist would be responsible for the preparation of the chapter on his State. In some States, the State Geologist himself became the sole author or wrote in conjunction with his colleagues; in others, the work was done by those in academic or commercial fields. A few State Geologists invited individuals within the U.S. Geological Survey to prepare the summaries for their States.

Although the authors followed guidelines closely, a diversity in outlook and approach may be found among these papers, for each has its own unique geographic view. In general, the papers conform to U.S. Geological Survey format. Most geologists have given measurements in metric units, following current practice; several authors, however, have used both metric and inch-pound measurements in indicating thickness of strata, isopach intervals, and similar data.

FOREWORD

This series of contributions differs from typical U.S. Geological Survey stratigraphic studies in that these manuscripts have not been examined by the Geologic Names Committee of the Survey. This committee is charged with insuring consistent usage of formational and other stratigraphic names in U.S. Geological Survey publications. Because the names in these papers on the Carboniferous are those used by the State agencies, it would have been inappropriate for the Geologic Names Committee to take any action.

The Geological Survey has had a long tradition of warm cooperation with the State geological agencies. Cooperative projects are well known and mutually appreciated. The Carboniferous Congress has provided yet another opportunity for State and Federal scientific cooperation. This series of reports has incorporated much new geologic information and for many years will aid man's wise utilization of the resources of the Earth.

H William Menard

H. William Menard
Director, U.S. Geological Survey

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