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By Helen M. Beikman

Trace Elements Investigations Report 823

UNITED STATES DEPARTMENT OF THE INTERIOR
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GEOLOGY OF THE POWDER RIVER BASIN, WYOMING AND MONTANA, WITH REFERENCE TO SUBSURFACE DISPOSAL OF RADIOACTIVE WASTES*

By

Helen M. Beikman

February, 1962

Trace Elements Investigations Report TEI-823

This report is preliminary and has not
been edited for conformity with Geological
Survey format.

*Prepared on behalf of the U.S. Atomic Energy Commission

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GEOLOGY OF THE POWDER RIVER BASIN WITH REFERENCE TO SUBSURFACE DISPOSAL OF RADIOACTIVE WASTES

By Helen M. Beikman

ABSTRACT

The Powder River Basin is a structural and topographic basin occupying an area of about 20,000 square miles in northeastern Wyoming and southeastern Montana. The Basin is about 230 miles long in a northwest-southeast direction and is about 100 miles wide. It is bounded on three sides by mountains in which rocks of Precambrian age are exposed. The Basin is asymmetrical with a steep west limb adjacent to the Bighorn Mountains and a gentle east limb adjacent to the Black Hills.

Sedimentary rocks within the Basin have a maximum thickness of about 18,000 feet and rocks of every geologic period are represented. Paleozoic rocks are about 2,500 feet thick and consist of marine carbonate rocks and sandstone; Mesozoic rocks are about 9,500 feet thick and consist of both marine and nonmarine siltstone and sandstone; and Cenozoic rocks are from 4,000 to 6,000 feet thick and consist of coal-bearing sandstone and shale. Radioactive waste could be stored in the pore space of permeable sandstone or in shale where space could be developed. Many such rock units that could be used for storing radioactive wastes are present within the Powder River Basin.

Permeable sandstone beds that may be possible reservoirs for storage of radioactive waste are present throughout the Powder River Basin. These include sandstone beds in the Flathead Sandstone and equivalent strata in the Deadwood Formation, the Tensleep Sandstone and equivalent strata in the Minnelusa Formation, and the Sundance Formation in rocks of pre-Cretaceous age. However, most of the possible sandstone reservoirs are in rocks of Cretaceous age and include sandstone beds in the Fall River, Lakota, Newcastle, Frontier, Cody, and Mesaverde Formations. Problems of containment of waste such as clogging of pore space and chemical incompatibility would have to be solved before a particular sandstone unit could be selected for waste disposal.

Several thick sequences of impermeable shale such as those in the Skull Creek, Mowry, Frontier, Belle Fourche, Cody, Lewis, and Pierre Formations, occur in rocks of Cretaceous age in the Basin. Limited storage space for liquid waste might be developed in impermeable shale by fracturing the shale and space for calcined or fused waste could be developed by mining cavities.

INTRODUCTION

This report on the geology of the Powder River Basin is one of a series of reports by the Geological Survey on sedimentary basins in the United States. It has been prepared for the Division of Reactor Development, Atomic Energy Commission, as a part of their radioactive waste disposal program. The regional geology and the stratigraphy of the Basin is described in order to provide a geologic summary for a preliminary evaluation of the radioactive waste disposal possibilities.

Safe disposal of radioactive waste necessitates that the waste be placed where it will be contained within certain limits until the fission products it contains have disintegrated to a safe level of radioactivity. The length of time for the disintegration varies according to the contained isotopes; some require only a few years to disintegrate, others several hundreds of years. Subsurface storage in rock is one possible way to safely dispose of radioactive waste.

Radioactive waste stored in subsurface rock must be placed where it will remain contained. Liquid radioactive waste has a higher specific gravity than unmineralized ground water. Therefore, one possibility in subsurface storage is in a structural basin, such as the Powder River Basin, where updip migration of liquid waste would be inhibited because of its higher specific gravity. The major geologic factors to be considered in evaluating rock units in the Powder River Basin as possible storage reservoirs for radioactive waste are that the rock unit be capable of receiving and containing the waste, and that it is not a reservoir for potable ground water or oil and gas, and one that is at suitable depth.

The Powder River Basin underlies an area of about 20,000 square miles and occupies most of northeastern Wyoming and part of southeastern Montana (fig. 1). It is a structural and topographic basin bounded on the west by the Bighorn Mountains, on the southwest by the Casper arch, on the south by the north end of the Laramie Mountains and by the Hartville uplift, and on the east by the Black Hills. The northeastern limit is the Miles City arch, a low arch that extends northwest from the Black Hills uplift to Porcupine Dome, and the northwestern limit is a low arch within the Ashland syncline that separates the Powder River Basin from the Bull Mountain Basin.

Rocks of Precambrian age, consisting of granite and lesser amounts of metasedimentary and other igneous and metamorphic rocks, form the cores of the mountain uplifts on three sides of the Basin (fig. 2). Paleozoic and Mesozoic rocks crop out in a steeply dipping belt along the east front of the Bighorn Mountains and in a more moderately dipping belt along the west flank of the Black Hills. In north and south directions away from the Bighorn Mountains and from the Black Hills, the dip of these rocks decreases and the widths of outcrop become greater. At the southern margin of the Basin, rocks of Miocene and Oligocene age overlap Paleozoic and Mesozoic rocks which are exposed only in small areas of the Laramie Mountains and Hartville uplift. The central and northern parts of the Basin are covered by thick continental deposits of Cenozoic age.

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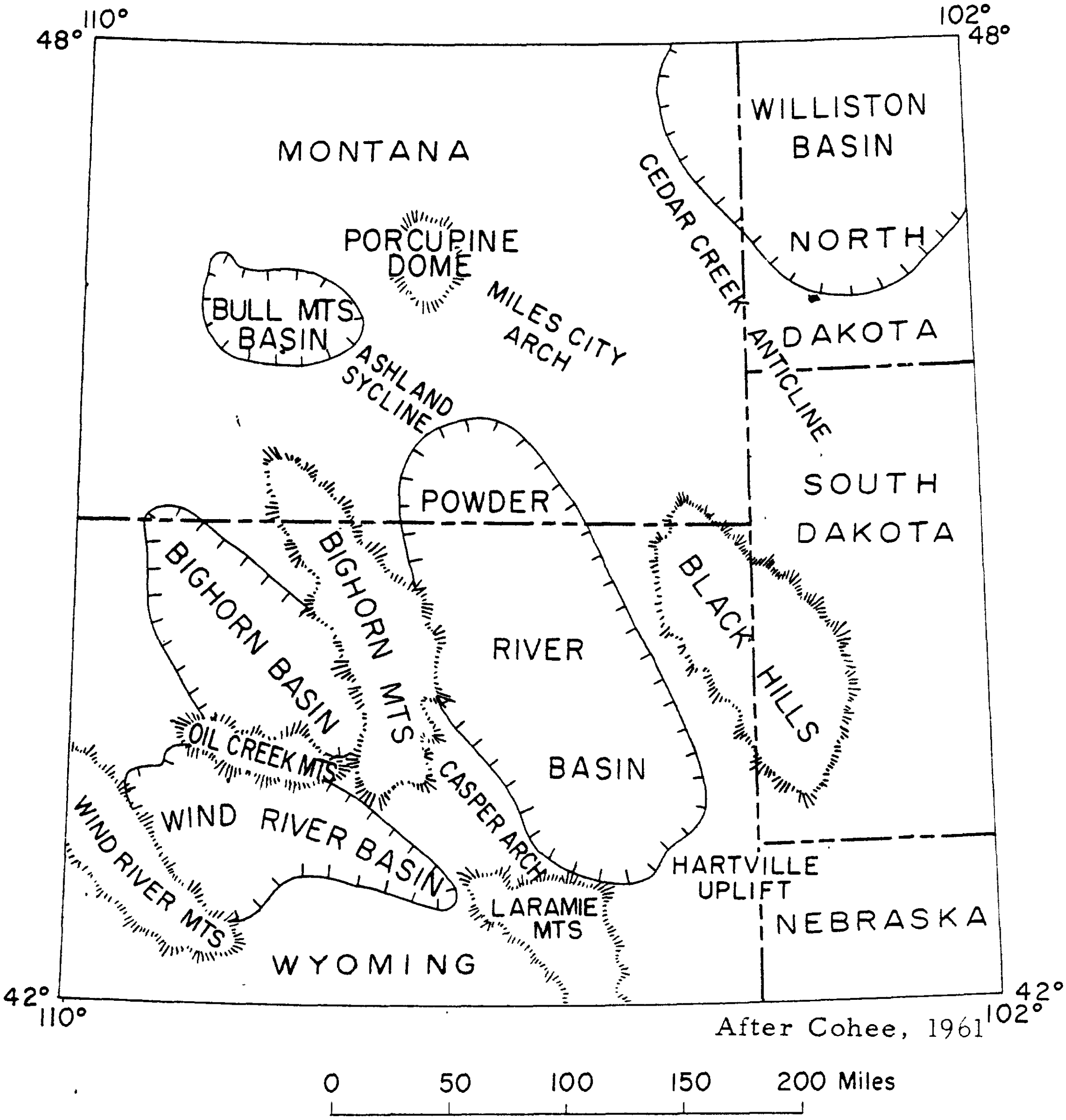

Figure 1. Index map showing the Powder River Basin and adjacent structural features.

The largest towns in the Powder River Basin are Casper, with a population of about 40,000 and Sheridan, with a population of about 12,000. Buffalo, Gillette, Sundance, Douglas, Newcastle, and Lusk all have a population of less than 5,000. The total population of the area, according to the 1960 census, is about 120,000 (The world almanac and book of facts for 1961).

The Basin is drained by the Powder River, for which it is named, and by the Belle Fourche, Cheyenne, and North Platte Rivers and their tributaries. The climate is semiarid and is characterized by large annual changes in temperature, which ranges from as low as -45° F to as high as 110° F. The maximum topographic relief within the Basin is about 1,000 feet and local relief is only several hundred feet. The floor of much of the Basin is characterized by badland topography, which together with a shortage of roads, makes access difficult in a few parts of the basin.

The Powder River Basin is about 230 miles long and 100 miles wide and is one of the largest Rocky Mountain intermontane basins. It is an asymmetrical syncline whose trough trends N. 15° to N. 20° W. parallel to the central Bighorn Mountains (fig. 3). The west limb of the syncline is very steeply dipping and at places the rocks are overturned to the east. The east limb has a gentle dip of 3° to 5° westward from the Black Hills. The deepest part of the Basin is on the west adjacent to the Bighorn Mountains. Paleozoic rocks are in places about 21,000 feet higher in elevation on the east flank of the Bighorn Mountains than they are in the deepest part of the trough of the Basin; thus structural relief is about 21,000 feet.

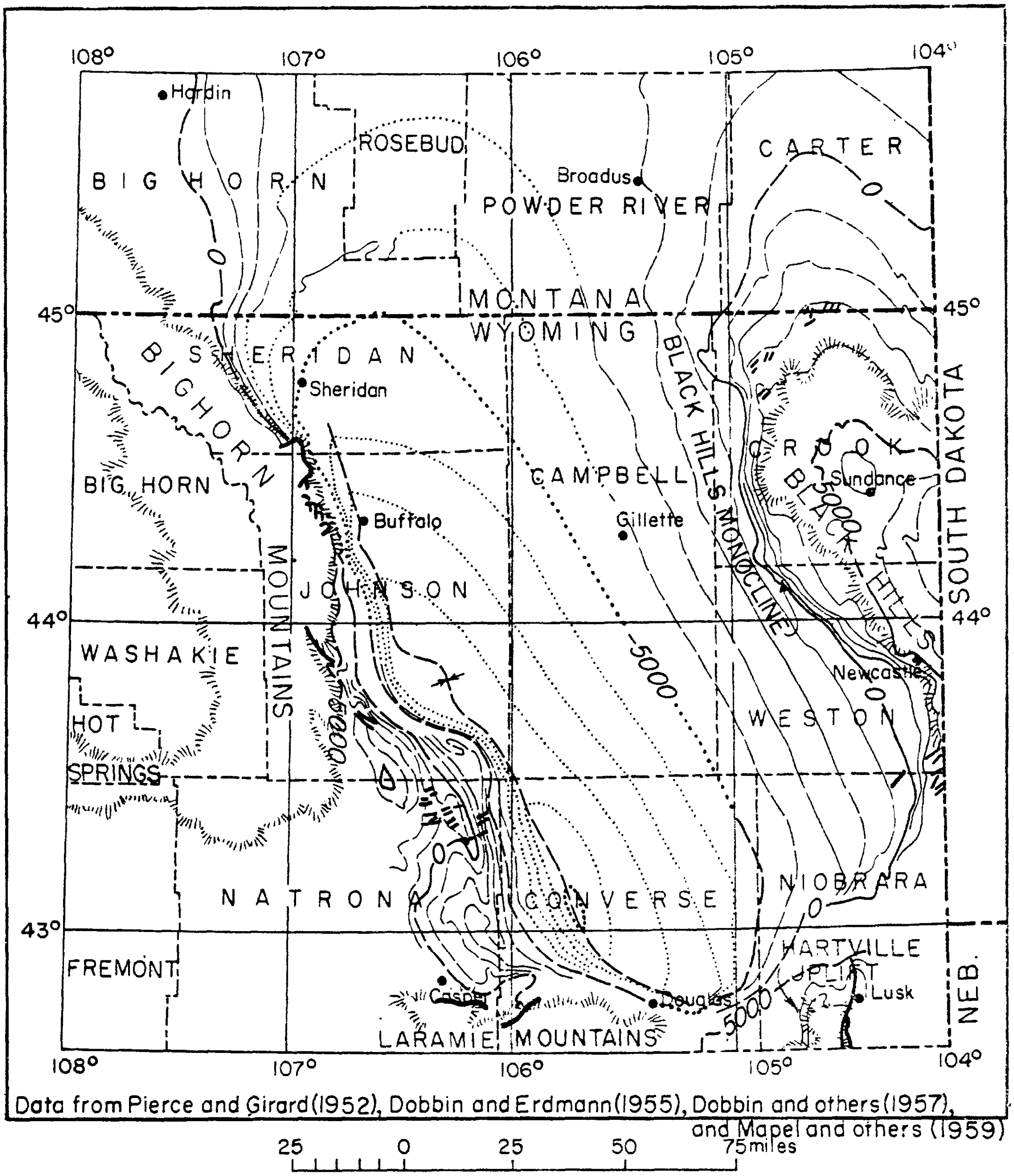

Figure 3.--Structure contour map of the Powder River Basin.

EXPLANATION

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Structure contour

Drawn on top of the Fall River Formation (or an equivalent horizon) of Early Cretaceous age. Contours dashed where approximately located; dotted where schematic. Contour interval is 1,000 feet; 5,000 feet in areas of maximum relief

Fault

Trough of syncline

The Basin was formed during Late Cretaceous and early Tertiary time when the bordering mountain masses were elevated. During the Paleozoic and Mesozoic, the area of the Powder River Basin was part of a relatively stable interior platform. This platform was at times flooded by epicontinental seas in which carbonate and clastic sediments were deposited. Rocks ranging in age from Cambrian to Cretaceous are essentially concordant. Several unconformities are present which represent intervals of erosion or of nondeposition. A major unconformity at the base of the Mississippian is indicated by the southward truncation of progressively older rocks, ranging in age from Devonian to Cambrian, beneath the Madison Limestone. The badland topography of the Basin resulted from Recent erosion which has largely removed the continental deposits that covered the Basin during Oligocene and Miocene time and has deeply dissected the underlying Eocene and Paleocene rocks.

Sources of data

This summary of the geology of the Powder River Basin has been drawn from many published and unpublished reports which are cited in the text. Most of the lithologic descriptions and thickness data, which are not individually credited, were obtained from recent reports on the geology of uplifted areas adjacent to the Powder River Basin. Richards (1955) was used for the northwest part, Hose (1955) and Mapel (1961) for the west-central part, and Robinson, Mapel, and Bergendahl (in prep.) for the eastern part. Reports by Sandberg and Hammond (1958) and Sandberg (1961) were sources for data on Devonian rocks. Much information concerning Jurassic and Triassic strata was taken from the folio reports on these systems (McKee and others, 1956 and 1959). The Guidebooks to the 4th and 13th Annual Field Conferences in the Powder River Basin (1949, 1958) and Wyoming Stratigraphy (1956) by the Wyoming Geological Association contain numerous papers that were very helpful in the preparation of this report.

STRATIGRAPHY

Sedimentary rocks aggregate a maximum thickness of about 18,000 feet in the Powder River Basin. Rocks of all geologic systems are represented; however, rocks of Silurian and Devonian age are limited in extent. Paleozoic rocks are about 2,500 feet thick and consist predominantly of marine carbonate and sandstone. Mesozoic rocks are about 9,500 feet thick, and consist mostly of claystone, siltstone, and sandstone of both marine and nonmarine origin. Cenozoic rocks are from 4,000 to 6,000 feet thick and are coal-bearing sandstone and shale. Quaternary deposits comprise alluvium, terrace gravel, and landslide debris.

Different nomenclature for equivalent units is used for a number of the outcropping rocks on the major uplifts surrounding the Basin because of variations in lithology, thickness, and age of the rock units. The correlation of the formation names used in the various uplifts is shown diagrammatically on several charts (figs. 6, 10, 14, and 15) and the changes in both nomenclature and lithology from west to east across the Basin are shown in figure 4. Where practicable, the stratigraphic units are described first on the west side of the Basin in the Bighorn Mountains and then correlated with equivalent units in the Black Hills to the east.

Cambrian and Ordovician rocks

Rocks of Cambrian and Early Ordovician age comprise a predominantly clastic sequence that underlies the Powder River Basin. They are about 1,000 feet thick near the Bighorn Mountains in the northern part of the Basin, but they thin progressively southeastward to 90 feet in the Laramie Mountains and to only 60 feet in the Hartville uplift (fig. 5).

In the Bighorn Mountains, the clastic sequence is divided into three formations (fig. 6). The Flathead Sandstone overlies Precambrian rocks. It is 260 to 500 feet thick and consists of fine- to coarse-grained quartzite sandstone with thin interbeds of shale and siltstone. It is overlain by the Gros Ventre Formation, as much as 700 feet thick. The Gros Ventre consists mostly of shale and sandstone with thin interbeds of limestone. The uppermost formation, the Gallatin Limestone, consists of grayish-red limestone. It thins southward along the flank of the Bighorn Mountains from 150 feet to a wedge edge. Paleontologic evidence suggests that part of the Gallatin is of Early Ordovician age (Shaw, 1954).

In the Black Hills, the Deadwood Formation of Late Cambrian age is equivalent in part to the three formations in the Bighorn Mountains. It consists of sandstone, shale, and some limestone, which are glauconitic in part (Darton and Paige, 1925, p. 5). The Deadwood thins southeastward from about 500 feet at the north end of the Black Hills to 200 feet near Newcastle, Wyoming (fig. 5).

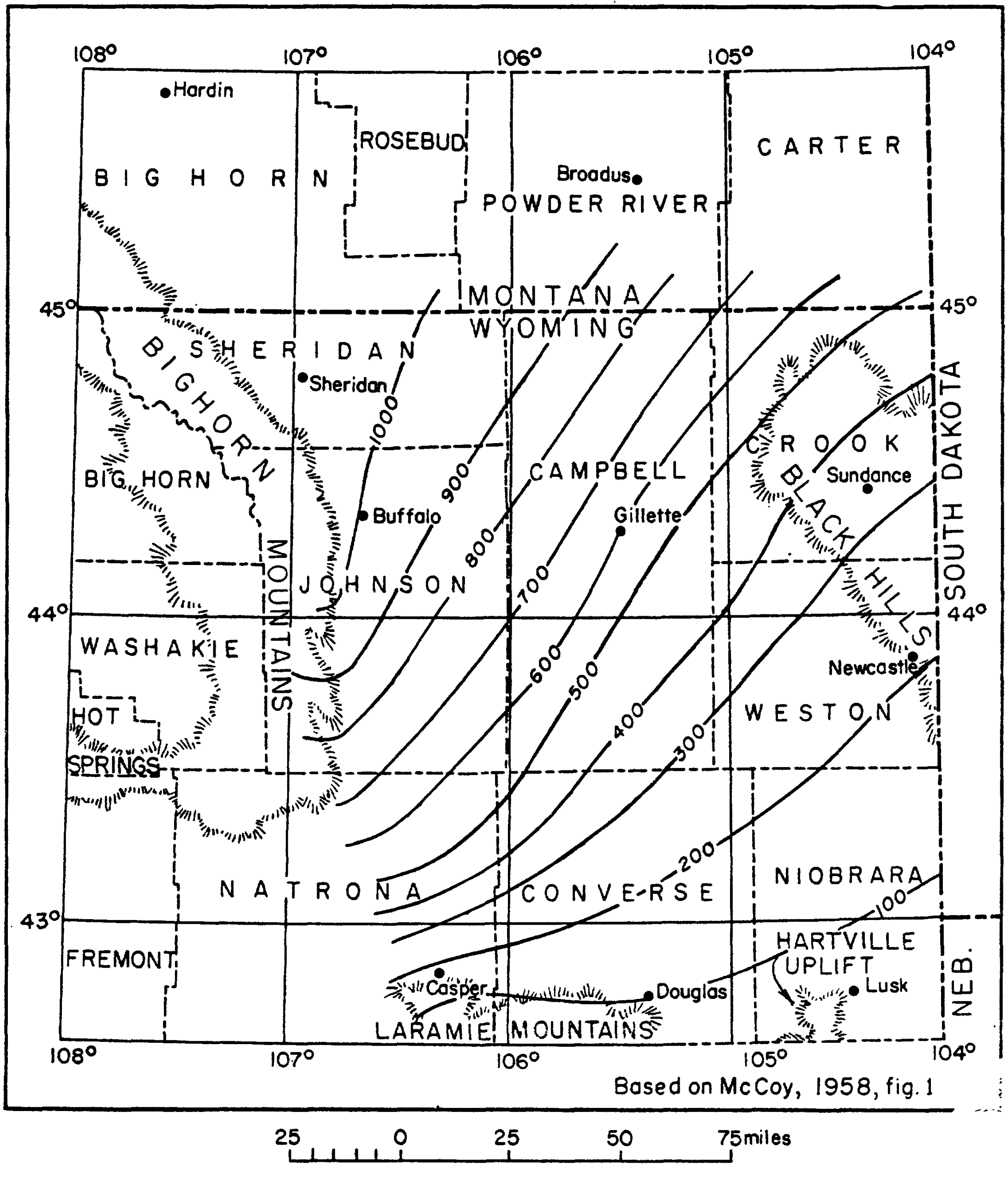


Figure 5.-- Thickness map of Cambrian and Ordovician rocks in the Powder River Basin. (Thickness interval is 100 feet).

System	Series	BIGHORN MOUNTAINS	SUBSURFACE OF POWDER RIVER BASIN	BLACK HILLS
JURASSIC	Upper	Morrison Formation Sundance Formation	Morrison Formation Swift Formation Rierdon Formation	Morrison Formation Sundance Formation
	Middle	Gypsum Spring Formation	Gypsum Spring Formation	Gypsum Spring Formation
	Lower			
TRIASSIC	Upper			
	Middle			
	Lower	Chugwater Formation	Chugwater Formation	Spearfish Formation
PERMIAN		Red shale and gypsum sequence Minnekahta Ls. equiv. Opeche Sh. equivalent	Red shale and gypsum sequence Minnekahta Limestone Opeche Shale	Minnekahta Limestone Opeche Shale
PENNSYLVANIAN	Upper		? ? ? ?	
	Middle	Tensleep Formation	Minnelusa Formation	Minnelusa Formation
	Lower	Amsden Formation		
MISSISSIPPIAN	Upper			
	Lower	Madison Limestone	Madison Limestone	Pahasapa Limestone Englewood Limestone
DEVONIAN	Upper	Jefferson Formation	Duperow Formation	
	Middle			
	Lower	Beartooth Butte Fm.		
SILURIAN			Interlake Group of Baillie (1951)	
ORDOVICIAN	Upper	Bighorn Dolomite	Stony Mountain Fm. ? Red River Formation ?	Whitewood Dolomite
	Middle	Harding(?) Sandstone	Winnipeg Formation	
	Lower			
CAMBRIAN	Upper	Gallatin Limestone and Gros Ventre Formation, undivided	Deadwood Formation	Deadwood Formation
	Middle	Flathead Sandstone		
	Lower			

Figure 6.-- Correlation chart of pre-Cretaceous rocks in the Powder River Basin

The thin Cambrian rocks in the Laramie Mountains consist of sandstone and conglomerate. In the Hartville uplift, a conglomeratic quartzite, 0 to 60 feet thick, may be correlative with a basal sandstone of the Deadwood Formation (Denson and Botinelly, 1949).

The Deadwood Formation and related rocks, 500-1,000 feet thick in the northern part of the Powder River Basin, are overlain by rocks of Middle and Late Ordovician age. However, the thin wedge of Cambrian rocks 60 feet thick at the south end of the Basin is overlain by rocks of Late Devonian or Early Mississippian age. This southward thinning is largely by disappearance of beds from the top of the sequence. Together with southward truncation of Upper Devonian, Silurian, and Middle and Upper Ordovician rocks, discussed later, it indicates a major regional unconformity beneath Mississippian rocks.

Ordovician rocks

Rocks of Middle(?) and Upper Ordovician age underlie the northern part of the Powder River Basin but are absent south of a line connecting the southern part of the Bighorn Mountains and the central part of the Black Hills (fig. 7). Northwestward from this line Ordovician rocks thicken uniformly to about 500 feet near the Wyoming-Montana border and in Montana they thicken northeastward to about 750 feet in Carter County. Ordovician rocks comprise a lower clastic sequence, 0 to 100 feet thick and an upper carbonate sequence, 0 to 650 feet thick (Richards and Nieschmidt, 1961). They unconformably overlie rocks of Early Ordovician and Late Cambrian age. In the

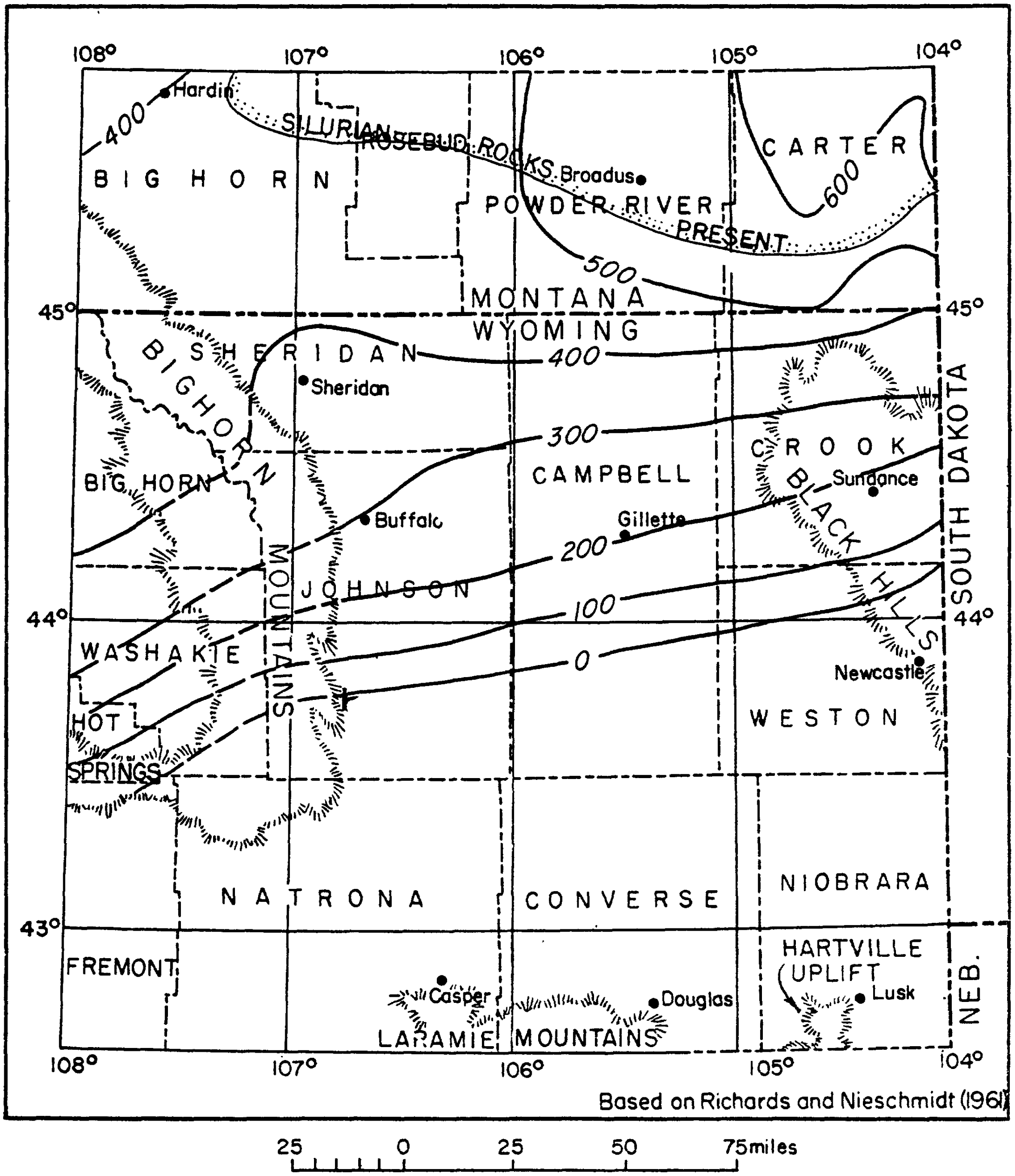


Figure 7.-- Map showing thickness of Ordovician rocks and limit of Silurian rocks in the Powder River Basin. (Does not include lower clastic sequence of rocks, 0 to 100 feet thick. Thickness interval is 100 feet; thickness lines are dashed where rocks have been removed by erosion.)

northern part of the Basin Ordovician rocks are either conformably overlain by Silurian rocks or unconformably overlain by Devonian rocks and to the south are truncated by Mississippian rocks.

In the Bighorn Mountains, Ordovician rocks are represented by the Harding(?) Sandstone and the Bighorn Dolomite, which includes the Lander(?) Sandstone Member at its base (Ross, 1957, pl. 44). The Harding(?) strata consist of fine- to coarse-grained quartzitic sandstone which ranges in thickness from a few inches to about 60 feet (Hose, 1955, p. 45, 46). The Bighorn Dolomite is 0-480 feet thick. The Lander(?) Sandstone Member at the base of the Bighorn is a 3-foot-thick medium-grained sandstone. Above the Lander(?) Member is a lower 285-foot unit of massive microcrystalline dolomite and dolomitic limestone overlain by thin-bedded slabby-and blocky weathering dolomite and an upper 200-foot unit of massive and thin-bedded dolomite (Richards and Nieschmidt, 1961).

The northern part of the Basin is underlain, in ascending order, by the Winnipeg, Red River, and Stony Mountain Formations (Ross, 1957; Richards and Nieschmidt, 1961). The Winnipeg Formation is from 0 to about 100 feet thick in the Powder River Basin (Fuller, 1961, fig. 7) and is composed of shale interbedded with numerous thin layers of quartzitic sandstone. The distribution of sandstone and shale is probably highly variable (Ross, 1957, p. 449). The Red River Formation, 0-500 feet thick, consists of 245 feet of cryptocrystalline to microcrystalline limestone and 250 feet of microcrystalline dolomite. The

Stony Mountain Formation consists of 0-150 feet of calcareous and argillaceous siltstone and limestone (Richards and Nieschmidt, 1961). The Red River and much of the Stony Mountain Formation correspond to the Bighorn Dolomite in the Bighorn Mountains (Ross, 1957, p. 444).

In the Black Hills, Ordovician rocks include about 70 feet of shale and siltstone overlain by 40 to 80 feet of massive, silty dolomite. The age and correlation of the shale and siltstone sequence has been uncertain (Darton and Paige, 1925, p. 7; Furnish, Barragy, and Miller, 1936; McCoy, 1958a; and Ross, 1957). According to Ross (1957, p. 468) this sequence is presumed to be of Middle Ordovician age and supposedly is correlative with the Winnipeg Formation in the subsurface and with the Lander(?) Sandstone Member of the Bighorn Dolomite in the Bighorn Mountains. The overlying dolomite sequence, the Whitewood Limestone of Darton and Paige (1925, p. 7), renamed the Whitewood Dolomite by Ross (1957, p. 443), appears to be stratigraphically equivalent to part of the lower beds in Red River Formation in the subsurface in the Powder River Basin (Richards and Nieschmidt, 1961).

Ordovician(?) and Silurian rocks

The Interlake Group of Baillie (1951), of Ordovician(?) and Silurian age, underlies the extreme northeastern part of the Powder River Basin (fig. 7). Rocks of the Interlake Group conformably overlie Ordovician rocks, to which they are lithologically similar and from which they are difficult to distinguish, and are unconformably overlain by Devonian rocks. The Interlake Group of Baillie (1951) is from 0 to about 150 feet thick in the Powder River Basin and consists mostly of cryptocrystalline to sublithographic dolomite (Richards and Nieschmidt, 1961).

Devonian rocks

Rocks of Devonian age underlie only the northern part of the Powder River Basin (fig. 8). Lower Devonian rocks are thin discontinuous channel-fill deposits of the Beartooth Butte Formation and Upper Devonian rocks are predominantly carbonate deposits, 0 to 210 feet thick, of the Duperow Formation and equivalent strata in the Jefferson Formation.

The Beartooth Butte Formation, which unconformably overlies Upper Ordovician and Silurian rocks, has been recognized in widely scattered outcrops and wells in northern Wyoming and southern and central Montana (Sandberg, 1961). It consists of silty, sandy, limestone conglomerate and in most places is less than 10 feet thick; however, at several localities it increases in thickness from a few feet to about 150 feet in less than half a mile. In the Powder River Basin, the Beartooth Butte Formation consists of continental deposits that fill sinkholes and channels in the underlying Upper Ordovician and Silurian rocks. The formation is thought to have been deposited near the eastern margin of an Early Devonian sea which invaded bays and estuaries on the west.

The Upper Devonian Duperow Formation rests unconformably on rocks of Silurian age as well as on the Stony Mountain Formation and upper part of the Red River Formation, both of Late Ordovician age

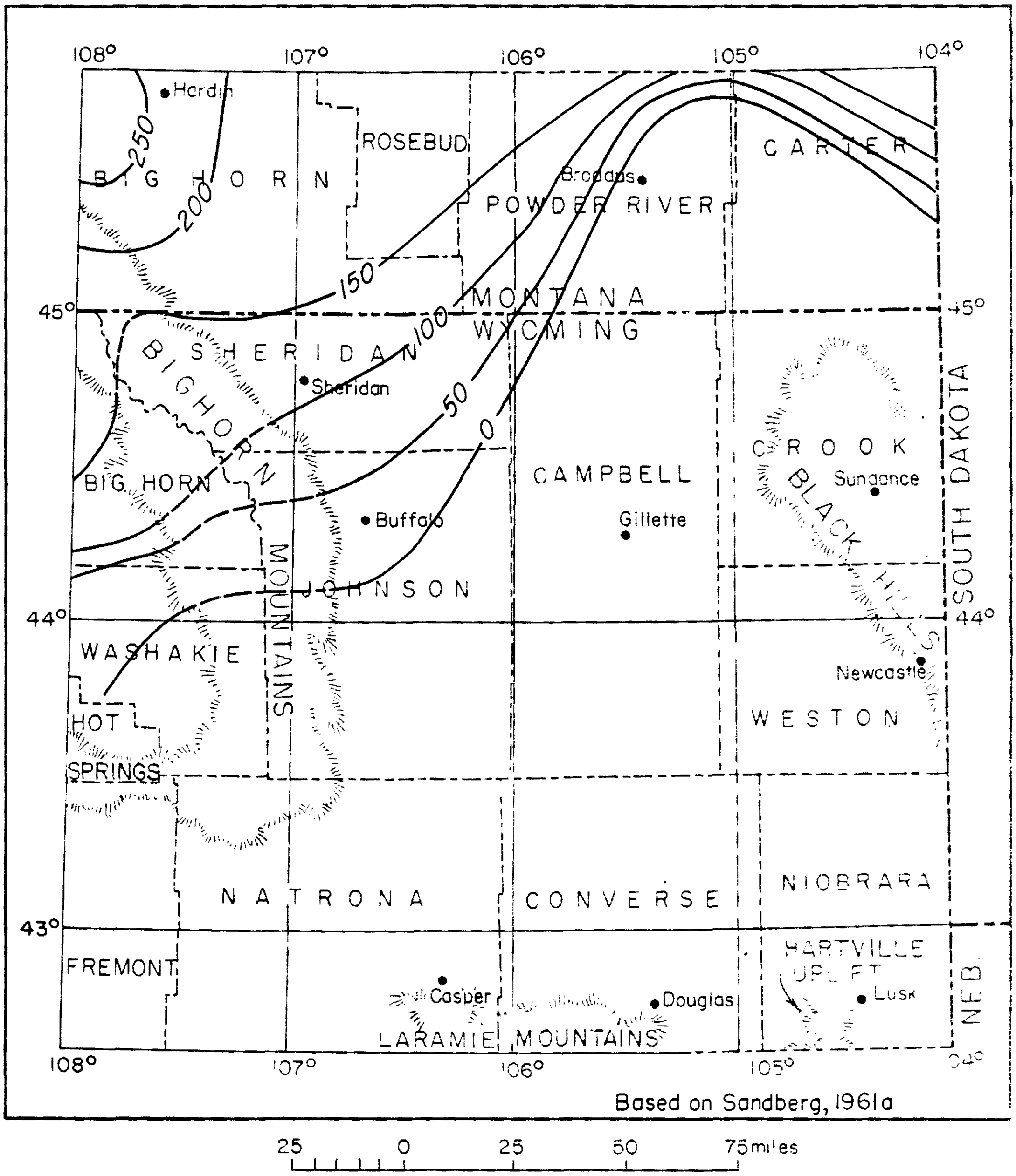


Figure 8.--Thickness map of Devonian rocks in the Powder River Basin. (Thickness interval is 50 feet; thickness lines are dashed where rocks have been removed by erosion.)

(Sandberg and Hammond, 1958). The Duperow Formation consists of limestone, dolomite, and anhydrite with some interbeds of shale and siltstone; dolomitic shale or shaly dolomite is predominant in the upper part. It is correlated with the Jefferson Formation of the Bighorn Mountains, which probably represents a near-shore facies of the lower part of the type Jefferson. The southward thinning of Upper Devonian strata in the Powder River Basin results from onlap at the base and truncation by the Madison Limestone of Mississippian age at the top.

Mississippian rocks

Following a period of uplift the Powder River Basin area was completely covered by Early Mississippian seas which transgressed from the north. The Basin received widespread deposits of carbonate rocks which southward truncate Upper Devonian, Silurian, and Upper and Middle Ordovician rocks. Mississippian strata are about 1,200 feet thick at the north end of the Basin and thin with relative uniformity to about 200 feet at the south end (fig. 9). This southward thinning is in part depositional but is largely due to pre-Chester or pre-Pennsylvanian erosion. The formation names used on mountain uplifts flanking the Basin are shown on figure 10.

In the Bighorn Mountains rocks of Mississippian age are represented by the Madison Limestone, a finely crystalline, thin-bedded to massive sequence of limy dolomite and limestone, 400 to 1,000 feet thick. In the Black Hills, Mississippian rocks are included in the Englewood Limestone below and the Pahasapa Limestone above

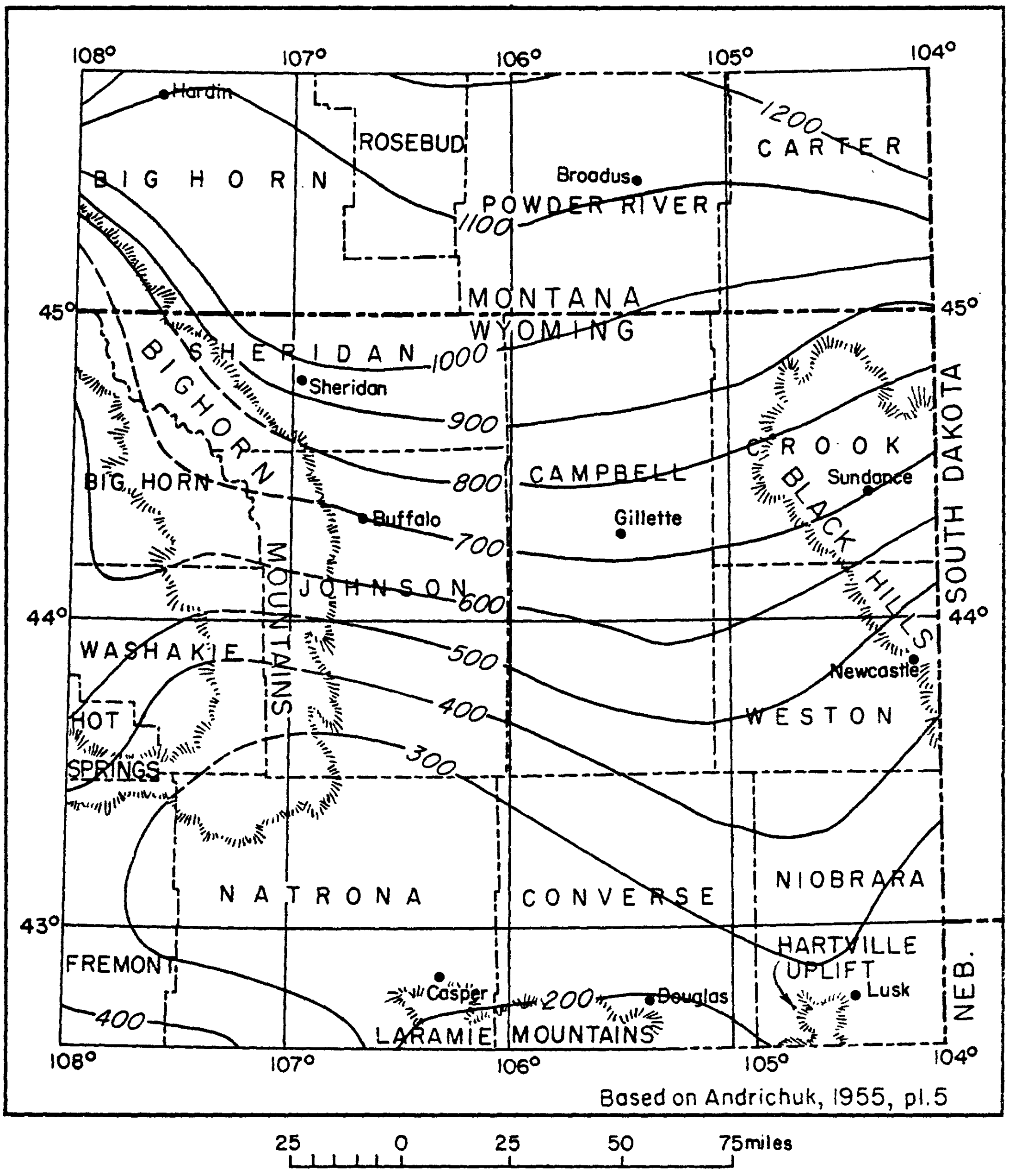


Figure 9.--Thickness map of Mississippian rocks in the Powder River Basin. (Thickness interval is 100 feet; thickness lines are dashed where rocks have been removed by erosion.)

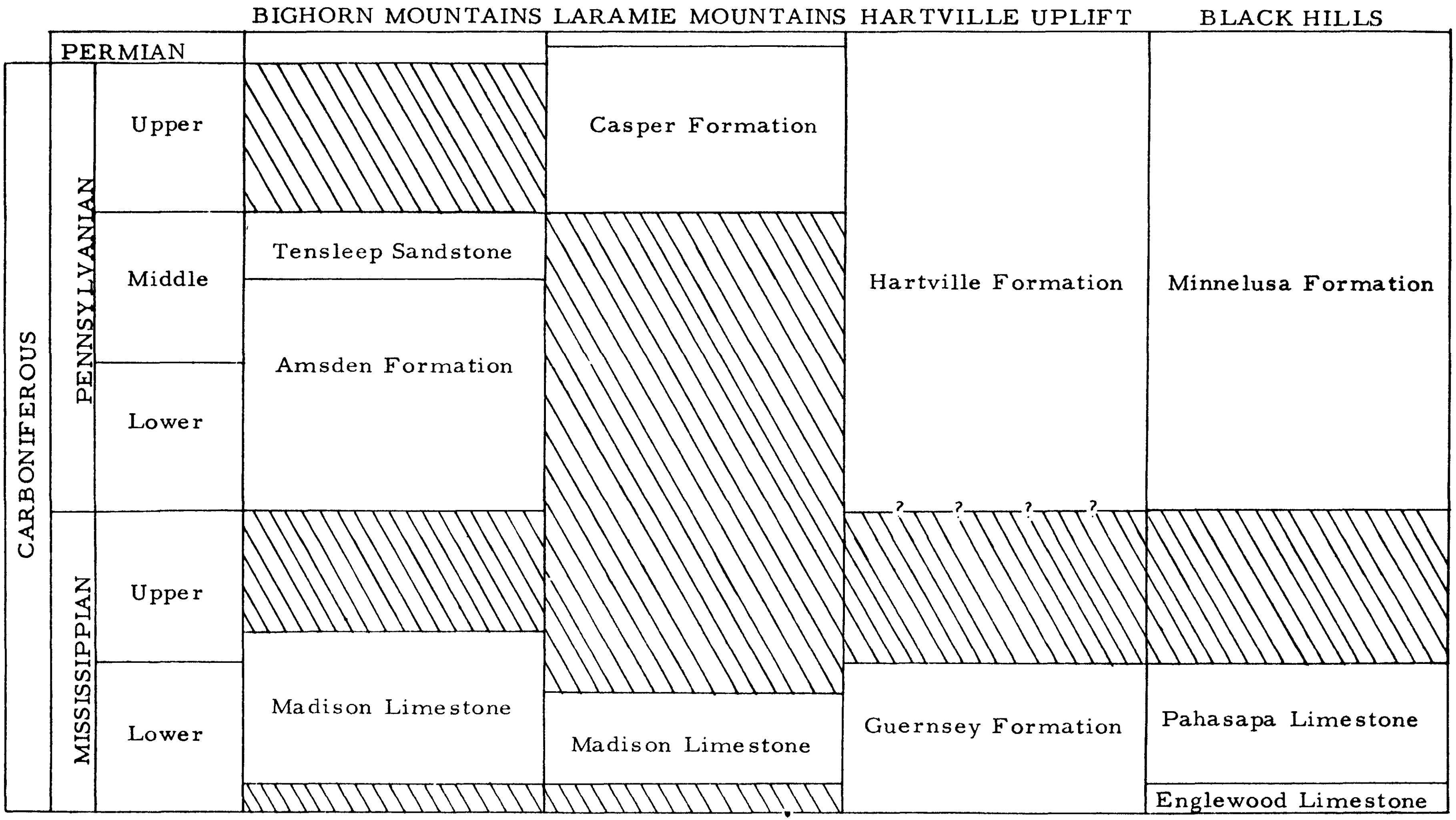


Figure 10.--Correlation chart of Carboniferous rocks in the Powder River Basin.

(Darton and Paige, 1925, p. 7-8). The Englewood is 30 to 60 feet thick and is typically a thin-bedded, lavender limestone which grades upward into limestone of the Pahasapa and in places grades downward into shale. The overlying Pahasapa ranges from 300 to 630 feet in thickness and is a fine-grained massive limestone which in places contains thin beds of shale or slabby limestone. In the northern part of the Hartville area, the Guernsey Formation includes 200-300 feet of rocks of Mississippian age, which consist of cherty coarsely crystalline dolomite that grades upward into cherty limestone. Fossils of Devonian age have been found at the base of the Guernsey Formation below a probable equivalent of the Englewood Limestone (Love and others, 1953).

Mississippian(?), Pennsylvanian, and Permian rocks

A diverse sequence of clastic, carbonate, and evaporite rocks, characterized by marked changes in thickness and lithology, disconformably overlies the Mississippian carbonate rocks and is overlain by a relatively uniform Permian red bed sequence. These rocks are largely Pennsylvanian in age but some possibly extend down into the Mississippian and some very probably extend up into the Permian. The formation names used for this heterogeneous sequence on the mountain uplifts flanking the Basin are shown on figure 10.

In the Bighorn Mountains, Pennsylvanian rocks, represented by the Amsden Formation below and Tensleep Sandstone above, are about 600 feet thick (fig. 11). The Amsden Formation, about 250 feet thick, consists of sandstone and shale in the lower half and limestone and dolomite in

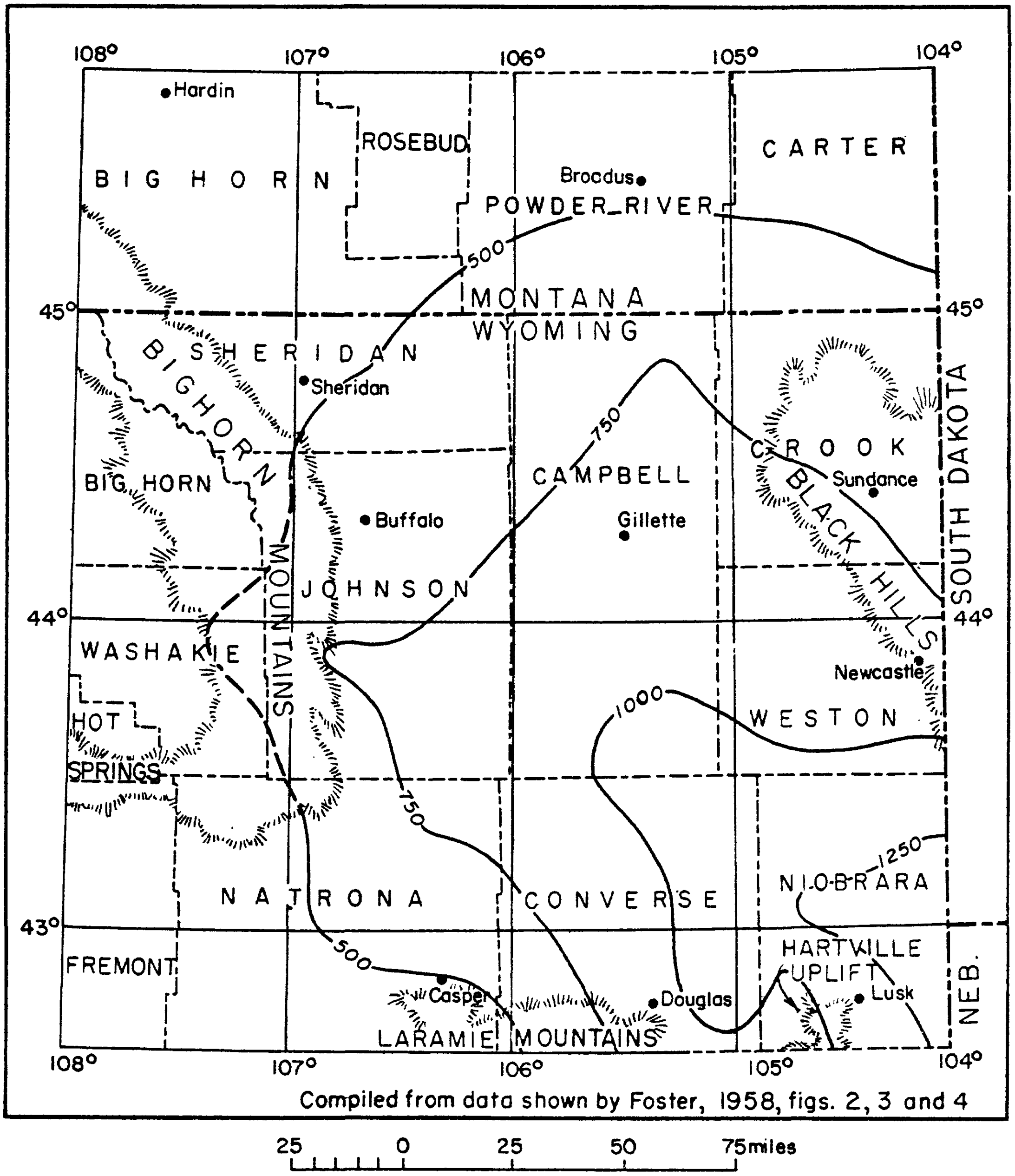


Figure 11.-- Thickness map of Mississippian(?), Pennsylvanian, and Permian rocks in the Powder River Basin. (Thickness interval is 250 feet; thickness lines are dashed where rocks have been removed by erosion.)

the upper half. The Tensleep Sandstone is less than 75 feet thick in the northern part of the Bighorn Mountains, but it thickens to more than 350 feet in the southern part. It is a fine- to medium-grained quartz sandstone with some interbedded limestone and dolomite in the lower part. The combined Amsden and Tensleep range in age from Early through Middle Pennsylvanian.

In the southwest part of the Basin along the north end of the Laramie Mountains, the Casper Formation, about 500 feet thick, consists predominantly of alternating thicker beds of sandstone and thinner beds of limestone (Thomas and others, 1953, p. 6). It ranges in age from Late Pennsylvanian to Early Permian.

On the Hartville uplift, the Hartville Formation includes as much as 1,300 feet of rocks between the top of the Guernsey Formation and the base of the Opeche Shale (Love and others, 1953). On the basis of gross lithology, the Hartville Formation can be divided into three units: a basal sandstone, 50 to 100 feet thick; a middle carbonate sequence, about 700 feet thick, consisting of limestone, dolomite, shale, and sandstone; and a sandstone and breccia sequence, whose upper part is 50 to 200 feet of soft porous sandstone. The Hartville Formation ranges in age from Late Mississippian(?) or Early Pennsylvanian to Early Permian.

In the Black Hills, rocks of Pennsylvanian age are included in the Minnelusa Formation, which ranges in thickness from 650 to 800 feet. It consists of interbedded sandstone, sandy dolomite and limestone, some shale and siltstone, and local beds of gypsum and anhydrite. The upper 250 to 300 feet of the formation are assigned to the Permian on the basis of correlation with the Hartville Formation to the south (Foster, 1958, p. 39-44).

The age relationships of the rock sequence between the Mississippian carbonate rocks below and the Permian red beds above are complex. In the Bighorn Mountains, the Amsden Formation and overlying Tensleep Sandstone probably are not younger than Middle Pennsylvanian (Thomas, 1949, p. 44). At the north end of the Laramie Mountains, the lower part of the Casper Formation is Late Pennsylvanian (Thomas, 1949, p. 7), slightly younger than the upper part of the Tensleep Sandstone. To the east in the Hartville uplift and Black Hills, respectively, the Hartville and Minnelusa Formations are equivalent in age to the combined Amsden, Tensleep, and Casper Formations. In Early Pennsylvanian time, a sea probably covered the entire Powder River Basin, except the area of the Laramie Mountains. In Late Pennsylvanian time, the sea probably covered the Laramie Mountain area, but retreated to the south and east from the area of the Bighorn Mountains. This sea covered the southern Black Hills and the Hartville uplift during the entire Pennsylvanian, as evidenced by continuous deposition there.

Permian and Triassic rocks

Permian rocks in the Powder River Basin are represented by a red-bed facies, about 300 feet thick, consisting of thin beds of marine limestone, red shale and siltstone, gypsum, and anhydrite. They attain a maximum thickness of about 380 feet in the southern part, but thin to less than 100 feet in the northern part. The lower part of the Permian sequence consists of a basal shale, the Opeche Shale, and an overlying limestone, the Minnekahta Limestone, which are recognizable throughout the Basin. The lithology of the Permian rocks above the Minnekahta Limestone grades from limestone and red shale in the southern part of the Basin to red shale and gypsum in the northern part. The boundary between Permian and Triassic rocks falls within the upper red-bed sequence.

Triassic rocks consist of nonmarine red siltstone and lesser amounts of red shale and fine-grained silty sandstone. Triassic strata are thickest in the southwestern part of the Basin and thin eastward and northeastward. An unconformity representing most of Triassic and all of Early Jurassic time is present between Triassic and younger rocks. Triassic rocks have been more deeply eroded to the east, which accounts for their thinning in that direction (fig. 12).

A break between Permian and Triassic rocks cannot be recognized in most places in the Powder River Basin area (McKee and others, 1959, p. 1). The boundary between the systems falls within the Goose Egg Formation of Burk and Thomas (1956) or equivalent strata on the west side of the Basin and within the Spearfish Formation on the east side.

In the southwestern part of the Basin, near Casper Mountain, the Goose Egg Formation of Burk and Thomas (1956), 380 feet thick, consists

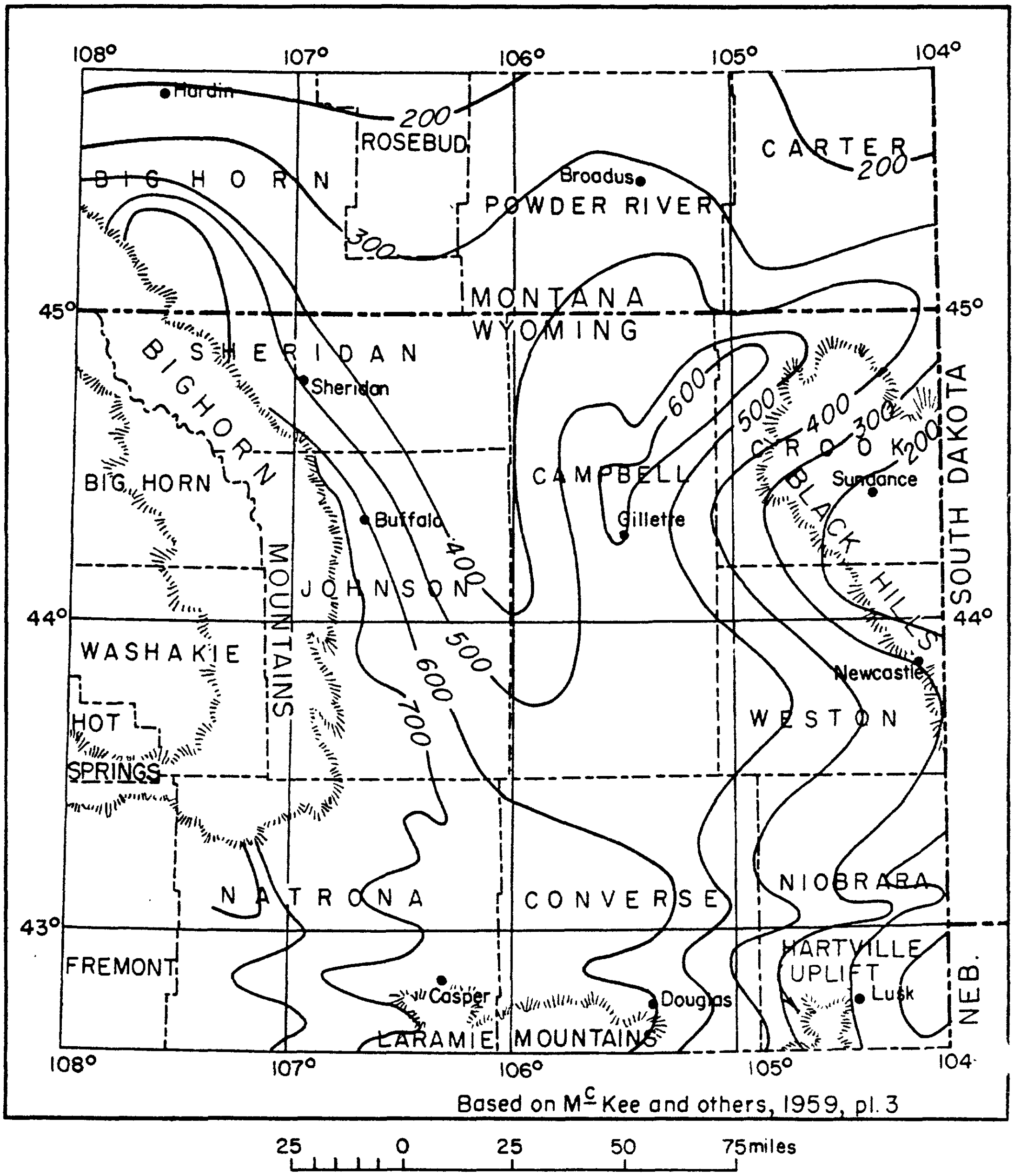


Figure 12.--Thickness map of Triassic rocks in the Powder River Basin. (Thickness interval is 100 feet.)

of eight alternating shale and limestone members. The lowermost member, the Opeche Shale Member of Burk and Thomas, 1956), is 70 feet thick and consists of shale and siltstone, and their overlying member, the Minnekahta Limestone Member, is a 10-foot-thick dense limestone. The remaining 300 feet is composed predominantly of shale and siltstone, some gypsum, and interbedded limestone members. To the north and east, the upper limestone members lens out into red shale and gypsum, and only the Opeche Shale and Minnekahta Limestone are recognizable. The Goose Egg includes beds that are placed in the lower part of the Chugwater Formation in northeastern Wyoming. Most of the Goose Egg Formation is Permian in age, but it includes strata of Triassic age in the upper part. The overlying Chugwater Formation is from 200 to more than 500 feet thick along the southern margin of the Basin. It consists of red siltstone with lesser amounts of red shale and fine-grained red silty sandstone, and a few thin beds of gypsum and anhydrite (Love, 1958, p. 64). The Chugwater thins eastward.

In the Hartville uplift, the Opeche Shale consists of about 60 feet of silty shale with some sandstone near the base (Denson and Botinelly, 1949). The Minnekahta Limestone is approximately 35 feet thick. Overlying the Minnekahta is a sequence of gypsum and red shale, ranging in thickness from 230 to 310 feet. The Opeche Shale, Minnekahta Limestone and gypsum and red shale sequence of this area are equivalent to the Goose Egg Formation of Burk and Thomas (1956) (McKee and others, 1959, p. 3). The Chugwater Formation in the

Hartville area consists of 150 to 435 feet of red siltstone and small amounts of red shale and fine-grained red silty sandstone.

In the Black Hills, the Opeche Shale is 60 to 90 feet thick and consists mostly of siltstone and shale. The Minnekahta Limestone is 40 feet thick. The overlying Spearfish Formation ranges in thickness from 450 to 825 feet and consists of red shale, siltstone, and sandstone, with thick beds of gypsum near the base (Robinson and others, in prep.). The Spearfish Formation includes all the beds between the Minnekahta Limestone and the Gypsum Spring Formation of Middle Jurassic age, therefore includes rocks of both Permian and Triassic age (McKee and others, 1959, p. 3). The Opeche Shale, Minnekahta Limestone, plus the lower gypsiferous sequence of the Spearfish Formation are equivalent in age to the Goose Egg Formation of Burk and Thomas (1956).

In the Bighorn Mountains Permian rocks consist of a sequence of interbedded gypsum, red shale and siltstone, and thin beds of limestone, which Darton (1906, p. 36-42) included in the basal part of the Triassic Chugwater Formation (Mapel, 1959, p. 24). Permian rocks are about 100 feet thick in the extreme northwest part of the Basin, where Richards (1955, p. 32-34) referred them to the Embar Formation. Southward they thicken to 250 feet, and consist of a basal 50-foot silty claystone which seems correlative with the Opeche Shale; a 50-foot red siltstone containing thin-bedded limestone which is at the same stratigraphic position as the Minnekahta Limestone; and an upper 150-foot sequence of interbedded gypsum and red siltstone

(Hose, 1955, p. 50, 51). The Chugwater Formation ranges in thickness from 450 feet in Montana to more than 800 feet in the southwest part of the Basin (Hose, 1955, p. 51). The basal Red Peak Member consists of interbedded siltstone, shale, and silty fine-grained sandstone about 700 feet thick. Above this is the Alcova Limestone Member, a 5- to 10-foot-thick slabby thin-bedded limestone. The upper member, the Crow Mountain Sandstone Member, consists of about 50 to 100 feet of fine-grained massive sandstone.

Jurassic rocks

Jurassic rocks are about 700 feet thick at the north end of the Powder River Basin and thin to about 200 feet at the south end. This southward thinning is both depositional and erosional.

Jurassic rocks represent deposits of three marine transgressive cycles, each of which extended farther south than the previous one, followed by deposits of a terrestial environment. The first incursion of the sea, in Middle Jurassic time, covered only the northern part of the Basin and resulted in deposition of the Gypsum Spring Formation in Wyoming and its equivalent, the Piper Formation in Montana. The second and third transgressions covered the entire area. During the second the "lower Sundance" strata of the Bighorn Mountains area and their equivalents, the Canyon Springs, Stockade Beaver, Stockade Beaver, Hulett, and Lak Members of the Sundance Formation of the Black Hills and the Rierdon Formation of Montana were deposited. During the third and final invasion of the sea, the "upper Sundance" strata and the equivalent Redwater Shale Member of the Sundance Formation of the Black Hills and the Swift Formation of Montana were deposited. The thickness of marine Jurassic rocks is shown on figure 13. The fluvial and lacustrine sediments of the Morrison Formation were deposited following the retreat of the "upper Sundance" Sea. The correlation of Jurassic rocks is shown on figure 14.

Rocks of Middle Jurassic age unconformably overlie redbeds of Triassic age and are unconformably overlain by the Sundance Formation of Late Jurassic age. In the northern part of the Basin, Middle Jurassic rocks assigned to the Piper Formation attain a maximum thickness of 150 to 200 feet. The Piper consists of three units: a lower 45-foot-thick unit of thick-bedded gypsum and thin layers of shale; a middle 85-foot-thick unit of argillaceous limestone with interbedded shale; and an upper 20-foot-thick unit of shale and siltstone (Richards, 1955, p. 39). The Gypsum Spring Formation in the northernmost Wyoming part of the Basin includes strata approximately equivalent to the Piper Formation; however, at most places to the south the lower gypsum and shale unit makes up the Gypsum Spring Formation. The Gypsum Spring Formation, 200 feet thick in the northern Wyoming part of the Basin, thins to a feather edge in the latitude of Mayoworth and Newcastle (Mapel and Bergendahl, 1956, p. 90). The contact of the Piper or Gypsum Spring Formation with overlying beds is an erosional unconformity that truncates Middle Jurassic beds from north to south (Imlay, 1956, p. 564).

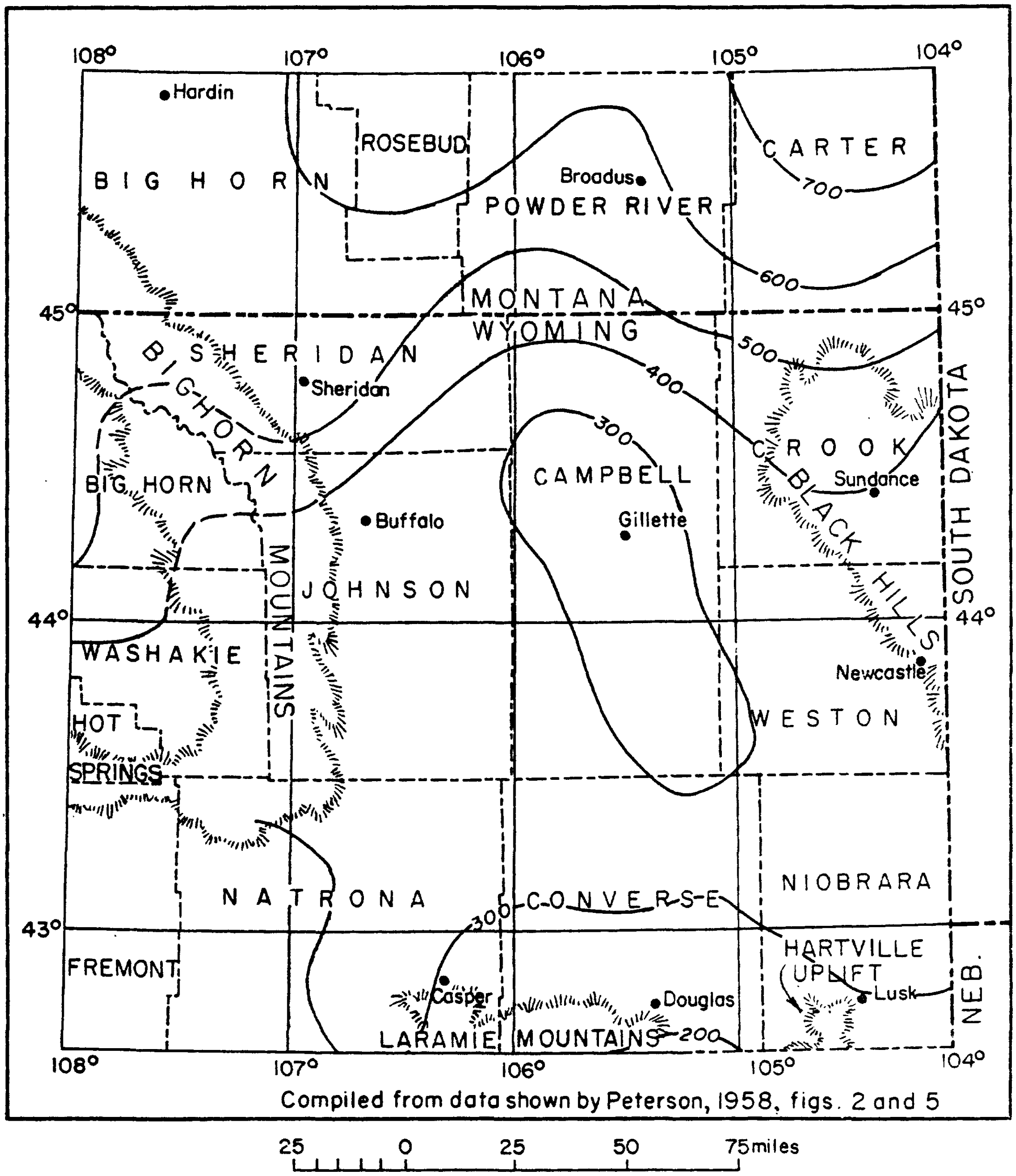
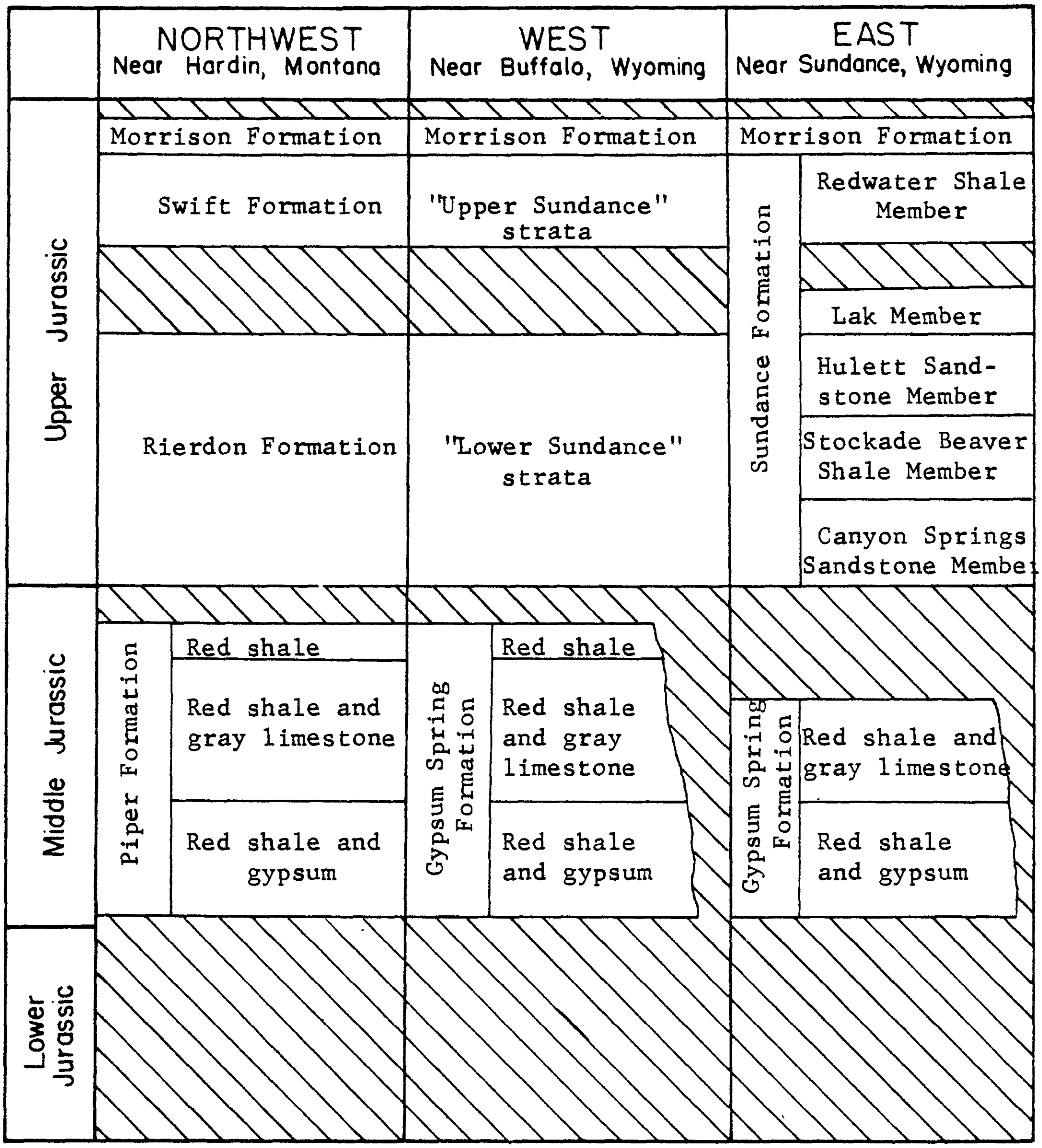


Figure 13. Thickness map of marine Jurassic rocks in the Powder River Basin. (Thickness interval is 100 feet; thickness lines are dashed where rocks have been removed by erosion).



(Imlay, 1947, table 1; modified by Mapel and Bergendahl, 1956, table 1.)

Figure 14. Correlation chart of Jurassic rocks in the Powder River Basin.

The Sundance Formation is generally divided into a lower non-glauconitic sequence ("lower Sundance" strata) and an upper glauconitic sequence ("upper Sundance" strata). These are separated from each other by a sharp lithographic break and by an unconformity (Love, 1958, p. 67).

"Lower Sundance" strata in the Black Hills include the Canyon Springs Sandstone Member at the base (Imlay, 1947, p. 247-251). This member, 0 to about 45 feet thick, is a slightly calcareous, fine-grained sandstone that thickens and thins abruptly in discontinuous channel-fill deposits. A basal sandstone along the southern margin of the Basin was described and tentatively correlated with the Canyon Springs Sandstone Member by Love (1958, p. 64-66). The basal sandstone ranges in thickness from 30 to 75 feet within a short distance and consists of a soft, porous, clean sandstone, a silty fine-grained calcareous sandstone, and an upper oolitic sandstone. This basal sandstone cannot be recognized within the deeper part of the Basin, where it and the other "lower Sundance" members of the Black Hills lose their identity (Peterson, 1957, p. 413). The overlying sequence in the "lower Sundance" consists of non-glauconitic shale and sandstone, which thins from about 300 feet in thickness in the northern part of the Basin to 125-150 feet in the southern part.

"Upper Sundance" strata are glauconitic and consist largely of shale and sandstone. Their thickness ranges from about 250 feet in Montana to about 50 feet along the southern margin of the Basin. In places a basal sandstone, ranging in thickness from a wedge edge to as much as 30 feet, is conspicuously developed (Love, 1958, p. 68).

A porous, thin-bedded, yellow-weathering, calcareous quartz sandstone of undetermined correlation occurs between glauconitic marine "upper Sundance" rocks and the nonmarine Morrison strata. Opinions differ as to whether this sandstone should be included in the Sundance or Morrison Formations, or be considered a separate formation (Love, 1958, p. 68-70). This sandstone, 2 to 25 feet thick, is present nearly everywhere in the Basin and may represent a transition zone between the two formations.

The Morrison Formation is the youngest formation of Jurassic age. It is present throughout the Basin except where it has been removed by Cenozoic erosion. The Morrison is remarkably uniform in thickness, ranging from about 100 feet to about 250 feet and averaging about 150 feet. The formation consists of a variegated sequence of claystone, siltstone, shale, and fine-grained sandstone deposited as a blanket on floodplains and in swamps.

A hiatus representing uppermost Jurassic and lowermost Cretaceous time occurs between the Morrison Formation and the overlying Cloverly Formation (or Lakota Formation of the Black Hills) (Reeside, in Yen, 1952, p. 26). In places in the Black Hills, folding accompanied by erosion took place during this interval as is shown by an unconformity at the base of the Lakota Formation, where the Morrison and much of the Sundance Formation have been removed (Robinson and others, in prep.).

Cretaceous rocks

Cretaceous rocks in the Powder River Basin have a total thickness greater than the aggregate thickness of all the underlying Paleozoic and Mesozoic rocks (fig. 4). They consist largely of sandstone and shale deposited during the last great marine inundation of the area and of some shale, sandstone, and coal-bearing strata deposited during the retreat of the sea. Cretaceous rocks on the west side of the Basin are coarser grained than those on the east side and contain sandstone beds that wedge out to the east into siltstone, shale, and calcareous shale. Major lithologic facies are of different ages in different parts of the Basin. As a result of facies changes, several sets of formation names are used around the margins of the Basin. The correlation of these various names is shown on figure 15.

Lower Cretaceous rocks

Lower Cretaceous rocks are divided into two lithogenetic units consisting of a lower varied sequence of continental deposits separated by a regional disconformity from overlying marginal-marine and marine deposits (Waagé, 1959). This disconformity, which is transgressive, marks the initial incursion of the epicontinental Cretaceous sea. It occurs between the Lakota Formation below and the Fall River Formation above in the Black Hills and at the base of the "rusty beds" in the upper part of the Cloverly Formation in the Bighorn Mountains. The thickness of Lower Cretaceous rocks in the Basin is shown on figure 16.

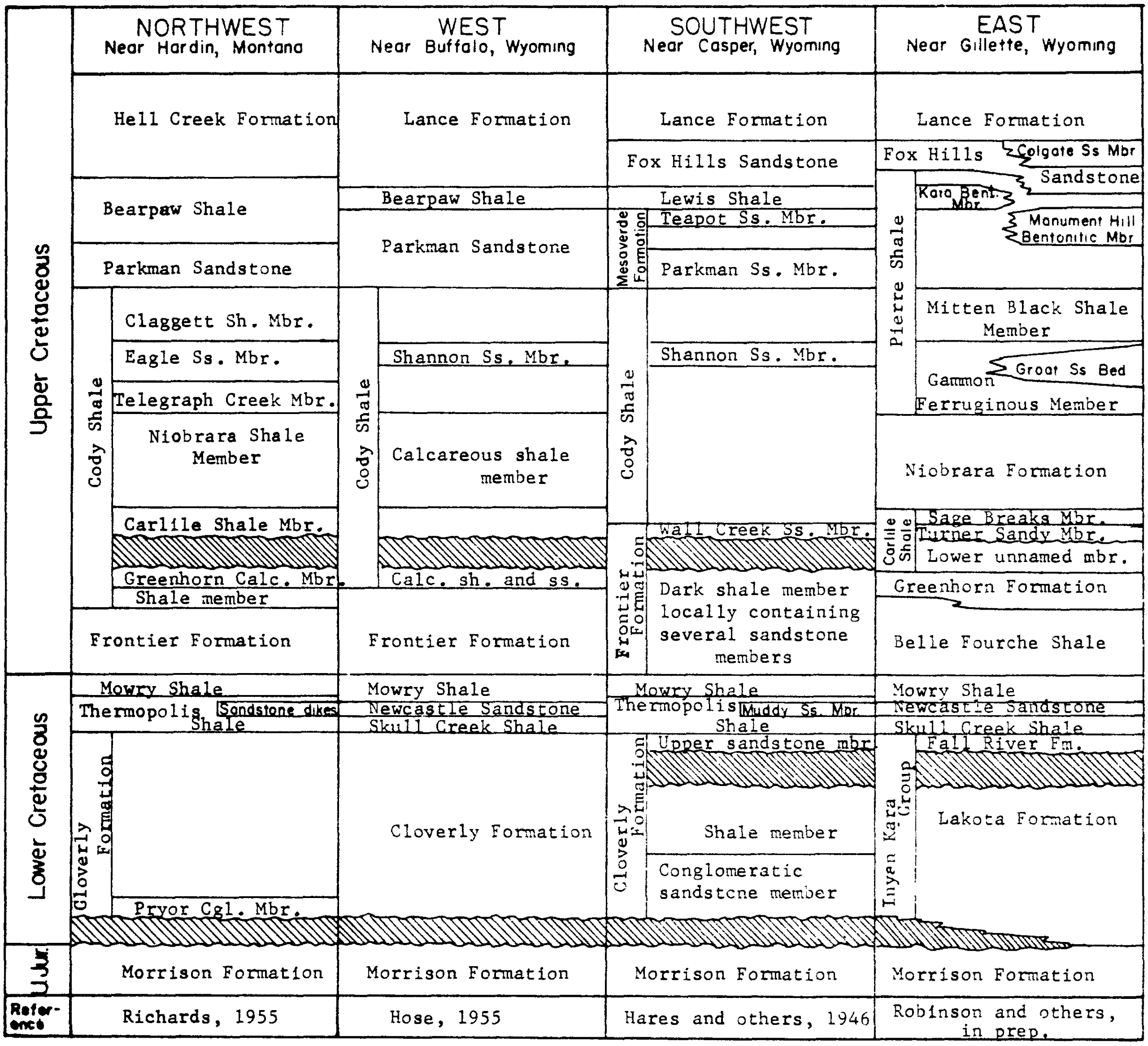


Figure 15. Correlation chart of Cretaceous rocks in the Powder River Basin.

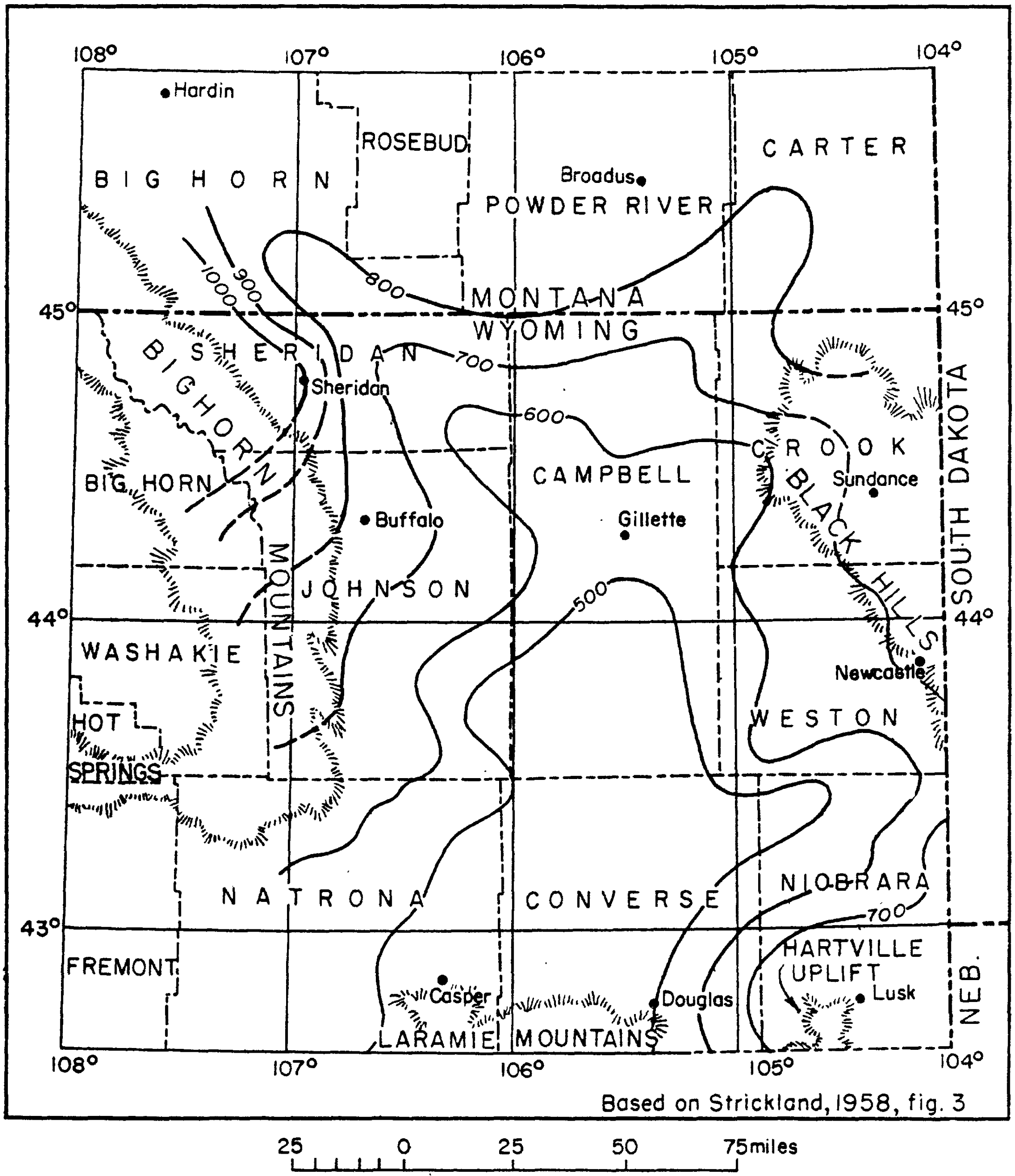


Figure 16.--Thickness map of Lower Cretaceous rocks in the Powde. RiverBasin. (Thickness interval is 100 feet; thickness lines are dashed where rocks have been removed by erosion).

The Lakota Formation is a heterogeneous sequence of sandstone and conglomeratic sandstone, and variegated sandy mudstone and claystone; the relative amounts of sandstone and finer grained clastics vary widely (Mapel and Gott, 1959). The Lakota Formation is as much as 550 feet thick at the southern end of the Black Hills where it contains the Chilson and overlying Fuson Members (Post and Bell, 1961). The lithology of the Chilson Member is extremely varied. In the lower part, it includes very fine grained well-sorted sandstone in lenticular bodies separated by the partings of carbonaceous siltstone and in the upper part it includes very fine grained and well-sorted rarely carbonaceous sandstone in lenticular bodies that are interbedded with and finger laterally into varicolored siltstone and claystone. The Fuson Member comprises variegated claystone and mudstone and channel sandstone that is locally conglomeratic. To the northwest, the Chilson Member pinches out and the Lakota Formation thins irregularly to less than 100 feet near Sundance, and to 100 to 250 feet near the Wyoming-Montana State line.

The Fall River Formation is fairly uniform in thickness, ranging from 110 to 150 feet and averaging 135 feet. It is predominantly thin-bedded siltstone, sandstone, and shale interstratified with thicker, more massive beds of sandstone. The basal few feet consist of carbonaceous siltstone (Mapel and Gott, 1959).

The Cloverly Formation in the Bighorn Mountains ranges in thickness from 135 to 165 feet. It includes a basal sandstone of almost pure quartz, 15 to 45 feet thick, overlain by a 120-foot-thick sequence of black shale interbedded with brown-weathering siltstone (Hose, 1955, p. 56). In the northwest part of the Basin, the Cloverly averages between 300 and 400 feet in thickness (Richards, 1955, p. 42-45). There it consists of a lower member, the Pryor Conglomerate Member, 30 to 150 feet thick, composed of resistant sandstone, commonly with chert-pebble conglomerate in the lower part. The upper part of the formation is made up of shale, siltstone, and thin-bedded flaggy sandstone.

The Skull Creek Shale and Newcastle Sandstone (and their equivalent, the Thermopolis Shale) occupy the interval between the top of the Cloverly Formation (and its equivalents, the Lakota and Fall River Formations) and the base of the widespread Mowry Shale (fig. 15). The Newcastle Sandstone is correlative with the Muddy Sandstone Member of the Thermopolis Shale and the Skull Creek Shale is correlative with the lower part of the Thermopolis underlying the Muddy Sandstone Member.

The Skull Creek Shale ranges in thickness from 125 to 275 feet on the west side of the Basin and from 180 to 270 feet on the east side. It consists of shale with a few interbeds of sandstone or siltstone and in some places beds of bentonite near the base.

The Newcastle Sandstone (and its equivalents) is a widespread formation in the Powder River Basin. It is a varied unit, consisting of lenticular beds of fine- to medium-grained sandstone, lesser amounts of siltstone and shale, and on the east side of the Basin, some coal and bentonite. To the northwest, the Newcastle grades into dark-gray shale cut by sandstone dikes (Richards, 1955, p. 45-47). It is 20 to 60 feet thick at most places, but attains a thickness of 100 feet near Newcastle.

The Mowry Shale, the uppermost formation of Early Cretaceous age, is present throughout the Powder River Basin. It consists of two units that grade into each other. The lower unit is nonresistant black shale that contains thin beds of bentonite. This lower unit is from 150 to 200 feet thick on the west side of the Basin and about 20 feet thick on the east side. The upper unit is gray, hard, siliceous shale, about 350 feet thick on the west side of the Basin and about 100 to 150 feet thick on the east side.

The lithology of the Mowry Shale is unusual because of its hardness. Some of the rocks it contains consist of very fine grained nearly pure silica, which causes the hardness. The origin of the silica in the Mowry was the subject of a study by Rubey (1929) who concluded that the silica was dissolved out of volcanic ash which had decomposed in sea water, and that the dissolved silica was then precipitated by decaying organic matter. The volcanic ash in the Mowry, some of which altered to bentonite and some of which decomposed, "suggests a long series of volcanic eruptions, perhaps in Idaho, from which airborne ash was carried, mostly eastward, over an inland sea and deposited in it." (Reeside and Cobban, 1960, p. 11).

Upper Cretaceous rocks

Upper Cretaceous rocks include a complexly interfingering set of beds between the top of the marine Mowry Shale and the base of the nonmarine Fort Union Formation of Paleocene age. Except for part of the Mesaverde Formation and the Lance Formation at the top of the sequence, the upper Cretaceous rocks are marine in origin; their thickness in the Basin is shown on figure 17.

The Frontier Formation is the lowermost formation of Late Cretaceous age on the west side of the Basin. It includes sandstone and shale, but is characterized chiefly by sandstone. The Frontier is thickest in the southwest part of the Basin and interfingers with and grades into shale (lower part of the Cody Shale) to the north and into shale and limestone (Belle Fourche Shale, Greenhorn Formation, and Carlile Shale) to the east. The base of the Frontier Formation is placed at the base of a persistent bentonite bed that overlies the Mowry Shale and the top is placed at the top of the uppermost persistent sandstone bed. Where the uppermost sandstone bed grades into shale, the next lower sandstone is designated as the top of the formation.

Because the top of the Frontier Formation is placed at the top of progressively lower sandstone beds, the age of the top of the formation becomes increasingly older along the east front of the Bighorn Mountains (fig. 15). Based on faunal correlations, near Casper, the top of the Frontier Formation is equivalent to beds near the top of the Carlile Shale; near Buffalo it is equivalent to beds in the upper half

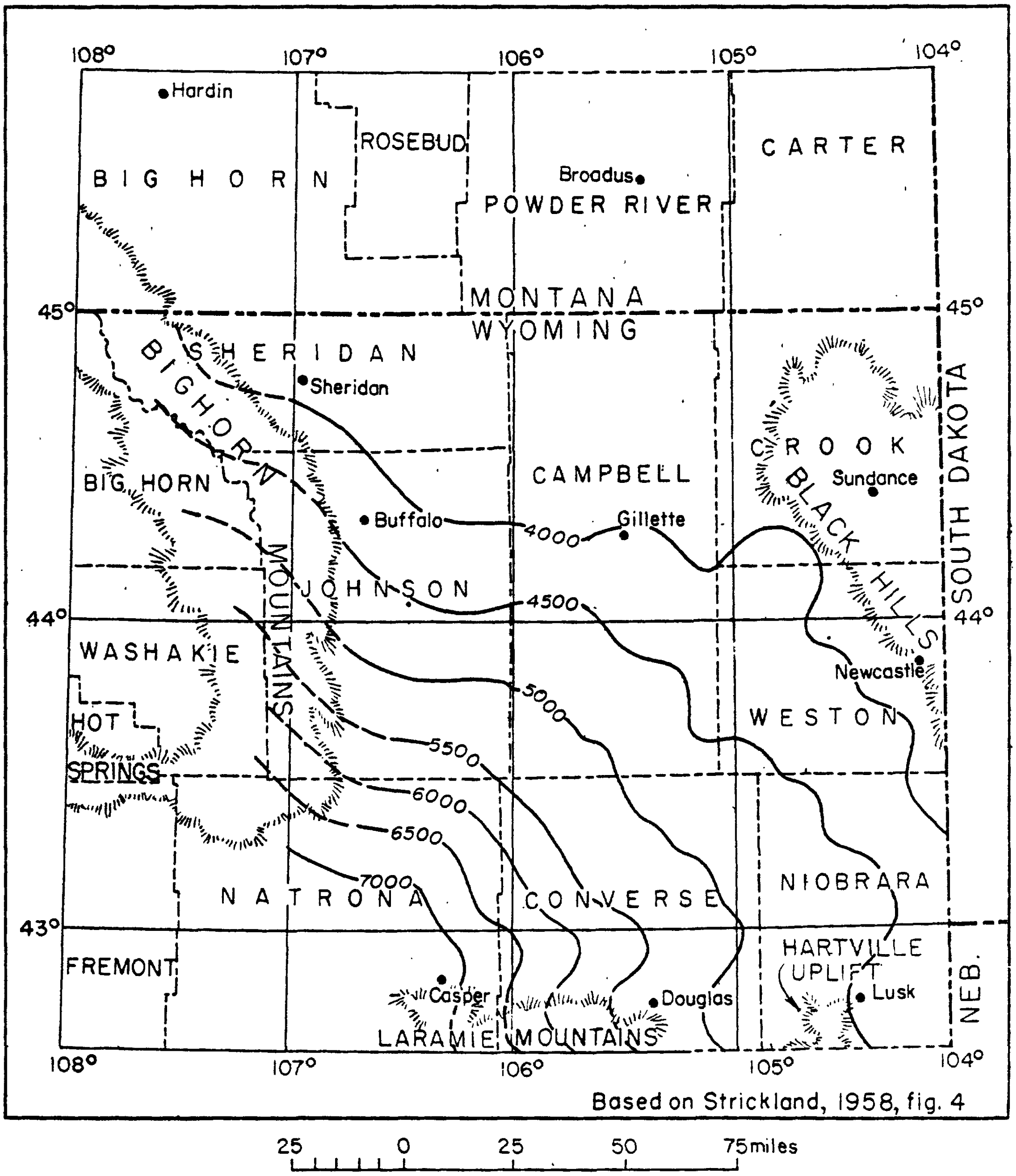


Figure 17.--Thickness map of marine Upper Cretaceous rocks in the southern Powder River Basin. (Thickness interval is 500 feet; thickness lines are dashed where rocks have been removed by erosion).

of the Greenhorn Formation, and near Hardin, Mont., it is equivalent to beds in the upper half of the Belle Fourche Shale (Cobban and Reeside, 1952, fig. 4).

In the southwestern part of the Basin, near the northeast corner of Natrona County, the Frontier Formation consists of more than 1,000 feet of shale interbedded with four sandstones, including the 120-foot-thick Wall Creek Sandstone Member at the top (Thom and Spieker, 1931, pl. 2, p. 63). To the north, near Kaycee, the lower part of the formation thins to 700 feet and the Wall Creek Sandstone Member thins to about 50 feet (Cobban and Reeside, 1952, p. 1954). In the area between Kaycee and Buffalo, the Wall Creek Sandstone Member grades into shale, and near Buffalo, the top of the formation is placed at the top of the next lower sandstone bed (Hose, 1955, p. 60). Here the total thickness of the formation is about 480 feet. Farther to the north near Hardin, Montana, the Frontier Formation consists predominantly of concretionary sandy shale with interbedded bentonite and a few lenses of sandstone and is about 260 feet thick (Richards, 1955, p. 49).

The Belle Fourche Shale is the lowermost Upper Cretaceous unit on the east side of the Basin. The Belle Fourche is 750 to 850 feet thick in northwestern Crook County, Wyo., and thins to about 450 feet to the south near Newcastle (Robinson and others, in prep.). This change in thickness is caused by interfingering and lateral gradation between noncalcareous shale in the upper part of the formation and calcareous shale, marl, and limestone in the overlying Greenhorn Formation. The basal 50 feet of the Belle Fourche is nonresistant grayish-black shale, above which are 400 to 500 feet of shale that contains few laminae of fine-grained sandstone, scattered ironstone concretions, and several beds of bentonite. The next higher 20 to 350 feet of strata consists of noncalcareous shale and a few thin bentonite beds and numerous limestone concretions. The Belle Fourche is lithologically very similar to the lower part of the Frontier Formation (Haun, 1958, p. 86).

The Greenhorn Formation overlies the Belle Fourche Shale and consists of shale, limestone, or marl. The limestone is best developed along the central part of the Black Hills uplift where it is represented by a thin concretionary facies, which thickens to a limestone-marl facies to the north and to the south. The formation ranges from 70 to 370 feet in thickness.

The Carlile Shale overlies the Greenhorn Formation. It ranges in thickness from 450 to 650 feet and consists of a dark marine shale that is sandy in the middle part. On the basis of the sandy part, the Carlile has been divided into three members: a lower unnamed member, the Turner Sandy Member, and the Sage Breaks Member.

The lower unnamed member of the Carlile Shale is 40 to 130 feet thick and consists of shale with a few calcareous concretions. The age equivalent of this member is absent on the west side of the Basin. The Turner Sandy Member is 150 to 170 feet thick and consists of a bed 5 feet thick of fine- to coarse-grained sandstone at the base overlain by shale and sandy shale containing a few thin beds and laminae of sandstone and silty limestone concretions. The Turner is the eastward equivalent of the Wall Creek Sandstone Member of the Frontier Formation (Haun, 1958, p. 87). The Sage Breaks Member is 200 to 300 feet thick and consists of shale with abundant limestone concretions.

The Niobrara Formation overlies the Carlile Shale. It consists of calcareous shale and marl with thin beds of bentonite in the middle part. It ranges in thickness from 150 to 225 feet on the east side of the Basin.

The Pierre Shale of the Black Hills area includes a sequence of marine shale, sandstone, and bentonite beds between the Niobrara Formation below and the Fox Hills Sandstone above. Equivalent rocks on the western side of the Basin include several sandstone beds. On the basis of these sandstone beds and other lithologic differences, the rocks of the west side of the Basin are divided into three formations: the upper part of the Cody Shale, the Mesaverde or Parkman Formation, and the Lewis or Bearpaw Shale (fig. 15).

The Cody Shale overlies the Frontier Formation on the west side of the Basin and includes a sequence about 2,500 to 3,500 feet thick consisting predominantly of shale and some sandstone. The Cody Shale correlates faunally with rocks ranging from the Belle Fourche through Claggett Formations.

The basal part of the Cody Shale is oldest in the northwest part of the Basin where it consists of about 200 feet of concretionary shale and several thin sandstone beds equivalent in age to the upper part of the Belle Fourche (Richards, 1955, p. 51). To the south, in the vicinity of Buffalo, rocks equivalent in age to the Greenhorn Formation constitute the lower part of the Cody; along the east front of the Bighorn Mountains, this unit consists of 200 to 300 feet of shale interbedded with some fine- to medium-grained sandstone. Equivalents of the Carlile Shale are present in the western part of the Basin and are represented by 160 to 280 feet of shale, silty shale, and fine-grained sandstone. The Niobrara Formation is represented by 400 to 950 feet of soft calcareous shale and thin bentonite beds. The next higher series of strata consist of laminated shale and fine-grained sandstone equivalent in age to the Telegraph Creek Member of the Cody Shale and part of the Eagle Sandstone of Montana. The only thick sandstone in the Cody Shale is the Shannon Sandstone Member. The Shannon, a fine-grained glauconitic sandstone, is about 200 feet thick along the southwest and west-central margins of the Basin. To the north in Montana, it grades into a silty shale equivalent in age to the Eagle Sandstone. In the western part of the Powder River Basin, the uppermost part of the Cody consists of shale, 350 to 900 feet thick equivalent in age to the Claggett Shale.

The Mesaverde Formation overlies the Cody Shale in the southwest part of the Basin. It is about 850 feet thick near Salt Creek, Wyo., about 40 miles north of Casper. It consists of three members: the Parkman Sandstone Member, 470 feet thick; an intermediate marine shale, 325 feet thick; and the Teapot Sandstone Member, 110 feet thick (Downs, 1949, p. 49). The Parkman Sandstone Member includes a basal 170-foot marine sandstone, a 190-foot coal-bearing shale, and an upper 110-foot sandstone (Thom and Spieker, 1931, p. 11, 12, and table 4).

To the north, near Buffalo, the lower members cannot be differentiated and the name Parkman Sandstone is used for beds equivalent to the Mesaverde Formation. In this area the Parkman is about 720 feet thick and consists mostly of sandstone, with some shale near the top, and an 8 to 10-foot bed of sandstone at the top. This upper sandstone is probably equivalent to the Teapot Sandstone Member of the Mesaverde Formation (Hose, 1955, p. 64). Near Hardin, Mont., the Parkman has thinned to about 250 feet of sandy shale and sandstone, and is made up of a lower 110-foot shale and an upper 140-foot massive sandstone (Richards, 1955, p. 63).

The Parkman Sandstone, from which both marine and fresh-water invertebrates and dinosaur bones have been collected (Darton, 1906, p. 59; Thom and others, 1935, p. 59) grades northward into the nonmarine Judith River Formation of Montana. It thins eastward and grades into shale in the marine Pierre Shale. It is approximately equivalent in age to that part of the Pierre Shale between the top of the Mitten Black Shale Member and the top of the Monument Hill Bentonite Member (fig. 15).

The Lewis Shale overlies the Mesaverde Formation. It is predominantly marine shale but contains numerous zones of sandy shale and lenses of very fine to fine grained calcareous sandstone. The Lewis is about 1,000 feet thick in the Salt Creek area in the southwest part of the Basin (Downs, 1949, p. 49). It is equivalent to the Bearpaw Shale in the northwestern part of the Basin. Near Buffalo, the Bearpaw is 200 feet thick and consists of shale with some laminae of fine-grained sandstone in the upper part (Hose, 1955, p. 49). Near Hardin, Mont., the Bearpaw Shale includes 850 feet of concretionary shale that is sandy in the upper few feet (Richards, 1955, p. 63). According to Dunlap (1958, p. 109) the Lewis or Bearpaw Shale was deposited during the last transgression of the Late Cretaceous sea. Discontinuous sandstones were deposited in the shale during several minor regressions. In the eastern part of the Basin rocks equivalent to the Lewis make up the upper part of the Pierre Shale.

The Pierre Shale is more than 2,700 feet thick along the southwest part of the Black Hills uplift but thins irregularly northwestward to 2,050 feet in northern Campbell County, Wyo. (Robinson and others, in prep.). The Pierre is divided into several members on the basis of differences in the shale and the presence of sandy and bentonitic units. In ascending order, these members are: the Gammon Ferruginous Member which includes the Groat Sandstone Bed; the Mitten Black Shale Member; and an unnamed upper part which includes the Monument Hill Bentonitic Member and the Kara Bentonitic Member near the top.

The Gammon Ferruginous Member of the Pierre Shale consists mostly of noncalcareous shale containing sideritic concretions. These concretions are several feet long in layers 5 to 10 feet apart. The Gammon Member is as much as 1,000 feet thick in parts of Campbell County, Wyoming, and thins rapidly southeastward. It is absent in parts of Weston County. The Groat Sandstone Bed occurs about 150 feet below the top of the Gammon Member. It consists of 35 to 125 feet of medium- to fine-grained glauconitic and ferruginous sandstone. The Groat Sandstone Bed is present along the northwest flank of the Black Hills, but to the south it is represented by silty shale or shale.

The Mitten Black Shale Member of the Pierre Shale consists of about 75 feet of platy dark shale containing several bentonite beds in the lower part, and about 75 feet of less resistant shale containing siderite and septarian limestone concretions in the upper part. The Mitten Black Shale Member is about 150 feet thick in central Carter County, Mont., and thickens southward to nearly 900 feet near Newcastle, Wyo. Where the Gammon Ferruginous Member is absent, the Mitten Member rests directly on the Niobrara Formation.

The upper part of the Pierre Shale contains black shale that is locally bentonitic and silty. It is about 800 feet thick in Carter County, Mont., and thickens to 1,500 feet to the south in Weston County, Wyo. The Monument Hill Bentonitic Member consists of bentonitic shale and occurs about 450 feet above the base of the upper part of the Pierre; it grades southward into nonbentonitic shale in northern Crook

County, Wyo. The Kara Bentonitic Member is about 700 feet above the base of the upper part of the Pierre and consists of about 100 feet of shale, bentonitic shale, and bentonite.

The Fox Hills Sandstone overlies the Pierre and Lewis Shales and is overlain by the nonmarine Lance Formation. The Fox Hills is an erratic nearshore sand facies deposited as the Late Cretaceous sea withdrew towards the southeast (Dunlap, 1958, p. 109). It becomes younger to the south. The Fox Hills has been recognized along the west flank of the Black Hills and along the southwest margin of the Basin; however, along the east flank of the Bighorn Mountains, it becomes a less distinct lithologic unit. In the Crazy Woman Creek area Hose (1955, p. 65) did not differentiate the Fox Hills. He included 100 feet of thin-bedded fine-grained sandstone, which he thought to be in part equivalent to the Fox Hills, in the basal part of the Lance Formation. Farther to the north near Buffalo, the Fox Hills could not be distinguished and beds he classified as Lance rest directly on the Bearpaw Shale (Mapel, 1961, p. 59).

Along the northwest flank of the Black Hills in Montana, the Fox Hills Sandstone consists of a lower member 50 to 100 feet thick, of fine-grained, thin-bedded sandstone interbedded with sandy shale and siltstone. These rocks are overlain by 50 to 100 feet of fine- to medium-grained sandstone, equivalent to the Colgate Sandstone Member as redefined by Thom and Dobbin (1924, p. 485-486). The Colgate Member grades laterally southward in Wyoming into sandstone and shale similar to that in the lower member (Robinson and others, in prep.). Where exposed on the margin of the Basin in Wyoming, the Fox Hills Sandstone ranges in thickness from about 100 feet in the north to about 300 feet in the south (Dunlap, 1958, p. 110).

The Lance Formation (Hell Creek Formation of Montana) is a varied nonmarine sequence of sandstone and shale that was deposited following the final withdrawal of the Upper Cretaceous sea. It is the uppermost formation of Cretaceous age in the Basin.

On the east side of the Basin, the Lance Formation consists of alternating beds of sandstone, sandy shale, and claystone. The sandstone beds range in thickness from an inch to more than 25 feet. The formation is about 500 feet thick in southern Powder River County, Mont., and thickens to more than 1,600 feet in northern Weston County, Wyo. (Robinson and others, in prep.).

On the west side of the Basin, the Lance Formation is about 600 feet thick in Montana (Thom and others, 1935, p. 61) and about 2,000 feet thick on the west-central side near Buffalo, in Wyoming. Here, a 500-foot-thick sequence of lenticular crossbedded sandstones, some of which are as much as 70 feet thick, interbedded with shale, occurs about 100 feet above the base of the formation (Hose, 1955, p. 65). These sandstones are dominantly fine- to medium-grained and quartzitic. The remainder of the formation consists of interbedded nonresistant sandstone and shale, and in the upper half, beds of carbonaceous shale.

Tertiary rocks

The Fort Union Formation of Paleocene age is interbedded nonmarine sandstone, shale, and coal (fig. 4). Its outcrop encircles the Powder River Basin except for a stretch of about 25 miles west of Buffalo (fig. 2). The thickness of the Fort Union ranges from about 1,500 feet to 2,200 feet in the northern and eastern parts of the Basin. On the west-central side, Hose (1955, p. 66) reported a thickness of 3,950 feet and on the southwest side near Sussex, Horn (1955) showed a thickness of 2,900 feet. According to Brown (1958, p. 111), "These differences in thickness are most likely indications of distance from the source of supply of the sediments and of varied conditions in transportation and deposition."

In the northeastern part of the Basin, the Fort Union Formation has been divided into three members, which from bottom to top are the Tullock, Lebo, and Tongue River Members; however, these members cannot be recognized in the southern and western parts of the Basin. The lower part of the formation is generally darker in color and contains only a few thin nonpersistent coal beds; the upper part is generally lighter and contains numerous thick coal beds. The top of the Fort Union Formation is placed at the top of the Roland coal bed or the equivalent horizon.

The Wasatch Formation of Eocene age, which is 1,050 to 3,500 feet thick (Berryhill and others, 1950, p. 11), forms the surface of most of the central part of the Basin. Its thickness ranges greatly, depending upon the amount of Recent erosion. Like the underlying Fort Union Formation, the Wasatch consists of continental deposits of sandstone, shale, and coal beds. Throughout the Basin there is no marked change in lithology between the two formations. North of Gillette, the Wasatch overlies an erosional surface in the Fort Union (Olive, 1957, pl. 4), but at most other places, the contact is conformable.

The Wasatch Formation contains two conglomeratic members in the area near Buffalo, Wyo. The lower member, the Kingsbury Conglomerate Member, consists of 100 to 800 feet of poorly indurated conglomerate, medium- to coarse-grained sandstone, siltstone, and shale. Pebbles and boulders in the Kingsbury are derived from Paleozoic and Mesozoic rocks. The Kingsbury unconformably overlaps the Fort Union, Lance, Bearpaw, and Parkman Formations. The upper conglomeratic member of the Wasatch is the Moncrief, which overlies the Kingsbury Conglomerate Member with an angular discordance of as much as 45 degrees. The Moncrief consists of about 1,200 feet of siltstone, sandy siltstone, and beds of conglomerate that become coarser upward and at places include coarse boulder beds. The boulders are mainly of Precambrian rock. East from the Bighorn Mountains both members grade almost imperceptibly into a finer grained facies and no angular discordance separates them. These relations indicate uplift and deep dissection of the Bighorn Mountains in the last two stages in Eocene time.

The White River Formation, as much as 300 feet thick, consists of sandstone, conglomerate, tuff, and bentonitic claystone. The

White River unconformably overlies older rocks in a few high divides in the Basin and in the adjacent mountains. These deposits are remnants of deposits that originally covered much, if not all, of the Basin. The White River Formation has been removed by erosion from most parts of the Basin (Love, 1952, p. 5).

Rocks of Oligocene and Miocene age surround the Hartville uplift, where they unconformably overlap and obscure older rocks. These strata, which attain a thickness of more than 2,000 feet, are separated into a lower claystone-siltstone unit, the White River Group, and an upper sandstone unit, Miocene, undivided (Denson and Botinelly, 1949).

Quaternary rocks

Quaternary rocks consist of surficial deposits of colluvium, alluvium, landslide debris, and terrace gravels. Alluvium includes clay, silt, sand, and gravel present along most of the stream beds. Landslide debris covers areas as large as several miles and consists of rock waste that has slumped downward on steep hillsides. Terrace gravels are deposits of silt, sand, and gravel that cap locally extensive terrace levels. The highest terrace gravel may be Tertiary in age.

STRUCTURE

The Powder River Basin is a relatively simple structural feature consisting of an elongate synclinal depression bounded on three sides by mountain uplifts (fig. 1). The northern limit is here considered to be the south flanks of two low arches and is shown by the minus 3,000-foot structure contour on figure 3. The Basin is asymmetrical, with its deepest part on the west side adjacent and parallel to the Bighorn Mountains. The surface of the Precambrian is about 21,000 feet lower in the deepest part of the trough than on the nearby flank of the Bighorn Mountains.

The western margin of the Basin is the most strongly deformed, especially along the east front of the Bighorn Mountains, where Paleozoic and Mesozoic strata have been folded into a narrow belt of steeply dipping rocks. Dips range mostly from 30 degrees eastward to vertical, but locally beds are overturned. This intense folding was accompanied by faulting, which is most pronounced in the area between Sheridan and Buffalo where strata have been thrust eastward as much as three miles. To the north and south of the central Bighorn Mountains, the dips of the rocks decrease and the width of their outcrops becomes correspondingly greater (fig. 2).

At the southern margin of the Basin, Paleozoic and Mesozoic rocks are sharply bent along the north fronts of the Laramie Range and Hartville uplift and dip steeply to the north.

On the east and north sides, the rocks at most places dip 3 to 5 degrees toward the axis of the Basin. This gentle dip is interrupted by the Black Hills monocline, a belt of steeply dipping rocks 1¼ to 6 miles wide, which has a structural relief of about 4,000 feet. The Black Hills monocline is about 90 miles long and extends in a northwest direction from Newcastle almost to the Wyoming-Montana State line (Pierce and Girard, 1952; Mapel and others, 1959). Where the fold is narrowest the dip of the rocks is almost vertical; elsewhere the dips are from 20 to 35 degrees. The rocks to the east of the monocline are folded into northwest-trending anticlines and synclines and nearly circular domes and depressions, and locally are cut by normal faults, most of which have a displacement of less than 100 feet. To the west of the monocline, the dip of the rocks flattens abruptly, and is uninterrupted by folds and faults.

Faults

Major faults in the Powder River Basin are restricted to the marginal areas and are associated with movements that produced the surrounding mountain uplifts. In the area between Sheridan and Buffalo on the west side of the Basin, small segments of the mountain front have been displaced eastward along high-angle reverse faults and accompanying tear faults; at some places in this area Paleozoic rocks have been thrust over Tertiary rocks. To the south near Mayoworth, a transverse fault zone, along which a series of *en echelon* folds have developed, cuts across the Basin margin. High-angle reverse faults also are found along the edges of the Laramie Mountains and the Hartville uplift along the south margin of the Basin. The Black Hills uplift, however, did not produce large-scale faulting.

Numerous transverse faults of relatively small displacement are present in southern Johnson and northern Natrona Counties. These faults were important in controlling oil accumulation in the Sussex area (Strickland, 1958, p. 134). A series of normal faults with small vertical displacement occurs in the southern Black Hills near the Niobrara-Weston County line. Also along the margin of the Basin are numerous relatively small folds whose axes roughly parallel the adjacent mountain uplifts. Most of the oil produced in the southwest and southeast parts of the Basin is from fields on these structural features.

Age of deformation

The Powder River Basin was formed during the Laramide orogeny in Late Cretaceous and early Tertiary time when the surrounding mountain masses were uplifted. The first evidence of local uplift is shown by an angular unconformity in the Fort Union Formation, near Buffalo, Wyo. (Mapel, 1959, p. 81). Conglomerate above this unconformity contains fragments derived from Paleozoic formations of nearby areas to the west. The 45-degree discordance between the Kingsbury Conglomerate Member of the Wasatch Formation and the underlying Fort Union Formation indicates that uplift followed deposition of the Fort Union. Subsequent uplift is indicated by local dips of as much as 45 degrees in the Kingsbury, which is unconformably overlain by the flat-lying beds of the Moncrief Member of the Wasatch Formation. Thrust faulting in the area took place after deposition of the Moncrief Member (Sharp, 1948).

ECONOMIC GEOLOGY

The most important mineral deposits found within the Basin are oil, gas, coal, and uranium. Deposits of lesser importance include bentonite, gypsum, limestone, and sand and gravel.

Oil and gas

Oil has been produced from the Powder River Basin since the 1880's and as of January 1, 1960, the cumulative production was about 738 million barrels. This constitutes about half of the total that has been produced from Wyoming, and more than has been produced from any other basin in the Rocky Mountain region. Gas is generally produced with the oil, although a few small gas fields have been developed.

Sandstones of Late Cretaceous age have been the major oil producing reservoirs. In decreasing order of importance, other oil producing rocks are strata of Early Cretaceous, Pennsylvanian, Jurassic, and Permian ages. Small quantities of oil have been produced from rocks of Tertiary and Triassic ages; oil in commercial quantities has not been produced from rocks older than Pennsylvanian.

As in most large sedimentary basins, most of the oilfields have been developed around the margin (fig. 18). The central deeper part of the Basin has been drilled to a lesser extent because of the greater depth of the oil-bearing strata. According to Strickland (1958, p. 132-147), updip loss of relative permeability is the primary factor in controlling oil accumulation in the Cretaceous strata in the Basin, and the three main types of traps responsible for the accumulation of oil are anticlinal, fault, and permeability traps.

Coal

Some coal of bituminous rank occurs in the Lakota Formation of Early Cretaceous age in Crook and Weston Counties, Wyo., on the east

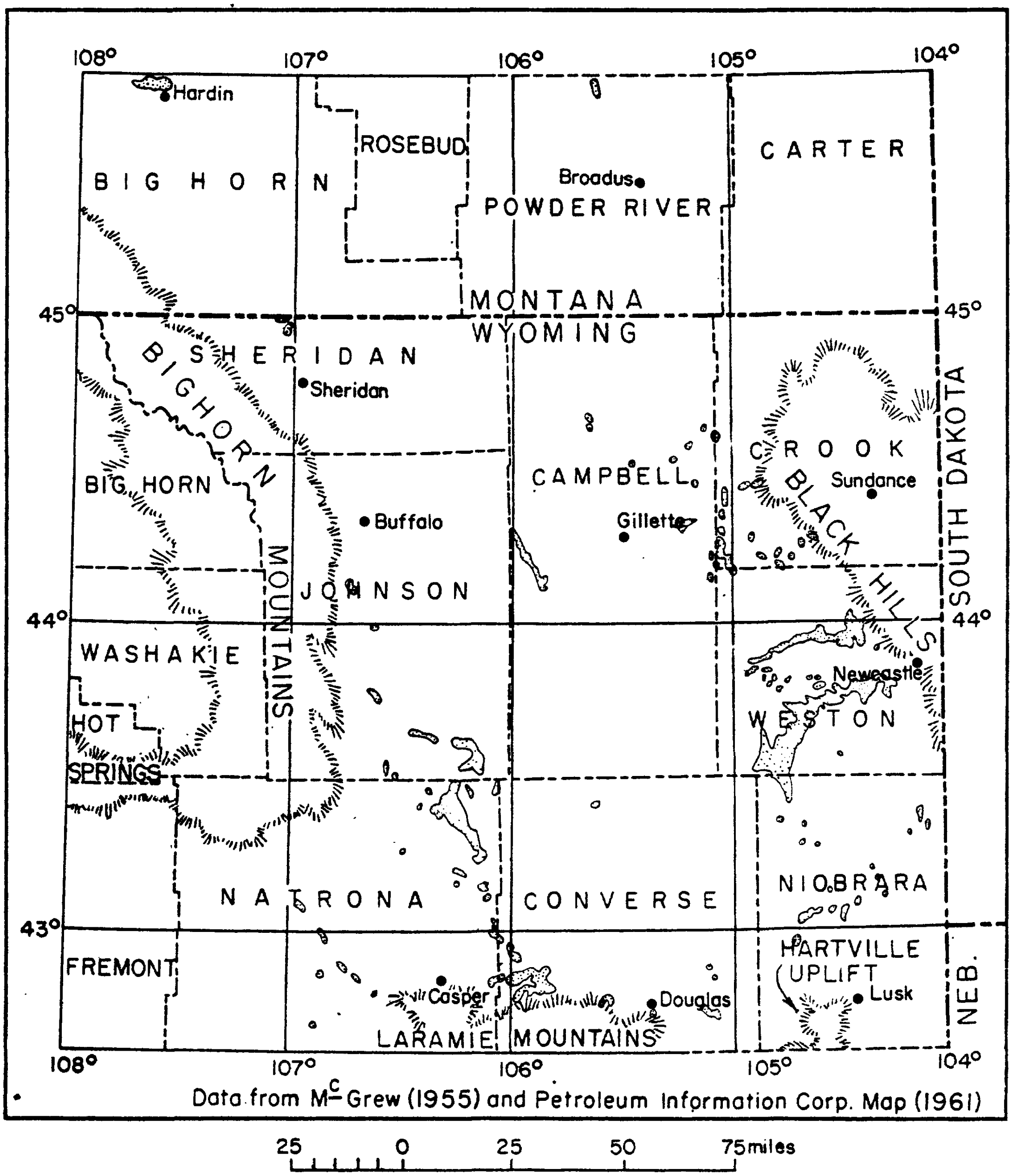


Figure 18.--Map showing oil and gas fields in the Powder River Basin.

side of the Basin, and coal of subbituminous rank occurs in the Lance Formation of Late Cretaceous age in Converse and Natrona Counties along the southern margin of the Basin. Most of the coal, however, occurs in the Fort Union and Wasatch Formations of Tertiary age in the central part of the Basin.

The coal beds of Tertiary age are generally thin and lenticular south of a line drawn from Buffalo to the northwest corner of Niobrara County. North of this line, the coal beds in both the Fort Union and Wasatch Formations are thick and persistent and presumably underlie hundreds of square miles. In general the thicker, more persistent coal beds are near the top of the Fort Union Formation. Two coal beds in the Basin are among the thickest known in the United States: a coal bed at the top of the Fort Union Formation attains a thickness of 90 to 106 feet about 6 miles east of Gillette and another bed, 115 to a reported 220 feet in thickness, occurs in the upper part of the Wasatch Formation near the north end of Lake De Smet in Johnson County.

The coal in the Fort Union and Wasatch Formations ranges in rank from subbituminous B to lignite. Coals in the Wasatch are generally lower in rank than those in the Fort Union and coals in the northwestern part of the Basin are slightly lower in rank than equivalent beds in other parts of the Basin.

According to the work of several writers, summarized by Mapel (1958, p. 218-224) from whom the information presented here on coal is taken, the coal reserves of the Powder River Basin are estimated to total about 210 billion short tons, in beds more than 2½ feet thick. Approximately half of the reserves are in the Montana part of the Basin and half are in the Wyoming part.

Uranium

Commercial deposits of uranium have been found at several localities within the Basin. In the central part, lenticular sandstones in the Wasatch Formation of Eocene age are the host rocks for uranium. The principal areas of mineralization are near the Pumpkin Buttes in Campbell and Johnson Counties (Love, 1952), near Dry Fork and Box Creek in Converse County, and near Lance Creek in Niobrara County (Mrak, 1958, p. 233-240).

In the Black Hills area, uranium deposits are in beds of sandstone in the Lakota and Fall River Formations of Early Cretaceous age. The principal areas from which ore has been produced in the northern Black Hills are the Elkhorn Creek, Hulett Creek, and Carlile areas in western Crook County (Robinson and others, in prep.).

GROUND WATER

Most of the water supply in the Powder River Basin is obtained from streams. Only a few studies of ground water have been made and detailed data regarding the occurrence of ground water are unavailable. On the basis of available information, wells drilled for water in the area are less than 3,000 feet deep; however, depths of about 2,500 feet are not uncommon. According to a summary by Whitcomb and others (1958) the Pahasapa Limestone and Minnelusa Formation are the only stratigraphic units on the east side of the Basin that yield large quantities of water; small quantities are obtained from the Fox Hills Sandstone and overlying units, and from the underlying Newcastle, Fall River, Lakota, Morrison, Sundance, and Minnekahta. The ground water possibilities of the remaining units are considered to be poor.

Thom and others (1935, p. 124-133) discussed the water-bearing properties of formations in the northwest part of the Basin. There, small quantities of water are obtained from the Lance Formation and overlying units and the underlying Parkman, Cloverly, Sundance, Tensleep, Amsden, and Madison were assessed as having good water-bearing properties.

WASTE DISPOSAL POSSIBILITIES

Possible reservoirs for disposal of radioactive waste include (1) permeable sandstone, (2) impermeable shale, and (3) carbonate and evaporite rocks.

Sandstone reservoirs

Sandstone beds are considered possible reservoirs for the subsurface disposal of liquid radioactive waste because they are more permeable than other beds. Many permeable sandstone units, confined between relatively impermeable units, occur throughout the rock sequence in the Powder River Basin. In rocks of pre-Cretaceous age, the more promising potential sandstone reservoirs are in the Flathead and Deadwood Formations, in the Tensleep and Minnelusa Formations, and in the Sundance Formation. However, most of the potential sandstone reservoirs are in the upper part of the sequence in rocks of Cretaceous age. These comprise sandstone beds in the Fall River, Lakota, Newcastle, Frontier, Cody, and Mesaverde Formations (fig. 4). All of these sandstone beds are known to be permeable at most places in the Basin; problems of containment that might arise should be investigated before any of the sandstone units are selected for disposal.

The Flathead Sandstone and sandstone within the Deadwood Formation overlie Precambrian basement rocks, which would be a barrier to downward seepage of liquid waste and are overlain by shale which may be sufficiently impermeable to prevent upward seepage. Throughout most of the Basin these formations are more than 10,000 feet below the surface and presumably are too deep to be utilized as a ground water source; thus far they have not been found to contain commercial amounts of oil or gas. If deep storage of waste is contemplated, these formations should be considered.

Sandstone beds that might be suitable for waste disposal are present in the Tensleep Sandstone in the western part of the Basin, in the Minnelusa and Hartville Formations in the east and southeastern parts, and in the Sundance Formation throughout the Basin. These strata would afford possibilities for waste disposal in the deeper, central part of the Basin. Any disposal that might be considered in areas around the margins of the Basin should be restricted to isolated sandstone lenses within the formations in which the waste would be trapped, as these formations are reservoirs for both water and oil. Isolated lenses might be found in units such as the basal sandstone of the Sundance Formation, which is a discontinuous channel-fill deposit.

Potential reservoirs in these pre-Cretaceous rocks are at shallow depth (0 to 5,000 feet) over approximately one-quarter of the total area of the Basin, at moderate depth (5,000 to 10,000 feet) over approximately one-quarter, and at great depth (more than 10,000 feet) over the remaining one-half.

In the upper part of the sequence in rocks of Cretaceous age, the Lakota and Fall River Formations on the east side of the Basin contain lenticular bodies of sandstone interbedded with finer grained clastic rocks. These lenticular sandstone beds, providing they are not a source of ground water, could be considered as possible isolated reservoirs for shallow to moderate depth waste disposal if the enclosing rocks are sufficiently impermeable.

The Newcastle Sandstone deserves particular consideration because it is present throughout all but the northern part of the Basin. At many places it grades into shale in an updip direction and is overlain by the impermeable Mowry Shale. However, the Newcastle is oil-bearing in many places, and therefore it may not be suitable for waste disposal.

The Frontier, Cody, and Mesaverde Formations all include thick sandstone beds. The Frontier Formation includes at least four such sandstone beds in the southwest part of the Basin; the Cody Shale contains the Shannon Sandstone Member; and the Mesaverde Formation includes the Parkman and Teapot Sandstone Members. These strata all grade eastward across the Basin into shale. The sandstone beds within them presumably lens out eastward and the enclosing shale would form barriers to fluid movement.

Potential reservoirs in Cretaceous rocks are at shallow depth over approximately one-quarter of the total area of the Basin, at moderate depth over approximately one-half the area, and at great depth over the remaining one-quarter.

Sandstone beds that afford less favorable potentials as waste disposal reservoirs, but which should not be eliminated from consideration, occur in the Chugwater, Morrison, Carlile, Pierre, and Fox Hills Formations. In some of these formations, the lithology of the strata enclosing the sandstone beds is varied and therefore unpredictable; the contained sandstone beds generally are thinner and less persistent than those in other formations.

Shale reservoirs

Thick sequences of shale in which limited storage space might be developed by hydraulic fracturing or by excavating cavities are present only in rocks of Cretaceous age. These include the Skull Creek and Mowry Shales, the lower part of the Frontier Formation and the Belle Fourche Shale, and parts of the Cody, Lewis, and Pierre Shales.

The Mowry Shale appears to be the most promising. The Mowry, like the underlying Newcastle Sandstone, is present throughout the Basin. It contains a thick upper unit of uniform lithology, consisting of siliceous shale which is impermeable except for the possibility of fractures which might be developed in local areas of deformation.

The Mowry Shale, and the other shale sequences mentioned--if they prove to be sufficiently impermeable--offer possibilities for the storage of calcined or fused waste in excavated cavities if economically feasible. These shales are near the surface in a band several miles wide at the margin of the Basin so excavations could be made at shallow depth.

Carbonate and evaporite reservoirs

The only relatively thick sequence of carbonate rocks are the rocks of Ordovician to Mississippian age. Space for storage of radioactive wastes is present in porous zones and solution cavities within this sequence; however, its suitability as a storage reservoir is doubtful because of the probable absence of impermeable barriers to migration. Storage in evaporites, such as salt, anhydrite, and gypsum is probably not feasible because the few beds of gypsum and anhydrite present are too thin or are too deeply buried.

Conclusions

The potential of the Powder River Basin for disposal of radioactive waste in many aspects is believed favorable. Many permeable sandstone units in the subsurface of the rock sequence of the Basin might be considered for use as reservoirs for liquid radioactive waste disposal, and several shale units might be used either as reservoirs for liquid waste entrained in cement grout or for storage of calcined or fused waste. Formations considered favorable for radioactive waste disposal occur at shallow, moderate, and great depths.

A most important factor to be considered in radioactive waste disposal is the certainty of containment for a length of time of hazardous radioactivity. Danger of contamination of the water supply could be minimized by storing radioactive waste in a strata below the depth of potable ground water. The waste might either be so situated in relation to the direction of movement of ground water within the strata that such migration as might occur would not be in the direction of outcrop, or the waste might be stored at a depth and distance sufficient to allow disintegration before the waste could migrate to outcrop areas. Waste stored within the depth of current ground water supply, which at present in this area is 3,000 feet, might be stored in aquifers which are confined by impermeable beds.

The permeability traps that have controlled oil accumulation in the Basin could be expected also to serve as natural barriers to the migration of liquid radioactive waste. Permeability traps caused by updip loss of permeability where sandstone bodies grade into shale are common in Cretaceous rocks. Other possible barriers to liquid migration are faults that bring impermeable units against permeable ones. Many faults of this type are known to form a tight seal, as shown by the retention of oil and gas in fault traps, but in others migration of fluids apparently does occur.

Local structural and stratigraphic traps are present that might constitute suitable sites for disposal of radioactive waste. These traps are carried much deeper in short distances on the west and south sides of the Basin than on other sides. The gently dipping east limb may have local depressions with several hundred feet of closure; however, reservoir rocks older than the Pierre Shale are carried underground several thousand feet on the west side of the Black Hills monocline, which limits areas in which the older rocks are at a shallow depth and easily accessible.

The surficial rocks and most of the Wasatch and Fort Union Formations, are not considered suitable for the subsurface storage of radioactive waste. The Wasatch Formation is a source of potable ground water. Also, both the Wasatch and underlying Fort Union Formation contain large reserves of coal, and although only small amounts of coal are now being mined, its future use should not be impaired.

The sparse population of the area favors the Powder River Basin as a waste disposal site, especially because, at least at present, slight use is made of ground water for water supply, compared to areas such as the Michigan basin (deWitt, 1961, p. 92, 93).

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