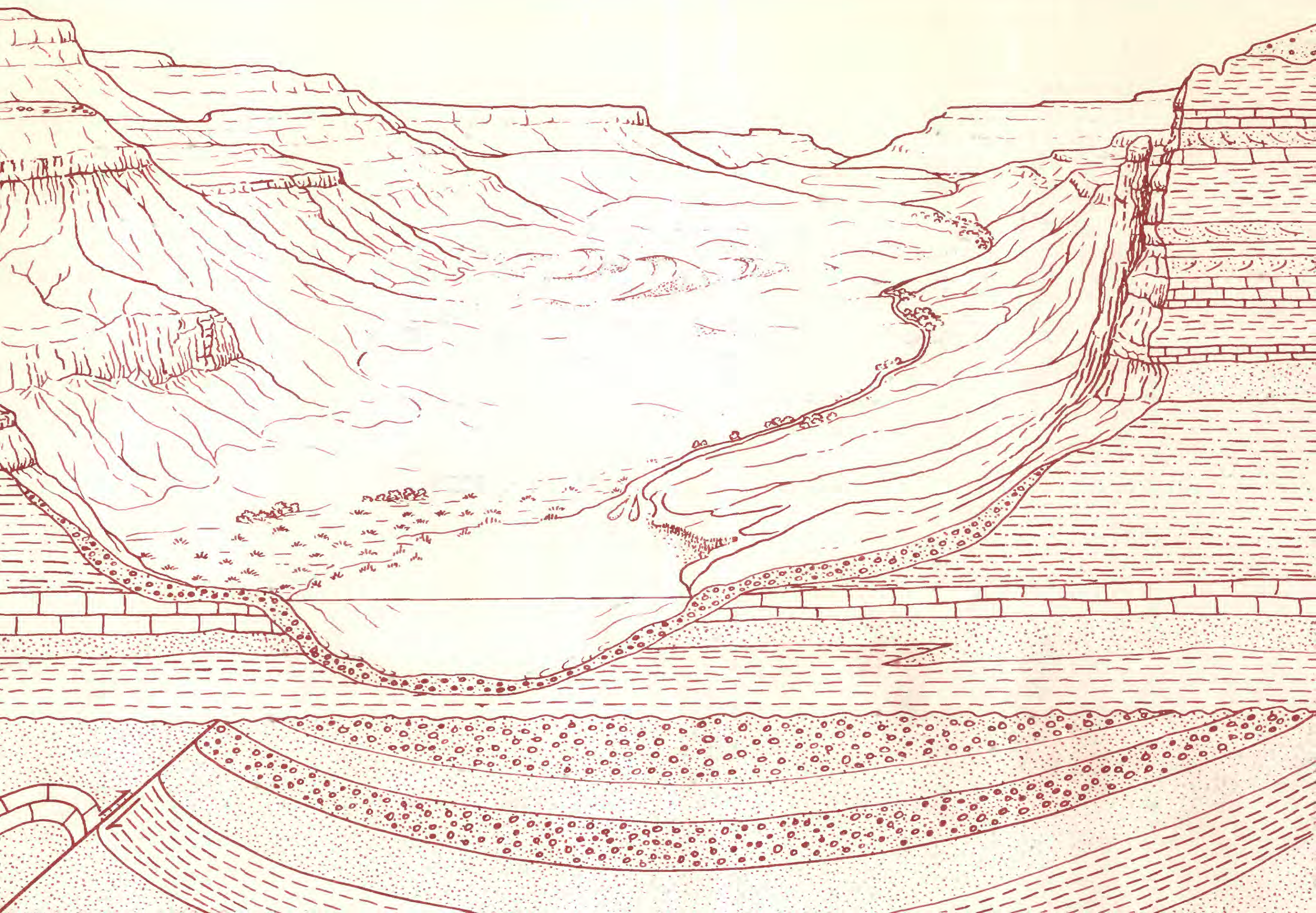
Resources in Sedimentary Rocks of the Powder River Basin and Adjacent Uplifts, Northeastern Wyoming

U.S. GEOLOGICAL SURVEY BULLETIN 1917–N



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Chapter N

Resources in Sedimentary Rocks of the Powder River Basin and Adjacent Uplifts, Northeastern Wyoming

By RAY E. HARRIS, RODNEY H. DEBRUIN, and RICHARD W. JONES

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

Prepared in cooperation with the Geological Survey of Wyoming

U.S. GEOLOGICAL SURVEY BULLETIN 1917

EVOLUTION OF SEDIMENTARY BASINS—POWDER RIVER BASIN

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
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CONTENTS

Abstract **N1**
Introduction **N1**
Resources **N2**
- Aggregate (including clinker) **N2**
- Bentonite **N3**
- Coal **N4**
- Gypsum **N5**
- Limestone **N6**
- Oil and gas **N6**
- Uranium **N8**

References cited **N9**

FIGURES

1. Index map of Wyoming showing the location of the Powder River Basin and adjacent uplifts **N2**

TABLES

1. Aggregate (including clinker) resources of the Powder River Basin and adjacent areas, Wyoming **N3**
2. Bentonite resources of areas adjacent to the Powder River Basin, Wyoming **N4**
3. Gypsum resources of areas adjacent to the Powder River Basin, Wyoming **N6**
4. Limestone resources of areas adjacent to the Powder River Basin, Wyoming **N7**
5. Estimated additional resources and speculative resources of uranium in the Wyoming basins at the end of 1990 **N9**

Resources in Sedimentary Rocks of the Powder River Basin and Adjacent Uplifts, Northeastern Wyoming

By Ray E. Harris[1], Rodney H. DeBruin[1], *and* Richard W. Jones[1]

Abstract

The Powder River Basin and the adjoining uplifts in northeastern Wyoming contain significant resources of aggregate (including clinker), bentonite, subbituminous coal, gypsum, limestone, crude oil, natural gas, and uranium. Major oil and gas fields and extensive surface mines for coal and bentonite are common. For aggregate, the resources of gravel and limestone in the region are about 6 billion short tons and almost 68 billion short tons, respectively. The total resource of minable bentonite near the margins of the basin is about 193 million short tons. Total reserves of strippable coal in the basin at the beginning of 1990 were about 23 billion tons. Minable resources of gypsum in the region total about 888 million short tons. The estimated mean amounts of undiscovered hydrocarbons in the basin are 2.25 billion barrels of recoverable oil and 2.76 trillion cubic feet of gas. The estimated additional resources of uranium in the region are 170 million pounds of U_3O_8 at $30 per pound (as of 1990).

INTRODUCTION

The mineral and energy resources of the sedimentary rocks in the Powder River Basin and adjoining uplifts of Wyoming include deposits of aggregate, bentonite, coal, crude oil, gypsum, limestone, methane, and uranium. In this report, we describe the locations, geological characteristics, grades, amounts, and uses of these resources in the Wyoming part of the Powder River Basin.

The Powder River Basin is a large asymmetrical downwarp in northeastern Wyoming (fig. 1) and southeastern Montana. It is bounded on the west by the Bighorn Mountains and the Casper Arch, on the south by the Laramie Mountains and the Hartville Uplift, and on the east by the Hartville Uplift, the Old Woman Anticline, and the Black Hills (fig. 1). To the north, in Montana, the Powder River Basin is separated from the Williston Basin to the northeast by the Miles City Arch and the Cedar Creek Anticline.

The most important resources in the region, in order of decreasing current value, are oil and gas, coal, uranium, bentonite, limestone, and aggregate (including clinker). Major quantities of oil and gas are produced from many stratigraphic units in the Powder River Basin. The largest volume of subbituminous coal in the United States is in the Paleocene and Eocene formations of the basin. These strata also contain a considerable amount of uranium. The largest amount of bentonite in the Nation is in Upper Cretaceous strata exposed along the western and eastern margins of the basin. Outcrops of limestone and other sources of aggregate are plentiful along the margins of the basin but are scarce near the center of the basin. Clinker (baked and fused sedimentary rocks), a relatively low quality aggregate, is the only source of aggregate in the middle of the basin. Gypsum is not presently being mined in the basin.

These resources in the Wyoming part of the Powder River Basin are depicted on four maps of northeastern Wyoming published by the Geological Survey of Wyoming in cooperation with the U.S. Geological Survey: (1) oil and gas (DeBruin and Boyd, 1990); (2) coal (Jones, 1990a); (3) industrial minerals and construction materials (aggregate, bentonite, gypsum, and limestone) (Harris and King, 1989); and (4) metallic and radioactive minerals (uranium and thorium) and lapidary materials (Hausel and others, 1990).

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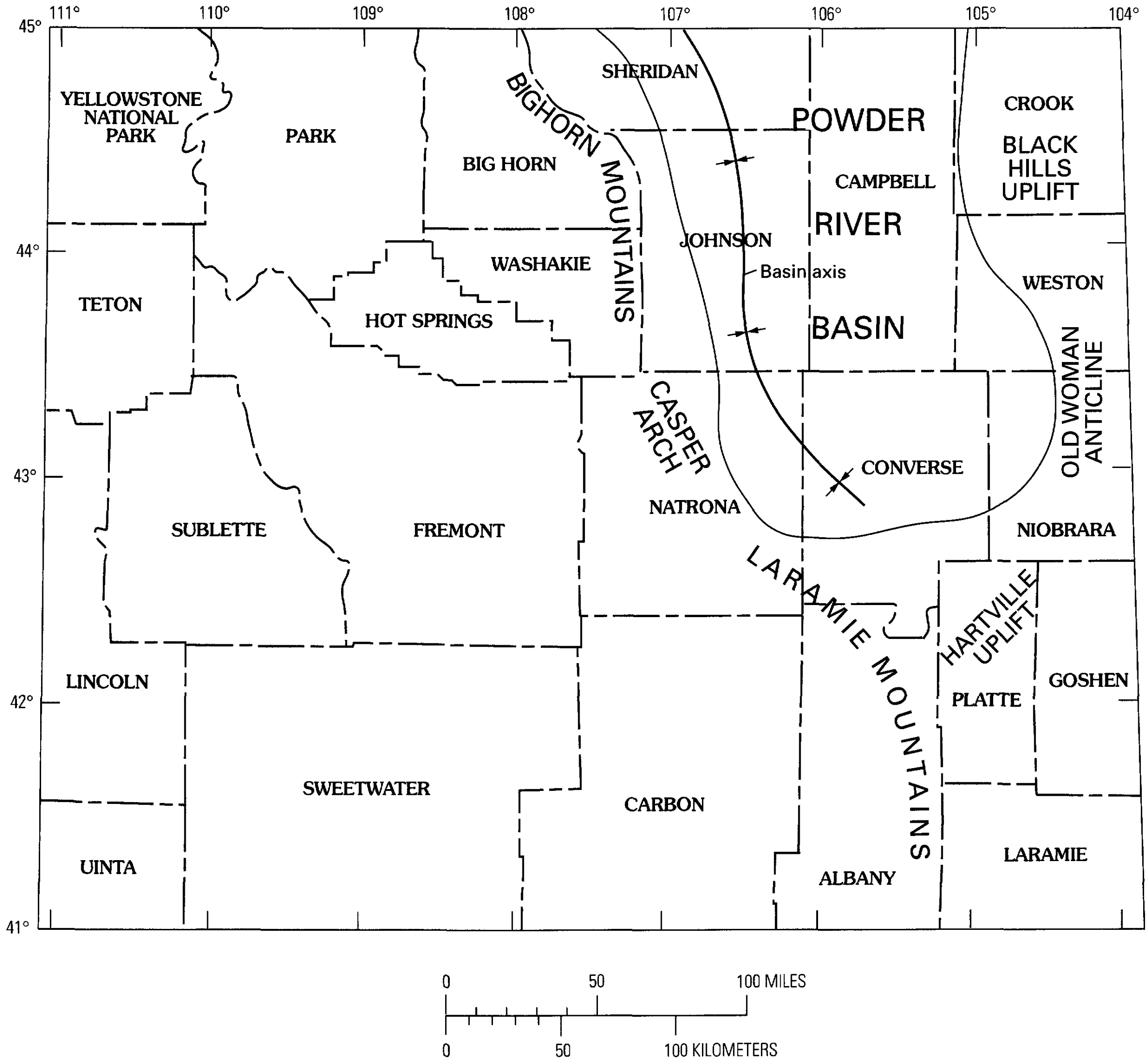

Figure 1. Index map of Wyoming showing the location of the Powder River Basin and adjacent uplifts.

of Wyoming and J.L. Brown and W.I. Finch of the U.S. Geological Survey reviewed manuscripts of this report. Finch also provided technical information concerning uranium resources. The writers wish especially to thank E.A. Merewether of the U.S. Geological Survey for his support and effort in the entire cooperative program.

RESOURCES

Aggregate (including clinker)

Aggregate is used mostly for construction and decoration. Construction aggregate consists of clasts of rocks that commonly are sized and mixed with cement or asphalt and used for many types of building. Examples of the uses of construction aggregate are the sub-base, base, and surfacing material for streets and highways; concrete for streets, highways, sidewalks, and buildings; riprap for controlling erosion along streams; and finer material for strengthening concrete. Decorative aggregate has similar uses but is selected on the basis of color and appearance as well as strength and durability. Decorative aggregate is mixed with cement to produce colors and patterns in concrete for the exterior of buildings and is also used for roofing gravel and landscaping.

Aggregate can be obtained from a variety of stratigraphic units and rock types in the Powder River Basin. Limestone yields the aggregate most suitable for construction; however, outcrops of limestone appropriate for quarries are present only on the margins of the basin. Additional information about limestone is included in a following

Table 1. Aggregate (including clinker) resources of the Powder River Basin and adjacent areas, Wyoming

Deposit type	Location	Estimated amount (short tons)
Limestone	Margins of surrounding uplifts	67,727,000,000[1]
Silicic shale	Margins of surrounding uplifts	Very large[2]
Tertiary conglomerate	Margins, local areas elsewhere	2,000,000,000
Clinker	Center and northwestern margins	2,400,000,000
Terrace gravels	Western margin of basin	1,500,000,000
Alluvial gravels	Major stream drainages	2,500,000,000
Windblown sand	Southern and eastern areas of basin	50,000,000,000

[1]See text.
[2]Not estimated, amount of suitable material has not been determined.

section. Silicic shale from the Upper Cretaceous Mowry Shale has been used for low-durability surfacing on unpaved roads. Clinker or scoria, which is baked and fused shale, has been used for the surfacing of both highways and unpaved roads and for decorative purposes, especially in landscaping. Gravel suitable for aggregate can be obtained from conglomeratic beds in the Paleocene Fort Union and the Paleocene and Eocene Wasatch Formations and from Quaternary terrace deposits and alluvium. Some of the gravels from the terrace deposits and the alluvium display a mixture of colors and therefore can be used for decorative aggregate in landscaping and construction. Sand deposits are abundant (Harris and King, 1989), especially in the stabilized and unstabilized dunes of Quaternary age in the southern part of the basin, and they can be a source for finer aggregate.

Outcropping deposits of aggregate are scarce in the center of the basin. The only relatively hard rock in the center of the basin is clinker, which has been used in applications commonly requiring a more durable rock, such as highway surfacing and railroad ballast. The use of clinker instead of limestone or other hard rock that must be transported a long distance is a tradeoff between durability and transportation costs.

Specifications for construction aggregate vary with each use. The specifications used to determine suitability include size, shape (length to width ratio and roundness of clasts), hardness (resistance to crushing), durability (resistance to wear or abrasion), reactivity with the binder, and weight. Specifications for decorative aggregate also include uniformity and usability of color, resistance to color changes caused by exposure, and other aesthetic qualities. In all cases, cost of transportation is such a large part of the total cost of the material at the point of use that the critical factor in determining suitability is the distance between the point of use and the source of the material.

Table 1 gives estimates of the amounts of aggregate in the Powder River Basin and adjacent areas. Small gravel deposits as yet have not been mapped at a useful scale, and, as shown on the map of industrial minerals and construction materials by Harris and King (1989), gravel pits are indicated in many areas where deposits of aggregate are not depicted. Therefore, these estimates are preliminary and include only major sources of aggregate. The total resources probably have been underestimated.

Bentonite

Bentonite is a clay that expands to many times its original volume when wetted; it is also characterized by a high cation-exchange capacity, by an ability to form viscous suspensions and thixotropic gels when mixed with large amounts of water, by a high adsorption capacity, and by an ability to form an impervious seal (Rath, 1986). The bentonite of Wyoming is a high-sodium bentonite and differs from bentonite in the southern United States, which contains much calcium and has different characteristics.

Stratigraphic units containing resources of bentonite include the Lower Cretaceous Thermopolis Shale and Newcastle Sandstone and the Upper Cretaceous Mowry Shale, Belle Fourche Shale, and Frontier Formation. In the region of the Powder River Basin, these units crop out on the eastern flank of the Bighorn Mountains, on the northern and western margins of the Black Hills, including the Old Woman Anticline, and on the eastern flank of the Casper Arch (Harris and King, 1989). Outcrops of the units that adjoin the Hartville Uplift (Love and Christiansen, 1983) contain no minable bentonite.

Bentonite is a relatively low cost and high volume industrial commodity that has many uses. At present, it can be mined economically only at outcrops and in areas where the overburden is 20 ft thick or less. Most of the processed bentonite is used in borehole-drilling mud. Other uses are as binders, fillers, and extenders (particularly in soap and cosmetics), pond liners and containment walls, and many other products. More bentonite is produced in Wyoming than in any other State, and much of Wyoming production is from the northern and western margins of the Black Hills. In 1989, 2,218,900 short tons of bentonite was mined in the region of the Powder River Basin and the Black Hills of

Wyoming (Wyoming State Inspector of Mines, 1990). The demand for bentonite recently has been increasing slightly, and it may increase more in coming years, particularly if bentonite is used in waste containment structures.

The specifications for refined bentonite vary with intended use. They include viscosity, cation exchange capacity, water loss, exchangeable cation composition, Fe^{2+}/Fe^{3+} ratio, net charge imbalance, selective adsorption of cations, degree of crystallinity, particle size and shape, and the type and amount of impurities (Rath, 1986).

Bentonite mining and refining is a unique interplay of mining and milling techniques. The natural deposits vary widely in physical and chemical properties, both from area to area in the same bed and within a bed in an area. Some of these differences are due to local variations in depositional environments, and some are due to diagenesis and (or) weathering. In the mining of bentonite, bentonites having the same specifications are mined from several pits and selectively stockpiled at the mill site. Pits are operated for short periods of time and remain inactive for relatively long periods of time. The stockpiled bentonites are then mixed to exact quality standards at the mill.

Table 2 gives estimates of minable amounts of bentonite near the surface for areas adjacent to the Powder River Basin. The deposits are in outcropping strata that dip away from the Bighorn Mountains, Black Hills, Casper Arch, and northern flank of the Laramie Mountains. Beds having dips greater than 20° were not minable in 1991 and are not included in the resource estimates. The bentonite resources of areas on the eastern flank of the Bighorn Mountains and the Casper Arch were estimated by using the industrial minerals and construction materials map of Harris and King (1989).

Table 2. Bentonite resources of areas adjacent to the Powder River Basin, Wyoming

Location	Resource estimate (short tons)
Black Hills[1]	100,000,000
Bighorn Mountains	60,000,000
Casper Arch	30,000,000
Laramie Mountains	3,000,000
Total	193,000,000

[1]Rath (1986).

Coal

The Powder River Basin of northeastern Wyoming contains extensive coal deposits in an area called the Powder River Coal Field. This coal field is more than 150 mi long and in places almost 100 mi wide; it is the second largest coal field in Wyoming. Of all the coal fields in Wyoming, this field contains the largest amount of coal. The Powder River Coal Field as used in this report should not be confused with the smaller Gillette Coal Field near the town of Gillette. The use of this name for the smaller area near Gillette was recently abandoned (Jones, 1990b).

The Powder River Coal Field is defined by the limits (outcrops) of the stratigraphically lowest (oldest) coal-bearing formation in the Powder River Basin. The western boundary of the coal field is defined by the base of the Mesaverde Formation; the eastern boundary of the coal field is defined by the base of the Lance (Hell Creek) Formation (Jones, 1990a). Formations of the coal field form an asymmetrical synclinal basin; the rocks dip gently westward in the eastern and central parts of the field and steeply eastward along the western flank of the field. Cretaceous coal-bearing rocks crop out in a relatively narrow band on the perimeter of the coal field and are overlain by Tertiary coal-bearing rocks in the middle of the coal field. In general, the Cretaceous rocks dip more steeply than the Tertiary rocks. Faults are rare in the coal field, although relatively small faults (displacements of 200–500 ft) have been recognized in the western part of the field.

The coal beds are in an 8,000-ft-thick sequence of nonmarine Upper Cretaceous and lower Tertiary strata. The coal was deposited as peat in swamps associated with various environments, including alluvial plain, fluvial (meandering, braided, and anastamosing streams), delta, and lacustrine. Lithologic units are not persistent, either laterally or vertically, but generally consist of sandstone, siltstone, shale, carbonaceous shale, minor limestone, minor conglomerate, and coal.

Coal of Late Cretaceous age is in the Mesaverde, Meeteetse, and Lance (Hell Creek) Formations. The Mesaverde Formation is about 500 ft thick and crops out in the western and southwestern parts of the coal field. It extends eastward in the subsurface and pinches out within the marine Pierre Shale. Most of the coal beds in the Mesaverde are thin (less than 2 ft thick) and are restricted to the southwestern part of the coal field. The Meeteetse Formation contains minor, very thin coal beds in the extreme southwestern part of the coal field; northward and eastward the Meeteetse pinches out and interfingers with the marine Bearpaw, Lewis, and Pierre Shales. The Lance Formation is 2,500 ft thick and crops out near the margins of the coal field except along the southern boundary. Strata assigned to the Lance in Wyoming are named the Hell Creek Formation in Montana. The thickest coal beds in the Lance are in the southwestern part of the coal field near Glenrock, where coal beds that average about 6 ft thick have been mined commercially (Glass, 1976).

Strata of early Tertiary age, the Paleocene Fort Union Formation and the Paleocene and Eocene Wasatch Formation, contain the largest and most extensive coal deposits in the Powder River Coal Field. The Fort Union Formation is 2,000–3,000 ft thick and occupies the interior of the coal field, either as outcrops in a wide area near the edges of the field or in the subsurface in the middle of the field where it underlies the Wasatch Formation. The upper part of the Fort Union, the Tongue River Member, contains the thickest and most persistent coal beds, especially in the eastern, central, and northern parts of the field. These coal beds commonly are more than 50 ft thick; the Wyodak bed in the eastern part of the coal field near Gillette generally is from 50 ft to more than 100 ft thick. The thickest coal bed reported in the Tongue River is about 200 ft thick; it is in the central part of the coal field at a depth of about 1,000 ft (Roberts, 1986). In the eastern part of the coal field, the Tongue River contains 8–12 significant coal beds.

The Wasatch Formation is 1,000–2,000 ft thick and crops out in much of the central part of the coal field. As many as eight thick, persistent coal beds are in the Wasatch Formation. Although many of these coal beds can be mapped and correlated for tens of miles along outcrops, the thickest and most persistent beds are in the western and central parts of the coal field (Glass, 1976). Although the Wasatch Formation contains thick coal beds, the coal beds generally are not as thick as those in the Fort Union Formation. An exception is the Healy coal bed near Buffalo, in the western part of the coal field. This bed reportedly is as thick as 220 ft (Mapel, 1959) and locally may be more than 250 ft thick. The Healy bed is reported to be the thickest coal bed in the United States.

Cretaceous coal in the Powder River Coal Field is subbituminous in rank. The few published analytical data for this coal indicate an average moisture content of 22.7 percent, an ash content of 7.9 percent, a sulfur content of 0.69 percent, and a heating value of 8,229 Btu per pound, all on an as-received basis (Glass, 1976).

Coal in the Fort Union Formation generally is subbituminous in rank. The highest as-received heating value of this coal is in the vicinity of Sheridan in the northwestern part of the coal field and in the central part of the coal field where coal beds are most deeply buried. The lowest as-received heating value of this coal is in the extreme northeastern part and the southern part of the coal field. As-received moisture content of coal in the Fort Union is 20–30 percent, ash content is 3–25 percent, and as-received sulfur content is 0.2–0.7 percent. Average as-received values for coal beds in the Fort Union that are being mined are 24.5 percent moisture, 7.3 percent ash, 0.5 percent sulfur, and 8,670 Btu per pound heating value (Glass, 1976).

Coals in the Wasatch Formation are stratigraphically higher and younger than those in the Fort Union Formation and, as such, they have been subjected to less thermal alteration (due to less depth of burial and a shorter burial history) and their rank is generally lower. Most of the coal in the Wasatch is subbituminous, but some may be lignite. The sulfur and ash contents of Wasatch coals are generally slightly higher than those of Fort Union coals; moisture contents of Wasatch and Fort Union coals are about the same.

The Powder River Coal Field contains most of the coal resources of Wyoming. The most recent estimate of in-place coal resources for this coal field, including coal beds of all thicknesses and depths (defined by Wood and Bour (1988) as identified-hypothetical and onshore-speculative), is about 1.03 trillion short tons (Wood and Bour, 1988). This is more than 70 percent of the 1.46 trillion tons of total in-place resources for Wyoming and about 20 percent of the 5.4 trillion tons of in-place coal resources for the United States (Wood and Bour, 1988). Using different criteria, Berryhill (1950) and Glass (1988) estimated original in-place coal resources for the Powder River coal field as 110.2 billion tons. This estimate pertains to subbituminous coal in the field that has been mapped and explored (beds at least 2.5 ft thick and at depths of less than 3,000 ft). The original demonstrated reserve base of strippable coal (overburden no thicker than 200 ft) in the Powder River coal field was estimated at about 21.2 billion tons (Smith and others, 1972). After additional coal reserves are added to that total (Glass, 1988) and after losses from production and mining are subtracted from the total, the demonstrated reserve base of strippable coal in this coal field as of January 1, 1990, is 23.4 billion tons.

Coal has been mined from the Powder River Coal Field since the 1880's. Total cumulative coal production through 1989 is more than 1.3 billion short tons; more than 1 billion tons of this total was mined in the last nine years. The Wyodak coal bed, which is mined by surface operations in the eastern part of the coal field (in Campbell County), is the source of almost all of this production. Coal production from 17 mines in 1990 exceeded 150 million tons.

Gypsum

The mineral gypsum ($CaSO_4 \cdot 2H_2O$) is used in the production of cement and wallboard, in plaster and fertilizer, and for other industrial purposes. In 1988, 14.0 million short tons of gypsum was mined in the United States (Davis, 1989). In Wyoming, two companies mine gypsum in the Bighorn Basin for wallboard, and one company mines gypsum near Laramie for use in the manufacture of cement. The total production of gypsum in Wyoming in 1989 was 423,775 short tons (Wyoming State Inspector of Mines, 1990).

Gypsum can be found near the margins of the Powder River Basin in outcrops of the Middle Jurassic Gypsum Spring Formation, the Triassic Chugwater Formation, the Lower Permian to Lower Triassic Goose Egg Formation, the Upper Permian and Triassic Spearfish Formation in the Black Hills, and the Lower Permian Opeche Shale in and near the Hartville Uplift.

Because gypsum is a relatively low cost, high volume material, it is not a resource where overlain by other rocks. Minable deposits of gypsum generally contain 85–95 percent gypsum and anhydrite ($CaSO_4$). Beneficiation plants near the deposits upgrade the material to pure gypsum

Table 3. Gypsum resources of areas adjacent to the Powder River Basin, Wyoming

Location	Geologic unit	Estimated amount of gypsum (short tons)
Northern Bighorn Mountains[1]	Gypsum Spring Formation	29,000,000
Southern Bighorn Mountains[2]	Gypsum Spring and Chugwater Formations	51,000,000
Total, Bighorn Mountains		80,000,000
Black Hills	Gypsum Spring and Spearfish Formations	733,000,000
Hartville Uplift[3]	Chugwater and Goose Egg Formations	2,000,000
Northern Laramie Mountains	Chugwater and Goose Egg Formations	73,000,000
	Total	888,000,000

[1]Area north of Buffalo, Wyoming.
[2]Area south of Buffalo, Wyoming.
[3]Thick units of gypsum are only in the Glendo area on the west side of the Hartville Uplift.

(Appleyard, 1983). Impurities in Wyoming gypsum deposits include calcite, clay, and sulfur.

Table 3 gives estimates of the resources of gypsum at outcrops near the margins of the Powder River Basin. The surface extent of the gypsum was determined using the map of industrial minerals and construction materials of Harris and King (1989). The amount of minable gypsum in each stratigraphic unit is variable, but it averages about 0.5 percent of the unit. This average amount was used to produce the estimates of table 3.

Limestone

The two most common uses for limestone are for construction aggregate and as a source of lime (CaO_3). Limestone aggregate can be important in construction in structural products such as precast concrete, reinforced concrete beams and girders, and floors and in highway construction (base, sub-base, and surfacing). Such aggregate does not require chemical specifications, but it must pass hardness, strength, and durability tests, usually specified for each job. Decorative and dimension stone are other construction-related uses for limestone; however, no limestone was quarried for this purpose in Wyoming in 1990.

Limestone, a rock composed primarily of the mineral calcite ($CaCO_3$), crops out near the margins of the Powder River Basin in the Lower Mississippian Pahasapa Limestone, the Mississippian Madison Limestone, the Upper Devonian and Lower Mississippian Guernsey Formation, the Lower Permian Minnekahta Limestone, the Upper Mississippian to Lower Permian Hartville Formation, the Pennsylvanian and Lower Permian Minnelusa Formation, and the Middle Pennsylvanian to Lower Permian Casper Formation (Love and Christiansen, 1983; Harris, 1987; Harris and King, 1989).

Limestone is used in cement, chemicals, and many other products, and in sugar beet refining. For these purposes, the limestone must contain more than 95 percent $CaCO_3$ and less than 0.5 percent silica (SiO_2). A purity of 97–99 percent $CaCO_3$ may be necessary for certain applications. Impurities in limestone other than silica commonly are dolomite, clay, and feldspar.

Most of the limestone resource in the Madison and Pahasapa Limestones and the Guernsey Formation is high-calcium limestone containing more than 95 percent $CaCO_3$. The amount of high-calcium limestone in the Minnekahta Limestone and the Minnelusa, Hartville, and Casper Formations is not known. Chemical and metallurgical limestone may be used locally in Wyoming in the refining of sugar beets. Beet-sugar refineries are located in Torrington, Wyoming, and east of Torrington in Mitchell, Scottsbluff, and Bridgeport, Nebraska. The limestone closest to these plants is in the Powder River Basin of Wyoming.

Limestone suitable for dimension and decorative stone has been found in the Madison and Pahasapa Limestones and the Minnelusa, Hartville, and Casper Formations. The thin-bedded limestone in the Minnekahta Limestone might be usable for moss rock.

Limestone is economically minable only at the surface. It is a high-volume low-cost commodity that is not a resource if costly methods of mining (including underground mining) are required. Outcrops of limestone are absent in the middle of the Powder River Basin. Consequently, construction projects in that area must obtain limestone from the margins of the basin at a cost several times that of the material at the quarry.

Table 4 gives estimates of the minable amounts of limestone in outcrops on the margins of the Powder River Basin. The extent of limestone outcrops was determined using the map of industrial minerals and construction materials of Harris and King (1989).

Oil and Gas

Although the Powder River Basin of northeastern Wyoming is primarily an oil-producing province, significant quantities of natural gas are associated with the crude oil. Oil and gas have been produced in the region from reservoir

Table 4. Limestone resources of areas adjacent to the Powder River Basin, Wyoming

Location	Geologic unit	Estimated short tons of limestone
Bighorn Mountains	Madison Limestone	1,890,000,000
Black Hills Uplift	Minnekahta Limestone	14,653,000,000
	Minnelusa Formation	195,000,000
	Pahasapa Limestone	815,000,000
Hartville Uplift	Hartville Formation	34,190,000,000
	Guernsey Formation	2,306,000,000
Laramie Mountains	Casper Formation	2,186,000,000
	Madison Limestone	1,492,000,000
	Total	67,727,000,000

beds that range in age from Pennsylvanian to Eocene. The most important reservoirs, in terms of cumulative production, are in the Pennsylvanian and Lower Permian Minnelusa Formation, the Pennsylvanian Tensleep Sandstone, the Lower Cretaceous Fall River Formation (informally called Dakota sandstone), the Lower Cretaceous Muddy and Newcastle Sandstones, the Upper Cretaceous Frontier Formation, the Upper Cretaceous Shannon and Sussex Sandstone Members of the Steele Shale, the Upper Cretaceous Parkman and Teapot Sandstone Members of the Mesaverde Formation, and the Teckla Sandstone Member of the Lewis Shale. Locations of oil fields noted in this report are illustrated in DeBruin and Boyd (1990).

Major accumulations of associated oil and gas have been found in sandstone reservoirs in large anticlines along the western and southern margins of the Powder River Basin. Most of these anticlines are related genetically to deeply buried reverse faults and have normal faults on their crests (Dolton and others, 1990). The principal reservoirs of these structures are in the Pennsylvanian Tensleep Sandstone, the Pennsylvanian and Lower Permian Minnelusa Formation, the Lower Cretaceous Fall River Formation, the Lower Cretaceous Muddy Sandstone, and the Upper Cretaceous Frontier Formation (sandstone in the Wall Creek Member). Major fields on large anticlines include Salt Creek, Lance Creek, Teapot Dome, Big Muddy, and North Fork. These five fields have produced more than 800 million barrels of oil and almost 0.9 trillion cubic feet of associated gas (Wyoming Oil and Gas Conservation Commission, 1990a). In terms of cumulative oil production, Salt Creek is the largest field in Wyoming and has produced more than 635 million barrels of oil and more than 0.7 trillion cubic feet of gas (Wyoming Oil and Gas Conservation Commission, 1990a). The First and Second Wall Creek sands (informal economic units) in the Frontier Formation have produced more than 500 million barrels of oil at the Salt Creek Field (Wyoming Oil and Gas Conservation Commission, 1990b).

Strata in the Pennsylvanian and Permian Minnelusa Formation in the northeastern part of the Powder River Basin in Wyoming produced almost 20 million barrels of oil in 1989 (Wyoming Oil and Gas Conservation Commission, 1990b). These reservoirs are mainly eolian sandstone within a cyclic sequence of carbonate rocks and sandstone of marine and nonmarine origin (Van West, 1972; Fryberger, 1984; George, 1984). Oil is trapped in the upper part of the Minnelusa in paleotopographic highs at the top of the formation, in preserved dune forms, in permeability pinchouts of depositional and diagenetic origin, and in folds (Van West, 1972; Fryberger, 1984). This play was one of the most active in the State in 1990, and more than 250 fields in the Powder River Basin now produce oil and minor associated gas from reservoirs in the Minnelusa. The Raven Creek Field is the largest, in terms of cumulative production, and almost 44 million barrels of oil had been produced by the end of 1989 (Wyoming Oil and Gas Conservation Commission, 1990a). The gravity of the oil is generally 20°–35° API, and it increases with depth. Most of the production is from reservoirs that are 6,000–12,000 ft deep.

Sandstone in the Fall River Formation contains oil and associated gas at fields along the northeastern margin of the Powder River Basin. Most of these reservoirs were deposited as point-bar sandstones that were sealed laterally by finer grained channel deposits (Berg, 1968; Mettler, 1968) and as barrier-bar sandstones that terminate in impermeable sedimentary rocks (Miller, 1963). The most significant fields in this play are Moorcroft West, Miller Creek, Kummerfeld, Donkey Creek, and Coyote Creek. These five fields have produced almost 65 million barrels of oil, mainly from Fall River reservoirs (Wyoming Oil and Gas Conservation Commission, 1990a). Most of the production has been from reservoirs that are 4,000–9,000 ft deep. The gravity of the oil generally is 35°–45° API.

Since 1986, several significant oil and gas fields were discovered in the Fall River Formation in the southern part of the Powder River Basin. These fields include Buck Draw North, Nutcracker, and Blizzard. Reservoirs in the Fall River in that part of the basin were deposited in deltaic environments (Rasmussen and others, 1985), most probably as distributary channel deposits (Hawkins and Formhals, 1985). These reservoirs are generally at depths greater than

12,000 ft and the gravity of the oil is about 45° API (Dolton and others, 1990). In 1989, Buck Draw North was the most productive field and yielded almost 4 million barrels of oil (Wyoming Oil and Gas Conservation Commission, 1990a). The reservoir of that field has been injected with hydrocarbon gas to increase oil production.

Sandstone reservoirs in the Lower Cretaceous Muddy and Newcastle Sandstones along the eastern margin of the basin have been interpreted as alluvial and estuarine deposits in valleys that were formed by erosion of the underlying Skull Creek Shale (Stone, 1972). The productive trend of the Fiddler Creek and Clareton fields is predominantly northeast-southwest.

In other parts of the basin, the reservoirs in the Muddy Sandstone are mainly sandstone that was deposited in nearshore marine and fluvial environments (Stone, 1972; von Drehle, 1985). The Muddy Sandstone in the Kitty (Larberg, 1980), Hilight (Prescott, 1970), and Recluse fields (Berg, 1976) contains stacked reservoirs of nearshore marine and fluvial sandstone. The Hilight Field is the largest field in Wyoming producing from the Muddy Sandstone, and it has produced more than 76 million barrels of oil and more than 250 billion cubic feet of gas since it was discovered in 1969 (Wyoming Oil and Gas Conservation Commission, 1990a). Most of the reservoirs in the Muddy and Newcastle are 3,000–13,000 ft deep; however, very shallow reservoirs are encountered in the Skull Creek and Osage fields (DeBruin and Boyd, 1990). The gravity of the oil generally is 35°–45° API (Dolton and others, 1990).

The sandstone reservoirs in the Sussex Sandstone and Shannon Sandstone Members of the Upper Cretaceous Steele Shale were deposited in the middle- to outer-shelf environments (Davis, 1976; Spearing, 1976; Tillman and Martinsen, 1984). Production from reservoir beds in the Sussex and Shannon is in the western half of the basin. The Shannon is most productive in the Hartzog Draw Field, which has produced more than 75 million barrels of oil since its discovery in 1976 (Wyoming Oil and Gas Conservation Commission, 1990a). The Sussex is most productive in the House Creek Field, which has produced more than 21 million barrels of oil since its discovery in 1968 (Wyoming Oil and Gas Conservation Commission, 1990a). These reservoirs are generally 8,000–10,000 ft deep, and the gravity of the oil is 30°–40° API.

The reservoirs in the Parkman Sandstone and Teapot Sandstone Members of the Upper Cretaceous Mesaverde Formation and in the Teckla Sandstone Member of the Upper Cretaceous Lewis Shale are marine sandstone (Runge and others, 1973; Isbell and others, 1976). Fields having production from these units are mainly in the central and south-central parts of the basin, and they trend northwest-southeast. The most important fields are Dead Horse Creek, Barber Creek, Well Draw, and Poison Draw. Cumulative production from these four fields is more than 50 million barrels of oil and almost 0.1 trillion cubic feet of gas (Wyoming Oil and Gas Conservation Commission, 1990a). The gravity of the oil is 35°–45° API.

The source rocks for the hydrocarbons in Paleozoic reservoirs in the Powder River Basin are probably black shale units in the middle member (Pennsylvanian) of the Minnelusa Formation (Clayton and Ryder, 1984). Momper and Williams (1984) believed that long-distance migration from source rocks in the Lower Permian Phosphoria Formation in western Wyoming and eastern Idaho and Utah accounts for the oil in the upper part of the Minnelusa Formation. They attributed hydrocarbons in Cretaceous reservoirs principally to source rocks in the Mowry Shale and Niobrara Formation of Late Cretaceous age. In the northern part of the basin, methane generated from coal beds in the Paleocene Fort Union Formation is produced from the coal beds and from adjacent sandstone in the Fort Union Formation.

More than 2.5 billion barrels of recoverable oil and more than 2 trillion cubic feet of mainly associated gas (Dolton and others, 1990) have been discovered in the Powder River Basin. Mast and others (1989) estimated that the mean amounts remaining to be discovered are 2.25 billion barrels of recoverable oil and 2.76 trillion cubic feet of gas.

Uranium

Uranium is a dense metallic element used in nuclear fission for the nuclear generation of electricity and for atomic weapons. For nuclear fission, the isotope U^{235} is enriched in steps from its natural concentration of 0.7 percent to 3.5–5 percent (W.I. Finch, U.S. Geological Survey, written commun., 1991). Uranium enriched to 90.0 percent or greater U^{235} is used in nuclear explosives. Minor uses for the depleted uranium derived from the enrichment process include additions to armor, armor-piercing projectiles, and weights.

Uranium-bearing minerals have been found in many rock units in the Powder River Basin and adjacent uplifts. Most of the economic deposits of these minerals are in the Paleocene Fort Union Formation and the Paleocene and Eocene Wasatch Formation. Minor concentrations of uraniferous minerals are along the margins of the basin and in the adjacent uplifts in the Middle Cambrian Flathead Sandstone, in black shale in the Pennsylvanian–Lower Permian Minnelusa Formation, in the Middle and Upper Jurassic Sundance Formation (notably the Canyon Springs Sandstone Member), in the Upper Jurassic Morrison Formation, in the Lower Cretaceous Fall River and Lakota Formations of the Inyan Kara Group, in Upper Cretaceous sandstone, especially in the Mesaverde and Fox Hills Formations, and in Oligocene and Miocene rocks (Hausel and others, 1990). Occurrences of uranium minerals beneath the Precambrian-Cambrian unconformity and beneath the Precambrian-Tertiary unconformity in the Hartville Uplift could indicate

Table 5. Estimated additional resources (EAR) and speculative resources (SR) of uranium in the Wyoming basins at the end of 1990

[Modified from Energy Information Administration (1991). In millions of pounds U_3O_8 as of 1990].

	$30 per pound	$50 per pound	$100 per pound
EAR	170	360	680
SR	90	160	250

similar concentrations of these minerals at depth in the Powder River Basin (Harris, 1986).

The estimated additional resources and speculative resources of uranium (see Finch, 1987, for definition of terms) for the Wyoming Basins Resource Region have been estimated by the U.S. Energy Information Administration (1991) (table 5). Curry (1976, p. 238) indicated that the resource of U_3O_8 (at $30 per pound) as of January 1, 1976, in the Powder River Basin was 28 percent of the uranium resources of the Wyoming Basins Resource Region. Furthermore, the U.S. Department of Energy (1979) presented a chart showing, in the terminology of that time, that 28 percent of the "possible" resources of U_3O_8 (at $50 per pound' as of January 1, 1979, in the Wyoming Basins Province was attributable to the Powder River Basin. Assuming this proportion to be accurate and applicable to the uranium endowment, the estimated additional resources and speculative resources of the Powder River Basin can be approximated from the numbers presented in table 5.

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