

GEOLOGIC OVERVIEW, COAL DEPOSITS, AND POTENTIAL  
FOR METHANE RECOVERY FROM COALBEDS  
POWDER RIVER BASIN,

DRAFT

BY

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## 1. SUMMARY

The Powder River Basin contains the most important coal deposits in the United States. Because of their size and availability, these deposits, by themselves, could make up the entire near- and intermediate-term energy shortfall of the U.S. This statement is deliberately made to stress the critical significance of these deposits. This significance is due to their great size, the number and thickness of individual beds, their relatively shallow depth, and their occurrence in an area of relatively low land value and easily mitigated environmental constraints. Following is a summary of the geology, coal deposits, and coalbed methane drainage potential of the basin.

The Powder River Basin is an elongate north-northwest trending basin in the Great Plains Physiographic Province of eastern Montana and Wyoming. It lies within a semiarid region where vegetation is sparse and, in places, barren. The topography is characterized by steep-walled drainage channels, ridges, buttes, and local badlands. Many of the coalbeds have burned along their outcrop, forming layers of baked rock and clinker, which cap the ridges and divides. Because of the badland topography, poor soils, arid climate, sparse population, and distance from major population centers, Powder River Basin land has low economic value.

Extensive geologic mapping has been performed in the Powder River Basin in recent years. Many of these map references are compiled into lists which are included in the appendices to this report.

Sedimentary deposition in the region now occupied by the Powder River Basin prior to Late Cretaceous time, was controlled by regional tectonic features that extended well beyond the present basin confines. Rocks of this time period consist of marine sandstones, shales, carbonates and evaporites. Beginning in Late Cretaceous time, a thinner, locally controlled sequence of continental deposits formed contemporaneously with the onset of the Laramide Orogeny and the final retreat of the seas. The Laramide Orogeny dominated the structural formation of the Powder River Basin as it now exists. During early Tertiary time, block faulting of Precambrian basement rocks gave rise to the Bighorn Mountains on the west and formation of Powder River Basin on the east. At the same time, the

overlying Paleozoic and Mesozoic sedimentary rocks were drapefolded over the more rigid underlying Precambrian blocks.

The general structural configuration of the younger continental coal-bearing formations is one of a gentle, asymmetrical syncline or trough, trending NW-SE, parallel to the Bighorn Mountain front. The deepest point along the structural axis is situated near Kaycee, 40 miles south of Buffalo in the Sussex Coal Field. However, during Tertiary time, when most of the coalbeds were formed, the locale of greatest subsidence and deposition was the Buffalo-Lake De Smet area. Rocks of Late Cretaceous and Tertiary age reach a maximum thickness of nearly 8000 feet at the basin axis. These younger formations dip as much as 10-25° along the western margin of the basin. Faults with maximum displacements of 100-400 feet occur along the western margin of the basin near the Bighorn Uplift, but are less common elsewhere in the basin.

The Powder River Basin contains the nation's largest coal resources. Most of the thick coalbeds occur in the upper member--the Tongue River Member--of the Fort Union Formation, and the overlying Wasatch Formation. These two sequences reach a maximum thickness of 3970 feet near the Buffalo-Lake De Smet area; however, most of the large and more extensive coalbeds occur east of the structural axis, at depths less than 2500 feet. Coalbeds do occur in the lower members of the Fort Union Formation, as well as the Lance and Mesaverde Formations, but they are generally thinner and less continuous. Some of these older coalbeds crop out in the southwestern portion of the Powder River Basin, near Glenrock and Douglas.

In addition to the nation's largest coal resources, the Powder River Basin also contains significant accumulations of oil and gas in Paleozoic and Mesozoic rocks and deposits of uranium in Cenozoic rocks. The Powder River Basin is the most active portion of the Rocky Mountain area in terms of oil and gas exploration and production. Most current drilling by oil companies has been in Cretaceous rocks, which can range from surface exposures to 12,000 feet or more in depth. (In contrast, most exploratory efforts for uranium are restricted to shallow drilling of the younger Tertiary sequences). Since most oil and gas drilling penetrates possible coal-bearing formations, "piggyback" experiments, in cooperation with oil drilling companies, is a feasible method of studying many of the coal

seams. Most exploratory drilling for uranium would be too shallow for this purpose.

The Coal resource of the Powder River Basin has been calculated from subsurface data to be 1.3 trillion tons. Most of it is in thick beds which are relatively near-surface--with most of the coal at a depth less than 2500 feet, even in the basin center.

Powder River Basin coal ranges in rank from lignite A through subbituminous A. Generally, Powder River Basin coals are low in sulfur with low to moderate ash contents, although ash content can vary considerably. Commonly, the coals have an as-received moisture content of 20 to 30 percent, and volatile matter and fixed carbon contents of 30-40 percent. The coal is non-coking and non-agglomerating. It loses moisture, slacks, and can ignite spontaneously when exposed to air.

The total number of coalbeds in the Powder River Basin is difficult to determine because the beds split, coalesce, and are sometimes discontinuous, with beds pinching out and new beds appearing. Some correlations between the beds of various fields have been made, but much remains to be done in this respect. In the Sheridan area of Wyoming, as many as 11 persistent coalbeds occur in the Wasatch Formation. In other areas, as many as 12-18 coalbeds occur, most of them within the Fort Union Formation. Most of the Wasatch beds occur under less than 200 feet of overburden. However, the Wasatch and Fort Union Formations together reach a maximum thickness of 3970 feet in the Buffalo area.

Two of the largest coalbeds in the basin are the Wyodak-Anderson and the Lake De Smet beds. The Wyodak-Anderson coalbed crops out over a north-south distance of 120 miles in the Gillette Coal Field. It, and the beds correlative to it, persist downdip to the deepest part of the Powder River Basin. The Wyodak-Anderson bed is locally up to 150 feet thick, but averages 50 to 100 feet in thickness. Based on these figures, the bed contains at least 100 billion tons of coal to a depth of 2000 feet. This is the largest tonnage in a single continuous coalbed anywhere in the U.S.

The Lake De Smet bed, which occurs in the Buffalo Coal Field, is thought to be the thickest coalbed in the U.S. and second thickest in the

world. It is 15 miles in length, 70 to 220 feet thick and one-half to two miles wide.

There are 14 active coal mines in the Powder River Basin. Another 20 mines are in various stages of permit and construction. Most of these are in the Gillette area of Campbell County, Wyoming, making it the nation's coal-energy capital. The population of the Gillette area reflects this energy boom, having risen from 7,194 in 1970 to 23,500 in 1979, and expected to reach as many as 43,500 by 1990.

All data collected to date indicate that the Powder River Basin should provide several favorable target areas for recovery of methane gas from coalbeds by use of shallow drill holes.

The area considered in this report as the prime methane exploration target within the Powder River Basin is discussed below. It encompasses portions of Campbell, Sheridan, and Johnson Counties in Wyoming and Big Horn and Powder River Counties in Montana. Factors used in delimiting the target boundaries include:

- A. Restricting the area to lands underlain by the Tongue River Member of the Fort Union Formation, and additionally to
- B. Areas in which shallow drill holes are known to flow anomalously large amounts of methane,
- C. Areas in which flowing artesian wells are concentrated, or
- D. Areas in which three or more individually thick coalbeds are coalesced together into a single superbud.

Fifteen shallow drill holes or wells have been identified to date in Campbell County as having contained anomalously large amounts of methane in product fluids. These holes were drilled either as water wells for local use or as shallow investigations of near-surface coalbeds (less than 500' depth); none were drilled for the basin's much deeper-lying oil and gas deposits. Fourteen of these wells are in the Recluse area of northeastern Campbell County and define a NW-SE trending elliptical area approximately 33 miles long and 16 miles wide. The fifteenth well is 50 miles to the south, 25.5 miles south of Gillette.

In at least three centers of deposition within the basin, individual coalbeds are coalesced into massive "superbeds". These three centers are

the Decker area, containing the 80-foot thick Anderson, Dietz No. 1 and Dietz No. 2 beds; the Lake De Smet area, containing the 220-foot thick Lake De Smet bed; and the Gillette area, containing the 125-foot thick Wyodak-Anderson bed.

The methane recovery target area at Recluse, defined by drill hole, occurs at the margin of one of these depositional centers where a superbed splits into two or more component seams. At such locations, methane gas release from the coal seams, and collection within interbedded coal seam and porous sandstone sequences, may be optimal. Identification of such natural gas collection traps should be useful for indicating areas within the Powder River Basin where underlying coalbeds could have anomalously large amounts of adsorbed methane.

Many flowing artesian wells occur within the Powder River Basin, and several of them are known to contain substantial amounts of natural gas. Origin of this gas is the coalbeds and carbonaceous zones in the Fort Union Formation. It has been shown that gas in an aquifer increases the height to which water rises in a well and can create a flowing artesian well by raising the water to the surface. This lifting action is created by expansion of the gas as pressure is reduced in water flowing from the aquifer. Because of this lifting action, some portion of the artesian wells in the basin flows that otherwise would not do so.

If one assumes that some significant--but as yet unknown--portions of the flowing artesian wells flow because they are tapping coalbeds with anomalously high methane content, then such artesian wells might serve as a useful exploration aid. Hydrologic maps covering the Powder River Basin show locations of at least 198 flowing artesian wells within the boundary of the Fort Union Formation. A non-random distribution of the wells has been determined, 68 being in the eastern half of Sheridan County, 71 in northeastern Johnson County, 29 in the northern half of Campbell County, and 16 located mostly in two separate areas in Converse County. Of the flowing artesian wells in Sheridan and Johnson Counties, at least five are known to contain methane.

Of the flowing artesian wells in Sheridan, Johnson, and northern Campbell Counties, most are located along the major drainages of Tongue River, Powder River, and two principal tributaries of the Powder--Little

Powder River and Clear Creek. The drainage system of the Powder River Basin is thought to be controlled by two fracture systems. The dominant fracture set is parallel to the northwest-southeast trend of the basin axis, and the secondary set is approximately perpendicular to the basin axis. Location of four of the artesian wells known to contain methane, along the Powder River south from Clear Creek, and one well near the Tongue River provides tentative evidence that free methane is more abundant in fractured coal-bearing strata adjacent to structurally controlled drainage channels than it is in land areas between such channels.

Within the regional target delimited on the map (Figure 1-1), smaller initial target areas can be defined based on probable structural and stratigraphic controls, including the following:

1. Major drainage channels that parallel any of the known fracture sets, especially those channels along which flowing artesian wells are concentrated.
2. Secondary channel ways with anomalously linear development parallel to the major, NW-SE or NE-SW fracture-set directions and along which are located flowing artesian wells or shallow-drill holes known to emit methane.
3. Zones along anticlinal fold axes, where rocks under tensional stress could be more highly fractured than rocks on fold limbs. Anticlinal crests present highly favorable zones where fractured rocks can act as hosts for methane migrating updip from coalbeds along fold limbs.
4. Zones along synclinal fold axes where methane desorbed from coal-particle surfaces can collect in open fractures.
5. Stratigraphic traps created where superbeds split into two or more individual coalbeds.
6. Coalbeds in the deeper portion of the basin, paralleling the basin synclinal axis. Adsorbed methane concentration should be greatest in such beds because of the greater hydrostatic pressure and the probable higher coal rank in more deeply buried coals.
7. The northwest trending, 33-mile long, elliptical area in Campbell County in which shallow drill holes flowing methane gas are concentrated. Geologic controls for this concentration probably are partly structural and partly stratigraphic.

Initial individual drill sites for collecting coalbed methane data could include:

- a. Sites beside holes known to flow methane or beside flowing artesian wells containing methane,
- b. Sites on the crests of small structural closures along fold axes, and
- c. Sites at the intersections of two or more favored linear structural features; e.g., the intersection of a fold axis and a linear stream channel or the intersection of two linear stream channels such as the conflux of Powder River and Clear Creek.

It is important to determine if methane gas can be practicably collected from shallow Powder River coalbeds as quickly as possible. These coalbeds are the principal target of the great strip mines being put into operation along the northwestern and entire eastern rim of the basin. As these pits are opened, any methane contained within and adjacent to stripping areas will be lost to the atmosphere. If such methane gas is to be salvaged, the operation must occur before new pits are opened and the entire rim of the Powder River Basin coal seams is exposed to updip migration of methane contained in the deeper, more central portion of the basin.

An initial program here recommended for investigating methane recovery potential of the Powder River Basin, includes:

1. Construction of a lineation map of the basin from topographic and geologic maps, from spacecraft synoptic imagery, and from aerial photographs.
2. Collection of all data possible from the literature, from geotechnical personnel currently working in the basin, and from local water-well drillers, concerning methane content encountered in drill holes and water wells.
3. Field measurements of fracture systems in coal-bearing strata of the central Powder River Basin.
4. Collection of well-bottom samples from both flowing and non-flowing artesian wells in the central Powder River Basin and measurement of contained methane.
5. Cooperation with the U.S. Geological Survey, the Montana Bureau of Mines and Geology, and the Wyoming Geological Survey in collection of coal core samples during their shallow-to-intermediate

depth drilling programs (generally less than 1000-foot depths), and performing methane desorption tests.

6. Performing "piggyback" tests with companies exploring for oil, gas and uranium, in collection of coal core samples for methane desorption tests..
7. Performing intermediate-to-long term gas-flow tests on selected shallow holes drilled either for the U.S. Geological Survey or Montana Bureau of Mines and Geology programs or drilled specifically for the Methane Recovery from Coalbeds Project. This task is especially important for the Powder River Basin because the low-rank coal samples collected by coring may be so porous as to lose essentially all adsorbed methane before the samples can be placed in sealed canisters at the surface.
8. Drilling of small anticlinal highs with three to five dewatering wells around the base of the high and one methane collection well at the top.

## 2. INTRODUCTION

The objective of this report is two-fold: 1) to summarize the general geology and occurrence of coal in the Powder River Basin of Wyoming and Montana; and 2) compile all existing information on the occurrence of methane associated with the coalbeds, identify areas of anomalously large amounts of methane and to define target areas for investigating the methane recovery potential.

We have organized the report into four main parts. The general geology of the Powder River Basin is summarized in Chapter 3 of this report. The younger sedimentary sequences are discussed in greater detail, as they contain most of the larger coalbeds. At the end of Chapter 3 a brief description is included of other energy resources of the Powder River Basin, namely uranium and oil and gas. The principal coal fields and coalbeds are described in Chapter 4. When possible, references have been included on the extent, thickness and quality of the coal. Chapter 5 compiles all known occurrences of methane in coalbeds in the Powder River Basin. Identification of methane exploration target areas and recommendations for further work are outlined in Chapter 6.

### 3. BASIN SETTING

#### 3.1 GEOGRAPHIC SETTING

##### 3.1.1 Geography

Powder River Basin is an elongate, northerly trending inter-montane basin lying between the Black Hills on the east and the Big Horn Mountains on the west (Figure 3-1). Bounding the basin on the north, in Montana, is the Yellowstone River and on the south, in Wyoming, the North Platte River (Figure 3-2). The basin boundary assumed for this report is used by Keefer and Schmidt (1973) on their "Energy Resources Map of the Powder River Basin, Wyoming and Montana," (in pocket).

The basin, situated between the flanks of two major mountain ranges, is somewhat resembles a dumbbell in shape (Figure 3-2). The basin's geographic axis, bearing  $N15^{\circ}W$ , lies approximately 7 miles east of and roughly parallels the straight line connecting Forsyth, Montana, on the Yellowstone River and Douglas, Wyoming, on the North Platte.

The basin has a maximum length, along its longitudinal axis, of 256 miles and an average length of approximately 228 miles. Maximum, minimum, and average widths of the basin are 132, 94, and 115 miles, respectively.

##### 3.1.2 Physiography

Powder River Basin is a north, north-westerly trending basin in the Great Plains Physiographic Province. The major structural features of the basin were formed during the Laramide Orogeny of Late Cretaceous and Early Tertiary time. The deeply synclinal structure is not reflected in the topography. Most topographic features are a result of differences in erosional characteristics of the Tertiary rocks, stream erosion, and subsidence due to the burning of coal seams. The smaller stream channels are parallel to a  $N35^{\circ}W$  fracture system resulting in a NW grain in the topography (Mapel, 1959). Many small streams have carved the soft shale and sandstone into local badlands. The natural burning of coal seams has formed many resistant baked rock and red clinker layers which cap ridges and divides.

The average elevation of the Powder River Basin is 5000 feet. Relief ranges from 3700 feet in the valley of the Powder River to 5700 feet in the foothills of the Big Horn Mountains. The summit of Cloud Peak in the Big Horn Mountains is at 13,165 feet.

Because of the badland topography, poor soils, arid climate, sparse population, and distance from major population centers, most of the Powder River Basin is low in land value.

### 3.1.3 Climate

The Powder River Basin lies within a semi-arid region of pronounced seasonal variation in temperature and precipitation. Vegetation is sparse to barren in places, and consists of sagebrush, grass and prickly pear, with willows and cottonwoods along the valley bottoms. The annual rate of evapotranspiration exceeds the area's rainfall, resulting in drought conditions and a short growing season. Irrigation is therefore necessary to revegetate stripmined areas (Toy and Munson, 1978).

Mean annual precipitation shown in Figure 3-3 ranges from a low of 9.2 inches at Dead Horse Creek near the basin center, to a high of 20.2 at Kirby 1S in the northwest. In general, precipitation is higher in the basin's northern portion.

Mean monthly precipitation for 12 stations in the basin area, shown in Figure 3-4 indicates that annual rainfall peaks in the spring - midsummer months at 2-4 inches per month, and drops to less than one inch a month during the winter months. The relatively low precipitation during July and August compounds the problem of revegetating strip-mined areas.

Precipitation varies greatly from area to area. Particularly noticeable is the Dead Horse Creek Station which receives 9.2 inches annually; however, only 10-12 miles to the east, Gillette 18<sup>0</sup>SW Station receives 16.1 inches. This variation may be attributed to a rainshadow effect of the Bighorn Mountains.

Temperature varies with altitude and season. Summer temperatures range from a mean minimum in July of 36 to 60<sup>0</sup>F, with the lower temperatures occurring in the Bighorn Mountains. Mean maximum for July ranges from 72 to 90<sup>0</sup>F, again, with the lower temperatures in the mountains. Winter temperatures range from a mean minimum in January of 0 to 12<sup>0</sup>F.

Mean maximum for January ranges from 28 to 36°F. (Dightman, 1960; Lowers, 1960). Normals, means, and extremes for temperature, precipitation, relative humidity, wind, and sunshine over a 30-year Period for three cities are shown in Table 3-1 (National Oceanic and Atmospheric Administration, 1977, 1978).

#### 3.1.4 Mapping Status

Extensive mapping has been done in the Powder River Basin in recent years. Selected recent maps, as well as the older maps, have been compiled into lists which are included as Appendices to this report. Where possible, in the limited amount of time available, many maps have been outlined on index maps, which are also included in the Appendices. This compilation was not intended to be an exhaustive literature search, but includes most of the work done in the Powder River Basin by the USGS and the state surveys of Montana and Wyoming. The following is a brief summary of this compilation.

Indexes to available U.S. Bureau of Land Management maps (Figure \_\_\_ and \_\_\_) for the Powder River Basin are given in Appendix A.

Appendix B contains references to earlier geologic mapping in the Powder River Basin (1859-1970) taken from four separate USGS state indexes to geologic mapping for Montana and Wyoming. The USGS indexes are out of print but updated versions are included in the pocket of this report.

Appendix C contains selected references and index maps to recent mapping (1970-present) in the Powder River Basin, compiled by the authors of this report. The map lists are broken down into three groups according to subject matter and scale. Appendix C-1 includes references to regional coal studies and regional geologic mapping at various scales. Appendix C-2 contains references to recent 7-1/2' quadrangle maps by the USGS - all at 1:24,000. These include geologic maps coal resource and development potential maps and surficial geology maps. Appendix C-3 contains references to various maps, charts and geophysical logs. These are grouped according to subject matter into four separate lists (but are not shown on index maps), including miscellaneous geological maps, land use maps by the USGS, geophysical maps and logs by the USGS, and stratigraphic charts and sections by the USGS and U.S. ERDA.

The agency holding negatives and indexes for all areal photography and spacecraft imagery is the EROS Data Center at Sioux Falls, South Dakota,\* or the NCIC at the Denver Federal Center.

### 3.2 CULTURAL FEATURES

Counties wholly or partially encompassed within the basin include Campbell, Converse, Sheridan, Johnson, Weston, Niobrara, Crook, and Natrona in Wyoming; and Powder River, Big Horn, Rosebud, Custer, Treasure, and Carter in Montana (Figure 3-2).

The major towns within the basin boundary are Casper (Population 39,361<sup>+</sup> - 44,000<sup>\*\*</sup>) Gillette (7,194<sup>+</sup> - 23,500<sup>\*\*</sup>), Sheridan (10,300<sup>+</sup> - 13,710<sup>\*\*</sup>) Buffalo (3,394<sup>+</sup>) and Douglas (2,677<sup>+</sup>)--all in Wyoming. Towns just outside the basin boundary include Newcastle (3,432<sup>+</sup>), Wyoming, to the southeast; and Miles City (9,300<sup>\*\*</sup>) and Forsyth (1,873<sup>+</sup>) to the north, on the Yellowstone River (Figure 3-2).

The area is serviced by the Burlington Northern Railway. A new 116 mile line connecting the towns of Reno and Orin, Wyoming, is scheduled for completion in the fall of 1979 (see Figure 3-5). Many highways crisscross the basin. The major interstate highways are I-90, I-25 and I-94.

The Powder River Basin is the most active area in the Rocky Mountain region in terms of oil and gas production. A number of major oil and gas pipelines cross the area.

Gillette, situated in the center of the basin in Campbell County, Wyoming, has become the coal-energy capital of the nation with seven operating coal mines in the region, three mines in development stages and seven more in permit stages. The energy boom is reflected in the population

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\*Address: EROS Data Center  
U.S. Geological Survey  
Sioux Falls, South Dakota 57198  
Phone: (605) 594-6511

<sup>+</sup>1970 Census

<sup>\*\*</sup>Campbell County Chamber Commerce (1979) and Sheridan County Chamber Commerce (1978).

growth of the Gillette area (see Table 3-2), which has increased from 7,194 in 1970 to 23,500 in 1979. Roughly 10 percent of the total population is employed in the coal industry. Coal contributed 13.60% to the assessed valuation of Campbell County in 1978; up from 0.93% in 1974. Oil and gas contributed 64% to the 1978 valuation, down from a high of 83% in 1975.

### 3.3 GEOLOGY

#### 3.3.1 Basin Structure of a Regional Nature

Powder River Basin is an elongate northerly trending structural basin lying along the eastern front of the middle Rocky Mountains (Figure 3-6 to 3-10). When considering the entire sequence of sedimentary rocks deeply buried in the basin, it is probably most accurately visualized as a broad, flatbottomed, but slightly tilted, structural trough downwarped between the Big Horn Uplift on the west and the Black Hills Uplift on the east (Figures 3-8 and 3-9).

Older sedimentary rocks -- those older than Late Cretaceous -- have relatively steep dips on both margins of the basin. Along the Big Horns, average dip of the sedimentary rocks ranges mostly from 10-55 degrees, with average dip of the base of the sedimentary sequence (Precambrian contact) being 12 degrees. Along the Black Hills, average dip ranges mostly from 5 to 25 degrees, with average dip of the base of the sequence being 5.4 degrees (Figure 3-8). Locally, dips along basin margins are much steeper.

Across the broad central portion of the basin, however, all sedimentary rocks have essentially uniform shallow dips to the west that range mostly from 0.3 to 1.5 degrees. For the base of the sedimentary sequence, this regional dip is an average 1.1 degrees and extends from the base of the Black Hills, westward 75 miles to the deepest portion of the basin, close to and just east of the front of the Big Horn Mountains (Figure 3-8). This western edge of the above described trough, is considered the structural axis of the basin. The marine strata, up to the beginning of the Laramide Orogeny, are all remarkably conformable with average regional dips ranging between 1.1 and 1.3 degrees (Figure 2-8). With retreat of the marine seas during early Laramide uplift, rocks of continental origin deposited during Late Cretaceous and Early Tertiary times show progressively shallower regional dips. For example, the Wyodak coalbed--whose upper

surface acts as the contact between the Paleocene Fort Union Formation and the Eocene Wasatch Formation--has a regional dip of only 0.4 degrees over an east-west distance of 25 miles (Figure 3-8). The structural form of these younger, non-marine rocks is that of a very gentle asymmetrical syncline (Figure 3-8). At the basin axis, thickness of these rocks is nearly 8,000 feet (Curry, 1971).

Laramide structural movements are considered by Curry (1971)--based on isopach maps constructed from electric-log data--to have commenced after deposition of the Lewis Shale (early Maestrichtian time) and to have mainly ceased before deposition of the White River Formation of Oligocene time. A summary of Laramide structural events is given in Table 3-3).

Powder River Basin is only one of a line of basins that lie along the entire front of the Rocky Mountains, extending from northern New Mexico to central Montana. In general, these basins--especially Denver Basin to the south, which is separated from Powder River Basin by the Hartville Uplift--have similar asymmetries in that their structural axes lie very close to the Rocky Mountain front. Of these basins, Powder River is the deepest, containing in excess of 18,000 feet of sedimentary rocks. At Buffalo, Wyoming, structural relief of the Precambrian surface across the mountain-basin interface is in excess of 25,000 feet. This relief occurs in a horizontal distance of only 25 miles, extending from a height of 13,175 feet above sea level at Cloud Peak in the Big Horns to a depth greater than 12,000 feet below sea level at the basin axis. This interface probably represents a boundary between two continental subplates. Thus, With the onset of the Laramide Orogeny in Late Cretaceous time, rise of the modern Rocky Mountains occurred at the margin of the western plate concurrent with downdrag along the margin of the eastern plate, causing formation of the line of basins along the front.

### 3.3.2 Basin Stratigraphy

Sedimentary rocks within the Powder River Basin are of two basic types--an older, thick contiguous sequence of Paleozoic and Mesozoic rocks mostly of marine origin, and a younger thinner sequence of Late Cretaceous and Cenozoic rocks of continental origin whose deposition begin with the final retreat of the marine seas during regional uplift accompanying onset of the Laramide Orogeny (Figure 3-11).

These rocks will be discussed in eight units representing major transgressions of the Marine seas in the area, each unit being separated by a major unconformity. Rock Unit VIII, which includes all beds of Tertiary age, will be discussed in the greatest detail as it includes most of the economic coal-bearing strata.

### 3.3.2.1 Pre-Coal Marine Deposits

Sedimentation in Powder River Basin was controlled by regional tectonic features Prior to Late Cretaceous time. During Paleozoic time the Powder River Basin Area was part of a sedimentary shelf, bounded by the Paleocordilleran Trough to the west and the Transcontinental Arch to the east. Marine seas transgressed the area generally from West to east. The following description is summarized from an article by the Geological Association of Wyoming (1965).

Rock Unit I. The first Paleozoic sea encroached the northwest area of the Powder River Basin during Middle Cambrian time, covered the entire basin by Late Cambrian time and regressed during the close of Early Ordovician time. The formations include sandstones with minor shales of the Flathead Formation, which grade upward into shales of the Gros Ventre Formation and finally carbonates of the Gallatin Formation. These formations thin eastward where they are referred to collectively as the Deadwood Formation. Later uplift resulted in erosion of the upper beds of Rock Unit I. Combined thickness of the Flathead, Gros Ventre and Gallatin formations is about 900 feet in the northeast area of the basin and about 90 feet in the south. The Deadwood Formation, on the east side of the basin, is about 500 feet thick in the north and is absent in the southeast.

Rock Unit II. The second transgression of the sea occurred during Middle Ordovician time. The Powder River Basin was again positioned in a shallow marine shelf environment between the deeper paleo-Williston Basin to the north and the Transcontinental Arch on the southeast. Sediments of Rock Unit II include the Harding Sandstone, Lander Sandstone and Big Horn Dolomite on the west, and the Alladin Sandstone, Icebox Shale, Roughlock Slate and Whitewood Dolomite on the east. The formations thin to the east and south from 430 feet in the northwest to about 100 feet thick in the northeast, and are absent in the southern portions of the basin.

Rock Unit III. During deposition of Rock Unit III, Powder River Basin was again the site of shallow-water deposition. The regional setting was generally unchanged. Sediments deposited during the third transgression include the Devonian sandstones, shales and limestones of the Darby Formation. Overlying these is the Madison Limestone of Mississippian age, which is divided into lower, middle and upper units, separated by two unconformities. Other members of Rock Unit III are the Madison equivalent Guernsey Formation on the southeast side of the basin and the Pahasapa Limestone and Englewood Formation in the Black Hills.

After Mississippian deposition, the area was uplifted, causing leaching and erosion of the Madison rocks. As a result, a karst topography developed on the Mississippian surface over the entire basin. The Madison ranges in thickness from about 1000 feet near the Montana/Wyoming state line to 200 feet in the southern part of the basin. The Guernsey Formation has a maximum thickness of about 300 feet in the southeast.

Rock Unit IV. The fourth transgression of the Paleozoic sea occurred during Pennsylvanian and Lower Permian time. Until this time, the sediments formed were primarily fine-grained clastics and carbonates. During deposition of Rock Unit IV, however, non-marine clastics were deposited over much of the area. The sea advanced over the basin from the southeast across the Transcontinental Arch as well as from the Cordilleran Trough in the southwest. The rocks of Pennsylvanian and Lower Permian age are called the Hartville Formation (850-1300 feet thick) in the southeastern portion of Powder River Basin, the Casper Formation in the southwest, the Tensleep Sandstone, Amsden Formation, and Darwin Sandstone Member on the west (300 feet thick), and the Minnelusa Formation on the east (700-900 feet thick). During this episode, the Ancestral Rockies in southern Powder River Basin were eroded and transgressed by the encroaching sea. Also at this time, the Montana Highlands to the northwest were rising, causing an increase in clastic sedimentation. At the termination of Lower Permian deposition, compressional stresses formed major NW-SE and minor N-S lines of folding. Subsequent erosion resulted in an irregular topography of hogbacks and cuestas.

Rock Unit V. Rock Unit V of Permian and Triassic time is comprised of sandstone, shale, carbonate and red-beds, which formed as the Phosphoria

Sea advanced eastward onto the Wyoming shelf. A barrier to free circulation, built up on the west, resulted in deposition of thin evaporite layers in the basin. Formations included in Rock Unit V, on the western side of the basin, are the Goose Egg Formations, which thins northward from about 350 feet in the southwest to 180 feet at Buffalo, and the Chugwater Formation which is 800 feet thick in the northwest and 700 feet thick in the southwest. Equivalent rocks on the east side of Powder River Basin are the Opeche Shale (25-75 feet thick in the southeast), and the Spearfish Formation (450 feet thick in the Newcastle area). Eroded remnants of the Alcova, Crow Mountain, Popo Agie and Nugget formations of Triassic age are found in the southwest portion of the basin.

Rock Unit VI. Jurassic sedimentation (Rock Unit VI) began with marine transgression from the north and west and the formation of restricted lagoons and mud flats. The Gypsum Springs Formation consisting of massive gypsum, claystone, and limestone was deposited over most of the northern Powder River Basin. Thickness ranges from 185 feet on the west to 125 feet on the east and thins southward. These sediments were not deposited in the south because of the presence of a broad, relatively high trend across the north-central basin. The second cycle of deposition, forming the lower Sundance sandstones, was also influenced by the presence of this arch. Calcareous beds of the Rierdon Formation formed to the north, while shales and sandstones of the Lower Sundance Formation were deposited to the south of the arch. Inundation continued, and sands of the upper Sundance Formation covered the whole basin. The Formation is 370-400 feet thick in the east, 280 feet in the northwest and 350 feet thick in the southwest. After deposition of the Sundance, the Jurassic sea retreated and the continental Morrison Formation and Early Cretaceous Lakota Formation were deposited. The Morrison consists of claystone and interbedded fine-grained sandstone. On the east side of the basin it is 150 feet thick to absent in places, and on the west it ranges from 220 to 130 feet thick. The Lakota Formation consists of lenticular sandstone, conglomeratic sandstone, and shale. It averages 100-300 feet in thickness.

Coal crops out near the base of the Lakota Formation at several places on the eastern margin of the Powder River Basin in Crook and Western Counties, Wyoming.

Rock Unit VII. Rock Unit VII, of Cretaceous age (Figure 3-12) was deposited following a period of regional tectonic change. Previous transgressions of the seas had been primarily from the west. Beginning in Jurassic time, the region developed into an orogenic belt which shed sediments eastward. The Early Cretaceous marine beds of this unit were deposited in a sea which encroached both the north and south, merging in the central Rocky Mountain and Great Plains regions. The Powder River Basin, situated in the center of the seaway, received sediments from several directions. The rocks of this unit can be divided into five transgressive-regressive cycles of shales and sandstones. They include sandstones of the Thermopolis Shale on the west and the Fall River Sandstone on the east. The beds thin basinward from both sides and are absent in the west-central portion of the basin. These were followed by the Thermopolis marine shale and Skull Creek Shale which formed over the entire area. The Newcastle Sandstone on the east and the Muddy Member of the Upper Thermopolis on the west formed during the second regressive cycle. Again, the sands were deposited from the east and west sides of the basin and are absent in large irregular-shaped areas in the center of the basin. Deposition of the marine Mowry Shale followed the sandstones. The shales were formed during a period of volcanic activity and contain ash, resulting in a hard siliceous shale. The third regressive cycle is represented by the Frontier Sandstone. The source area to the east was eliminated about this time, and the Frontier Sandstone, which was derived from sediments to the west was formed only along the western margin and southwest portion of the basin. The Frontier sandstone represents a series of five oscillating transgression-regression cycles. During this time, the Belle Fourche Shale and Greenhorne Limestone formed to the east. Deeper water then covered the entire area forming the Cody Shale, Carlile Shale and Niobrara Formation. During and after deposition of the Cody, movements in the western Cordilleran area caused periodic influxes of sandstones into the western area of the basin. These include the Shannon and Sussex Sandstone members of the Cody Shale, the Parkman and Teapot Sandstones of the Mesaverde Formation and the Teckla Sandstone of the Lewis Shale. These are equivalent to the Pierre Shale on the east. Coals are reported from the 500 foot thick Mesaverde Formation in the southwestern portion of the basin. They are described variously as clean, dirty or shaly beds, generally less than

one foot thick although a few beds are up to 3 feet thick, locally (Glass, 1976). The repeated transgressions and regressions are apparently related to the beginning of the Laramide Orogeny (Geological Association of Wyoming, 1965).

### 3.3.2.2 Coal-Bearing Continental Deposits

The final retreat of the sea was followed by continental deposits of Late Cretaceous age (Figure 3-13). These are called the Lance Formation in Wyoming and the Hell Creek Formation in southeast Montana. These two formations consist of alternating, passively bedded sandstone and dark-colored claystone and shale. The formations thicken southward from 500-600 feet in Big Horn County, Montana, to 2500 feet thick in Converse County, Wyoming. Although evidence of Laramide deformation is present in rocks of this age in other areas, there is no evidence in the Powder River Basin of the Laramide Orogeny during Lance time. The basal part of the Lance Formation contains small, local beds of impure coal in the southwestern part of the Powder River Basin. Some of the coal seams are reported to average three to six feet thick (Mapel, 1958; Glass, 1976; Curry, 1971).

Rock Unit VIII. Early Tertiary time began with a large influx of sediment into flood-plains, estuaries and swamps of the newly formed Powder River Basin. The open sea was situated to the east and northeast. The stratigraphic position of the Cretaceous-Tertiary boundary has been disputed over the years. It is now generally accepted, however, that Tertiary rocks begin with the "lowest persistent bed of lignite" found directly above the latest dinosaur remains (Calvert, 1912; 1958; Matson and Pinchock, 1976).

The Tertiary rocks covering most of the Powder River Basin are the Fort Union Formation of Paleocene age and the Wasatch Formation of Eocene age. Fort Union and Wasatch time was characterized by cyclic deposition in a near-shore environment that was periodically being uplifted and subsided. Periods of stability led to the development of extensive coal-forming swamps. Obernyer (1979) has described the Fort Union and Wasatch Formations from outcrops along the western margin of the basin in the Lake De Smet area. In this area, Obernyer interprets the conglomerate member of the Fort Union and the Kingsbury Conglomerate and Moncrief Gravel Member of the Wasatch to represent the products of an alluvial fan fronting the Big

Horn Uplift. These coarse deposits give way eastward to fine- and medium-grained sandstones, siltstones, mudstones, claystones and thick coals of an extensive alluvial plain environment. Bryson and Bass (1973), in describing the Moorhead Coal Field to the northeast, state that the Tongue River Member consists of an alternating sequence of massive, faintly-crossbedded sandstone, 40-100 feet thick, overlain by a thin layer of shale and clay, a thick coal bed, and finally shale and other rocks of varying thickness. These sedimentary sequences are thought to have formed in an extensive flood-plain environment, with the open sea to the east and northeast. The thick sandstone beds were probably deposited in littoral environments and the principal coalbeds formed in large coastal swamps and marshes.

Because the source area was to the west-northwest, the Fort Union and Wasatch differ in lithology and thickness from place to place. These units are described as follows from the northern and southern parts of the basin, respectively:

o Northern Powder River Basin

WASATCH FORMATION (0-400 ft or 0-120 m) -- Brownish gray to light-gray fine- to coarse-grained lenticular beds of sandstone and interbedded gray shale and coal. Contains a fossiliferous zone of clams and snails as much as 30 feet (9.1 m) thick. Zones of clinker crop out along the coal horizons. Base of unit is mapped as the top of the thick and persistent Roland coalbed, as defined by Baker (1929). Conformable contact with underlying unit.

FORT UNION FORMATION

Tongue River Member (0-2,500 ft or 0-760 m) -- Light-yellow to light-gray fine- to medium-grained thick-bedded to massive locally crossbedded and lenticular, calcareous sandstone and siltstone; weathers to a buff color. Commonly contains buff to light-gray shaly siltstone and shale, and brown to black carbonaceous shale. Contains numerous coalbeds; as much as 80 feet (24 m) thick. Burning of the coal along outcrops has formed thick red and lavender clinker and baked shale beds. Base of unit is mapped as the change from predominantly siltstone and sandstone to predominantly shale of underlying unit.

Lebo Shale Member (0-600 ft or 0-180 m) -- Predominantly dark shale containing interbeds of light-gray and brown to black carbonaceous shale, siltstone, and locally thin coalbeds. Shales contain altered and devitrified volcanic ash and brown ferruginous concretions. Base of unit is mapped as the change from predominantly shale to predominantly fine-grained sandstone and shale of under-

lying unit. Conformable contact with underlying unit; however, the Lebo exists locally as scoured channel deposits developed well into the Tullock Member.

Tullock Member (0-800 ft or 0-240 m) -- Lower part of member is interbedded medium-gray to light-gray shale, fine-grained light-gray sandstone and siltstone, and thin but persistent coalbeds; grades upward to light-gray carbonaceous shale. Locally at the top is a resistant sandstone that forms a well-developed rimrock. Base of unit is mapped as the change from fine-grained thin-bedded sandstone, siltstone, shale, and coalbeds to predominantly massive channel sandstone and dark-gray shale of underlying unit (Brown, 1952; Dunlap, 1958).

o Southern Powder River Basin

WASATCH FORMATION (LOWER EOCENE) -- Gray, brown, and reddish-pink conglomeratic to fine-grained arkosic sandstone, siltstone, carbonaceous shale, and coal; all of fluvial and paludal origin. In general, the sandstone is coarser grained and contains two to three times more heavy minerals than those in the underlying Tertiary rocks. Conglomerate, 2-4 feet (0.6-1.2 m) thick and composed primarily of black chert pebbles, is present locally at the base. Unconformably overlies the Lebo Member of the Fort Union Formation. Contains some of the largest coal and uranium deposits in the Powder River Basin. 0-1,800 feet (0-549 m) thick.

LEBO MEMBER OF FORT UNION FORMATION (PALEOCENE) -- Light- to dark-gray very fine grained to conglomeratic sandstone interbedded with varying amounts of siltstone, claystone, carbonaceous shale, and coal; all of fluvial and paludal origin. Ganister (hard, dense quartzite) boulders and slabs containing numerous leaf and root impressions derived from beds of silicified swamp muck within the Lebo Member occur locally on the surface. Thin-bedded calcareous ironstone concretions interbedded with massive white sandstone and light- to dark-gray slightly bentonitic shale occur throughout the unit. Locally, coalbeds are more than 4 feet (1.2 m) thick. Conglomeratic coarse-grained sandstone interbedded with shale occurs in the southern and southwestern parts of the basin. In general, the sandstones included in the Lebo are finer grained and better sorted than those in the Wasatch. Also the percentage of heavy minerals in the Lebo sandstones is very low. 1,700-2,800 feet (518-853 m) thick.

TULLOCK MEMBER OF FORT UNION FORMATION (PALEOCENE) -- Interbedded sandstone, siltstone, shale, carbonaceous shale, and thin coalbeds. Sandstone is tan to buff, massive to thin, and evenly bedded. Shales generally are dark gray and brown. Distinguished from the underlying upper Cretaceous Lance Formation by the presence of thin coalbeds, the lack of dinosaur-bone fragments, and a stratified appearance due to the presence of thin coalbeds and carbonaceous shales interbedded with persistent thin to massive sandstone beds. Strike and dip measurements are easily obtainable. The drab appearance and massive sandstones of the Tullock make it easily

distinguishable from the conformably overlying Lebo Member which generally has a lighter overall aspect and a predominance of siltstone and shale. 1,000-1,500 feet (305-475 m) thick.

The Fort Union crops out in a band around the margin of the basin (Figure 3-14), averaging 60 miles wide on the north, 25 miles wide on the east and 5 miles on the south and west sides. Structural deformation and its effects on Eocene deposition is responsible for limited exposures on the west side of the basin along the Bighorn Mountains (Obenyer, 1979; Mapel, 1958). The Fort Union is about 2100 feet thick in the east and reaches its maximum thickness of 5215 feet at the center of the basin (Curry, 1971; Grazis, 1977). Dips are 10 to 25° near the Big Horns and otherwise relatively flat averaging 2 to 3° (Mapel, 1958).

The Fort Union is subdivided into three members: in ascending order, they are the Tullock, Lebo Shale and Tongue River members. The Tullock Member consists of friable light-colored sandstone, dark to light-gray shale and thin beds of coal. It is as much as 1100 feet thick in the southern part of the basin and thins northward to about 200 to 250 feet in Montana. Curry (1971) states that, "Tullock deposition...marks the first evidence of Laramide deformation in the Powder River Basin." The overlying Lebo Shale Member is 150 to 400 feet thick and consists mostly of soft-clay shale, thin beds of sandstone and siltstone, locally containing ferruginous concretions and thin beds of coal. Curry (1971) states that the Lebo mudstones provide evidence of the first typical Laramide structural movements in the Powder River Basin. The fact that mudstones were deposited rather than coarse clastics suggests that basin subsidence was the first major movement rather than uplift of adjacent areas.

The Tongue River Member consists of 2000 feet of yellow-weathering sandstone and coal in Montana which thins southward to about 800 feet at Sheridan and 600 feet near Gillette (Mapel, 1958). The Laramie Range, Bighorn Mountains, Black Hills and Casper Arch were uplifted at this time. The most persistent coalbeds in the basin occur in the Tongue River Member of the Fort Union. The largest Fort Union coal seam, the Wyodak-Anderson, frequently ranges from 50-100 feet thick (Glass, 1976).

In the Lake De Smet area near Buffalo, Wyoming, Obenyer (1979) has divided the Fort Union into two members: a lower member of sandstone,

silty sandstone, siltstone, and mudstone; and an upper conglomerate member which overlies the lower beds with angular unconformity. The conglomerate member consists of subangular to rounded granule- to boulder-size pieces of Paleozoic sediments which crop out to the west.

The contact of the Fort Union Formation of Paleocene age and the overlying Wasatch Formation of Eocene age is still a controversy. In some areas, the contact is a recognizable unconformity, but in other areas the contact is conformable and not easily defined even after detailed study. The Wasatch is 1000-2000 feet thick and is lithologically similar to the Tongue River Member of the Fort Union. It is composed of thin lenticular sandstone, gray clay, carbonaceous shale and coal. It is drab-yellow to light-gray in outcrop. The Wasatch Formation is undifferentiated over most of the basin, except along the west margin, where Opornyer (1979) has subdivided it into three members: the Kingsbury Conglomerate Member (0-800 feet thick), an unnamed finer grained sequence (0-2500 feet thick) and the Moncreif Member (0-1400 feet thick). The Kingsbury Conglomerate lies with angular unconformity on the Fort Union and truncates the upper member of the Fort Union Formation. It grades upward and laterally to the east into finer grained sequences of sandstones, siltstones, mudstones, and occasional thin shales. Overlying the finer sequence is the Moncreif Member, which becomes increasingly coarser-grained upwards, eventually becoming a boulder conglomerate. The exact age and stratigraphic position of the Moncreif Member is still disputed. The areal distribution of the Wasatch is restricted to an elliptical area in the center of the basin 170 miles long by 60 miles wide (see Figure 3-14). The Wasatch Formation has generally shallow dips of less than  $4^{\circ}$  - except along the western margin near the Big Horn Mountains.

The Wasatch is "another prolific coal-bearing formation" (Glass, 1976). It is reported to contain the thickest coalbed in the nation. The Lake De Smet coalbed in the Lake De Smet area is reported to be as much as 220 feet thick, locally.

The relative thickness of the members of the Fort Union and Wasatch Formations is shown in isopach maps (Figures 3-15 and 3-16) and electric-log correlations (Figures 3-17 and 3-18).

Clinker beds covering as much as several square miles have formed from the burning of coal seams in the Tongue River and Wasatch. Clinker consists of fused sandstone and shale formed by the heat of combustion. The burning usually does not affect underlying rocks, but may cause alteration of as much as 50 feet of overlying rocks (Mapel, 1958).

The White River Group of Oligocene age formed after the tectonic movements related to the Laramide Orogeny had stopped. The sedimentary rocks consist of volcanic ash, claystone, and siltstone. The White River Formation was deposited on an erosion surface of considerable relief (Whitcomb, 1965), and the thickness differs from place to place. It is found mainly in the extreme southeastern portion of the Powder River Basin where it is about 560 feet thick. Isolated remnants are also found in Campbell County, in the Big Horn Mountains and in the Black Hills.

The Arikaree Formation of Miocene age consists of tuffaceous sandstone and locally derived conglomerates. It is present mainly in the southeast portion of the basin where it is about 600 feet thick (Hodson, Pearl and Druse, 1973).

The White River and Arikaree Formations represent a period of erosion and deposition where nearly buried the Rockies prior to uplift during Late Cenozoic time.

### 3.3.3 Basin Hydrology

#### 3.3.3.1 Surface Water

The Powder River Basin is drained by tributaries of the Missouri River system. The principal drainage is to the N-NE into the Yellowstone River, and includes the Powder, Little Powder, Tongue, Big Horn and Little Big Horn Rivers. Others, including the Bell Fourche and Cheyenne Riders, drain to the east around the Black Hills Uplift. The North Platte River, bounding the basin on the south, drains to east and has essentially no tributaries draining the Powder River Basin (Figures 3-19). Both perennial and ephemeral streams occur in the region. Bordering the mountain areas, stream flow is mainly from precipitation and snow melt, and is highest during winter snow melt runoff in May and June (Figure 3-20). Streams originating within the basin are mainly ephemeral, flowing only during time of high surface runoff (Figures 3-21 and 3-22). Major stream patterns are

dendritic, however, the secondary and tertiary systems are fracture controlled and are dominantly parallel. The secondary tributaries are parallel or subparallel to northeast fracture systems, whereas many of the tertiary stream channels follow the northwest fracture system which is parallel to the basin structural axis. Sparse vegetation and erodable Tertiary rocks result in large sediment loads.

The largest use of surface water is for irrigation along stream valleys. Surface water also supplies the municipal needs for the towns of Sheridan, Buffalo, Dayton, Ranchester, and Kaycee (Lageson et al, 1978; Breckenridge, et al, 1974; Hodson, Pearl, and Druse, 1973).

#### 3.3.3.2 Ground Water

The principal aquifers in most areas of the Powder River Basin are the Tertiary sandstones of the Fort Union and Wasatch formations. In the southeast area of the basin, the principal aquifer is the Tertiary Arikaree Formation. In some areas, significant quantities of water occur in alluvial deposits along stream valleys (Figure 3-19).

Pre-Tertiary Aquifers. Pre-Tertiary rocks consist principally of tightly cemented coarse- and fine-grained sandstone, thick beds of shale and massive porous beds of limestone. Potential aquifers include sandstone of the Lance Formation; the Fox Hills, Fall River and Lakota sandstones; sandstone in the Sundance Formation; the Tensleep Sandstone; and the Madison and Pahapsa Limestones (Figure 3-23). In the Gillette area, these formations range from 2200 to 10,000 feet in depth. Many of these rocks do not have a large primary permeability, rather, water is held in fractures, joints and solution cavities.

The Madison Limestone of Mississippian age is deeply buried except in the outcrop area in the Big Horns. It consists of a thick sequence of light yellowish brown to white limestone and dolomite about 200 to 1000 feet thick. Water occurs where the limestones are cavernous and fractured. The major flowing wells near Tensleep, Wyoming, tap the Madison and yield 1100 to 2800 gpm. The equivalent Pahapsa Limestone to the east yields water to several wells in excess of 500 gpm.

The Amsden Formation overlies the Madison and is largely cherty dolomite and shale. It is relatively impermeable.

The Tensleep Sandstone of Pennsylvanian age consists of gray to white sandstone with thin beds of dolomite. It is fine- to medium-grained, well-sorted, friable, thick-bedded, with large-scale crossbedding. It is 50 to 500 feet thick and dips steeply toward the basin. The Tensleep Sandstone has sufficient primary permeability to yield moderate to large supplies of water (20-1000 gpm). The Tensleep is considered second to the Madison as a potential irrigation source. Artesian pressure is usually less than in the Madison.

Correlative with the Tensleep Sandstone is the Minnelusa Formation which is composed of sandstone, dolomite and limestone. It is generally more densely cemented, but does yield water from 20 gpm to as much as 1,000 gpm in areas where fracturing has increased the permeability.

The Permian and Triassic Chugwater Formation, Goose Egg Formation, Spearfish Formation, Minnekahta Limestone and Opeche Shale consist of shale, gypsum and limestone. Yield from these formations is generally small (10 to 20 gpm).

The Gypsum Spring, Sundance and Morrison Formations consist of gypsum, limestone, and fine-grained sandstone and claystone. Water yields of 10 to 50 gpm are possible in some areas, but generally these formations are not considered good aquifers.

The Cloverly, Fall River and Lakota formations of Lower Cretaceous age consist of shale, siltstone and sandstone. Yields range from 5 to 20 gpm for most wells, but yields of 100 gpm or more are possible from fractured areas.

The Skull Creek Shale is a dark gray to black shale 200 to 270 feet thick. It is not considered an aquifer.

The Newcastle, or Muddy, Sandstone is a light-gray, fine to medium-grained sandstone, 20 to 100 feet thick with relatively high permeability. Where saturated it may yield 10 gpm.

The Mowry Shale is 180 to 525 feet of gray to black siliceous shale. It is generally not considered an aquifer, although areas of secondary fracturing may yield as much as 10 gpm.

The Frontier Formation, Cody Shale and Pierre Shale consist of about 4000 feet of gray-black marine shale with lesser amounts of interbedded siltstone and sandstone. Except for the Shannon, Sussex and Groat Sandstone members, these rocks are not considered Potential aquifers. Yields of 20 to 50 gpm are possible from the sandstone beds.

The Fox Hills Sandstone consists of 125 to 700 feet of fine- to medium-grained marine sandstone. It yields as much as 200 gpm water in some areas. It is a principal aquifer in some areas of the northern Powder River Basin in Montana.

The Lance Formation of Upper Cretaceous age is a continental formation of interbedded light-colored sandstone and dark shale, with lenticular deposits of carbonaceous shale. It ranges in thickness from 500 feet to 3000 feet. It is considered a principal aquifer in some places, although yields are small (less than 20 gpm).

The Tertiary Aquifers. The Tertiary sandstones of the Fort Union and Wasatch formation are the Principal aquifers in most of the Powder River Basin (see Table 3-9). The Fort Union and Wasatch formations are continental deposits, formed in lacustrine, alluvial, and flood-plain environments. Fort Union time was characterized by large, shallow, inland lakes and marshes. Sedimentary rocks formed at this time include sandstones, shales and coal. During Wasatch time, the Powder River Basin was the site of sluggish, meandering streams and marshes. Channel sands, which persist for several miles, along with beds and lenses of coal were formed at this time (Littleton, 1950).

Water in the Fort Union occurs in thin, lenticular beds of fine-grained gray sandstone, jointed coal, red clinker beds and red shale (Table 3-4). Gas and water are discharged together from some wells that penetrate coal and other carbonaceous material of the Fort Union. Most gas is methane from the coalbeds, and its occurrence is described in more detail in Section 5 of this report. Gas in an aquifer affects the height to which water will rise in a well and may bring the water to the surface due to expansion of the gas and a resulting lifting action (Lowry and Cummings, 1966).

The Fort Union normally yields adequate water for domestic and stock use. The quality of the water differs from well to well, but the dissolved solids content commonly exceeds the limit recommended by the U.S. Public Health Service. The water is usually not used for irrigation because of a potential salinity or sodium hazard.

Water in the Wasatch is contained largely in irregularly bedded lenticular sandstone and in jointed coal and clinker beds. The water is generally under some artesian pressure in the interior of the basin, and occurs under water-table conditions in outcrop areas. The Wasatch yields water for domestic and stock use (10-500 gpm). The dissolved solids content generally exceeds the limit recommended by the Public Health Service. Water from the Wasatch Formation is not usually used for irrigation because of a Potential sodium hazard (Littleton, 1950; Lowry and Cummings, 1966).

The White River Formation consists of claystone and siltstone with some channel deposits of coarse sand and gravel. It ranges to 550 feet thick in the southeastern portion of the basin. Generally, the White River Formation is of low permeability. Yields of 5 to 20 gpm are possible in fracture zones, fissures and coarse-grained channel deposits (Whitcomb, 1965; Hodson, et al, 1973).

In Niobrara County, Wyoming, the Principal aquifer is the Arikaree Formation of Miocene age. The Arikaree is predominantly a massive sandstone with beds of siltstone, thin lenticular layers of hard concretionary sandstone, soft volcanic ash, and a generally persistent coarse basal conglomerate. The Arikaree yields water to domestic, stock, and irrigation wells. Permeability is not uniform, but water quality is good (Whitcomb, 1965).

Water in most formations is under some artesian Pressure along the western margin and interior of the basin because of the uplift of the Big Horn Mountains. Precipitation is the main source of recharge in areas of rock outcrops. In the interior of the basin, the near-surface aquifers are recharged by irrigation and the infiltration of surface water.

Alluvial Aquifers. Alluvium, terrace, and flood-plain deposits of Quaternary age, formed in stream valleys, contain significant quantities of water in some areas. The alluvium consists of sand, silt and clay, with a

few lenses of fine gravel. It is usually less than 50 feet thick although it may be up to 100 feet thick in some places.

Irrigation is a major source of recharge and is responsible for adequate supplies of ground water in the alluvium in some areas. Water in the alluvium has a low sodium hazard, but a medium to very high salinity hazard. Some wells in alluvium contain excessive amounts of iron as dissolved solids (Littleton, 1950; Lowry and Cummings, 1966; Whitcomb, Cummings and McCullough, 1966).

#### 3.3.4 Energy Resources Other Than Coal

In addition to the nation's largest coal resources, the Powder River Basin also contains significant accumulations of oil and gas in Paleozoic and Mesozoic rocks and deposits of uranium in Cenozoic rocks. Powder River Basin is the most active area in the Rocky Mountain area in terms of oil and gas exploration and production. Most drilling by oil companies at the present time has been in Cretaceous rocks, which can range from surface exposures to 12,000 feet or more in depth. In contrast, most exploratory efforts for uranium are restricted to shallow drilling of the younger Tertiary sequences. Since most oil and gas drilling penetrates possible coal-bearing formations, "piggyback" experiments, in cooperation with oil drilling companies might be a feasible method of studying many of the coal seams. Most exploratory drilling for uranium would be too shallow in this regard.

## 4. COAL RESOURCES

### 4.1 REGIONAL SETTING

Powder River Basin contains the most important coal deposits in the United States. Because of their size and availability, these deposits, by themselves, could make up the entire near- and intermediate-term energy shortfall of the U. S. This statement is deliberately made in order to stress the critical significance of these deposits. These deposits are so important because of their great size, the number and thickness of individual beds, their relatively shallow depth, and their occurrence in an area of relatively low land value and environmental importance.

Coal resource of the basin, greater than in any other region in the country, has been calculated from available subsurface data to be 1.3 trillion tons. Most of this resource is in thick beds which are relatively near-surface, with most coalbeds being at a depth of 2500 feet or less, even in the basin center (Elmer Schell, U. S. Geological Survey, oral communication).

Most of the earlier coal-resource calculations were restricted to outcrop areas along strike of the coalbeds, and for relatively short distances downdip, and until recently, little was known about the extent of the coalbeds downdip to the center of the Powder River Basin. For that reason, the early calculations of coal-resources grossly understate the coal that almost certainly exists (Averitt, 1975).

In 1950, Berryhill, et al, estimated the total amount of coal-resources in the Wyoming portion of the Powder River Basin to be 94.88 billion short tons. In 1975, Glass updated that estimate to a total of 110 billion short tons (Glass, 1975a). These figures include identified resources of coal 2.5 feet and thicker, in measured, indicated and inferred categories between 0-3000 feet of cover. More recently, Mapel and Swanson (1977) have estimated the <sup>2</sup>coal resource of the Montana portion of the Powder River Basin to be 178 billion short tons, to a depth of 1,500 feet and Glass (1976) based on information from Averitt (1975) and Hamilton et al (1975) has updated his previous figure for the Wyoming portion of the basin to include an additional 500 billion short tons of undiscovered - speculative and hypothetical resources to as much as 6000 feet in depth.

The USGS is currently performing an extensive study of the coal resources in the Powder River Basin. In this evaluation, oil and gas well logs have been examined and coal resources determined for the basin in depth increments of 500 feet. However, subsurface control for this evaluation is limited to the eastern two-thirds of the basin, where oil and gas exploration has been concentrated. These detailed studies show that the Powder River Basin of Wyoming-Montana contains 1.3 trillion tons of coal (Rupert, et al, 1975). Strippable coal reserves for Wyoming and Montana are shown in Tables 4-1 and 4-2.

Subsurface logs indicate that strata in the basin contain 5 major coal zones, which generally are concentrated in a vertical section of 1000-1200 feet. In addition, these studies have indicated that probably 50 percent or more of the total coal in the basin would be in beds 15 to 50 feet thick and 30 to 40 percent in beds greater than 50 feet thick. As yet, no detailed evaluation has been made by the USGS on an individual bed basis (Rupert, et al, 1975).

Coal in the Powder River Basin ranks as lignite A through sub-bituminous A. The American Society for Testing and Materials (1964, p 74) classifies coals on a moist, mineral-matter free basis with a calorific value of 6,300-8,300 BTU per pound as lignite A, 8,300-9,500 BTU as subbituminous C, 9,500-10,500 as subbituminous B, and 10,500-11,500 as subbituminous A. Lignites in the Powder River Basin are restricted to a small area in the northeast corner.

As-received heat values from coals in the Montana Portion of the basin range from 6,500 BTU per Pound in the Knowlton deposit, just outside the northeast boundary of the basin, to 9,850 BTU in the Decker deposit on the west side of the basin. In the Wyoming Portion of the basin, the coals range from 7,550 BTU per pound in Converse County to 9,300 BTU per pound in the Sheridan area. The average of the Wyoming coals is relatively low - 8,300 BTU per pound as-received (Glass, 1978; Matson and Blumer, 1973). Typical as-received analyses for some of the major coalbeds are shown in Table 4-3. Unfer (1951) as quoted by Glass (1978) has summarized the general distribution of the various ranks of coal:

"While the older coals in any give field are generally higher in rank than the younger beds, the rank of individual beds also

seems to increase toward the troughs of the structural basins. Both of these variations in rank have been attributed to increases in depth of burial."

Usually, Powder River Basin coals are low in sulfur and have low to moderate ash contents, although the ash content can vary considerably. The coals usually have an as-received moisture content of 20 to 30 Percent, and volatile matter and fixed carbon contents of 30-40 Percent. The coal loses moisture, slacks, and can ignite spontaneously when exposed to air.

Most of the thick coalbeds occur in the upper member -- the Tongue River Member of the Fort Union Formation, and the overlying Wasatch Formation. These two sequences reach a maximum thickness of 3970 feet near the Buffalo-Lake De Smet area (Curry, 1971); however, most of the thick coalbeds range from surface exposures to less than 2500 feet in depth. Coalbeds do occur in the lower members of the Fort Union Formation, as well as the Lance and Mesaverde Formation (Figure 4-1), but they are generally thinner and less continuous. Some of these older coalbeds crop out in the southwestern portion of the Powder River Basin, near Glenrock and Douglass.

Fort Union and Wasatch time was characterized by cyclic deposition in a near-shore environment that was periodically being uplifted and subsided. Periods of stability led to the development of extensive coal-forming swamps. Sedimentary rocks which are characterized by repeating sequences of sandstones overlain by shale, a thick coalbed and then shale are thought to have formed in an extensive floodplain environment, with the open sea to the east and northeast. The thick sandstone beds were probably deposited in littoral environments and the principal coalbeds formed in large coastal swamps and marshes.

The general structural configuration of the continental coal-bearing formations is one of a gentle, asymmetrical syncline. The rocks, of Late Cretaceous and Tertiary age reach a maximum thickness of nearly 8000 feet at the basin axis. The formations dip as much as 10 to 25° along the western margin of the basin, near the Big Horn Uplift, and flatten to less than 1° in the interior of the basin. Faults with maximum displacements of 100-400 feet occur along the western margin of the basin near the Big Horn Uplift, but are less common elsewhere in the basin.

Several joint and fracture studies have been done in coal-bearing rocks of the Powder River Basin; the results of these studies are summarized by Henkle, Muhm and DeBuyl (1978) and illustrated here in Figures 4-2 and 4-3 and Table 4-4. In summary, Stone and Snoeberger (1976) studies the Felix coalbed in the Hoe Creek area, 20 miles southwest of Gillette. They found fracture orientations to be subparallel to the regional strike and dip of the coal-bearing rocks. They also noted that the fracture set which is subparallel to the regional dip is twice as permeable as the fracture set which is subparallel to the regional strike. Glass (1976) reported similar joint orientations in the Badger and School coalbeds in the southern Powder River Basin. He also reported two pairs of joint orientations in the Anderson-Canyon coal in the Gillette area. They consist of one set which is subparallel to the regional strike and dip (NW-NE) and another pair which trends NS-EW. The Tongue River member in the Sheridan-Decker area of Wyoming and Montana was studied by Lee, Smith and Savage (1976), who reported three major joint orientations. The  $N45^{\circ}W$  and  $N37^{\circ}E$  pair are subparallel to the regional strike and dip; and the third set trends  $N13^{\circ}E$ . Henkle, Muhm and DeBuyl (1978) studied a small area near Gillette, and found two sets of fractures. They concluded that at least one of the pairs of cleats and joints in their study area was inherited from existing joint patterns in the underlying Precambrian basement rocks, and formed as a result of tensile stresses following uplift and erosion of overlying sediments. Another joint set in their area was found to be subparallel to the regional strike and dip of the coal-bearing rocks. These workers noted excellent correlation between cleat orientation of coal seams and joint orientation of the overburden.

The total number of coalbeds in the Powder River Basin is difficult to determine because the beds split, coalesce, and are commonly discontinuous, with beds pinching out and new beds appearing. In the Sheridan area of Wyoming, as many as 11 persistent coalbeds occur in the Wasatch Formation. In other areas, as many as 12-18 coalbeds occur, most of them within the Fort Union Formation. Most of the Wasatch beds occur under less than 200 feet of overburden. However, the Wasatch and Fort Union Formations together reach a maximum thickness of 3970 feet in the Buffalo area.

Two of the largest coalbeds in the basin are the Wyodak-Anderson and the Lake De Smet bed. The Wyodak-Anderson coalbed crops out over a north-south distance of 120 miles in the Gillette Coal Field. It, and the beds correlative to it, persist downdip to the deepest part of the Powder River Basin. The Wyodak-Anderson bed is locally up to 150 feet thick, but averages 50 to 100 feet in thickness. Based on these figures, the bed contains at least 100 billion tons of coal to a depth of 2000 feet. This is the largest tonnage in a single continuous coalbed anywhere in the U. S. (Averett, 1975).

The Lake De Smet bed, which occurs in the Buffalo Coal Field is thought to be the thickest coalbed in the U. S. and second thickest in the world. It is 15 miles in length, 70 to 250 feet thick and 0.5 to 2 miles wide (Cbernyer, 1978).

The Powder River Basin contains 21 coal fields, shown in Figure 4-4. In Wyoming, the coal field boundaries have been clearly defined. In Montana, however, the coal fields and their boundaries are much less clearly defined. The coalbeds in each field are typically given different names, and until recently, very little correlation between these fields had been attempted. Even now, the nomenclature is confusing. We have attempted here to synthesize the enormous amount of data available on the Powder River Basin coals, but we were somewhat limited because of the casual and occasionally conflicting use of coalbed names in the literature and within the energy industry. It is hoped that the current mapping efforts by the USGS may help to clearly define the nomenclature as well as the extent of the coalbeds.

Some correlations have been made recently between some of the coal fields. Glass (1976) has shown in a fence diagram the current understanding of the eastern and western coal fields of the Wyoming portion of the basin (Figure 4-5), Mapel and Swanson (1977) have correlated the coal fields of the Montana portion, and Olive (1957) presents a very general correlation between the Montana and Wyoming coal fields (Figures 4-6 and 4-7). The coals of the southern Powder River Basin, however, have not been correlated positively with each other, or with coalbeds to the north. In order to simplify the discussion of the coalbeds, we have divided the Powder River Basin into the four sections shown in Figure 4-2. Each will

be discussed separately, and when correlations between these sections have been made, it will be pointed out.

There are 14 operating coal mines in the Powder River Basin. Twenty more are in various stages of permit and construction (Table 4-5). Most of these mines are in the Gillette and Sheridan areas of Wyoming (Figure 4-8). There are 19 proposed and existing mines along the north-south trend of the Wyodak-Anderson coalbed in Campbell County.

This was not intended to be an exhaustive compilation of literature available on the coalbeds. It does, we hope, summarize the general character, extent, and quality of the coals. Since most studies in the Powder River Basin have been directed toward defining the strippable reserves of coal, detailed information on the deeper coalbeds is somewhat lacking. We have included what information on these as was available.

#### 4.2.1 Eastern Coal Fields

Coal fields here grouped into the eastern field include the Gillette, Pumpkin Buttes, Powder River, Little Powder River, and Spotted Horse (Figure 4-4). These fields, mostly in Campbell County, are grouped together because they all lie along the central portion of the very gently dipping eastern limb of the asymmetrical syncline containing the non-marine, coal-bearing strata of the Fort Union and Wasatch Formations (Figure 3-8). Regional dip of these beds is only 0.4 degrees to the west, as measured along a 25-mile east-west section of the Wyodak coalbed (contact between the Fort Union and Wasatch Formations in recent USGS mapping). Because of small folds within Fort Union and Wasatch strata, dips generally in the range of 2 to 4 degrees occur locally, however, in individual coalbeds.

In the U. S. Geological survey bulletins, where the five coal fields comprising the eastern fields of Powder River Basin are principally described, coalbeds identified and discussed are as follows, with the youngest beds being first:

##### o Spotted Horse Field (Olive, 1957)

Eleven names beds - ULM No. 1, ULM No. 2, Scott, Felix, Arvada, Roland, Smith, Anderson, Dietz No. 1, Canyon and Wall.

- o Pumpkin Buttes Field (Wegemann, et al, 1928)

Eight named beds - A through H.

- o Gillette Field (Dobbin & Barnett, 1927)

Nineteen named beds, as composited Trim exposures in the northern, central, and southern parts of the field - A through S.

- o Little Powder River Field (Davis, 1912)

Ten named beds - A through J.

- o Powder River Field (Stone & Lupton, 1910)

Five names beds - Lower Ulm, Felix, Arvada, Roland, and Smith.

In the above reports, letter names of beds are restricted to the individual field, and are not directly correlative -- A for A or B for B -- to other fields. For example, Felix bed which has its type locality in the Powder River Field, is B bed in the Gillette Field (Dobbin & Barnett, 1927) and E bed in the Pumpkin Buttes Field (Wegemann, et al, 1927).

In current mapping by the U. S. Geological Survey in Campbell County, still a different nomenclature set has been devised. In a 25-mile east-west section in the Caballo Creek area south of Gillette, Grazis (1977) has identified from drill hole data the following 25 beds, including splits (youngest listed first): A, Lower Ulm, Scott; F or Felix (splits  $F_1$  &  $F_2$ ); C", C', C, Wyodak (splits  $W_1$ ,  $W_2$  &  $W_3$ ), N, O, P (splits  $P_1$  &  $P_2$ ), Q, 8, (splits  $S_1$  &  $S_2$ ; T, U, V, and X (splits  $X_1$  and  $X_2$ ).

Stratigraphic columns for coalbeds occurring in Campbell County coal fields, recently compiled by the Wyoming and U. S. Geological Surveys are shown in Figure 4-9. Typical cross sections through the Wasatch and Fort Union coalbeds are shown in Figure 4-10. A typical log response is shown in Figure 4-11, and average analyses of coal samples from Campbell County are given in Table 4-6. The thicknesses and characteristics of some of the Fort Union coalbeds compiled from 7 recent U. S. Geological Survey quadrangle maps is given in Table 4-7.

#### 4.2.1.1 Principal Wasatch Coalbeds

Ulm No. 1 Bed. The Ulm No. 1 bed, originally names by Taff (1909) in the Sheridan Field, is stratigraphically the highest of the named coalbeds

in the eastern coal fields. Ulm No. 1 is identified by name by Olive (1957) as occurring at only one location in the Spotted Horse Field. This one remnant that has escaped erosion occupies an acre of land on top of a high butte in the southern Part of the field (Sec. 14, T53N, R75W). Here, the bed is 11 feet thick.

A bed, about 2 feet thick, correlative to Ulm No. 1, occurs in a small area on the divide between Powder and Belle Fourche Rivers in the Pumpkin Buttes Field. Wegemann, et al, (1928) identified this bed as A bed in the sequence of eight beds (A-H) they described for the Field. Graziis (1977) describes a similar 2-foot thick bed as being the highest bed, both stratigraphically and topographically, in the Caballo Creek area southwest of Gillette (Pleasantdale quadrangle). To the west, Ulm No. 1 evidently thickens gradually to where it becomes an important economic bed in the Sheridan and Buffalo fields.

Ulm No. 2 Bed. Ulm No. 2 bed, described in Olive for occurrences in the Spotted Horse Field, is 75 feet below Ulm No. 1. The bed crops out near the tops of divides in the southern portion of the field. In many places the bed has burned, forming a thick erosion-resistant clinker cap for many of the highest ridges and buttes. Where unburned, the bed ranges in thickness from 4 to 22 feet; an average thickness is probably about 12 feet in the Spotted Horse Field.

South of the Spotted Horse Field, coalbeds in the Powder River and Pumpkin Buttes Fields, occurring at the same stratigraphic horizon as Ulm No. 2, are identified as the Lower Ulm and B beds, respectively. As in the spotted Horse Field, the Lower Ulm occurs high on buttes and divides, is commonly burned, and the resulting clinker caps the ridges. In the Powder River Field the Lower Ulm ranges in thickness from 10 to 15 feet. In the Pumpkin Buttes Field the correlative B bed -- which lies 80 to 100 feet below A bed -- ranges from 6 to 11 feet and averages 10 feet in thickness. To the west, Ulm No. 2 correlates with the Healy bed in the Sheridan-Buffalo areas.

Haddock, Kent and Bohor, 1976, identify two new coalbeds, the Truman and Parnell beds which crop out in the Croton and Truman Draw Quadrangles. The Truman bed is 4 to 20 feet thick in 1 or 2 benches. The Parnell bed splits from the base of the Truman bed near the Parnell Ranch and is

thought to be equivalent to the Ulm No. 2 of the Sheridan Field. It contains 2.7 to 12 feet of coal in 1 to 4 benches, and is as much as 80 feet below the Truman bed.

Scott Bed. The Scott bed has its type locality in the southern part of the Spotted Horse Field (NE1/4, Sec. 14, T53N, R74W) about one mile northwest of the Scott homestead, for which it is named. The bed, about 65 feet below Ulm No. 2, is persistent throughout the southern part of the field. Average thickness is less than 4 feet; maximum thickness in the field is 10 feet.

To the south, in the Pumpkin Buttes Field, Wegemann, et al (1928), describe the outcrops of C bed -- correlative to the Scott bed -- in T47N, R74W, as comprising two benches of coal, each about 2 feet thick, separated by thin shale parting. Grazis (1977) identified the Scott bed in a drill hole in the Gaballo Creek area (west edge of the Pleasantdale quadrangle) as being 7 feet thick.

The three beds -- Ulm No. 1, Ulm No. 2, and Scott -- are referred to as the upper Wasatch coal zone.

The Daly coalbed was named by McLaughlin and Hayes (1973) for exposures in the Olivia NW (Townsend Spring) quadrangle, where it is 50 to 150 feet below the Scott bed. It is a zone with as many as 6 separate benches of coal, containing a total of 1.4 to 12.4 feet of coal. Partings between the benches are as much as 8 feet thick but usually less than 2 feet.

Felix Bed. The Felix bed, including its two principal benches or splits, is the middle Wasatch coal zone. For much of the eastern coal fields area, it comprises the principal coal resource of the Wasatch formation. The bed was named by Stone and Lupton (1910) for a thick exposure in a stream bed at Felix, a station on the Burlington Railroad.

In exposures available to Stone and Lupton, in the Powder River Field, the Felix was indicated to comprise from two to four benches with total coal thickness of 6 to 30 feet. To the north, in the Spotted Horse Field, Olive (1957) stated that the Felix has an average thickness of 15 feet and a maximum thickness of 33 feet. In the Gillette Field, Dobbin and Barnett (1927) showed the B, or Felix, bed gradually thickening across the field

from the south to north, with thickness ranging in the south from 1 to 14 feet, in the central portion of the field from 5 to 15 feet, and in the north from 4 to 21 feet. Glass (1978), however, evidently based on recent data available from mining operations and drill hole logs, states that bed thicknesses as great as 50 feet occur in the southern Gillette Field.

In the Caballo and Hoe Creeks area, about 20 miles south of Gillette, Graziis (1977) describes the Felix bed as occurring mostly in two benches,  $F_1$  and  $F_2$ . The upper bench,  $F_1$ , ranges in thickness from 5 to 12 feet and averages 20 to 25 feet. The parting separating  $F_1$  and  $F_2$  ranges from 0 to 80 feet; Where the parting is absent and the two benches are coalesced into a single bed, the Felix is referred to as the F bed by the USGS. It is the Felix bed on Hoe Creek that is utilized for the Lawrence Livermore Labs experiments in underground gasification.

The Felix in outcrops south of Gillette is 60 to 100 feet below Ulm No. 2 (Graziis, 1977); to the north in the Spotted Horse Field, it is 190 feet below the Scott at the Scott's type locality, and 280 feet below the Scott, a few miles to the west (Olive, 1957).

C Bed(s). The C bed coal zone comprises the lower of the three coal zones of the Wasatch Formation. The C bed was named by Dobbin and Barnett (1927) for exposures in the Gillette Field and was stated by them to consist of a series of individual coal lenses separated by numerous shale partings. The most definitive description of this coal zone is by Graziis (1977) from surface and subsurface data in the Caballo Creek study area. Here, three beds of economic value occur -- the C", C' and C beds, with C" being the uppermost. The C" bed is 100 to 350 feet below the Felix; C' is 80 to 90 feet below C"; and C -- the most valuable of the three beds -- is 60 to 160 feet below C'. As throughout the entire coal-bearing stratigraphic section, along the eastern line of the basin, non-coal intervals both between and within coal zones thicken to the west, towards the basin center.

Within the four-quadrangle Caballo study area (from east to west; Saddle Horse Butte, Gap SW, Scaper Reservoir, and Pleasantdale) bed thickness ranges from 0 to 6 feet and averages 3 feet for C" and ranges from 0 to 14 feet for C'. The C bed within the quadrangle area has a maximum thickness of 42 feet; however, only 4 to 5 miles to the west,

subsurface data show the bed to be 75 feet thick (Secs. 12 & 13, T47N, R75W; Double Tanks quadrangle). Depth of overburden for C bed within the four-quadrangle area ranges from about 100 feet on the east, to 1350 feet on the west. An analysis of a drill core sample of C bed on an as-received basis, is: moisture, 9.7 percent; volatile matter, 39.6 percent; fixed carbon, 42.8 Percent; ash, 7.9 percent; sulfur, 1.4 percent; and heating value, 10,500 Btu/lb (Grazis, 1977).

#### 4.2.1.2 Principal Fort Union Coalbeds

Arvada bed. The Arvada bed is placed by Olive (29(1957) within the Wasatch Formation, a few feet above its base. The Wyoming Geological Survey, however, identifies the Arvada as the uppermost bed within the Fort Union Formation (Breckenridge et al, 1974, Figure 4-9; Glass, 1976, Figure 4-5). Evidence for placing the Arvada within the Fort Union is that the unconformity which separates Fort Union from Wasatch strata, cuts the Arvada bed. The Wyoming Geological Survey stratigraphic placement will be accepted in this report. The bed was named by Stone and Lupton (1910) for a small coal mining operation at Arvada, on the Powder River Field, the Arvada is underlain by a fossiliferous sandstone, abundant with gastropods, which acts as a marker for the Arvada. Stone and Lupton (1910) traced the Arvada through outcrops along the Powder River, Clear Creek, and Wildhorse Creek, with average thicknesses ranging from 5 to 10 feet; the Arvada is placed by Stone and Lupton as being 375 to 400 feet below the Felix.

Roland bed. The Roland bed has been positively identified only in the Spotted Horse Field in the eastern coal fields. In the Spotted Horse Field, the Roland is 65 feet below the Arvada bed, is quite lenticular, and has a maximum thickness of 6 feet (Olive, 1957). The bed occurs mostly in the area west of Powder River and Clear Creek. The bed thins to the east, but thickens to the west to become economically important in the Sheridan Field.

The Roland bed has been the subject of several misidentifications or correlations in the older literature. Stone and Lupton (1910) miscorrelated a local bed in the Powder River Field with the Roland (Olive, 1957). A major misidentification that has caused much confusion throughout the years, was by Dobbin and Barnett (1927) when they miscorrelated D bed (the

Anderson, Wyodak-Anderson, or Wyodak bed) of the Gillette Field with the Roland.

Smith bed. The Smith bed, occurring principally in the Spotted Horse and western Little Powder River Fields, is about 180 feet below the Roland bed (Olive, 1957). The bed, where present in these fields, mostly ranges in thickness from 5 to 12 feet. The Smith bed was miscorrelated with the stratigraphically lower Canyon bed of the Gillette area for many years (Glass, 1978).

Swartz bed. The Swartz bed is shown in three recent quadrangle maps by the USGS in the southern part of the Spotted Horse Field. It is combined with the Anderson bed in the east portion of the field and separates to as much as 500 feet above the Anderson westward. In the three quadrangle area, it is 9 to 35 feet thick.

Anderson bed. The Anderson is the most persistent and widespread coalbed in Powder River Basin. It is most prominently developed along the eastern rim of the basin, in Campbell County. Elmer Schell (Area Geologist, USGS Conservation Division; personal communication) stated that he has personally traced the continuous outcrop line of the Anderson from the Montana-Wyoming border southward for over 120 miles. For part of this area, the Anderson coalesces with the underlying Canyon bed to form the thick Wyodak, or Wyodak-Anderson, bed centered at Gillette. The Wyodak bed is discussed separately, following the Canyon bed.

To the west, the Anderson -- or beds correlative to it -- has been traced through drill hole geophysical logs to the deep, central portions of the basin. In the Sheridan Field on the western portion of the basin, the Anderson is correlated with the Dietz No. 1 bed, or to the bed immediately above it. In the northern extension of the Sheridan Field in the Decker area of Big Horn County, Montana, the Anderson is identified as a separate bed above Dietz No. 1. A few miles northwest of the Decker Mine, the Anderson, Dietz No. 1 and Dietz No. 2 all combine to form a superbed 80 feet thick.

In the Spotted Horse Field, the Anderson, an average 160 feet below the Smith bed, ranges in thickness mostly from 6 to 32 feet, where unburned. The bed averages 15 feet in thickness and contains the largest

reserves of any bed the field (Olive, 1957). Over much of the north-central and north-eastern portion of the field, the Anderson is burned, producing a clinker bed as much as 100 feet thick.

In recent U. S. Geological Survey mapping in 7 quadrangles of the Spotted Horse and Powder River Coal Fields, the Anderson ranges from 5 to 42 feet thick, and averages 20 to 33 feet thick (Table 4-7).

Dietz bed. The Dietz bed is as much as 200 feet below the Anderson in 7 recent quadrangle maps. In places the Dietz is combined with the overlying Anderson or underlying Canyon, or both. Where separate, it ranges from 6 to 46 feet in thickness. In the Spotted Horse Field, Olive (1957) describes it as a series of discontinuous lenses.

Canyon bed. The Canyon coalbed is persistent over all but the southern and western edges of the basin and is as much as 225 feet below the Dietz in 7 recent USGS quadrangle maps. It is the lowest of the beds that coalesce eastward to form the Wyodak "superbed". Where separate, the Canyon coalbed is 5 to 98 feet thick, lenticular, and consists of 1 to 4 benches with thin partings of shale. The Canyon bed is correlated with the E bed of the southern part of the Gillette Field and with the Dietz No. 3 bed (Taff, 1909) of the Sheridan Field.

Wyodak bed. In this report, the Wyodak, or Wyodak-Anderson, bed is restricted to that area within which the Anderson bed coalesces with the underlying Canyon to form the classic "superbed" of the Gillette area. The bed is named after the Wyodak Mine, located 4.5 miles east of Gillette -- Wyodak being a contraction of the state names Wyoming -- Dakota.

To the north of the Gillette area, the Wyodak is thought to split into at least five beds, each ranging in thickness from 5 to 31 feet, and each being separated by shale or claystone partings that individually range in thickness from 4 to 33 feet (Glass, 1978). The Anderson would be the uppermost of these splits. To the south, the Wyodak splits into two beds -- the upper bed being the Anderson, or D bed of Dobbin and Barnett (1927), and the lower bed being the Canyon, or E bed of Dobbin and Barnett. To the west, Glass (1978) describes the Wyodak as splitting into two beds -- the Anderson and Canyon -- with each bed being 10 to 65 feet thick. In recent mapping by the U. S. Geological Survey in the Caballo Creek study area

south of Gillette (Grazis, 1977), the Wyodak, when coalesced into a single bed, is designated the W bed. Where it separates, three principal splits are designated  $W_1$ ,  $W_2$ , and  $W_3$ , with  $W_1$  being uppermost and  $W_2$  being the thickest and most persistent bed.

Wyodak bed thickness probably averages about 70 feet throughout the Gillette region where the Anderson and Canyon are coalesced, with minimum thickness being about 25 feet (Glass, 1978) and maximum thickness being about 150 feet (Averitt, 1975). The Wyodak, in most places, contains a parting that represents the Anderson-Canyon contact; the parting commonly is about 8 inches thick and about 38 feet above its base (Glass, 1978). At the Wyodak Mine, the bed averages 90 feet in thickness and has approximately 50 feet of overburden. At the Belle Ayr Mine, 15 miles southeast of Gillette, the bed has an average thickness of 70 feet, and only a few feet of overburden.

In an area of about 800 square miles, (40 miles N-S and 20 E-W) centered on Gillette, thickness of the Wyodak has been mapped from bore hole geophysical logs (Denson and Keefer, 1974). Within this area the Wyodak is calculated to contain 41 billion tons of coal, with 7 billion being within stripping depths; i.e., within 200 feet of the surface. Averitt (1975) estimates that the Wyodak, along with the Anderson bed to the north and south of Gillette, conservatively contains over 100 billion tons of coal. This makes the combined Wyodak-Anderson the largest deposit of coal, in a single continuous bed in the United States, and one of the largest in the world. Once the full extent of the bed is known -- in its extensions westward to basin center in the Sheridan and Buffalo fields and northwestward to the Decker Mine area in Montana -- resource tonnage values will be increased substantially even above these figures.

Cook bed. The Cook coalbed is 25 to 350 feet below the Canyon in 7 recent USGS quadrangle maps. It is 3 to 45 feet thick in 1 or 2 benches.

Wail bed. The Wail coalbed is 40 to 200 feet below the Canyon in the Spotted Horse Field (Olive, 1957). It occurs as 1 to 4 beds containing a total of 3 to 66 feet of coal. Average coal thickness is generally 9 to 38 feet (Table 4-7).

Pawnee beds. The Pawnee occurs as one or two beds 800 to 1700 feet below the Wall bed. The two Pawnee beds are 80 to 170 feet apart. The Upper Pawnee is 4 to 36 feet thick and may be split into two benches. The Lower Pawnee is 3 to 17 feet thick, and is less extensive than the Upper Pawnee.

Cache bed. The Cache coalbed is 500 to 1800 feet below the Pawnee. It occurs in 1 to 2 benches totalling 4 to 33 feet in thickness. The Cache coalbed is 100 to 2200 feet below the surface in southern Campbell county, and is the lowest named coalbed in the area. Recent quadrangle mapping by the USGS shows as many as 6 unnamed beds each 3 to 4 feet thick in a 300 to 400 foot section below the Cache (Table 4-7).

#### 4.2.2 Western Coal Fields

The western Powder River Basin region includes the Sheridan, Buffalo, Barber, and Sussex Coal fields (Figure 4-2). In this region, as many as 11 persistent coalbeds occur in the Wasatch Formation of Eocene age and as many as 12 coalbeds occur in the upper-half of the Fort Union Formation of Paleocene age. Stratigraphic columns for coalbeds in Johnson and Sheridan Counties are shown in Figures 4-12 and 4-13. Coals also occur in the lower-half of the Fort Union, but are thinner and less persistent. Very thin and discontinuous coal lenses occur in the Lance Formation of Cretaceous age.

The coal fields of this region form a part of the western margin of the Powder River Basin. The major structural configuration is one of an asymmetrical syncline or trough, trending NW-SE, parallel to the Bighorn Mountain front, steeply dipping on the west flank, and dipping gently ( $1-4^{\circ}$ ) on the east side. The deepest point along the axis is situated near Kaycee, 40 miles south of Buffalo in the Sussex coal field. However, during Tertiary time, when most of the coalbeds were formed, the point of greatest subsidence and deposition was the Buffalo Lake De Smet area (Obernyer, 1979).

Major tectonic events of the Laramide Orogeny are evident in this region. During early Tertiary time, block faulting of the Precambrian basement rocks, gave rise to the Bighorn Mountains on the west and the formation of the Powder River Basin on the east. At the same time, the overlying Paleozoic sediments were drape-folded over the more rigid Precambrian blocks. Foster, Goodwin and Fischer (1969) have suggested that a nearly vertical subsurface fault extends along the mountain front from the Casper Arch to Sheridan, with a maximum vertical displacement near Buffalo of 4000 feet. In addition, several local flank thrust faults occur along the eastern margin of the Big Horn Uplift. One of these, the Poney Creek Thrust, resulted in the formation of conglomerates of the Moncrief Member of the Wasatch Formation near Buffalo. Obernyer (1978) suggests that the very large Lake De Smet coalbed, which is a thick linear bed parallel to and near the Bighorn Uplift, may have been controlled by a basement fault, active during Eocene time.

The coals of the Wasatch Formation are lower subbituminous C to upper lignite in rank. Fort Union coals are only slightly better in quality and are generally ranked subbituminous C. Typical analyses of these coals are shown in Tables 4-8, 4-9 and 4-10.

There are three existing coal mines in the western Powder River Basin. The Black Mountain Mine is a 3 man-locally owned and operated mine near Sheridan. The Ash Creek Mine is a strip mine scheduled to begin operation sometime this year, 15 miles north of Sheridan. The Big Horn Strip Mine is located 8 miles south of Sheridan and produces 3.0 million tons a year. The Fort Union Monarch and Dietz No. 3 beds coalesce at the Big Horn Mine to form a bed 44 feet thick which is being mined together with the overlying 12-foot thick Dietz No. 2 bed. At least 3 other mines have been proposed for the Sheridan Coal Field; Texaco, Inc., has tentative plans for a coal gasification project on the Lake De Smet bed in the Buffalo Field.

#### 4.2.2.1 The Wasatch Coalbeds

The total number of coalbeds in the Wasatch Formation is difficult to determine, because the beds split, coalesce, and are sometimes discontinuous, with beds pinching out and new beds appearing. The coals are generally subbituminous C or in the upper lignite range. Much of the Wasatch coals are under less than 200 feet of overburden, although some may be appreciably deeper. Maximum thickness of the Wasatch Formation is 1500 feet in the Buffalo-Lake De Smet area.

Monument Peak. Monument Peak is the highest thick coalbed in the region. It is about 800 feet above the base of the Wasatch Formation, and is 10 to 20 feet thick where it is present north of Lake De Smet in the Buffalo Coal Field (Figure 4-12).

Walters, Healy, Cameron, Murray and Ucross. The next 5 stratigraphically lower major coalbeds of the Buffalo Coal Field, the Walters, Healy, Cameron, Murray, and Ucross, are thought by Obernyer (1978) to be the eastward splits of the Lake De Smet coalbed (Figures 4-12 and 4-14). The Walters bed is 150 to 175 feet below the Monument Peak. It is tentatively correlated by Culbertson and MaPel (1976) with the Uim No. 1 bed in the Sheridan Field. These beds are extensively burned over most of the area, but are 14 to 52 feet thick where they remain, and are split by many small

partings of shale. Obernyer (1979, p 63) has identified the Walters as the uppermost coalbed correlatable with the Lake De Smet bed to the west. The Healy coalbed is 6 to 200 feet below the Walter and Ulm 1. It varies from 7 to 30 feet in thickness, although the Lake De Smet bed, which is also called the Healy bed in some reports, is locally up to 250 feet thick in the Lake De Smet area. The upper portion of the Healy bed is extensively burned. The Shuman and Timar coalbeds are local and discontinuous. The Shuman contains as much as 9 feet of coal about 10 miles northeast of Buffalo. The Timar bed contains as much as 8 feet of coal at a location a few miles southeast of Buffalo. The Cameron zone is 90-130 feet below the Healy bed, and is composed of two coalbeds. The upper one is 4 feet thick at several places and is as much as 7.5 feet thick north of Lake De Smet. The lower Cameron bed consists of one or more lenticular beds of coal 3 to 35 feet below the upper bed. Coal is as much as 19 feet thick in this zone. The Dry Creek bed is a local lense of coal as much as 9 feet thick about 8 miles east of Buffalo. Elsewhere, this stratigraphic interval is carbonaceous shale with thin seams of coal. The Murray bed is 180 to 200 feet below the Healy. Coal in the Murray bed is 4 to 10 feet thick, and separated by 1 to 6 feet of shale. The Murray coalbed grades laterally into carbonaceous shale. The Ucross bed is 80 to 110 feet below the Murray bed. It extends from the Buffalo Field as far south as the northern Part of the Sussex Field, and is the lowest persistent coalbed in the Wasatch Formation in that area. In the area north of Lake De Smet, it consists of a 40 foot zone of carbonaceous shale containing discontinuous lenses of coal at several horizons. The bed contains as much as 23 feet of coal in several benches near Box Elder Creek. Culbertson and Mapel (1976) have correlated the Ucross with the PK bed in the Sheridan Field. The PK bed is named for the PK Ranch in Wyarno quadrangle and averages 4 to 18 feet thick. The PK bed is locally split into three benches in an interval about 30 feet thick. The main coalbed in the PK zone has been burned along most of its outcrop. Local beds of this same stratigraphic interval (Ulm - PK) in the Sheridan Coal Field include the Upton Gulch, Dow and Arkansas beds (Figure 4-15). The Upton Gulch bed is a local lense of coal as much as 8 feet thick, 10 to 50 feet below the Ulm No. 2 bed, about 20 miles east of the town of Sheridan. The Dow bed is locally up to 10 feet thick in a small area 10 to 15 miles southeast of Sheridan. The Arkansas bed is a 10

to 50 foot zone of carbonaceous shale containing several beds and seams of coal, 2 to 10 feet thick. It is named for the Arkansas Creek in the Jones Draw quadrangle. The coals in this zone have a maximum combined thickness of 15.3 feet, about 20 miles southeast of Sheridan.

Lake De Smet Bed. The Lake De Smet bed (Figure 4-14) is thought to be the thickest coalbed in the U.S. and the second thickest in the world (Texaco press release, 1975; Obernyer, 1978). It is a linear bed, parallel to and near the Big Horn Mountains in the Lake De Smet area. It is 15 miles in length, 70 to 250 feet thick, and 0.5 to 2 miles wide. Many thin lenticular partings of sandstone and shale occur in the coal, and become more abundant to the west. The western boundary of the coal is relatively sharp; however, to the east the Lake De Smet bed splits into the 5 coalbeds previously discussed. The partings between these beds, which average a few feet to over 200 feet in thickness develop to their average thickness in a distance of only 20 to 500 feet. The environment of deposition of the Lake De Smet bed is described in more detail by Obernyer (1978, 1979). Obernyer (1978) states that the coalbed's orientation parallel to and near the Bighorn Uplift and its great thickness in a region otherwise characterized by abundant high energy input during the sedimentation process may have been controlled by a basement fault, active during Eocene time. Obernyer also has computed that based on an average accumulation of peat of 0.5 feet per century, that the life span of the Lake De Smet coal swamp was 100,000 to 200,000 years.

Lake De Smet occupies a basin which is thought to have formed by the burning of the Lake De Smet coalbed. The lake basin is 3 miles long, 1 mile wide and 60 feet deep.

Bar N, Burgess, Heppner, and Wyarno. Four small coal zones occur near the base of the Wasatch Formation in the Sheridan Coal Field and have been described in Cuibertson and Mapel (1976). They are the Bar N, Burgess, Heppner, and Wyarno (Figure 4-13 and 4-15). The Bar N zone is named for the Bar N Draw in the Bar N Quadrangle and consists of 2 to 3 beds in a zone 30 to 50 feet thick. The maximum combined thickness of coal is 11.9 feet and occurs in an area about 15 miles northwest of the town of Sheridan. The Bar N coal zone is persistent over most of the area north and west of Sheridan in the Sheridan Coal Field. The Burgess zone is named

for the Burgess Ranch in Wyarro and Bar N Draw quadrangles and contains two beds about 5 to 8 miles west of Sheridan. The two beds are locally over 5 feet thick and are separated by 15 to 35 feet of shale. The Heppner bed is a 4 to 6 foot thick coalbed in a small area about 6 to 10 miles west and northwest of Sheridan. It is named for Heppner Draw in the Bar N Draw quadrangle. The Wyarro coal zone is about 650 feet above the base of the Wasatch at the Wyarro Post Office from which it gets its name. It is the lowest persistent coalbed in the Wasatch formation in the region, and consists of 30 feet of carbonaceous shale, with interbedded coal as much as 10.5 feet thick. All four of these beds thin and pinch out southeastward from the Sheridan area.

#### 4.2.2.2 The Fort Union Coalbeds

The coalbeds of the Fort Union Formation are deeply buried in the Buffalo and Barber coal fields and have not been identified in those places. A few small beds near the top of the Fort Union are identified in the Sussex Field to the south, where they are designated by the letters "A" through "H" (Figure 4-12). These are thought to occur in the stratigraphic interval between the Roland and Anderson coalbeds, although they have not been correlated positively. In the north part of the region, in the Sheridan Field, several coalbeds are described by Taff (1909) in the uppermost 2000 feet of the Fort Union Formation. Some of these Fort Union coals are identified in recent maps, coal sections and electric log correlations. A reference list of these maps is included in Appendix C of this report.

Roland of Baker (1929). The uppermost Fort Union coal in the Sheridan Field is the Roland bed of Baker (1929). It is persistent over most of the Sheridan Field and ranges from 4 to 29 feet in thickness. It is used in many reports as the boundary between the Fort Union and Wasatch Formations. Figure 4-16 is an electric log correlation section showing the typical response of the Roland and several other Fort Union coalbeds.

Roland of Taff (1909). The Roland bed of Taff (1909) which was mined locally by a Mr. Rolend, 1 to 2 miles southwest of Monarch is stratigraphically below the Roland bed of Baker (1929). It has been identified in recent mapping in T57-58N, R83-84W, north of Sheridan, and ranges from 2 to 13 feet thick. According to Taff (1909), it thins out to the south.

Smith. The Smith bed is named for the Smith Mine, one mile southeast of Dietz here it was mined locally in the early 1900's. The Smith bed has been tentatively identified in recent mapping in T56-57N, R80-84W where it is 5 to 19 feet thick, 90 feet below the Roland of Taff (1909) and 110 to 320 feet below the Roland of Baker (1929).

Anderson. The Anderson coalbed is tentatively identified in some of the recent mapping of the Sheridan Field in T56-58N, R80-83W where it is 5 to 28 feet thick and 70 to 210 feet below the Smith bed. It is equivalent to the Dietz No. 1 of Taff (1909).

Dietz. Three Dietz beds are recognized in the Sheridan region, and were named by Taff (1909) for their proximity to the town of Dietz. Dietz No. 1 of Taff (1909) is equivalent to the Anderson bed, and Dietz No. 2 and 3 of Taff (1909) are referred to as Dietz No. 1 and 2 (below the Anderson) in some recent literature (Matson and Pinchock, 1976; Mapel, 1976). Other recent reports and maps (Glass, 1978; and Culbertson and Klett, 1975 a, b) use the combination Anderson-Dietz 1 - Dietz 3. To compound the terminology problem, in some reports the Dietz No. 3 is correlated with the Canyon coalbed (Glass, 1978; Olive, 1957) and in other reports (Matson and Pinchock, 1976; Culbertson, 1975 and Mapel, 1976) the Canyon is shown stratigraphically below the Dietz No. 3. At any rate, as many as 4 major coalbeds occur within a stratigraphic interval of 300 to 420 feet in the Sheridan Field, and these coalesce eastward to form the thick Wyodak-Anderson coalbed of the Gillette Coal Field. In the Sheridan Field, these separate beds are each 5 to 30 feet thick.

Monarch. The Monarch is the thickest coalbed in the Sheridan Field. It averages 5 to 25 feet thick and is burned in many places. It is shown to be 47 feet thick in a drill hole near Ranchester, Wyoming (Barnum, 1975) and is as much as 57 feet thick in other places, although it is sometimes combined with the Dietz No. 3 bed (Glass, 1978). The Monarch is correlated with the Wall bed to the east. The Wall bed is shown in recent maps in R56-58N, R80-83W where it ranges from 3 to 30 feet thick and is 100 to 200 feet below the Canyon bed.

Carney. The Carney coalbed is described by Taff (1909). It occurs about 100 feet below the Monarch in the towns of Carneyville and Monarch. It is described as occurring in two benches, 4-10 feet thick and separated

by 1 to 4 feet of shale. Coalbeds occurring at this stratigraphic level in recent mapping in the Sheridan Field have not been correlated positively with named beds.

Masters. The Masters coalbeds occur about 86 feet below the Carney beds. According to Taff (1909), they consist of two coalbeds, each 6.5 feet thick, and separated by 2 to 3 feet of shale in T57N, R85W. As with the Carney, the coalbeds shown at this stratigraphic interval in recent maps have not been correlated with the named beds.

Roberts. The Roberts bed is the lowest coalbed shown in recent quadrangle maps in T56N, R80-82W. The Roberts is about 450 to 600 feet below the top of the Lebo Shale Member of the Fort Union Formation and is 1150 to 1300 feet below the Wall (Monarch) bed. It is 13 to 31 feet thick (Culbertson and Klett, 1975 a, b).

Coal in the Sussex Field. The Sussex Field is situated south of the Buffalo and Barber Coal Fields. Several Fort Union coalbeds have been identified by Wegemann (1912) and they are thought to occupy the approximate stratigraphic interval between the Roland and Anderson beds, although correlation of these beds with those of other fields, generally have not been made as there has been no recent geological work done in this region. Wegemann (1912) found that the coals of this area crop out in 6 separate areas, and he concluded that these areas represent basins of deposition which were not necessarily connected with each other. The "basins" occur along the western margin of the Powder River Basin and are numbered 1 through 6 from north to south.

The northernmost basin ("basin No. 1") contains several occurrences of coal thought to be in the Lance Formation. They range from 15 to 32 inches in thickness; although a coalbed is locally 54 inches thick in sec. 10 T37N R78W. "Coal basin 2" is located south of the first one. It contains a group of Fort Union coals referred to as A-H. They range from a few inches to as much as 6.5 feet in thickness. The E bed is the most extensive in this area and ranges from 20 inches to 46 inches in thickness. Bed F, which is 19 to 36 inches thick is thought to be equivalent to the F bed in the Dry Cheyenne and Gillette Fields to the east. "Basin 3" contains four coalbeds, 20-32 inches thick. At one point, the beds contain a total of 4 feet of clean coal. "Basin 4" is the most important, economically.

It contains two coalbeds which can be traced over most of the "basin." The lower bed averages 11.8 feet in thickness over a distance of 7 to 10 miles. It is up to 50 feet thick in places. The bed thins to 18 to 36 inches in the south and is thought to persist at that thickness for another 8 to 9 miles. The upper bed is thinner as well as irregular in thickness. It is generally 9 to 47 inches thick, and broken with numerous shale partings. "Basin 5" contains one important bed which is 20 inches thick in most places, and up to 55 inches in 4 benches at one locality. "Basin 6" contains two beds, 100 feet apart. The lower bed is generally 24 to 36 inches thick. At one locality, it is as much as 13 feet thick. The upper bed ranges from a few inches to 45 inches thick and is as much as 9 feet thick locally.

#### 4.2.3 Northern Coal Fields

The Northern Powder River region includes all of the Montana portion of the Powder River Basin and contains nine coal fields (Figure 4-4). They are the Rosebud, Forsyth, Tullock Creek, Mizpah, Ashland, Coalwood, Birney, Broadus, Moorhead and North Extension Sheridan. Coal is present in all three members of the Fort Union Formation as well as the overlying Wasatch Formation; however, all of the important coalbeds occur in the Tongue River Member of the Fort Union Formation. A coal deposit location map, stratigraphic correlation charts and typical analyses for the northern fields are given in Figures 4-17 through 4-21, and Table 4-11. There are 6 coalbeds considered to be the most important in respect to the quality and magnitude of the coal reserves that they contain: the Anderson, Dietz, Canyon, Wall, Knobloch and Rosebud. Numerous smaller coalbeds are present locally, but will not be described in detail here. The thickest deposits and best quality coal are found in the Decker area. Four coal mines are presently operating in the northern Powder River Basin area, all of them along the west side of the basin.

The general structural configuration of the northern region of the Powder River Basin in Montana is that of a broad south-westward plunging synclinal fold, the axis of which is generally coincident with the Tongue River Valley (Mapel and Swanson, 1977). Many smaller folds are superimposed on the general basinal structure, and faults with displacements of a few feet to nearly 200 feet are present locally. The faults which affect

the upper part of the Fort Union Formation and the basal part of the Wasatch Formation, generally trend northeastward and may extend for several miles.

The steepest dips are associated with the uplift of the Bighorn Mountains on the west margin of the basin. Dips generally are 1 to 4° out are reported to be as much as 30° E-NE near the southwest corner of the region, adjacent to the Bighorn Uplift. The northwest portion of the region has been influenced by the Big Snowy Uplift resulting in gently southward dipping strata. Between these two uplifts is a southeast trending structural low, in which the rocks have been gently warped and faulted (Baker, 1929; Rogers and Lee, 1923). Rocks along the north margin of the Powder River Basin have been affected by the Porcupine uplift which has resulted in several small faults with throws of about 60 feet. A structural depression or southeastward-pitching trough separates the Porcupine uplift on the north from the Bighorn and Big Snowy uplifts on the west. The rocks within this depression, which may as far south as Ashland, are folded into several small anticlinal and synclinal folds. Nearly all dips are less than 19° (Dobbin, 1929; Bass, 1932). The north-central portion of the region is influenced by the Tongue River Syncline, which is a broad northeast plunging syncline, coincident with the Tongue River Valley, dividing the Black Hills Uplift on the east from the Porcupine Dome on the north. Small faults with displacements of 75 feet or less and gentle dips of 1 to 3° are associated with the syncline. Steeper dips are present, but are thought to be related to slumping of the beds during deposition (Bass, 1932; Pierce, 1936). A low anticline trends eastward across the central portion of the region, crossing Otter Creek. Dips remain relatively flat (1 to 3°) throughout most of the center of the area, although local dips of 20° may occur in areas of slumping where coalbeds have burned. A few widely spaced west-southwest trending faults occur in the central portion of the area (Warren, 1959; Lewis and Roberts, 1978). Along the eastern margin of the basin, the rocks dip due west as much as 75 feet per mile. Some very small local folds and small northeast trending normal faults with throws of 50 to 200 feet are present in the eastern portion of the region (Bryson and Bass, 1973).

Coal in the northern Powder River Region increases in rank from lignite A in the northeastern part of the region to subbituminous south/westward. The coal is non-coking and non-agglomerating, with low ash and low sulfur contents. It loses moisture and slacks when exposed to air. Chemical analyses for the major coalbeds are summarized in Table 4-11.

#### 4.2.3.1 Coal in the Wasatch Formation

Felix and Arvada. The youngest coal-bearing formation in the region is the Wasatch of Eocene age, which is present only in the extreme south and southwest area near the Wyoming border. The basal part of the Wasatch is exposed in that area and contains two relatively small coalbeds: the Felix, which is 250 feet above the Roland (the uppermost coalbed in the Fort Union Formation), and the Arvada, which is 75 to 100 feet above the Roland in the Moorehead Coal Field. Thin lenses of coal are reported to occur in the Wasatch Formation in the northward extension of the Sheridan Field (Bryson and Bass, 1973; Warren, 1959).

#### 4.2.3.2 Coal in the Fort Union Formation

Roland of Baker (1929). The Roland of Baker (1929) is the uppermost coalbed within the Fort Union Formation in this region. It is present in the south-central portion of the area, where it is commonly 5 to 13 feet thick. In many of the older reports on the region, the Roland was considered to mark the contact of the Fort Union with the overlying Wasatch. However, the exact position of the contact is still disputed. About 150 feet below the Roland is the Smith bed. It is present in the southern portion of the region and averages 2 to 3 feet thick.

Anderson. The Anderson is stratigraphically the highest of the important coalbeds, and is about 290 to 370 feet below the top of the Roland coalbed. It ranges from 15 to 80 feet thick and is persistent over most of the southern half of the region. The highest quality coal from the Anderson bed is found at the Decker deposit, where the Anderson combines with the underlying Dietz No. 1 bed to form a seam 50 feet thick. This seam is being mined by the Decker Mining Company at the Decker No. 1 mine. North and east of the Decker deposit, the quality of the coal decreases. West of the Decker area, the Anderson is combined with the Dietz No. 1 and No. 2 beds to form a seam 80 feet thick, but to the east at the Deer Creek

deposit, the three beds are separate, and the Anderson is 20 feet thick. Further east at the Hanging Woman Creek area, the Anderson bed is 15 to 36 feet thick and in the Moorehead coal field, it is 14 to 30 feet thick. To the north, at the Poker Jim Lookout deposit, the Anderson is again combined with the Dietz to form a bed 58 feet thick. The Anderson and Dietz No. 1 beds are thought to be equivalent to the Garfield bed in the north and east portions of the region (Matson and Pinchock, 1976; Mapel and Swanson, 1977).

Dietz. The Dietz No. 1 and No. 2 beds (Dietz No. 2 and No. 3 of Taff, 1909) are major coalbeds in the southern third of the region, lying as much as 250 feet below the Anderson in places on the east side of the Tongue River. Elsewhere, the two beds may be combined with each other, or the top bed or both beds may be combined with the Anderson. Where separate, the beds are each up to 20 feet thick. The best quality Dietz coal is found at the Decker and Kirby deposits, and is being mined along with the Anderson bed at the Decker No. 1 mine. The quality decreases to the east of these deposits (Matson and Pinchock, 1976).

Canyon. The Canyon coalbed is one of the most widespread of the important coalbeds in the region. It is 80 to 200 feet below the Dietz No. 2 bed and is up to 30 feet thick. As with the overlying coals, the quality of the Canyon coalbed is best in the Decker and Kirby areas; although, the largest reserves are present in the West Moorehead and Diamond Butte deposits. At these two deposits, the Canyon bed averages 17 to 24 feet thick and 16 to 25 feet thick, respectively. The Canyon coalbed is not being mined at the present time (Watson and Pinchock, 1976).

Ferry and Cook. Two small coalbeds, the Ferry and the Cook, are identified between the Canyon and underlying Wall coalbeds. The Ferry coalbed consists of discontinuous lenses of coal which are 6 to 17 feet thick at the Three Mile Buttes deposit and 24 feet thick at the Home Creek Butte deposit, where it occurs 76 feet below the Canyon coalbed. The Cook coalbed forms two benches in the Birney-Broadus Field. The upper bench ranges from 0 to 19 feet thick and the lower bench from 5 to 14 feet thick. The parting between them is 12 to 75 feet thick (Matson and Blumer, 1973).

Wall. The Wall coalbed is an important bed, about 180 to 230 feet below the Canyon coalbed. It is thickest and most persistent over the

southwestern portion of the region and it contains some of the highest rank coals in the region. The Wall bed is 50 to 60 feet thick at the Canyon Creek and Kirby deposits. East of the Tongue River-Hanging Woman Creek area, the Wall seems to split into two or more coalbeds.

Several smaller coalbeds are found between the Wall and Knobloch coalbeds. They are, stratigraphically from upper to lower, the Elk, Pawnee, Dunning, E, X, C and D, Brewster-Arnold, Cache, T, Sawyer, and A coalbeds. The Elk, Pawnee, Dunning, Brewster-Arnold and T beds are all found in the Birney-Broadus Coal Field. The Cache and T are in the Moorehead Coal Field, and the E, X, C and D, Sawyer and A beds are in the Ashland Coal Field. There mapped, these beds are 7 to 36 feet thick (Watson and Blumer, 1973; Mape] and Swanson, 1977).

Knobloch. The Knobloch is an important coalbed, 350 to 400 feet below the Wall bed, and is widespread over most of the region. The Knobloch reaches a maximum thickness of 66 feet in the Otter Creek and Ashland deposits, and splits into 3 benches a short distance south of Ashland. The highest quality coal in the Knobloch is in the Poker Jim Creek-O'Dell Creek deposit. More strippable reserves of coal are present in the Knobloch than in any other mapped unit in the Tongue River Member (Matson and Pinchock, 1976; Matson and Blumer, 1973).

One small coalbed, the Lay Creek bed, occurs 30 to 88 feet below the Knobloch in the Mizpah Coal Field where it is 2 to 6 feet thick. It is irregular both in thickness and quality, and may actually be a split off the Knobloch coal bed coalbed (Matson and Blumer, 1973).

Rosebud. The Rosebud is stratigraphically the lowest of the important coalbeds in the region. It is 60 to 80 feet below the Knobloch and 350 feet above the base of the Tongue River Member in the northwestern part of the region. The Rosebud bed is being mined at the Colstrip deposit by Western Energy Company, and at the Big Sky Mine by Peabody Coal Company, and at Sarpy Creek by Westmoreland Coal Company, where it is 15 to 35 feet thick. Its equivalent in the Tullock Creek Coal Field in the northwestern corner of the area is Bed Q. The coal thins southward and eastward. East of the Tongue River, the Flowers-Goodale and Broadus beds are at the approximate stratigraphic level of the Rosebud. The Broadus in the Broadus deposit is 5-26 feet thick. It has been correlated with the 9 to 12 foot

thick Flowers-Goodale bed, 50 miles to the northwest of Broadus (Matson and Blumer, 1973; Matson and Pinchock, 1976; Mapel and Swanson, 1977).

Terret and Dominy. The Terret and Dominy beds occur in the basal portion of the Tongue River Formation. The Terret bed is 45 feet below the Flowers-Goodale bed in the Beaver Creek-Liscom Creek deposit, where it is 6 to 10 feet thick. The Dominy coalbed is in the Miles City Coal Field immediately north of the basin boundary. It consists of two benches, the upper one averaging 19 feet thick and the lower one 6 feet thick (Matson and Pinchock, 1976).

Coal also occurs in the Tullock and Lebo Shale Members of the Fort Union. Usually these beds are less than 3 feet thick, are lenticular, and contain thin partings of shale. The Big Dirty coalbed, at the base of the Lebo Shale Member, is as much as 11 feet thick in places within the Forsyth Field. The Lance Formation and older rocks in the northern region of the Powder River Basin are not considered coal-bearing formations.

#### 4.2.4 Coal Fields of Southern Powder River Basin

Three coal fields are recognized in the southern portion of Powder River Basin -- the Lost Spring, Dry Cheyenne and Glenrock Fields (Figure 4-4). The Dave Johnston Mine, the only operating coal mine in the region, at present, is 14 miles north of Glenrock, in the Glenrock Field. Coal-bearing rocks of this area include the Fort Union and Wasatch Formations of Tertiary age, and the marine Lance and Mesaverde Formations of Cretaceous age. The coal-bearing rocks dip basinward, 15 to 25° around the periphery of the basin, and flatten to 1 to 5° within a few miles of the basin margin. Most of the coal zones have not been correlated, positively, with those of other fields to the north, as there has been very little recent geologic work performed in the area.

Coalbeds of the Dry Cheyenne Field. Dry Cheyenne (Figure 4-2) is a small coal field covering 290 square miles, south of the Gillette and east of the Sussex Fields. Exposed rocks in the field include the Tongue River Member of the Fort Union, and the overlying Wasatch Formation, which generally dip 2 to 4° west toward the axis of the Powder River Basin. Three small synclinal flexures are superimposed on the basin structure. The Dry Fork of the Cheyenne River in the center of the field is coincident

with the axis of a shallow syncline. The outcrops dip about 75 feet per mile toward the river near the junction with Willow Creek. In the southwest corner of the field, the rocks again form a broad open syncline with shallow dips. The axis trends SE-NW and plunges to the north. In the northwest corner of the field, the rocks form a northward pitching syncline with dips of about 100 feet per mile on either side (Wegemann, et al, 1928).

Three coalbeds are exposed in the field; none are mined at the present. The lowest bed, Bed H in the Fort Union Formation, ranges from less than 1 foot to 4.3 feet thick. It is thought to be equivalent to the Roland, or Bed D, of the Gillette Field. Bed G is 220 feet above H in the Wasatch Formation and averages two feet thick. It is thought to be equivalent to the Lower Bed of the Sussex Field. Bed F, 160 feet above G, is lenticular and ranges in thickness from a minimum of one foot to a maximum of 11.5 feet. Bed F is possibly equivalent to the Upper Bed of the Sussex Field and to Bed C of the Gillette Field. All of the coals in the Dry Cheyenne Field are subbituminous. Analyses of coal samples are shown in Table 4-12 (Wegemann, et al, 1928).

Coalbeds of the Lost Spring Field. The Lost Spring Coal Field covers an area of 1,060 square miles. It is situated south of the Gillette Field and east of the Dry Cheyenne Field. The rocks of the Lost Spring Coal Field form parts of the south and east margins of the Powder River Basin. Steep dips occur along the south and southeast margins of the basin, but flatten to nearly horizontal about one mile into the basin. The lower coalbeds dip as much as  $15^{\circ}$ N near Douglass and  $25^{\circ}$ SW near the eastern edge of the field. At the northeast corner of the field, the rocks dip only slightly to the west and strike nearly N-S. A slight anticlinal structure with local dips up to  $5^{\circ}$  is present near the junction of the two forks of Twentymile Creek, about 10 miles northwest of the town of Lost Spring (Winchester, 1912).

The coalbeds of the Lost Spring Coal Field are within the Fort Union Formation, and form two distinct coal-bearing groups, separated by 600 to 700 feet of strata. The beds of the lower group crop out along the south and west margins of the basin. They are all less than 6 feet thick and lenticular. Although there are no active mines producing from these beds

at the present time, several mines have, in the past, operated in an area about 10 miles long, W-NW of the town of Lost Spring. Beds of the upper coal zone crop out in the northern part of the field. The coals of this group are thicker and more persistent than the coals of the lower group. The beds are designated by letters beginning with the lowest (in contrast with most areas of the Powder River Basin). Bed E is the highest and can possibly be correlated with J Bed of the Gillette Field to the north. It has a maximum thickness of 9.6 feet. Bed B is lower and is thought to be equivalent to Bed K of the Gillette Field. Coals of the Lost Spring Field are subbituminous in rank. They are bright, black and hard when fresh, but crumble rapidly when exposed to dry atmosphere for a short time (Berryhill, et al, 1950; Winchester, 1912).

Coalbeds of the Glenrock Field. The Glenrock Coal Field (Figure 4-4) covers an area of 1,500 square miles in Converse and Natrona Counties. South of the Dry Cheyenne and Sussex fields, it is in the southwest corner of the Powder River Basin. Four coal zones are present in the 5800 feet of strata exposed in the field. One mine, the Dave Johnston Strip Mine is operating in the area. The oldest mines in the field, now closed, opened near Douglass in 1883.

The rocks of the Glenrock Coal Field form part of the southern edge of the Powder River Basin where they are folded and faulted near the Laramie Range. Dips in the Lance Formation range up to 35° N-NE just northeast of Glenrock, and up to 70° NE near the town of Cole Creek. The Tullock Member of the Fort Union dips as much as 28° NE at a location about midway between Glenrock and Douglass. Elsewhere dips are variable and decrease away from the basin edge. Near the Dave Johnston Mine, the rocks dip 2 to 7° E-NE (Denson & Horn, 1975).

The lowermost coal zones in the Glenrock Field are the A and B beds in the Cretaceous Mesaverde Formation (Figure 4-22). These coals are 1.8 to 3 feet thick and have been mined only locally (Glass, 1978; Shaw, 1909). Though subbituminous in rank, they are described as blacker, cleaner, more brittle and more lustrous than the overlying coals of the Lance and Fort Union Formations (Shaw, 1909).

The Glenrock-Big Muddy coal zone is 1400 feet above the "A" Bed. It contains two lenticular beds of coal in the basal 200-300 feet of the Lance

Formation. This coal-bearing zone is about 15 miles in length and extends from just east of Glenrock to just northeast of Casper. The coalbeds near Glenrock are up to 6.8 feet thick, and less than 5 feet thick near the town of Big Muddy and Casper. These coals are subbituminous in rank although of slightly better quality than the younger Fort Union coals (Glass, 1968; Berryhill, et al, 1950; Shaw, 1909).

The Douglass-Inez coal zone of the Fort Union Formation is 2500 feet above the base of the Glenrock-Big Muddy zone. The coal-bearing zone is 1000 feet thick and contains two beds, each over 5 feet thick and lenticular, and several smaller beds which are present locally. The two thicker beds are referred to in the more recent literature as the Badger and School beds, and are both thought to be near the top of the Fort Union; although Denson, Dover and Osmonson, 1978, have placed them near the base of the Wasatch Formation. Coal in the school bed is 110 to 180 feet below the Badger, averages 35 feet in thickness, and is subbituminous in rank. It thins to 22 feet thick toward the north, and the quality deteriorates to the south with increasing amounts of shaley partings. The School seam possibly is the equivalent of the Smith coal of surrounding areas. Overlying the School bed is the Badger coal seam, which Duell (1969) tentatively correlates with the Roland bed of the Powder River, Gillette and Sheridan Coal Fields. The Badger, 17 to 20 feet thick, is subbituminous in rank, and improves slightly in quality toward the north with the absence of shaley partings. The coal yields to weathering and deteriorates on exposure. The Badger seam is being stripped-mined along a 12 mile length at the Dave Johnston Mine. Stripping began in 1958; and in 1970, the mine was the nation's largest producer with 1.8 million short tons. The mine is currently producing 3.1 million tons/year, all of which is being shipped 14 miles to the Dave Johnston Power Plant (Wyoming Dept. of Economic Planning & Development, 1978; Duell, 1969; Shaw, 1909; Berryhill, et al, 1950; Miller, 1972). Analyses coal samples from the Glenrock Coal Field are given in Table 4-13 and 4-14. Typical gamma ray logs are shown in Figure 3-23.

## 5. POTENTIAL METHANE RESOURCE

### 5.1 METHANE DATA IN EXISTING REPORTS

#### 5.1.1 Methane Encountered in Shallow Drill Holes

Fifteen shallow drill holes or wells have been identified to date in Campbell County that have anomalously large amounts of methane contained in product fluids. These holes were drilled either as water wells for local use or as shallow investigations of near-surface coalbeds (<500' depth); none were drilled for the much deeper-lying oil and gas deposits of the basin. Fourteen of these wells are in the Recluse area of northeastern Campbell County and define a northwest-southeast trending elliptical area approximately 33 miles long and 16 miles wide, Figure 5-1. The fifteenth well is separated from the above group of wells by a distance of 50 miles; it lies to the south, 25.5 miles south of Gillette. Following is a brief description of these 15 holes.

Holes 1-7. Holes 1-7 were all drilled by the USGS in July and August of 1975 (Hobbs, 1978) to depths ranging between 400 and 500 feet (Figure 5-2). All holes were drilled to penetrate the Anderson and Canyon seams (splits of the Wyodak) and the Cook seam which underlies the Canyon. During drilling, methane content at the drill collar was measured with a hand-held methanometer. Essentially, methane was encountered in all seven holes, starting in sandstone beds just above the top coalbed, and continuing through all coalbeds and interlying sandstone-shale beds, to holebottom. Methane in the gas flow at the collar ranged from as little as 0.1-0.2 percent in shale interbeds, to massive blowouts where gas flow rates were in excess of 1,000,000 cubic feet per day.

Some of the most pertinent data on individual wells are as follows. Hole 6 probably encountered the greatest concentrations of methane of any of the holes. Methane surges occurred when drilling through the Canyon seam and finally below the seam, at a depth of 325', the hole blew out during core retrieval. Gas flow rate was estimated at 1,000,000 cfd, with the gas coming from a soft, poorly cemented sandstone. This occurred where methane content in the gas flow at the collar just prior to the blowout had been measured at 1 to 2 percent. The blowout continued for

about one-half to one hour before water inflow into the hole stopped the gas flow. The hole was capped, and during a drawdown test several months later, all water pumped out was highly charged with methane.

Hole 5 blew out at two different depths -- at about 190 foot depth, below the Anderson seam, and at about 390 feet within the Canyon seam, near its base. Water inflow from the Anderson and Canyon seams, respectively, stopped both blowouts. Gas flow rates were estimated to be between 800,000 and 900,000 cfd. Especially important in this hole, is the fact that the second blowout occurred within a major coal seam (the Canyon).

In Hole 2, methane concentrations up to 1 percent of the return air were measured in the lower 200 feet of hole. In Hole 1, during geophysical logging, gas flow out of the hole was very low, but methane content of the gas flowing registered the 60 percent maximum reading of the methanometer.

Holes 8-10. These three holes are listed in the report by Olive (1957) on the Spotted Horse Coal Field as shallow wells in which substantial gas flows were encountered. Though not specifically so stated by Olive, it is presumed that these wells were water wells because of their shallow depths -- total depths given for two of the wells being 245 and 415 feet. Olive states that ranchers in the area use sealed tanks for capture of the natural gas produced in their water wells -- the gas being used for domestic and ranch-heating purposes.

For the above holes -- 8, 9 and 10 -- initial gas flow rate was 1,000,000, 1,000,000, and 500,000 cubic feet per day from depths of 225, 400, and 265 feet, respectively. Gas associated with other shallow water wells drilled into near-surface coal zones is also reported by Olive to occur in areas adjacent to Powder River and Clear Creek -- the conflux of which is 25 miles to the northwest of holes 8-10 and which lies to the west of the ellipse drawn on the map in Figure 5-1.

Hole 11. Hole 11 is a water well mentioned in the report of the Spotted Horse Coal Field by Olive. This well, in the SE 1/4 sec. 30, T58N, R75W, was drilled for the Dobrenz ranch in 1916 and has been supplying by-product gas to the ranch since that time. Olive reported that gas pressure from the well was sufficient to lift a weight of 600 pounds (there is no

mention, however, what pressure this force relates to). The Dobrenz ranch house's location is shown on Olive's geologic map of the Spotted Horse Field, which places the well in the center of a local structural low.

Hole 12. This is a well driven to provide water for the school at Recluse. The school building is shown on the 7-1/2' Recluse topographic quadrangle map as being one-half mile west of the hamlet of Recluse. We have not been able to determine any quantitative data on gas flow from the well, only that substantial gas flow was encountered. It was drilled by a local water-well driller and no technical people were on site at the time.

Hole 13. Hole 13 is reported to have hit gas in or adjacent to the Canyon bed. This hole, drilled by local drillers with no geotechnical personnel in attendance, is about 7 miles northwest of hole 6. This hole blew out, forming a surface crater 6 to 8 feet in diameter. Gas flow was so great that the only way it could be stopped was by pumping cement into the hole.

Hole 14. Hole 14 is a water well in section 7, T55N, R73W, where a large gas flow was encountered at 90 to 100 foot depth in a sandstone bed between the Smith and Anderson coalbeds.

Hole 15. Hole 15, is the USGS Hole No. US-754 (drilled in 1975). Bob Matson (Montana Geological Survey, personal communication) states that this hole was drilled with the intent of reaching the lower split of the Wyodak seam -- the Canyon beds -- but that they hit gas at 280' and were only able to drill another 10' and had to quit because of the large gas flow which blew the hole out. The hole had intersected coal at 100' (5' of coal) and at 180' (32' of coal -- probably the upper split of the Wyodak; i.e., the Anderson seam). Hole location was the W 1/2, NW 1/4, Sec. 24, T46N, R71W (Neil Butte 7-1/2 quadrangle).

#### 5.1.2 Methane in Artesian Wells

A large number of flowing artesian wells occur within the Powder River Basin. A number of these wells are known to contain substantial amounts of natural gas. Origin of this gas is the coalbeds and carbonaceous zones in the Fort Union Formation (Lowry and Cummings, 1966; Whitcomb, et al., 1966).

It was shown by Meinzer (1942) that gas in an aquifer increases the height to which water rises in a well and can create a flowing artesian well by raising the water to the surface. This lifting action is created by expansion of the gas as pressure is reduced in the water flowing from the aquifer. It is stated by Lowry and Cummings (1966) and Whitcomb, et al. (1966) that, because of this lifting action, some portion of the artesian wells in the basin flow that would not otherwise do so.

Assuming that some significant -- but as yet unknown -- portion of the flowing artesian wells, are flowing because they are tapping coalbeds with anomalously high methane content, such artesian wells might be a useful exploration aid. Hydrologic maps covering the Powder River Basin show locations of at least 198 flowing artesian wells within the boundary of the Fort Union Formation. Distribution of these 198 wells is shown on the map of Figure 5-3. This map indicates a non-random distribution of the wells with 68 being in the eastern half of Sheridan County, 71 in northeastern Johnson County, 29 in the northern half of Campbell County, and 16 located mostly in two separate areas in Converse County. Of the flowing artesian wells in Sheridan and Johnson Counties, at least five are known to contain methane (Table 5-1, Figure 5-3). The area of northern Campbell County with anomalously large numbers of flowing artesian wells also coincides with the elliptical area around Recluse that contains the 14 shallow drill holes in which anomalously large quantities of methane were encountered (Section 5.1.1).

Of the flowing artesian wells in Sheridan, Johnson, and northern Campbell Counties, most are located along the major drainages of Tongue River, Powder River, and two principal tributaries of the Powder -- Little Powder River and Clear Creek (Figure 5-3). A secondary zone of occurrences comprises a narrow belt along the western margin of the Fort Union Formation, extending from north of Tongue River to south of Clear Creek (Figure 5-3). Reason for apparent concentration of flowing wells along the main drainage channels is probably three-fold:

- (1) Concentration of rural development (and wells) along river alluvial flats

- elevations*
- (2) Lower well-head evaluations along river channels than on the intervening ridges, and
  - (3) Possible concentration of free methane in coalbed open fractures along the structurally controlled major drainage channels.

Location of four of the flowing artesian wells, known to contain methane, along the Powder River south from Clear Creek, and one well near the Tongue River provides tentative evidence that reason number three above, is real; i.e., that free methane is more abundant in fractured coal-bearing strata adjacent to structurally controlled drainage channels than it is in land areas between such channels.

### 5.1.3 Possible Structural and Stratigraphic Controls of Methane in the Coalbeds

All data collected to date have indicated that the Powder River Basin should provide several favorable target areas for recovery of methane gas from coalbeds by use of shallow drill holes. The basin is one of the largest coal-bearing basins in the west and has the largest reserves of coal of any basin or region of the U.S., 1.3 trillion tons. Coal in the basin is mostly in thick beds, and is all within potentially economic drilling depths, the deepest coalbeds being at 2500 feet in the basin center. Tertiary structure of coal-bearing formations in the basin is relatively simple, comprising a generally northwest-southeast trending gentle asymmetrical syncline lying between the Black Hills Uplift on the east and the Big Horn Mountains on the west (Figure 3-12). Because the synclinal axis lies close to the western margin of the shallow basin, dips on the eastern limb are quite low, averaging less than 1°. Superimposed on this simple basin structure is a fracture system which generally comprises two fracture sets that control local surface drainage and topography. The dominant fracture set parallels the northwest-southeast trend of the basin axis, the secondary fracture set being approximately perpendicular to the basin axis. Roughly concordant with the northwest-southeast and northeast-southwest trends of the two fracture sets is a system of very local small synclinal-anticlinal folds that seem to be confined stratigraphically to the coal-bearing zones within the Fort Union and Wasatch Formations. These local folds are probably syngenetically related to the original deposition of the sediments. That is, they may in part have been "draped"

over topographic undulations on the depositional surface and in part caused by slumping of saturated sediments on shallow basin slopes prior to lithification. It is the resulting small but numerous anticlinal highs that seem such promising specific targets for collecting any methane adsorbed within Fort Union and Wasatch coalbeds, as in the Spotted Horse and Sheridan Fields, Wyoming, and northern extension of the Sheridan Field in Montana (Figures 5-4 to 5-8).

Coal in the Paleocene Fort Union Formation and the immediately overlying Eocene Wasatch Formation occurs in at least stratigraphically separable beds. Because the basin is so large and the study of subsurface coal relationships so limited, correlation of coalbeds from place to place in the basin is still uncertain. What is known, though, is that the basin contains the greatest concentration of thick coalbeds in the nation. In at least three centers of deposition within the basin, individual coalbeds are coalesced into massive "superbeds." These three centers are:

1. A square-mile area just West of the Decker Mine, Big Horn County, Montana, where the Anderson, Dietz No. 1, and Dietz No. 2 coal seams are coalesced into a bed 80 feet thick.
2. A north-south trending belt approximately 15 miles long and 1 to 2 miles wide at Lake De Smet, Sheridan County, Wyoming, where five coal seams are coalesced into a bed whose thickness ranges from 70 to more than 250 feet. This combined bed -- now called the Lake De Smet Bed -- is the thickest known coalbed in the U. S. and thought to be the second thickest in the world.
3. The area surrounding Gillette, Campbell County, Wyoming, where the Anderson, Canyon "A", and Canyon "B" seams, coalesce into a single bed (the "Wyodak" or "Anderson Wyodak") ranging in thickness from 70 to more than 125 feet.

The methane recovery target area at Recluse defined by drill hole 1-14 (discussed in Section 5.1.1) occurs at the margin of one of these depositional centers where a superbed splits into two or more component seams; that is, at the northern margin of the Wyodak superbed centered on Gillette. Hole 15 lies just to the south of the Gillette depositional center. At such locations, it may be that methane gas release from the coal seams, and collection within interbedded coal seam and porous sandstone sequences, may be optimal. Identification of such natural gas

collection traps should be useful for indicating areas within the Powder River Basin where underlying coalbeds could have anomalously large amounts of absorbed methane.

In the Recluse area (Hobbs, 1978), the apparent preferential sequence of individual coal and sandstone beds for production of methane from the shallow wells drilled is:

1. The sandstone beds between the Anderson and Canyon bed(s),
2. The Canyon coalbeds,
3. The Sandstone bed below the Canyon,
4. The sandstone sequence between the Canyon coalbeds, and
5. The Anderson coalbed.

Shallow drill hole data in the Recluse area indicate that coalbeds and porous sandstone sequences interbedded with and closely overlying the coalbeds all act as reservoirs for methane desorbed from the coal as well as reservoirs for ground water. Though poorly cemented, highly porous sandstone beds seem to be the most efficient reservoirs in the Recluse area coal-zone sequence; the coalbeds themselves are also good to excellent reservoirs. In the sequence preference given in the preceding paragraph, the deeper coalbed -- the Canyon -- seems to be the best coal reservoir.

In Figures 5-4 to 5-8, representative areas in Campbell and Sheridan Counties, Wyoming, and Big Horn County, Montana, are shown which contain possible structural and stratigraphic traps in which methane associated with coal-bearing strata could collect. In Figure 5-4 to 5-6, a number of closures on structural highs are identified which are promising methane drilling targets. In Figure 5-4, six such highs are identified in the Recluse area of Campbell County that are in close association to five of the shallow drill holes that contained large amounts of methane (discussed in Section 5.1.1). In Figure 5-5, 18 such highs are identified, four of which are along the sinuous axis connecting a series of anticlinal folds, just south of, and subparallel to the Powder River. Just to the north of this line of anticlinal highs is the Dobrenz Ranch water well which has been producing by-product methane since 1916. It is of extreme interest that this well is in the center of a shallow structural low. This may indicate that coal-bearing strata subjected to tensional stresses along fold axes -- including both synclinal and anticlinal folds -- may be sufficiently fractured in the central Powder River Basin to act as

collecting zones for free methane desorbed from coal-particle surfaces. In Figure 5-6, three more such structural highs are shown aligned along a NW-SE trending anticlinal axis in the Clear Creek area, east of Lake De Smet and Buffalo. In Figures 5-7 and 5-8, two possible methane drilling targets are shown in the area northwest of the Decker Mine, Big Horn County, Montana. One target is a structural high in the superbed represented by the coalesced Anderson-Dietz No. 1-Dietz No. 2 coalbeds. The other target is a possible stratigraphic trap where the above superbed splits into two beds. Methane desorbed from the coalbeds could be entrapped within porous sandstones between the two thick coalbeds.

## 5.2 METHANE RECOVERY FROM COALBEDS PROJECT DATA

No data have been obtained from the Powder River Basin, as yet, in the Methane Recovery from Coalbeds Project. The only two drill core coal samples collected to date for determination of adsorbed methane that we know of, are from the Recluse area. Desorption tests on these samples indicated only a small methane content of the samples, about 8-9 c.f. per ton of coal (Hobbs, 1978). We strongly suspect that the gas remaining in these samples at the time of testing had little relationship to methane contained in the coalbeds in place. The samples were from the Canyon and Cook coal seams collected at depths of approximately 375 feet. Coals of the Spotted Horse Field range in rank mostly between lignite and subbituminous C. Because of their low rank and lack of ever having been buried much, if any, deeper than their present shallow depths, the coals are very porous. Thus, any coal samples will probably lose almost all adsorbed methane very quickly -- i.e., during drilling and retrieval, prior to placing of the samples in sealed cannisters at the surface.

## 6. CONCLUSIONS AND RECOMMENDATIONS

### 6.1 CONCLUSIONS

The Powder River of Wyoming and Montana presents an unusually promising opportunity for collecting large amounts of methane gas from relatively shallow coalbeds. The basin is very large and contains the greatest concentration of thick coalbeds in the nation. Though the coals are of low rank, which normally indicates small amounts of absorbed methane per unit volume of coal, the great thickness of many of the coal seams indicate large volumes of methane contained per unit area of coalbed. In addition to great thickness for individual seams, the basin is noted for the large number of thick seams that are intercepted by a single drill hole at shallow depths. For example, a single drill hole in Campbell County, Wyoming, intercepts 16 coalbeds greater than 5 feet thick, of which 10 beds are greater than 20 feet thick and 1 is greater than 60 feet thick (375 feet of coal within 2500 feet of the surface; Apache-1 Geer wildcat well; Sec. 31, T47N, R73E). Because of the high porosity of these low-rank coals and the great total thickness of coal encountered at shallow depths, large amounts of methane should be recoverable per unit length of drill hole.

It is important to determine if methane gas can be practicably collected from shallow Powder River coalbeds as quickly as possible. It is these coalbeds that are the principal target of the great strip mines being put into operation along the northwestern and entire eastern rim of the basin. As these pits are opened, any methane contained within and adjacent to stripping areas will be lost to the atmosphere. Thus, if such methane gas is to be salvaged, it must be done before new pits are opened and the entire rim of the Powder River Basin coal seam is exposed to updip migration of methane contained in the deeper, more central portion of the basin.

The area that we consider the prime methane exploration target within the Powder River Basin, is outlined in Figure 6-1. This area encompasses portions of Campbell, Sheridan, and Johnson Counties in Wyoming and Big

Horn and Powder River Counties in Montana. Factors used in delimiting the boundaries of this target area include:

1. Restricting the area to lands underlain by the Tongue River Member of the Fort Union Formation, and additionally to
2. Areas in which shallow drill holes are known to flow anomalously large amounts of methane,
3. Areas in which flowing artesian wells are concentrated, or
4. Areas in which three or more individually thick coalbeds are coalesced together into a single superbed.

Within the regional target delimited on the map of Figure 6-1, smaller initial target areas can be defined based on probable structural and stratigraphic controls, including the following:

- a. Major drainage channels that parallel any of the known fracture sets, especially those channels along which flowing artesian wells are concentrated. Included principally are Tongue River, Little Powder River, and especially Powder River and Clear Creek. These drainages probably are fault, or at least fracture controlled. Coal-bearing strata, along and adjacent to these channel ways, are probably fractured to a greater degree and should contain more free methane, than rocks, away from the channel ways.
- b. Secondary channel ways with anomalously linear development parallel to the major, NW-SE or NE-SW fracture-set directions and along which are located flowing artesian wells or shallow-drill holes known to emit methane. An example is Hay Creek, southeast of Recluse, which is located in a 245-foot deep hole which had an initial gas emission rate of a million cubic feet per day (Hole 8, Figure 5-1).
- c. Zones along anticlinal fold axes, where rocks under tensional stress could be more highly fractured than rocks on fold limbs. Anticlinal crests present highly favorable zones where fractured rocks can act as hosts for methane migrating updip from coalbeds along fold limbs.
- d. Zones along synclinal fold axes where methane desorbed from coal-particle surfaces can collect in place in open fractures along the stressed rocks.
- e. Stratigraphic traps created where superbeds split into two or more individual coalbeds. An example is the area northwest of the Decker Mine, Big Horn County, Montana, where the Anderson splits from the Dietz No. 1 and No. 2 coalbeds (area B, Figure 5-7).
- f. Coalbeds in the deeper portion of the basin, paralleling the basin synclinal axis. Absorbed methane concentration should be greatest

in such beds because of the greater hydrostatic pressure and the probable higher coal rank in the more deeply buried coals.

- g. The northwest-trending, 33-mile long, elliptical area in Campbell County in which shallow drill holes flowing methane gas are concentrated (Figure 5-1). Geologic controls for this concentration are probably partly structural and partly stratigraphic.

Initial individual drill sites for collecting coalbed methane data could include:

- a. Sites beside holes known to flow methane or beside flowing artesian wells containing methane.
- b. Sites on the crests of small structural closures along fold axes, and
- c. Sites at the intersections of two or more favored linear structural features; e.g., the intersection of a fold axis and a linear stream channel or the intersection of two linear stream channels such as the conflux of Powder River and Clear Creek.

## 6.2 RECOMMENDATIONS

An initial program here recommended for investigating methane recovery potential of the Powder River Basin includes:

1. Construction of a lineation map of the basin from topographic and geologic maps, from spacecraft synoptic imagery and from aerial photographs.
2. Collection of all data possible from the literature, from geotechnical personnel currently working in the basin, and from local water well drillers, pertaining to methane content encountered in drill holes and water wells.
3. Field measurements of fracture systems in coal-bearing strata of the central Powder River Basin.
4. Collection of well-bottom samples from both flowing and non-flowing artesian wells in the central Powder River Basin and measurement of contained methane.
5. Cooperating with the U.S. and Montana geologic surveys in collection of coal core samples in their shallow-to-intermediate depth drilling programs (generally less than 1000-foot depths) and performing methane desorption tests.
6. Performing "piggyback" tests with companies exploring for oil and gas and for uranium in collection of coal core samples for methane desorption tests.

7. Performing intermediate-to-long term gas-flow tests on selected shallow holes drilled either for the U.S. or Montana Geological Survey Programs or drilled specifically for the Methane Recovery Program. This task is especially important for the Powder River Basin because the low rank coal samples collected by coring may be so porous as to essentially lose all absorbed methane before the samples can be placed in sealed cannisters at the surface.
8. Drilling small anticlinal highs -- locate 3 to 5 dewatering wells at base of high end methane production well on top of high.

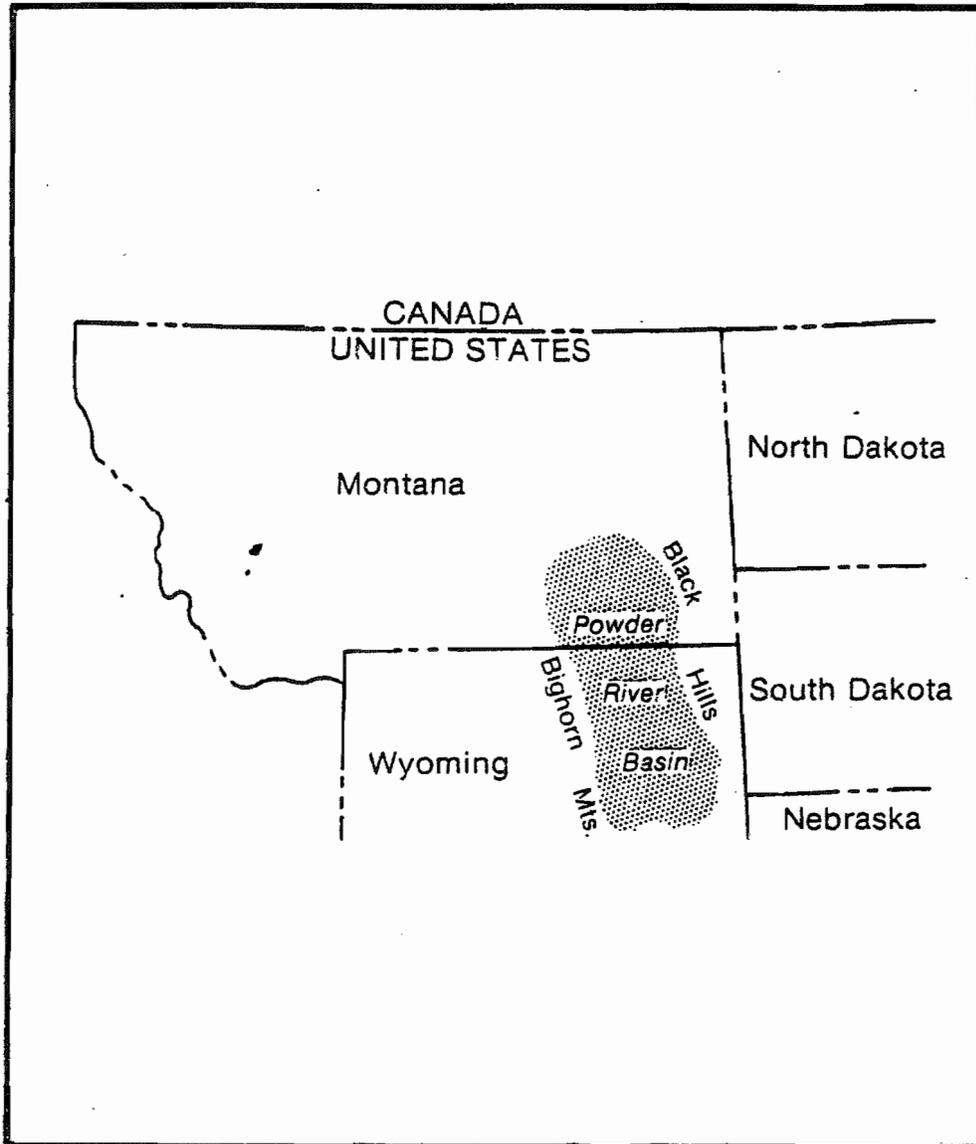


Figure 3-1 Index Map Showing the Location of the Powder River Basin

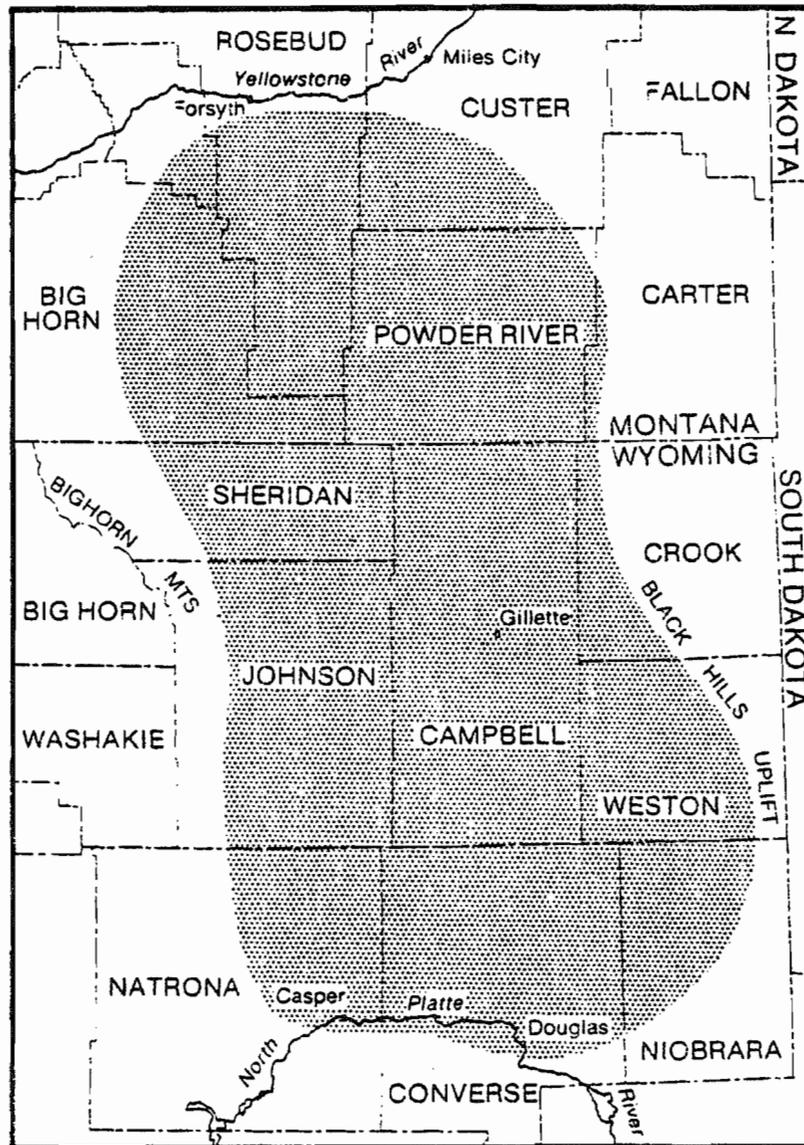


Figure 3-2 Index Map Showing Powder River Basin in Relation to Geographic and Cultural Features.

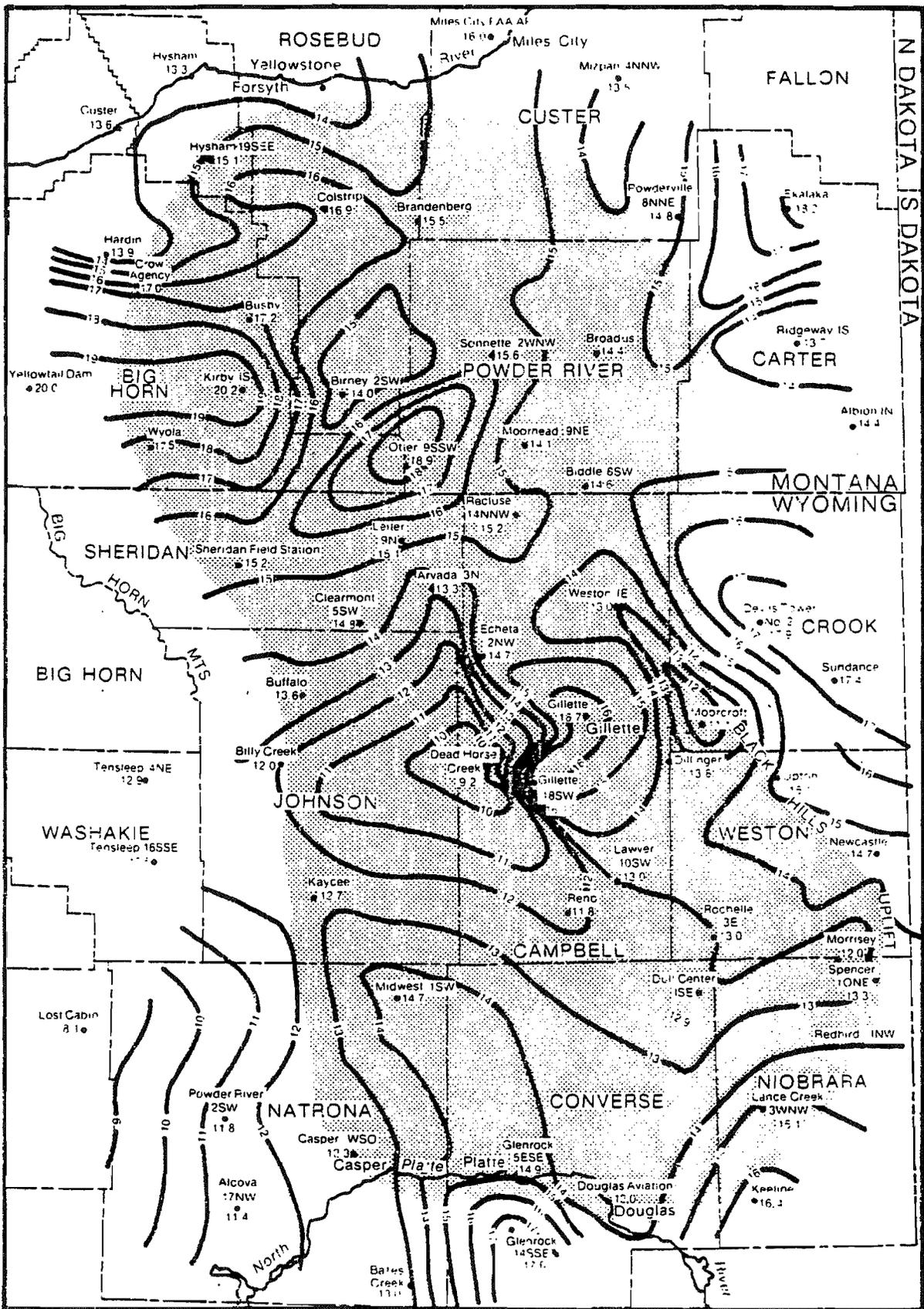


Figure 3-3 Mean Annual and Monthly Precipitation in Inches (Toy and Monsch, 1978)

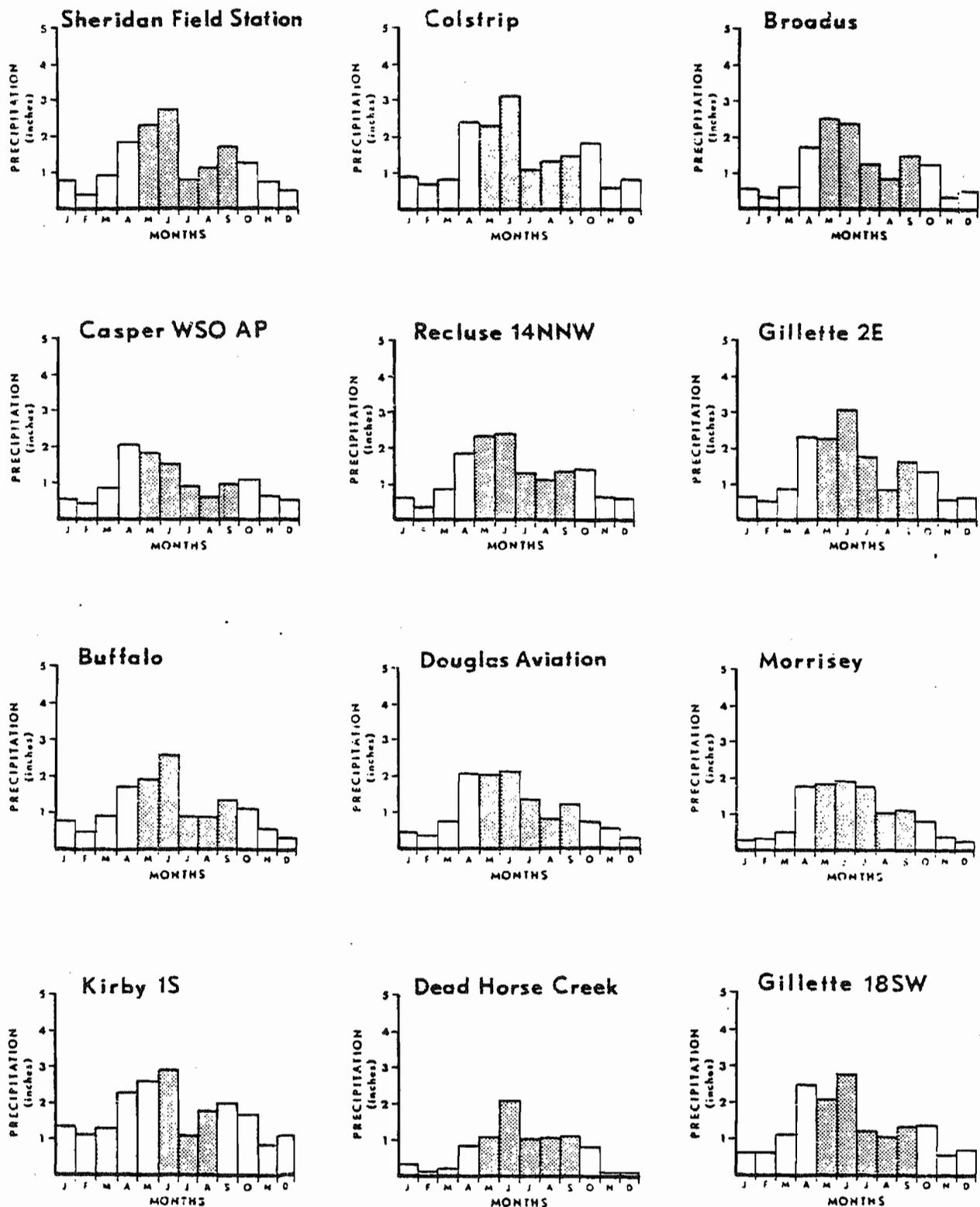


Figure 3-4 Monthly Precipitation in Inches for Twelve Stations in the Powder River Basin Area (From Toy and Munson, 1978).



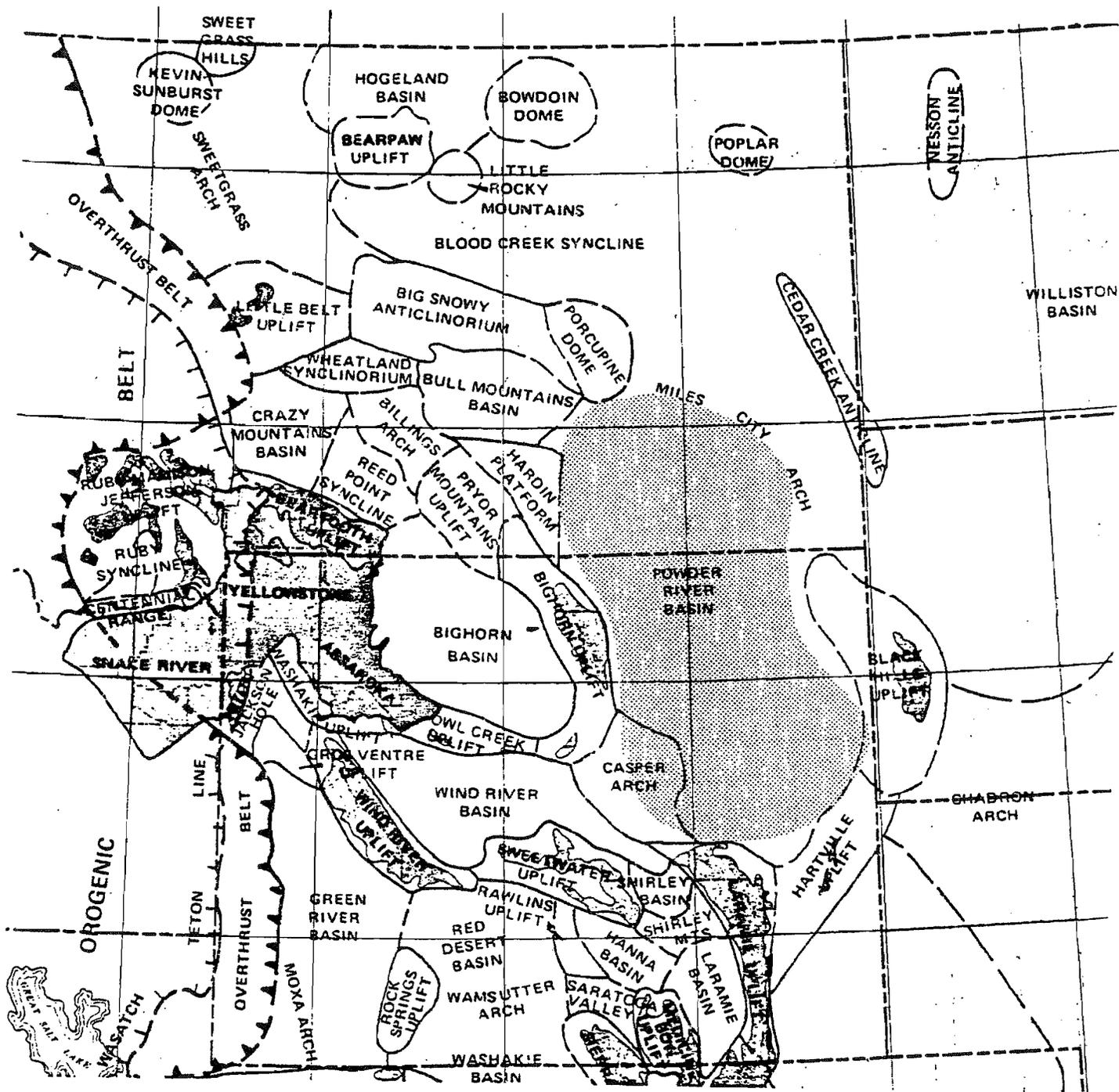


Figure 3-6 Major Tectonic Elements Associated with Development of Powder River Basin. (Modified from Grose, 1972).

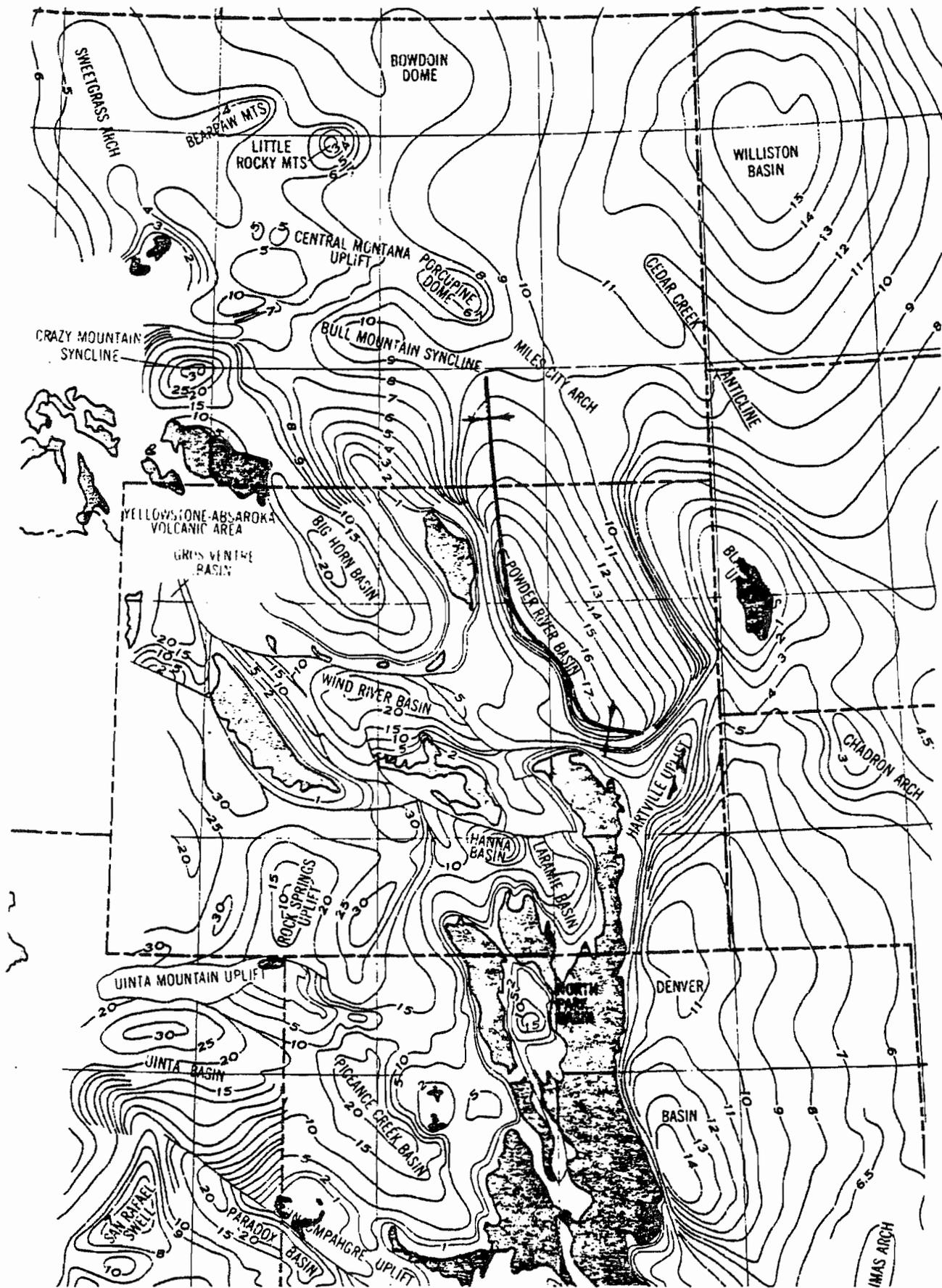
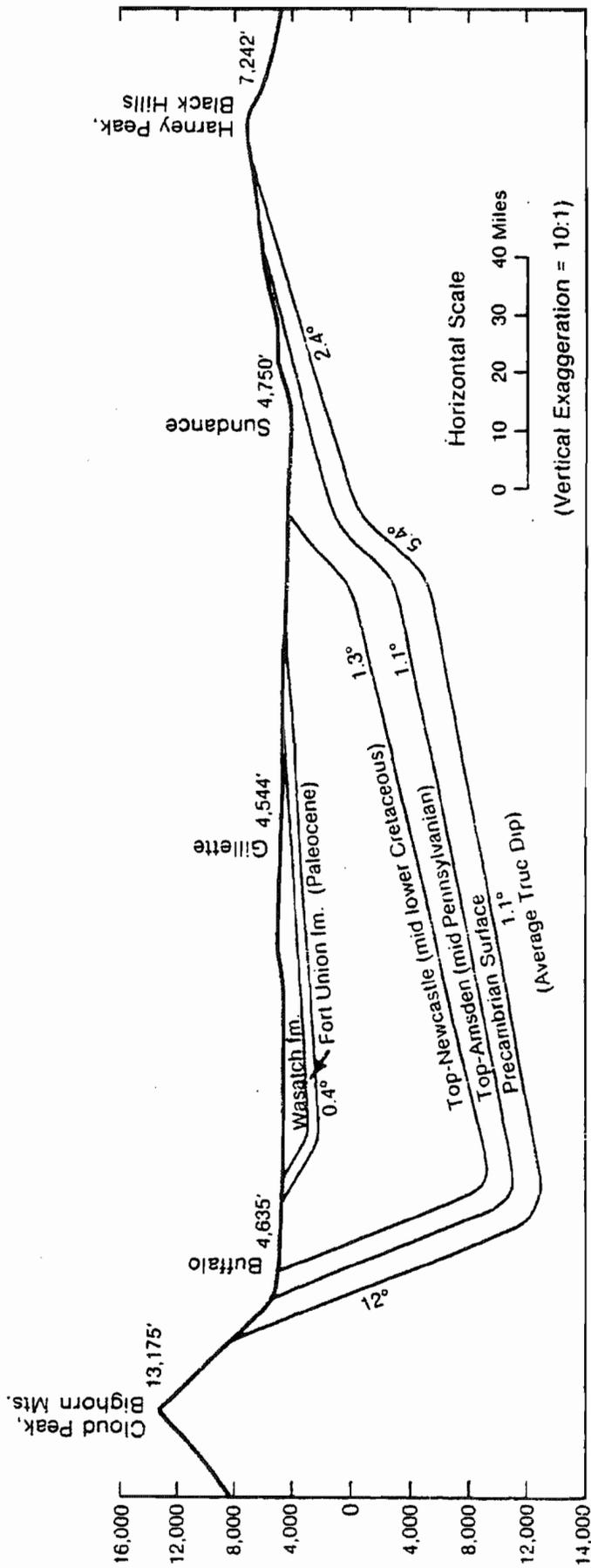


Figure 3-7 Structural Contour Lines on Top of the Precambrian Basement showing Thickness of Sedimentary Rock Sequence in Powder River Basin and Associated Structurally Negative Areas (Modified from Kent, 1972).



**Figure 3-8** East-West Section Across Powder River Basin Showing Slightly Tilted, Trough-Like Structure in Older Sedimentary Rocks. (Section Along 12th Standard North Parallel 9 Miles South of Gillette; Surface Topographic and Cultural Landmarks Projected into Plane of Section. Location shown on Fig. 3-7.)

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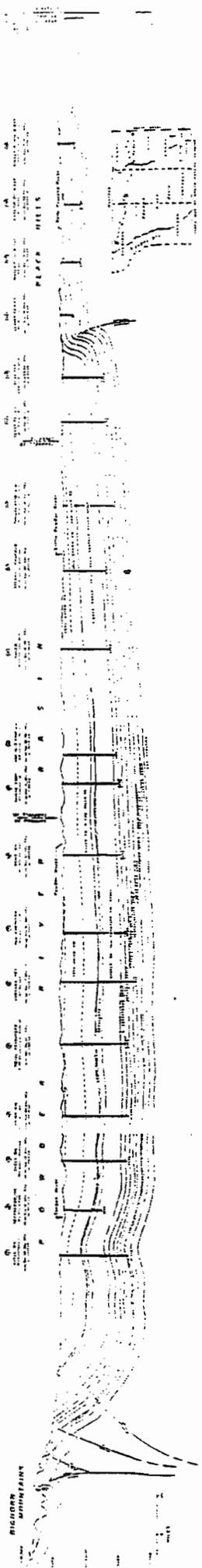
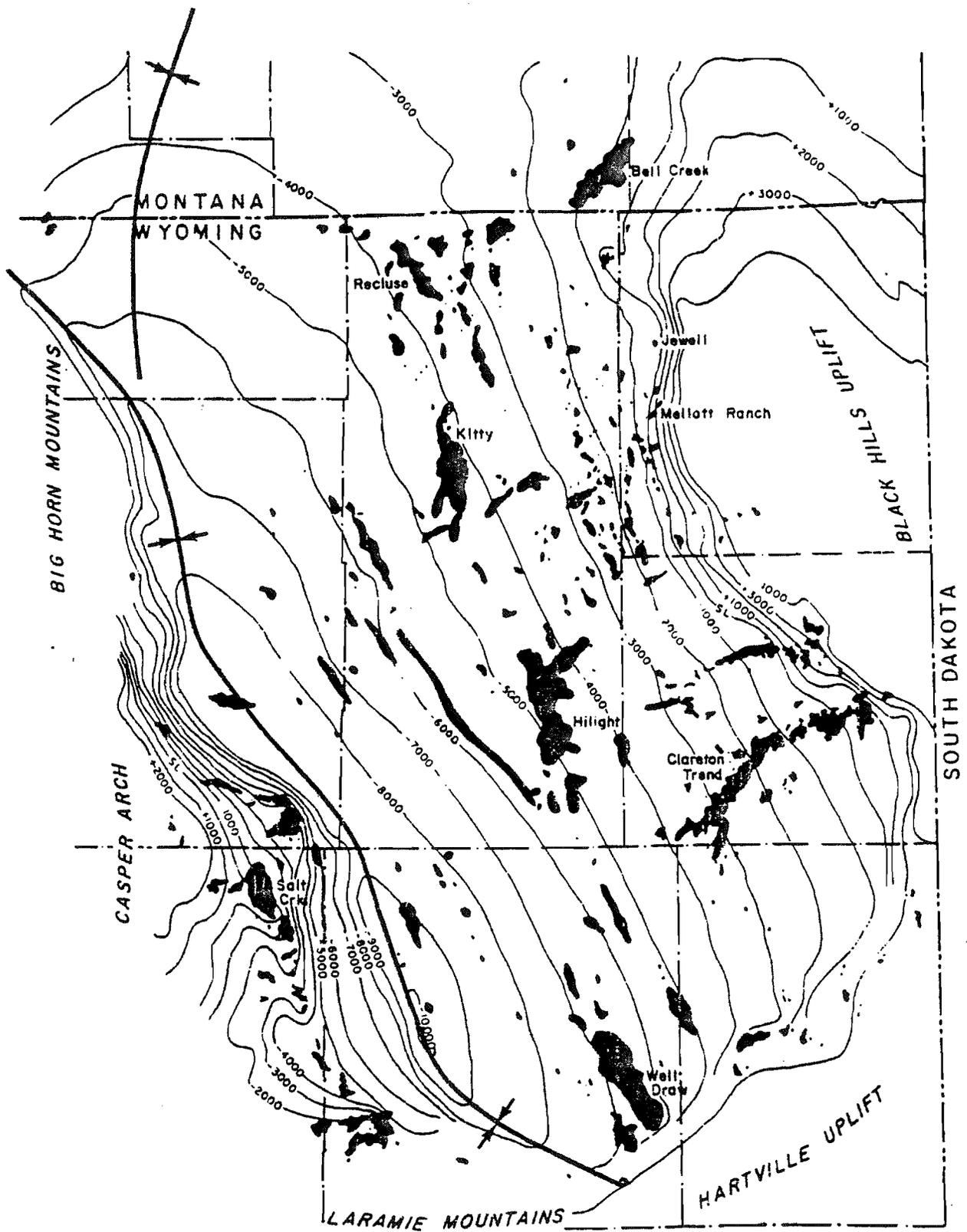


Figure 1. A detailed technical drawing of a ship's hull, showing the profile of the hull, the deck, and the internal structure. The drawing is oriented vertically on the page. It includes various labels and annotations, such as 'RIGGING' at the top, 'MAST' in the middle, and 'HULL' at the bottom. The drawing shows the hull's curvature, the placement of the mast, and the internal structural elements like the keel and ribs. There are also some smaller diagrams and tables integrated into the main drawing, providing additional technical details.

3. The third part of the document is a list of names and titles of the members of the committee.



**Figure 3-10** Structural Map of Powder River Basin, Contours on Top of the Dakota Formation. Shown Also are Oil Fields of the Basin and Their Relationship to Basin Structural Grain (Modified from Orro, 1976).



W POWDER RIVER BASIN

E POWDER RIVER BASIN

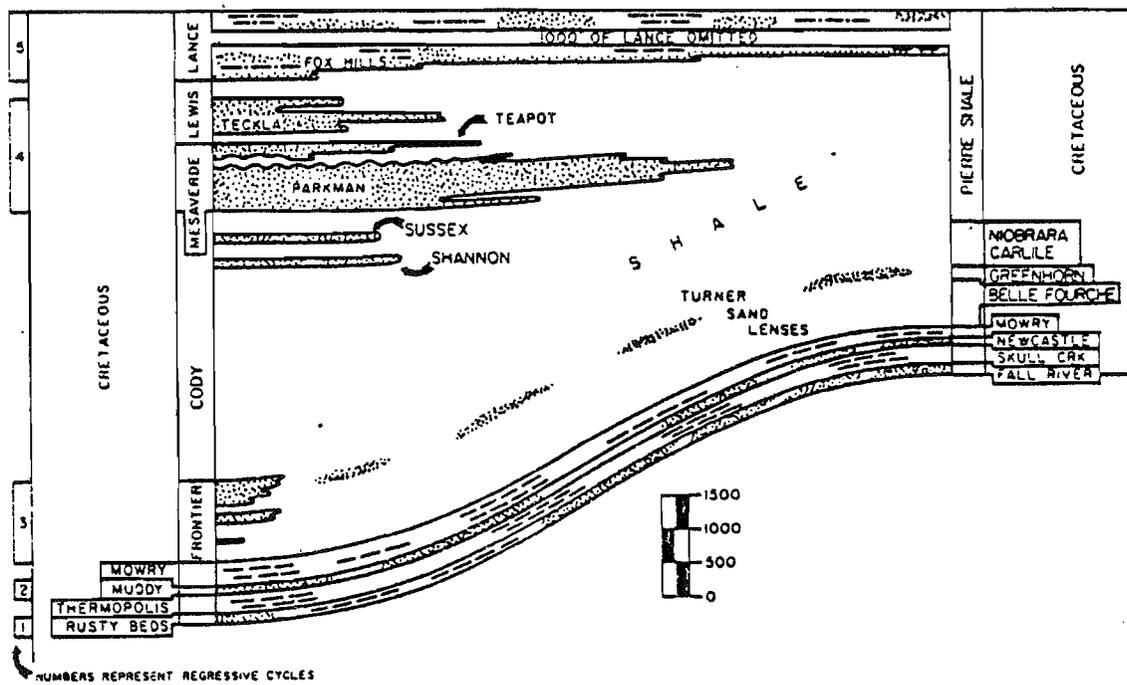


Figure 3-12 Rock Unit VII West-East Cross Section of Cretaceous Rocks, Powder River Basin (From Wyoming Geol. Assoc., 1965)

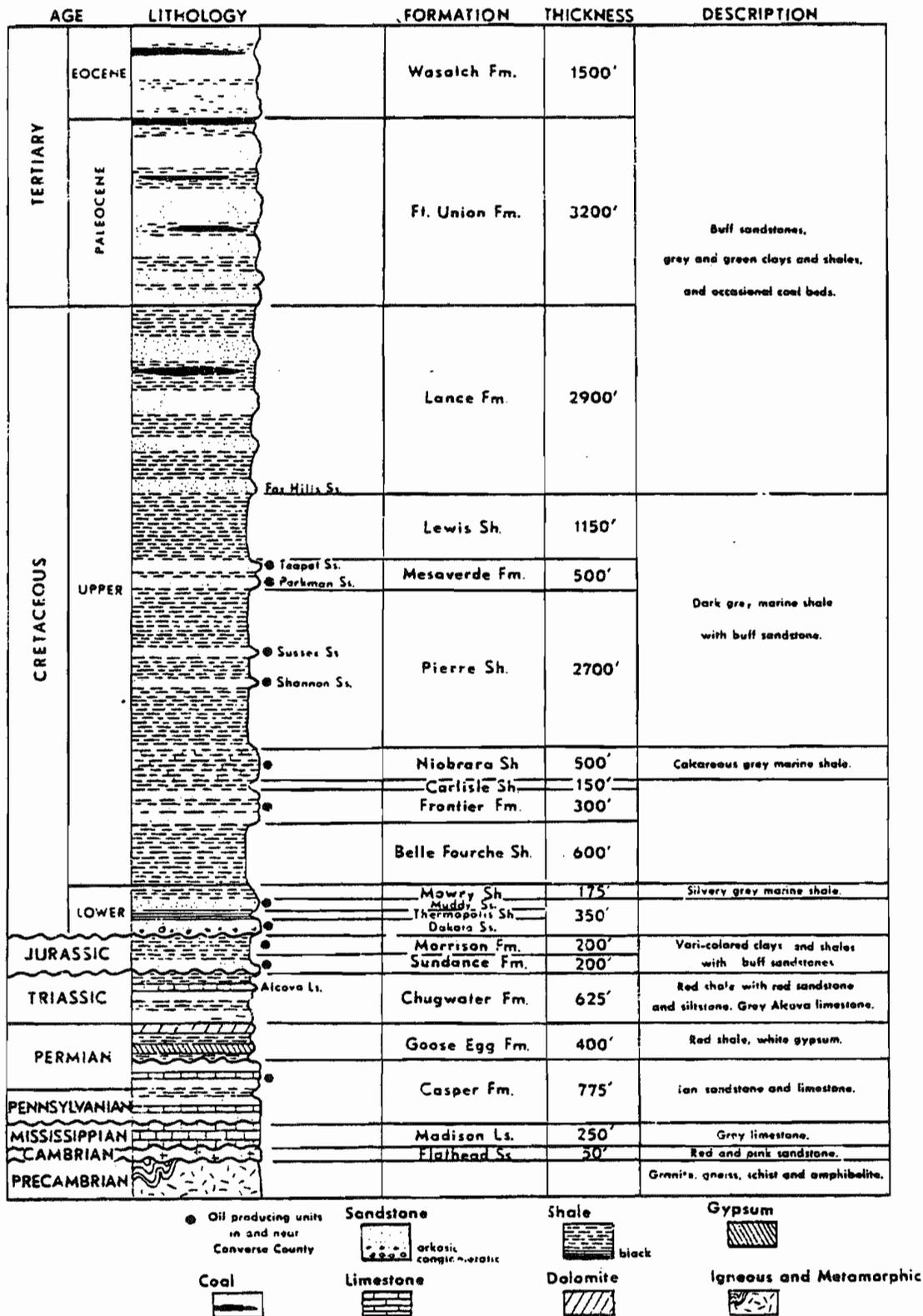
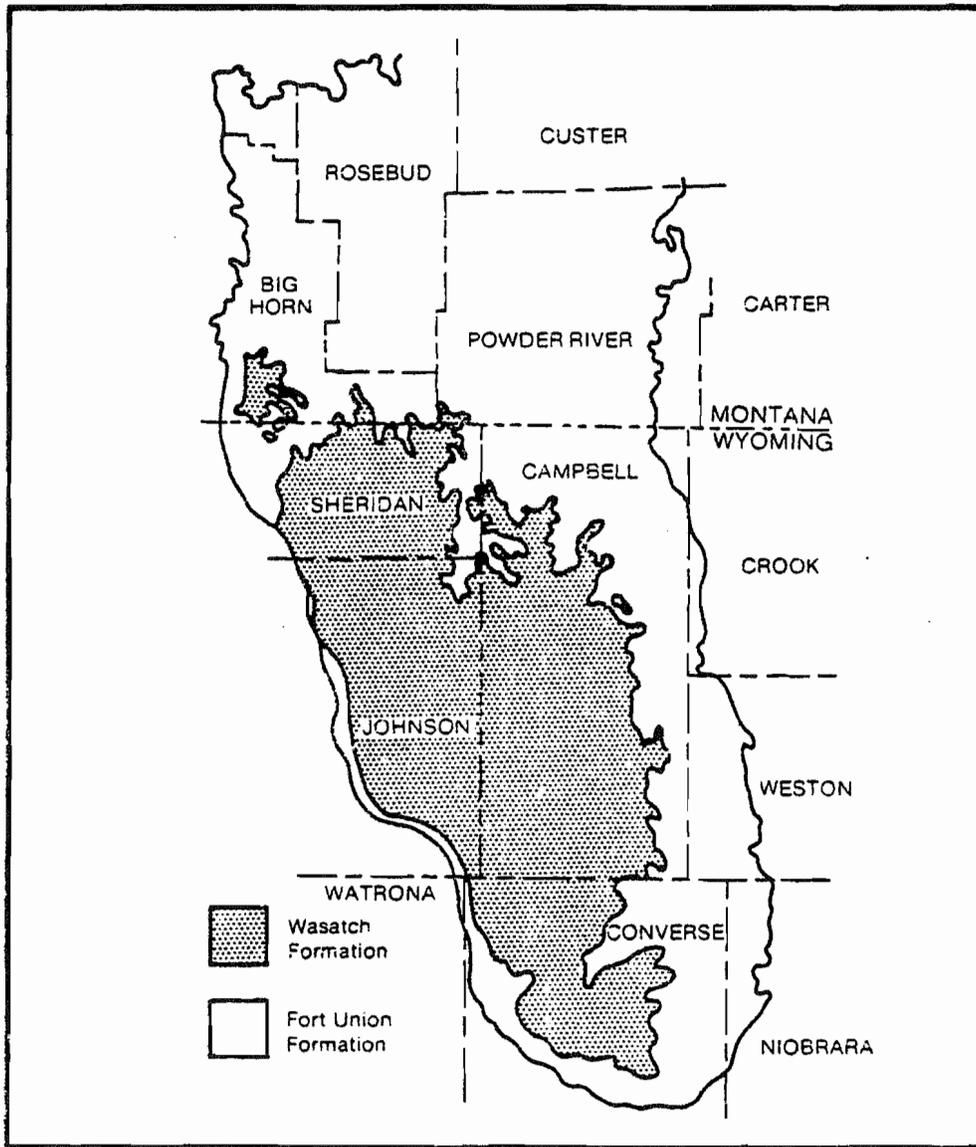


Figure 3-13 Representatives Stratigraphic Column Showing Relationships Between Major Coal-Bearing Formations and Oil-Bearing Sandstones, Converse County, Southwestern Powder River Basin (Lane, Root, Glass, 1972).



**Figure 3-14** Map Showing Extent of the Wasatch Formation of Eocene Age and the Fort Union Formation of Paleocene Age (Modified from Mapel, 1958).

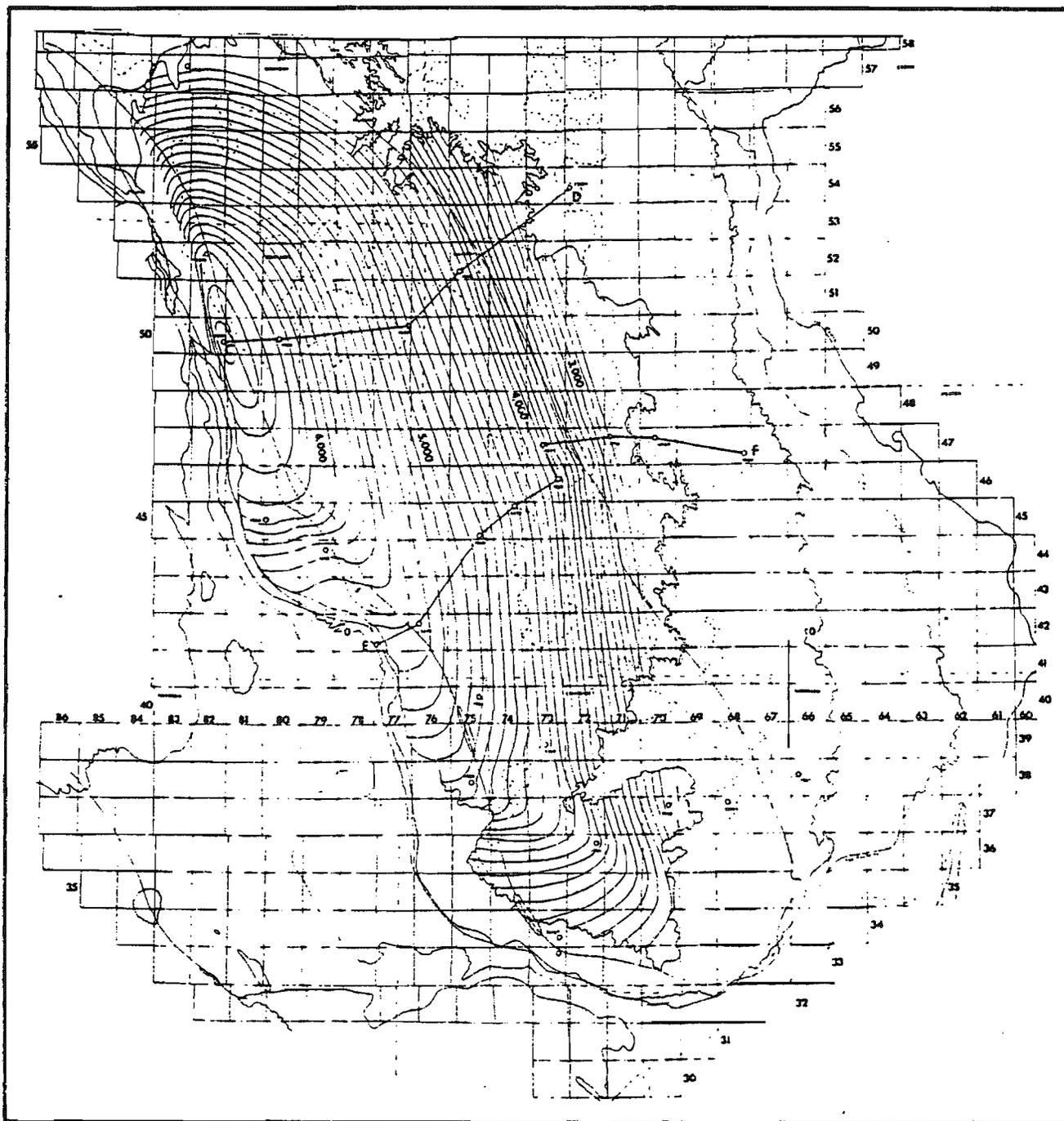


Figure 3-15 Isopach Map of Fort Union and Wasatch Powder River Basin. Dashed Lines Indicate Areas of Thick Coal Outcrops (From Curry, 1971).

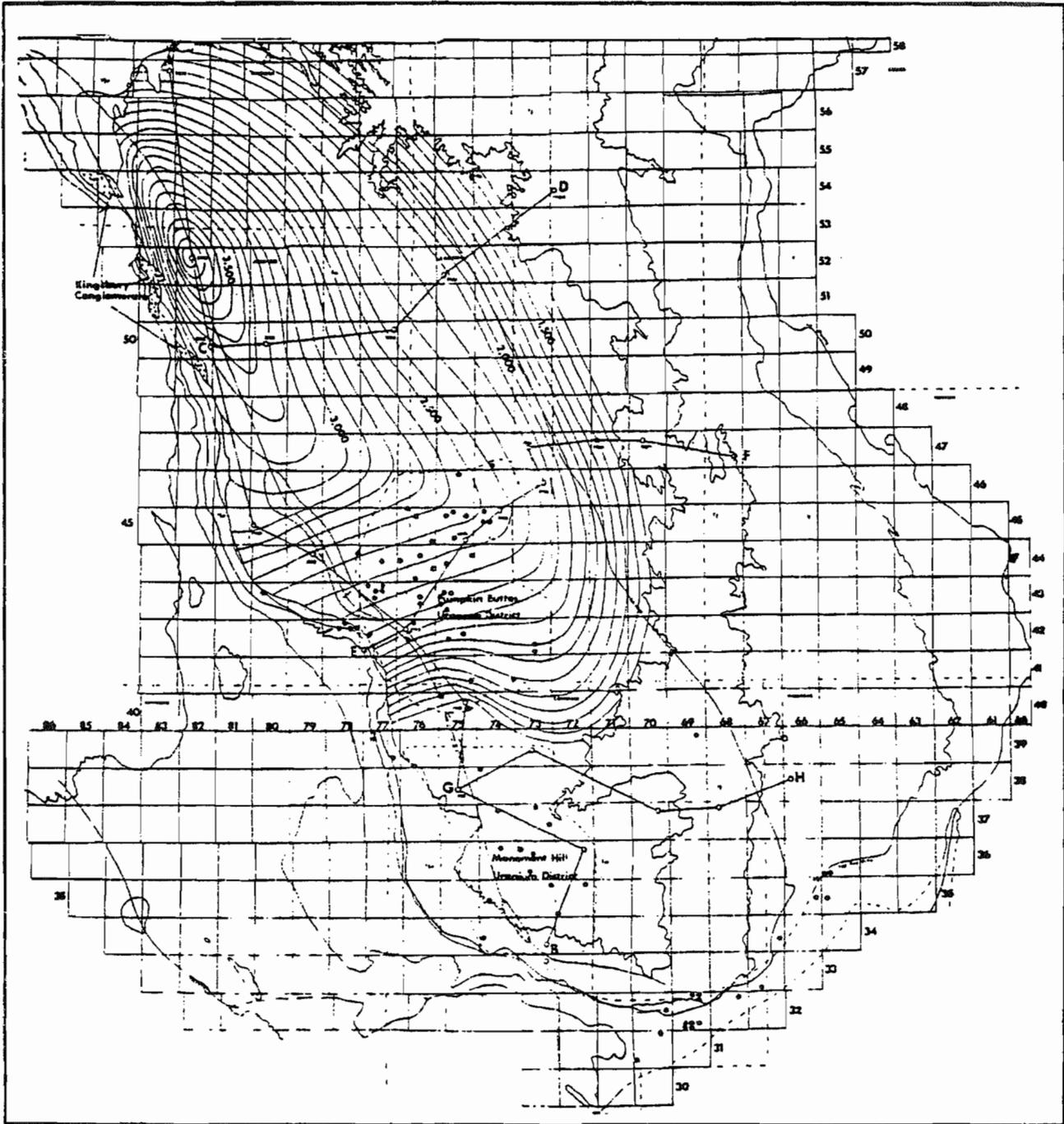


Figure 3-16 Isopach Map of Tongue River Member and Wasatch Formation, Powder River Basin (From Curry, 1971).

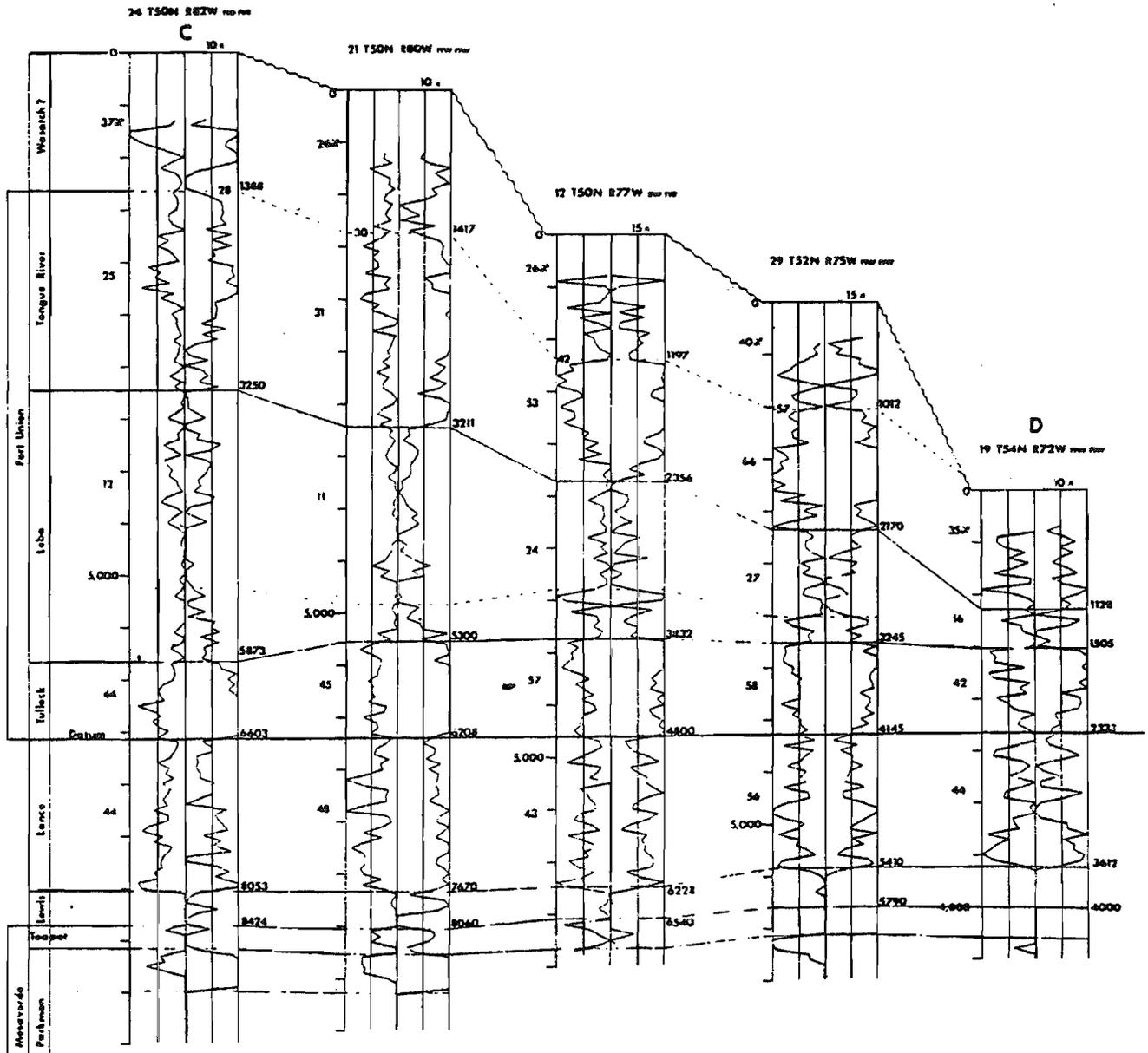


Figure 3-17 Cross-Section C-D Showing Electric Log Correlations (From Curry, 1971).



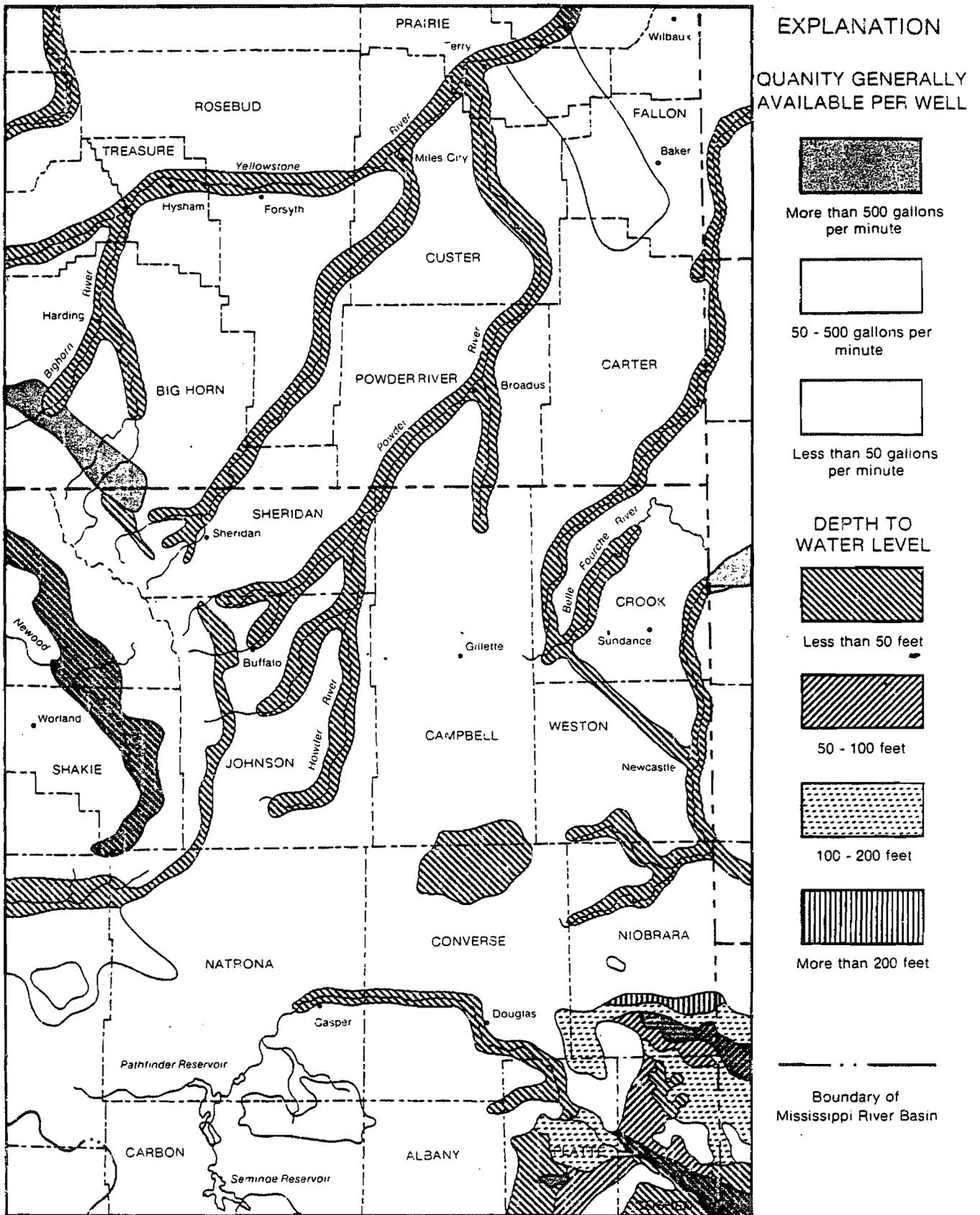
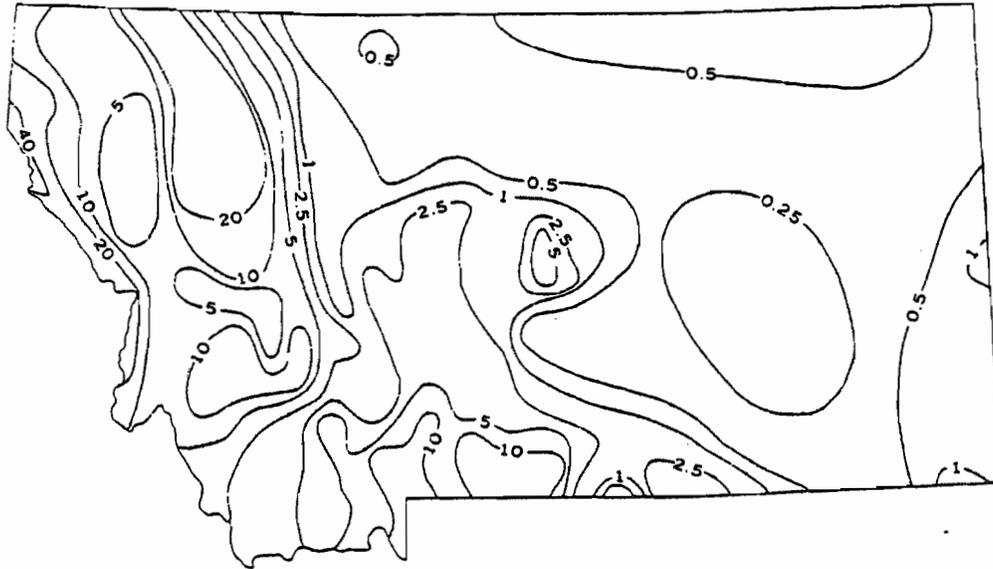


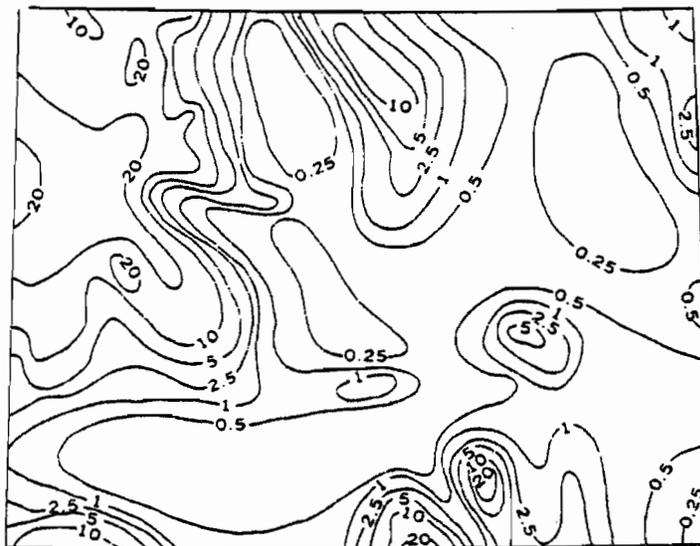
Figure 3-19 General Availability of Ground Water in the Powder River Basin Area of the Missouri River Drainage Basin (From: LaRocque, 1966).

# MONTANA



AVERAGE ANNUAL RUNOFF, IN INCHES

# WYOMING



AVERAGE ANNUAL RUNOFF, IN INCHES

Figure 3-20 Average Runoff in inches from U.S. Geological Survey, 1976 (a) Montana (b) Wyoming

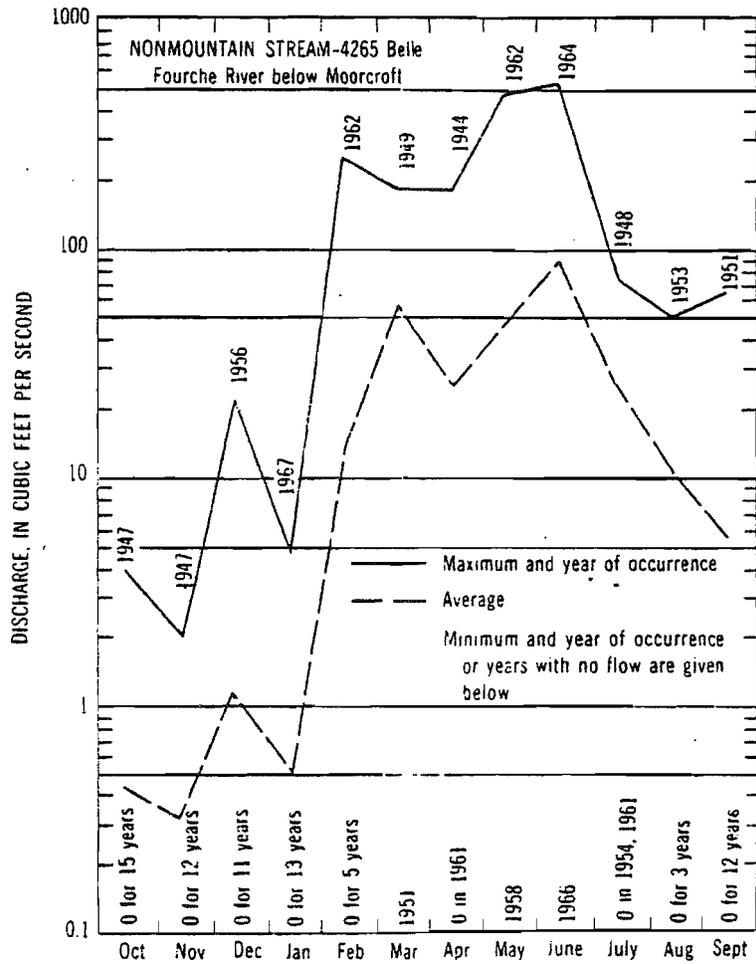


Figure 3-21 Discharge Hydrograph of Monthly Flows Showing Average Maximum and Years of No Flow for Belle Fourche River (Hodson, Pearl and Druse, 1973).

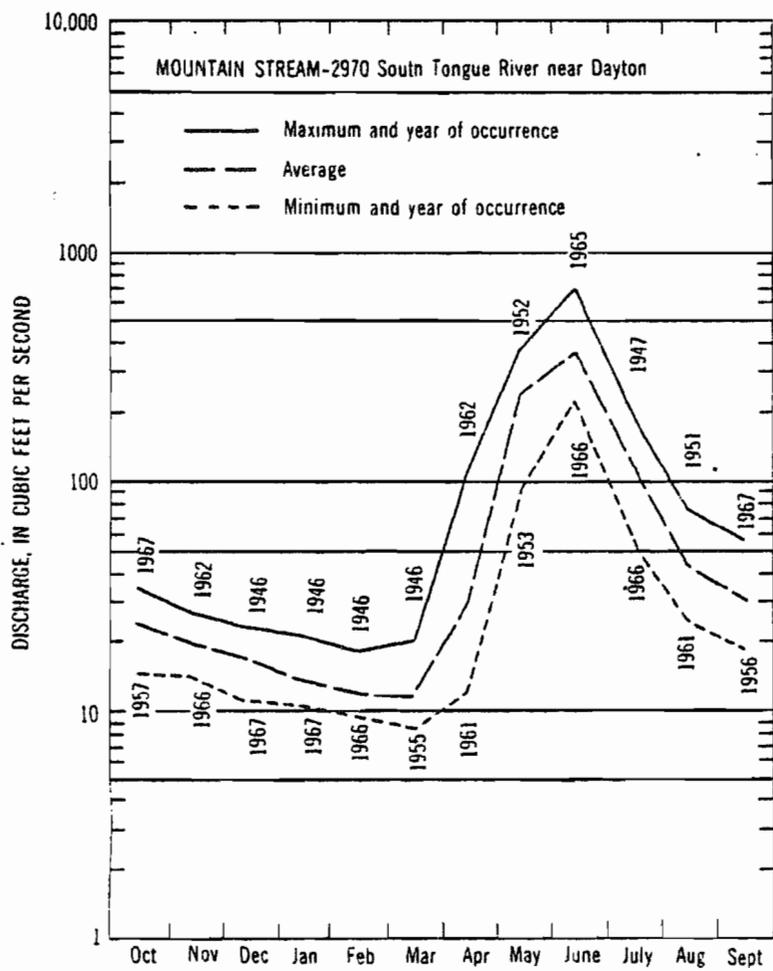


Figure 3-22 Discharge Hydrograph of Monthly Flows showing Mean Minimum and Maximum for South Tongue River (Hodson, Pearl and Druse, 1973)

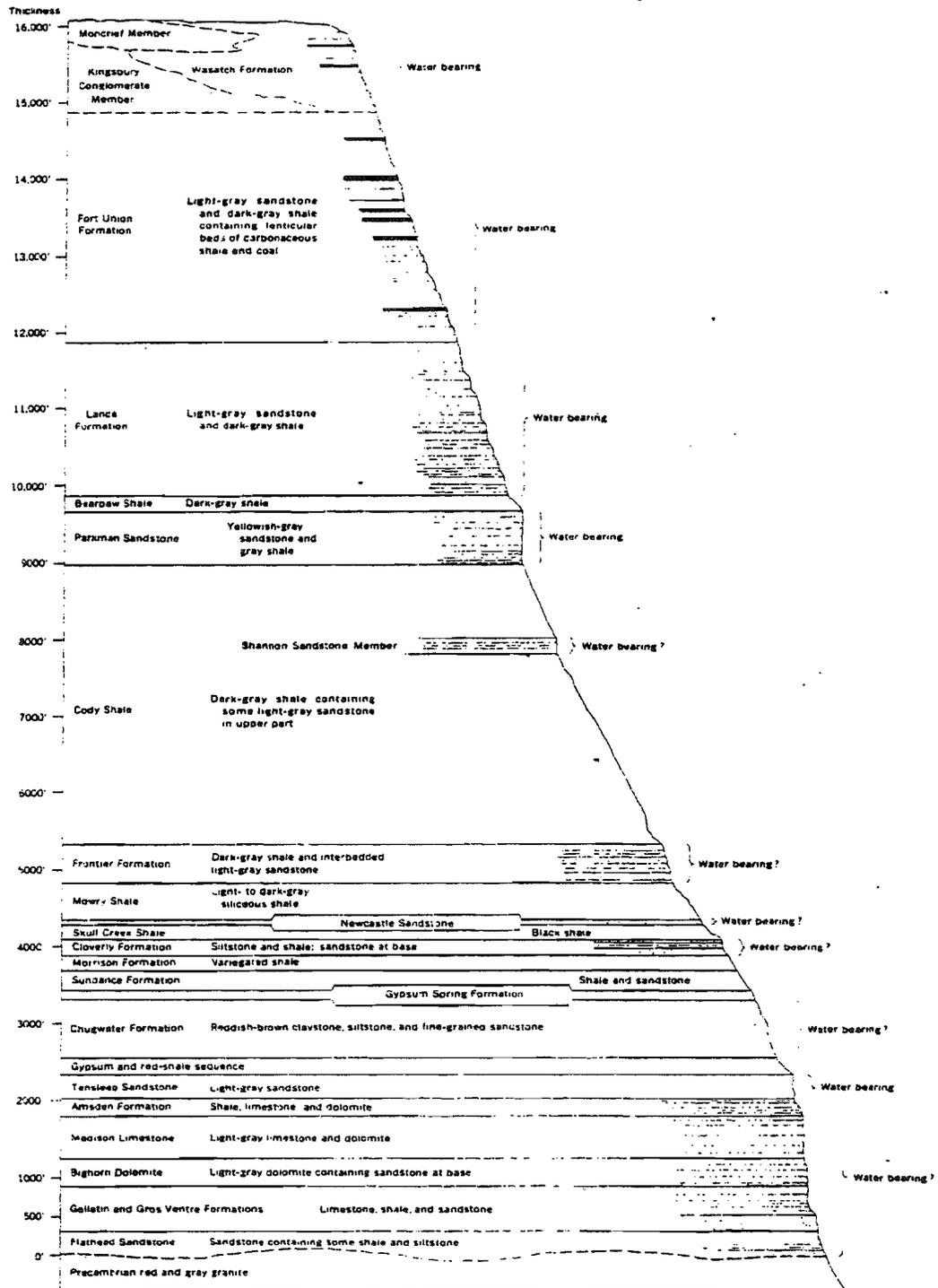


Figure 3-23 Generalized Columnar Section Showing Rocks of Northern and Central Johnson County, Wyoming (From: Whitcomb, Cummings and McCullough, 1966).

NORMALS, MEANS, AND EXTREMES

MILES CITY, MT MUNICIPAL AIRPORT MOUNTAIN 46° 26' N 105° 52' W 2629 FT. 1976

Month	Temperatures °F				Normal				Precipitation in inches				Relative Humidity pct				Wind				Mean number of days				Average station pressure								
	Normal		Extremes		Heating		Cooling		Water equivalent		Snow, ice pellets		Humidity pct		Speed		Direction		Precipitation		Thunderstorms		Heavy fog, visibility		Temp. above 50° and below 32°		Max and Min		mb.				
	Daily maximum	Daily minimum	Record maximum	Record minimum	Year	Month	Year	Month	Year	Month	Year	Month	Year	Month	Year	Month	Year	Month	Year	Year	Month	Year	Month	Year	Month	Year	Month	Year	Month	Year			
JAN	20.1	4.7	62	-37	1969	1338	0	0.49	1.78	1971	0.08	1901	0.52	1844	17.2	1971	7.5	1904	74.70	70	74	0.6	NW	27	26	32	32	32	32	32	32	4	
FEB	32.8	10.4	65	-31	1923	1215	0	0.65	1.89	1920	0.07	1922	0.41	1842	17.0	1927	5.0	1927	59.62	55	77	9.7	NW	27	26	32	32	32	32	32	32	4	
MAR	47.8	19.7	83	-27	1924	997	0	1.24	4.22	1923	0.10	1922	1.36	1847	18.9	1927	10.5	1927	59.62	55	77	10.9	NW	27	26	32	32	32	32	32	32	4	
APR	48.9	43.4	84	-24	1924	888	19	2.06	5.33	1923	0.24	1922	2.39	1925	18.6	1927	10.5	1927	59.62	55	77	11.9	NW	27	26	32	32	32	32	32	32	4	
MAY	77.4	52.3	104	-9	1951	1117	114	3.32	9.78	1944	0.94	1901	2.71	1944	2.0	1930	2.0	1930	78.48	41.65	10.4	11.1	SE	27	26	32	32	32	32	32	32	4	
JUN	88.9	59.8	109	0	1960	901	301	1.55	4.58	1948	0.10	1971	2.02	1902	0.0	1930	0.0	1930	88.38	31.54	9.7	11.1	SE	27	26	32	32	32	32	32	32	4	
JUL	97.2	57.7	110	9	1946	36	248	1.20	4.00	1951	0.10	1971	1.65	1943	0.0	1930	0.0	1930	88.38	31.54	9.7	11.1	SE	27	26	32	32	32	32	32	32	4	
AUG	73.3	46.2	105	20	1942	217	64	1.19	4.87	1941	0.10	1971	1.65	1943	0.0	1930	0.0	1930	88.38	31.54	9.7	11.1	SE	27	26	32	32	32	32	32	32	4	
SEP	42.1	35.5	48.8	93	1922	508	0	0.71	6.31	1971	0.02	1953	1.18	1953	12.6	1949	3.8	1949	74.51	47.05	9.8	11.1	SE	27	26	32	32	32	32	32	32	4	
OCT	43.1	21.7	32.4	75	1955	978	0	0.51	1.39	1904	0.02	1953	1.18	1953	16.6	1925	8.0	1925	77.93	61.74	9.8	11.1	SE	27	26	32	32	32	32	32	32	4	
NOV	32.2	11.7	22.0	69	1959	1333	0	0.48	1.78	1968	0.02	1957	0.50	1941	18.0	1925	7.0	1925	77.93	61.74	9.8	11.1	SE	27	26	32	32	32	32	32	32	4	
DEC	32.0	11.0	31.0	37	1969	7889	782	13.93	9.76	1964	0.02	1957	0.50	1941	18.0	1925	7.0	1925	77.93	61.74	9.8	11.1	SE	27	26	32	32	32	32	32	32	4	
YEAR	57.5	32.9	110	91.0	1969	7889	782	13.93	9.76	1964	0.02	1957	0.50	1941	18.0	1925	7.0	1925	77.93	61.74	9.8	11.1	SE	27	26	32	32	32	32	32	32	32	4

(a) Length of record, years, through the current year unless otherwise noted. DATE OF AN EXTREME - The most recent in cases of multiple occurrence.  
 (b) 70° and above at Alaskan stations.  
 \* Less than one half.  
 † Trace.  
 PREVAILING WIND DIRECTION - Record through 1963.  
 WIND DIRECTION - Numerals indicate tens of degrees clockwise from true north. 00 indicates calm.  
 FASTEST WIND - Speed is fastest observed wind value when the direction is in tenths of degrees.

Table 3-1 Normals, Means, and Extremes for Temperature, Precipitation, Relative Humidity, Wind, and Sunshine Data; Miles City, Montana; Casper and Sheridan, Wyoming. (National Oceanic and Atmospheric Administration, 1977; 1978.)

CASPER, WY NATRONA COUNTY INTL AIRPORT MOUNTAIN 42° 55' N 106° 28' W 5338 FT 1977

Month	Temperatures °F			Normal Degree days Base 65 °F	Precipitation in inches			Relative Humidity pct			Wind			Mean number of days			Average station pressure mb											
	Normal	Extremes	Record		Normal	Water equivalent	Snow (in pellets)	Year	Month	Year	Month	Year	Month	Year	Month	Year		Month	Year									
Jan	32.4	13.7	32.4	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Feb	31.7	13.1	31.7	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Mar	41.6	21.9	41.6	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Apr	51.3	29.9	51.3	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
May	61.3	37.3	61.3	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Jun	71.3	47.3	71.3	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Jul	81.3	57.3	81.3	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Aug	91.3	67.3	91.3	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Sep	101.3	77.3	101.3	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Oct	111.3	87.3	111.3	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Nov	121.3	97.3	121.3	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Dec	131.3	107.3	131.3	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
YR	58.4	32.4	45.4	104	498	11.22	5.29	1971	Y	1969	3.00	1974	APR	56.3	1973	10.3	1976	APR	57.7	1971	10.1	1975	10.0	1978	10.0	1972	JAN	75.93

SHERIDAN, WY SHERIDAN COUNTY AIRPORT MOUNTAIN 48° 48' N 106° 58' W 3964 FT 1977

Month	Temperatures °F			Normal Degree days Base 65 °F	Precipitation in inches			Relative Humidity pct			Wind			Mean number of days			Average station pressure mb											
	Normal	Extremes	Record		Normal	Water equivalent	Snow (in pellets)	Year	Month	Year	Month	Year	Month	Year	Month	Year		Month	Year									
Jan	31.3	12.3	31.3	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Feb	30.6	11.6	30.6	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Mar	40.6	19.6	40.6	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Apr	50.6	27.6	50.6	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
May	60.6	35.6	60.6	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Jun	70.6	43.6	70.6	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Jul	80.6	51.6	80.6	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Aug	90.6	59.6	90.6	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Sep	100.6	67.6	100.6	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Oct	110.6	75.6	110.6	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Nov	120.6	83.6	120.6	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
Dec	130.6	91.6	130.6	1071	0	0	27	13	13	13	13	13	13	13	13	13	13	5										
YR	58.3	31.3	45.3	104	498	10.16	5.24	1944	Y	1976	3.01	1948	APR	56.8	1973	10.1	1974	APR	57.0	1971	10.0	1975	10.0	1978	10.0	1972	JAN	75.81

(a) Length of record, years, through the current year unless otherwise noted.  
 (b) 70° and above is Alaska station.  
 (c) Less than one half.  
 (d) Trace.  
 (e) FASTEST WIND - speed in mph, value shown the direction is in tenths of degrees.  
 (f) Y Trace.

Table 3-1 (Continued)

	1976	1977	1978	1979	1980	1985	1990	Average Annual Change 1976-1980		Average Annual Change 1980-1990	
								Amount	Percent	Amount	Percent
<b>Low Forecast</b>											
Gillette Urbanized Area	15,720	18,540	20,450	23,240	24,460	28,540	31,320	1,748	11.1%	686	2.8%
Campbell County	20,620	23,750	26,080	29,200	30,510	34,860	37,950	1,978	9.6%	711	2.4%
<b>High Forecast</b>											
Gillette Urbanized Area	15,720	18,540	21,500	24,100	28,660	42,730	43,540	2,588	16.5%	1,488	5.2%
Campbell County	20,620	23,750	27,040	30,610	36,490	54,020	54,700	3,174	15.4%	1,821	5.0%
<b>Difference High-Low Total</b>											
Amount			960	1,410	5,980	19,160	16,750				
Percent			4.5%	5.8%	17.6%	55.0%	44.1%				

Gillette and Campbell County Planning Area.  
Source: Gladstone Associates

**Table 3-2 High-Low Population Forecasts, Gillette and Campbell County, Wyoming (1976-1990).**  
From: Campbell County Chamber of Commerce, 1979.

1. Late Maestrichtian Lance: Subsidence increased southward but there is no evidence of local basin subsidence.

2. Early Paleocene Tullock: First slight subsidence was present in the southern and southwestern parts of the basin, but there was no prominent subsidence along the axis of the basin.

3. Middle Paleocene Lebo: First strong subsidence along the axis of the Powder River Basin is found but there is no evidence of influx of coarse clastics from adjacent uplifts. Middle Paleocene marks the first strong evidence of the Laramide Orogeny.

4. Late Paleocene Tongue River: Strong subsidence continued along the axis of the basin and the influx of sandstone is the first indication of uplift and erosion of the adjacent mountain uplifts.

5. Eocene Wasatch: Mountains continued to be uplifted and were eroded to their Precambrian cores. Conglomerate fans along the flank of the Bighorn Mountains were deposited and subsequently deformed.

6. Oligocene White River: Orogenic movements abruptly stopped before the Oligocene and White River volcanic rocks filled the basin and buried the Precambrian cores of the mountains.

7. Post Oligocene: Moderate subsidence of the mountain uplifts along faults, caused local tilting of the White River toward the sinking mountain blocks.

ERA	SYSTEM	SERIES	GEOLOGIC UNIT		AVAILABILITY AND CHEMICAL QUALITY OF GROUND WATER
			WESTSIDE BASIN	EASTSIDE BASIN	
CENOZOIC	TERTIARY	Eocene	Wasatch Formation		<p>Yields water from lenticular sandstone, and to a lesser extent from jointed coal and clinker beds. Yields can be expected to range from 10 to 50 gpm in north part of basin becoming generally greater southward with 500 gpm or more possible in south part of basin. Well 50-72-35dd near Gillette had a specific capacity of about 4 gpm per foot of drawdown. Seven wells on the Buffalo Ranch (T. 44N., R. 72W.) had specific capacities, as reported on drillers' logs, ranging from 5 to 14 gpm per foot of drawdown. Yields of 200 gpm or more may be possible locally from Moncrief and Kingsbury Conglomerate Members in northwest part of basin, but these rocks characteristically abut against the mountain flanks, are moderately dissected, and are probably largely drained. Dissolved solids range from less than 200 to more than 8,000 mg/l, but commonly range between 500 and 1,500 mg/l. No relation of dissolved solids to depth is discernible, but water mineralization decreases in general southward. Sodium sulfate and sodium bicarbonate are the most dominant water types.</p>
		Paleocene	Fort Union Formation		<p>Yields water from fine-grained sandstone, jointed coal, and clinker beds. Maximum yields are about 150 gpm. Average specific capacity of four wells in southwest Crook County was 0.3 gpm per foot of drawdown, and for four wells at Wyodak coal mine in Campbell County was 0.9 gpm per foot of drawdown (Whitcomb and Morris, 1964, table 1 and p. 40). Well 50-72-22cac near Gillette had a specific capacity of 0.7 gpm per foot of drawdown (Littleton, 1950, p. 14). Average specific capacity for 85 wells in Sheridan County computed from yield-drawdown data from drillers logs was 0.42 gpm per foot of drawdown (Lowry and Cummings, 1966, p. 21). Dissolved solids range from about 200 to more than 3,000 mg/l, but commonly range between 500 and 1,500 mg/l. Water type is mostly sodium bicarbonate, and to a lesser extent sodium sulfate.</p>
MESOZOIC	CRETACEOUS	Upper Cretaceous	Lance Formation		<p>Generally yields less than 20 gpm, but yields of several hundred gallons per minute may be possible from the complete section of the formation. Most wells have been drilled in outcrops of the Lance for domestic and stock purposes and tap only a small part of the formation. The specific capacity of three wells in Crook County ranged from 0.4 to 1.7 gpm per foot of drawdown (Whitcomb and Morris, 1964, p. 15). Dissolved solids range from about 200 to more than 2,000 mg/l, but commonly range between 500 and 1,500 mg/l. No dominant water type is prevalent.</p>
			Fox Hills Sandstone		<p>Yields of as much as 200 gpm are available from sandstone beds in east part of basin. Several wells south of Rozet produce about 200 gpm from the Fox Hills for water flooding. Well 56-71-15dd, Campbell County, flows 75 gpm from a depth of about 2,000 feet, and has a shut-in pressure of 54 psi (pounds per square inch) at the surface. Maximum yields in west part of basin will probably be less than 100 gpm. Well 40-78-15abb, Natrona County, had a specific capacity of only 0.37 gpm per foot of drawdown (Crist and Lowry, 1972, p. 61). Dissolved solids are mostly less than 1,000 mg/l in east part of basin, but generally range between 1,000 and 2,000 mg/l in west part. No dominant water type is prevalent.</p>
			Lewis Shale		<p>Lewis Shale — Sandy zones may yield as much as 10 gpm, but most of the formation does not yield water.</p>
			Mesaverde Formation		<p>Mesaverde Formation — Yields of as much as 50 gpm are possible from sandstone beds, and as much as 200 gpm where fracturing has increased the permeability, generally near geologic structures. Well 37-78-7dcd, Natrona County, yields about 120 gpm. Dissolved solids can be expected to range from about 300 mg/l to more than 2,000 mg/l. Most water will be sodium sulfate type.</p>

Table 3-4 Geologic Formations and Potential Water Supply from Hodson, Pearl and Druse, 1973

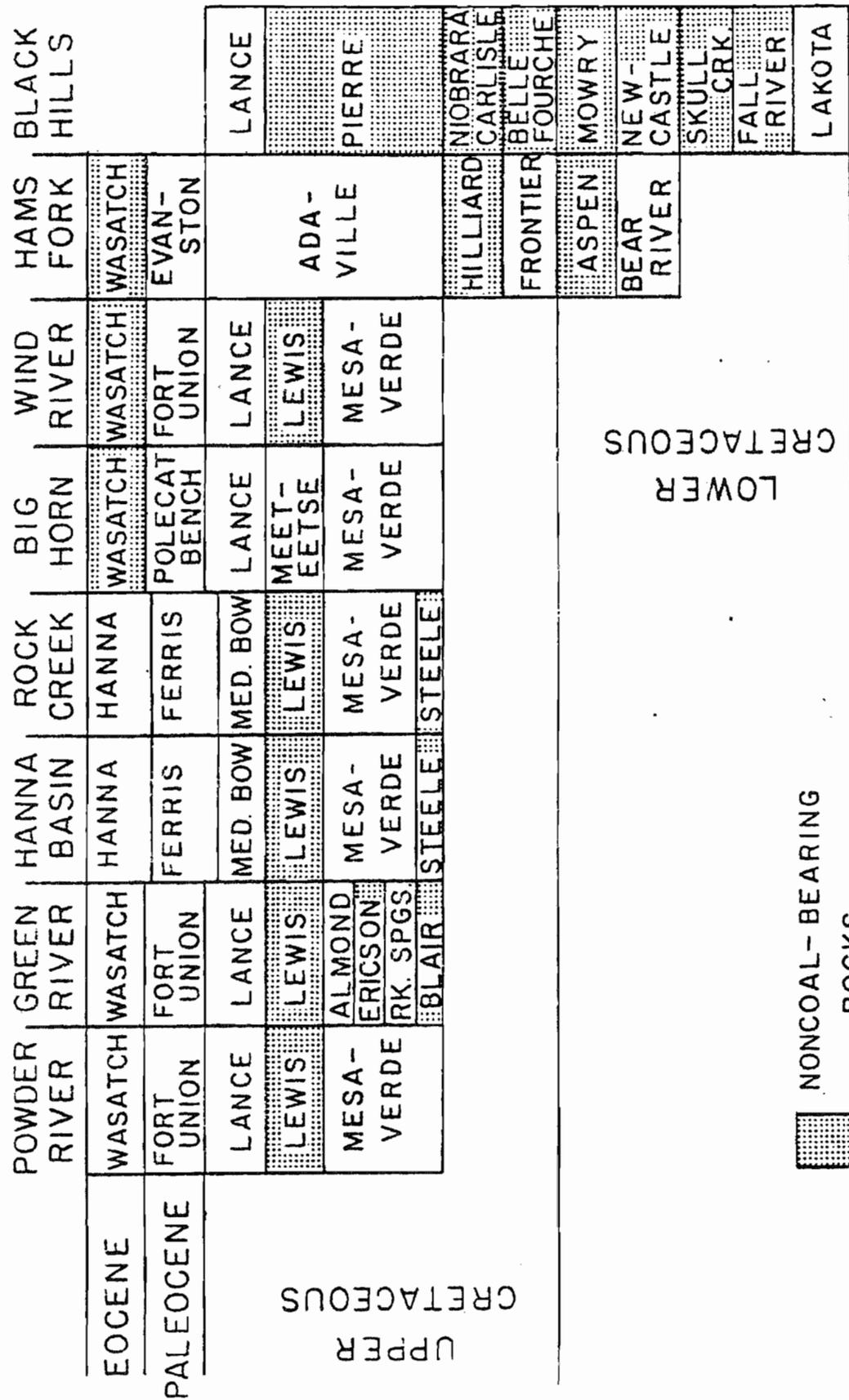


Figure 4-1 Major Coal-Bearing Formations of Powder River Basin and Correlation to Other Areas in Wyoming and the Black Hills (Glass, 1978).

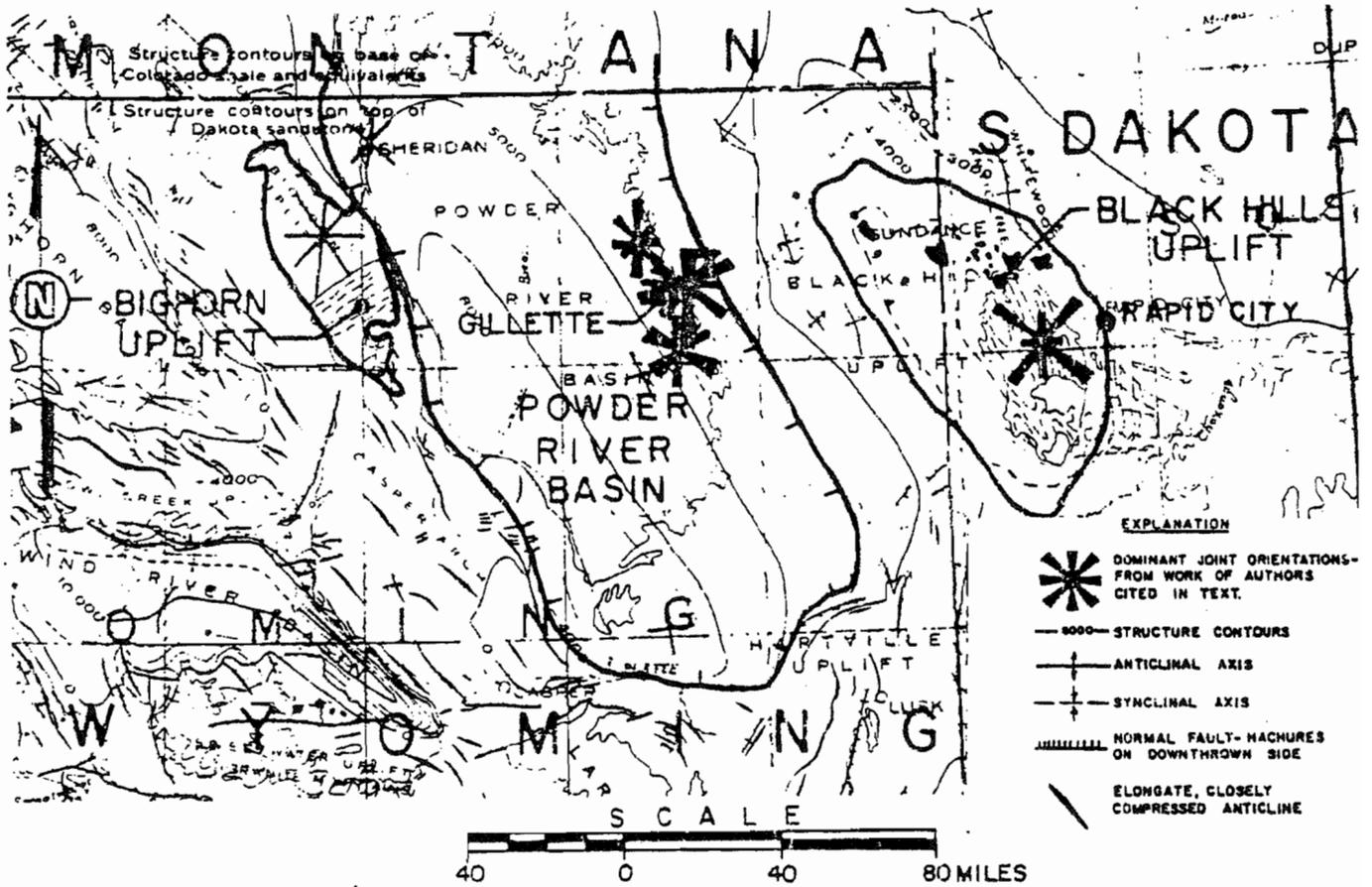
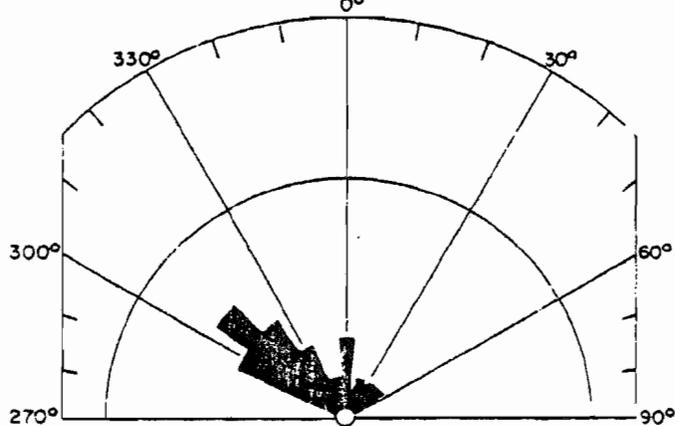
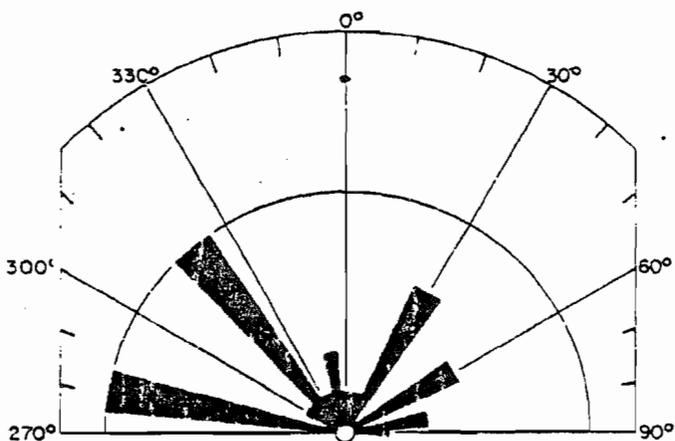
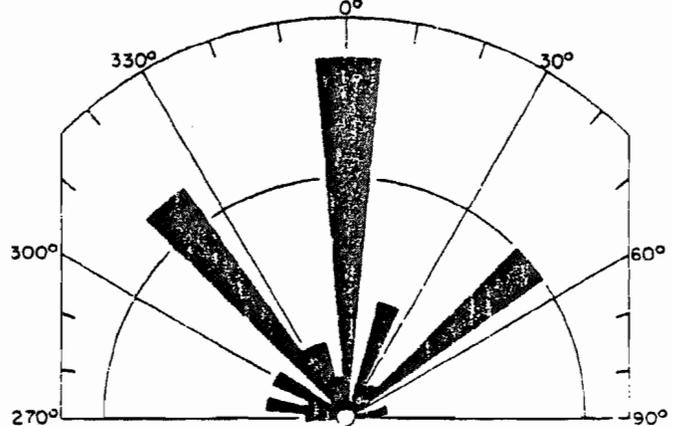


Figure 4-2 Dominant Joint Orientations of Rocks in the Powder River Basin and Surrounding Areas (Hinkle, Muhm and DeBuyl, 1978).

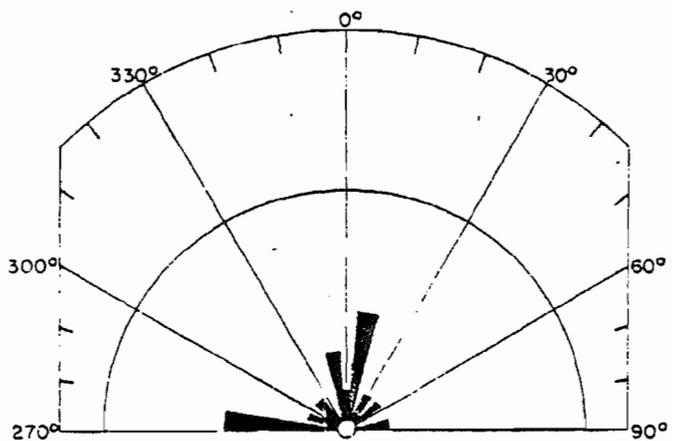
PHOTO-GEOLOGIC FRACTURE TRACE ORIENTATIONS  
(20 LOCATIONS)



STREAM LINEATIONS  
(38 DIRECTIONS)



ORIENTED CORE MEASUREMENTS  
ROLAND SEAM COMPOSITE



ORIENTED CORE MEASUREMENTS  
UPPER SMITH SEAM

Figure 4-3 Dominant Lineations and Fracture Orientations as Determined by Hinkle, Muhm, and DeBuyl (1978) in Their Study Area Near Gillette, Wyoming.

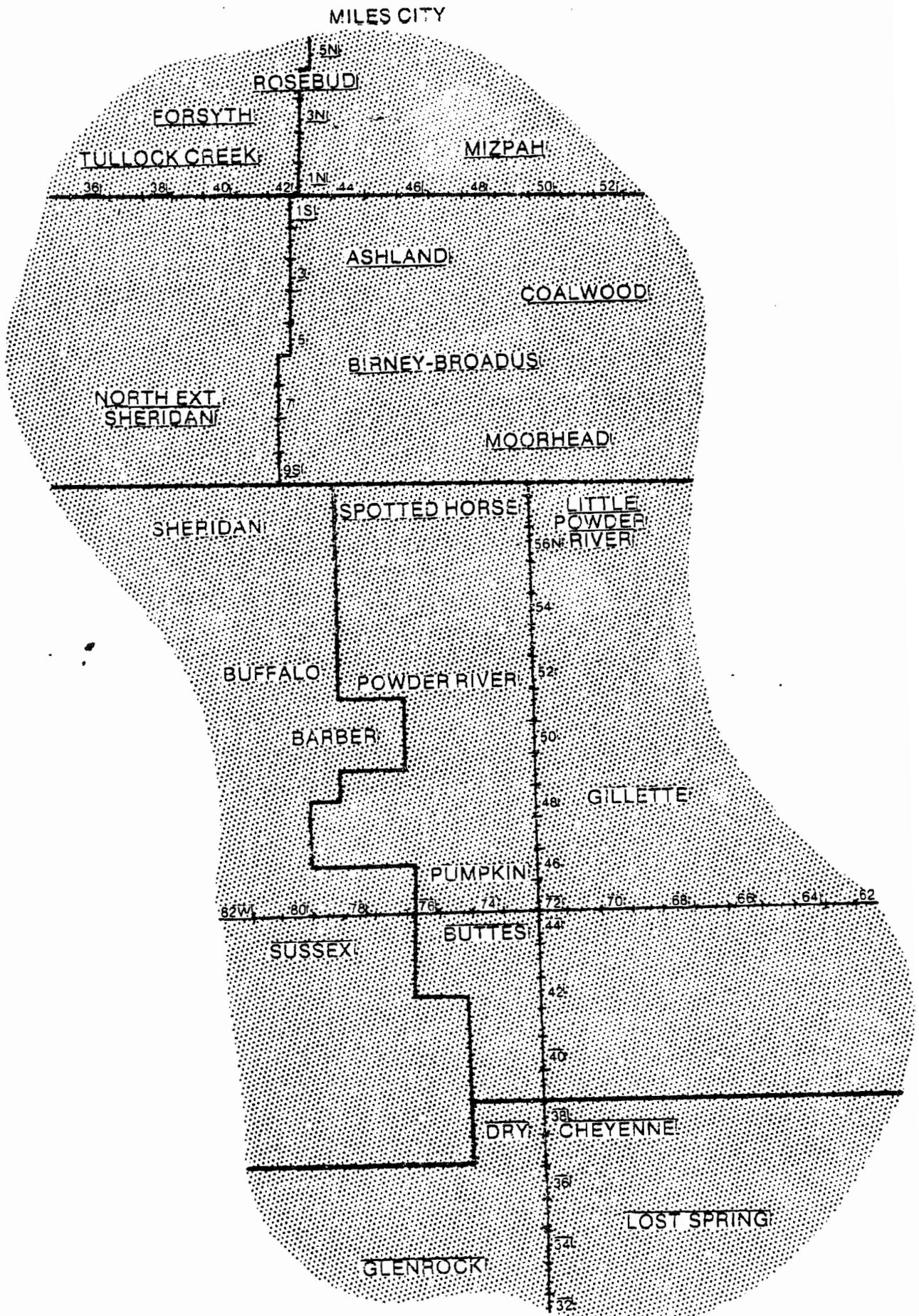
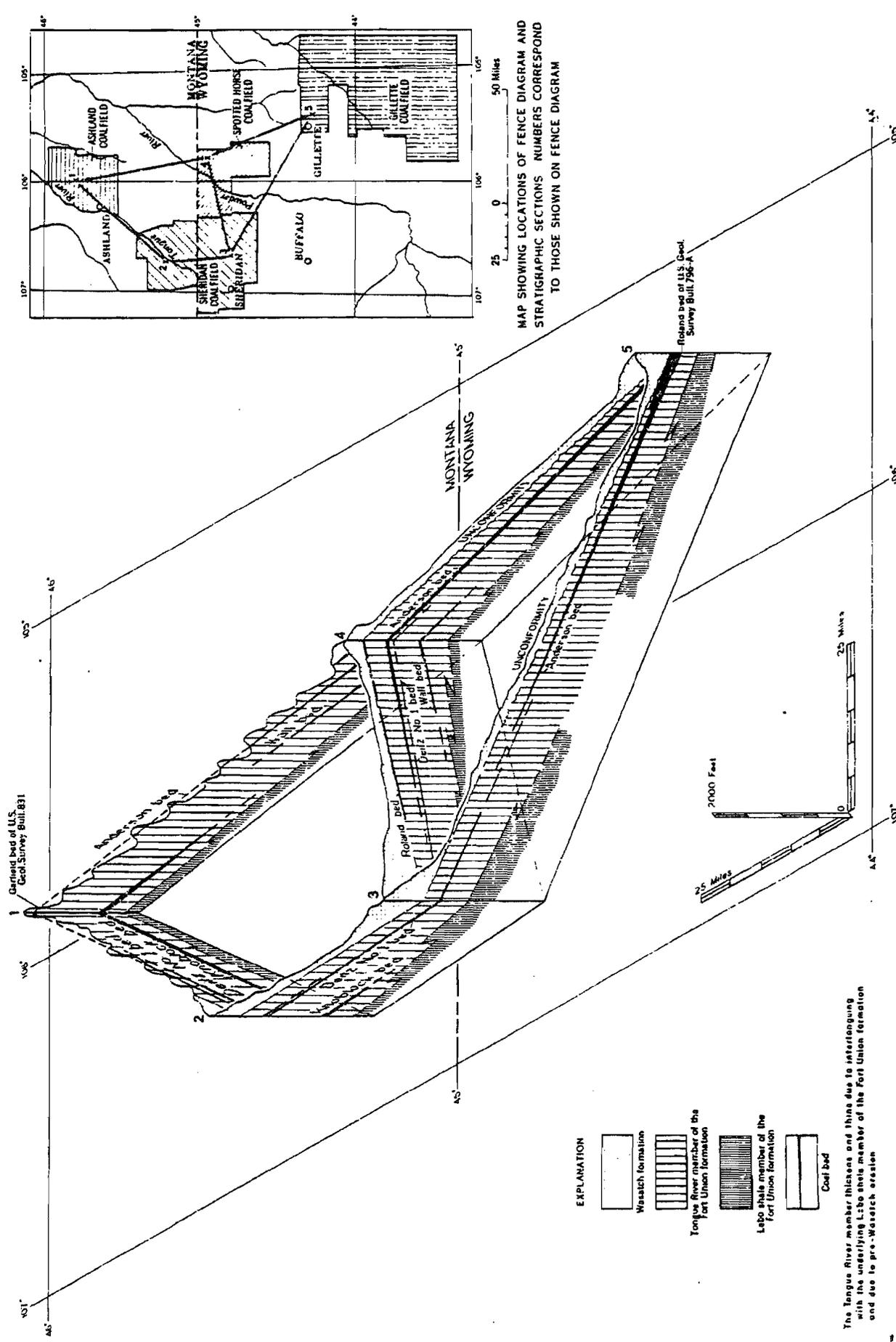


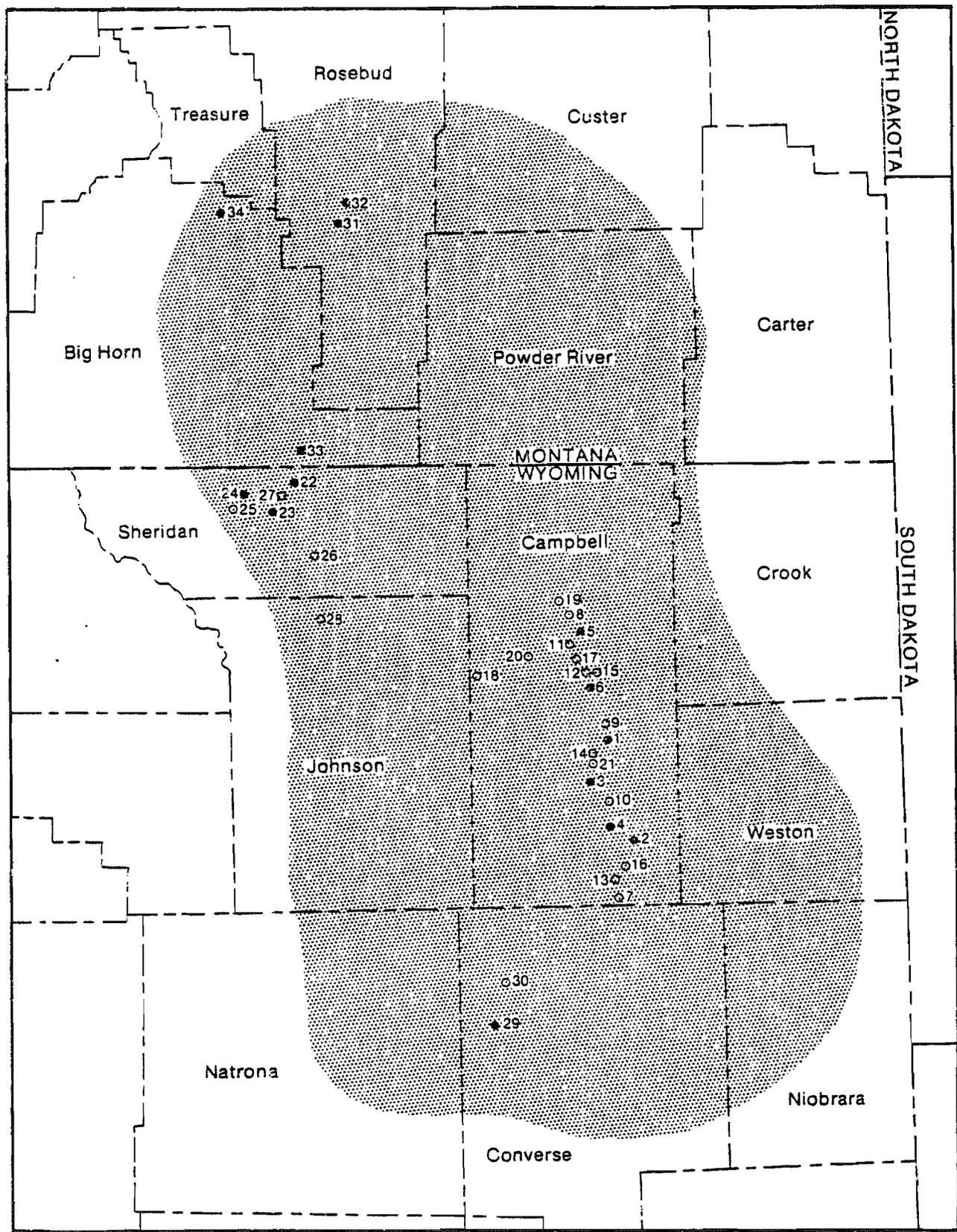
Figure 4-4 Location of Powder River Basin Coal Fields.







**Figure 4-7** Fence Diagram Correlating Coal Beds of Tongue River Member of Fort Union Formation in Northern Wyoming and Southern Montana (Olive, 1957).

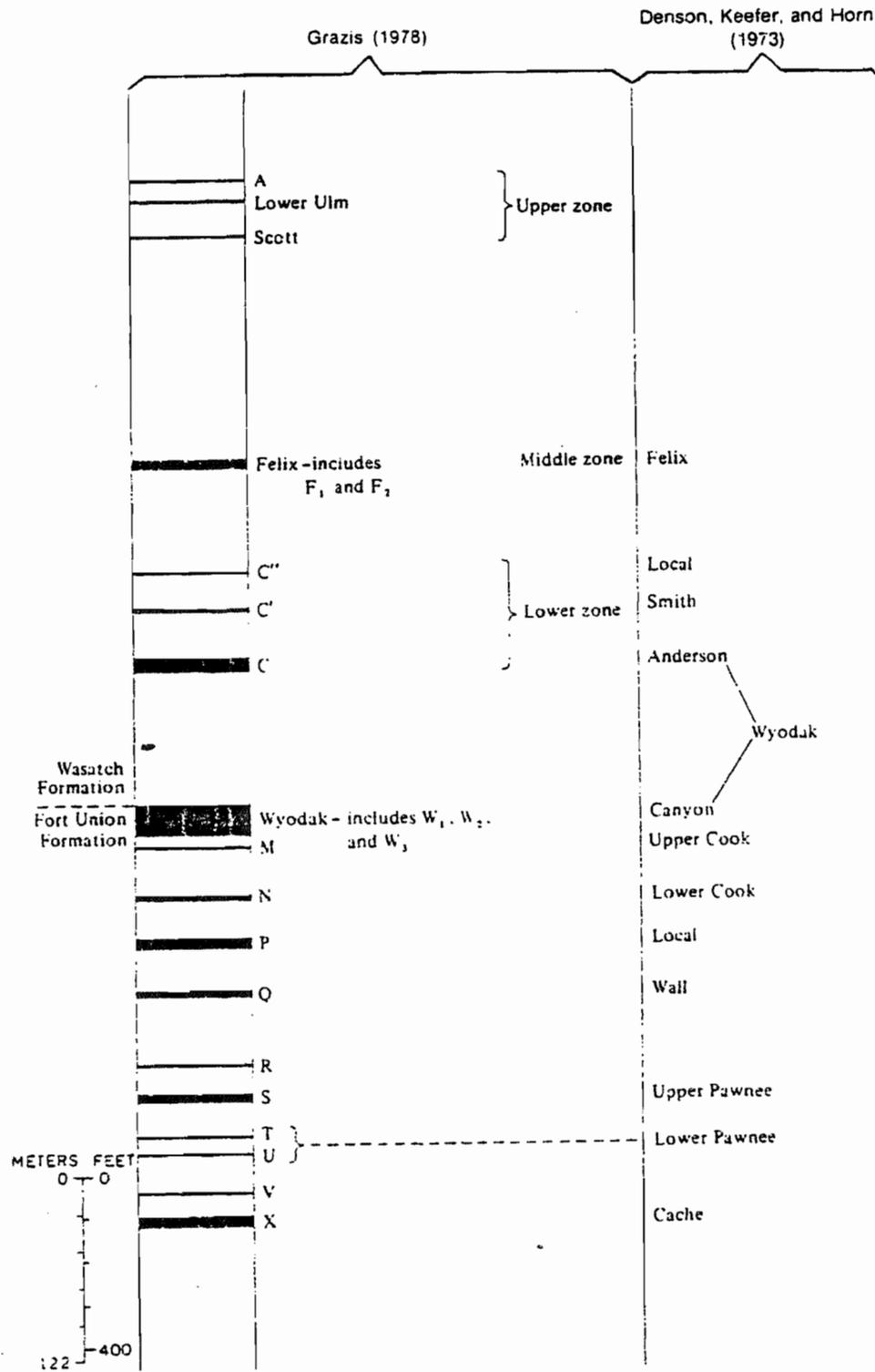


● Active Mines

○ Proposed Mines

**Figure 4-8** Location of Coal Mines in the Powder River Basin

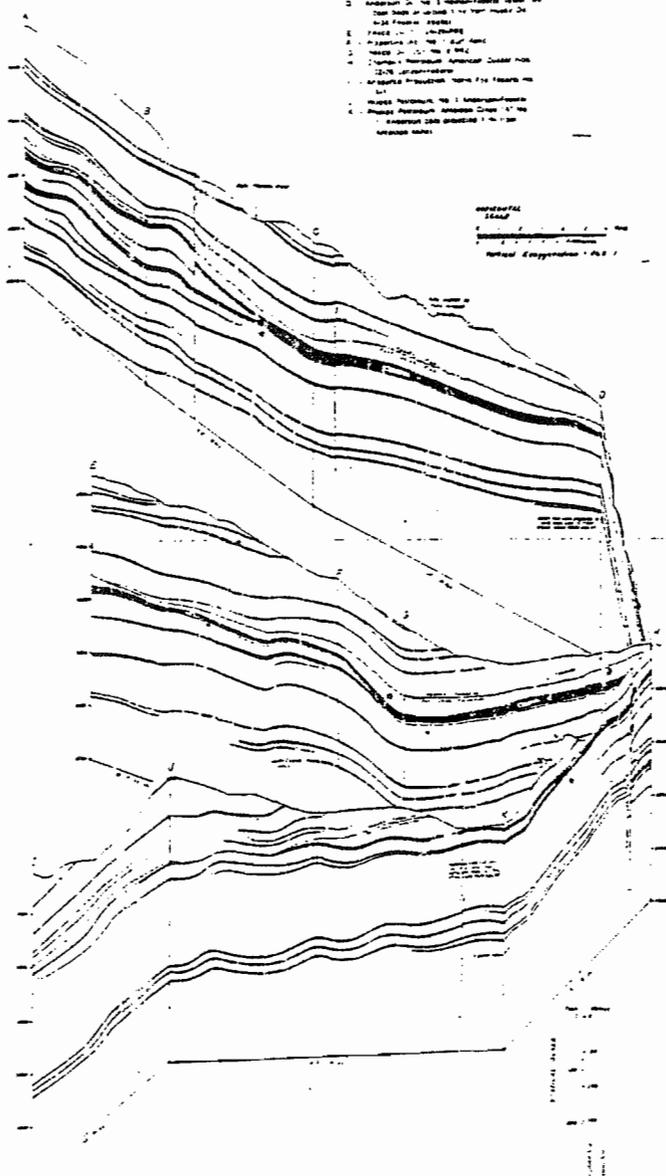
Source: Mapel and Swanson, 1977; Wyoming Department of Economic Planning and Development, 1978.



**Figure 4-9** Stratigraphic columns of Fort Union and Wasatch Coal Beds in Campbell County as Compiled from Drill-Hole Geophysical Logs by the U.S. Geological Survey. Difficulties in Correlation of Beds and Placement of the Fort Union-Wasatch Contact is Demonstrated.

UNIT AND NAME LIST FOR SECTION C (WEST) -  
 (Continued from page 1)

- 1. Sandstone, 20' to 25' thick
- 2. Sandstone, 10' to 15' thick
- 3. Sandstone, 10' to 15' thick
- 4. Sandstone, 10' to 15' thick
- 5. Sandstone, 10' to 15' thick
- 6. Sandstone, 10' to 15' thick
- 7. Sandstone, 10' to 15' thick
- 8. Sandstone, 10' to 15' thick
- 9. Sandstone, 10' to 15' thick
- 10. Sandstone, 10' to 15' thick
- 11. Sandstone, 10' to 15' thick
- 12. Sandstone, 10' to 15' thick
- 13. Sandstone, 10' to 15' thick
- 14. Sandstone, 10' to 15' thick
- 15. Sandstone, 10' to 15' thick
- 16. Sandstone, 10' to 15' thick
- 17. Sandstone, 10' to 15' thick
- 18. Sandstone, 10' to 15' thick
- 19. Sandstone, 10' to 15' thick
- 20. Sandstone, 10' to 15' thick



UNIT AND NAME LIST FOR SECTION C (WEST) -  
 (Continued from page 1)

- 1. Sandstone, 10' to 15' thick
- 2. Sandstone, 10' to 15' thick
- 3. Sandstone, 10' to 15' thick
- 4. Sandstone, 10' to 15' thick
- 5. Sandstone, 10' to 15' thick
- 6. Sandstone, 10' to 15' thick
- 7. Sandstone, 10' to 15' thick
- 8. Sandstone, 10' to 15' thick
- 9. Sandstone, 10' to 15' thick
- 10. Sandstone, 10' to 15' thick
- 11. Sandstone, 10' to 15' thick
- 12. Sandstone, 10' to 15' thick
- 13. Sandstone, 10' to 15' thick
- 14. Sandstone, 10' to 15' thick
- 15. Sandstone, 10' to 15' thick
- 16. Sandstone, 10' to 15' thick
- 17. Sandstone, 10' to 15' thick
- 18. Sandstone, 10' to 15' thick
- 19. Sandstone, 10' to 15' thick
- 20. Sandstone, 10' to 15' thick

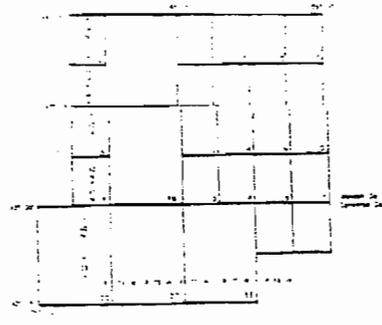


Figure 4-10. Geologic Diagram Showing Coal Bed Thickness and Structure in the Southeast Portion of the Powder River Basin, Carbon, Denver and Dickinson 1975

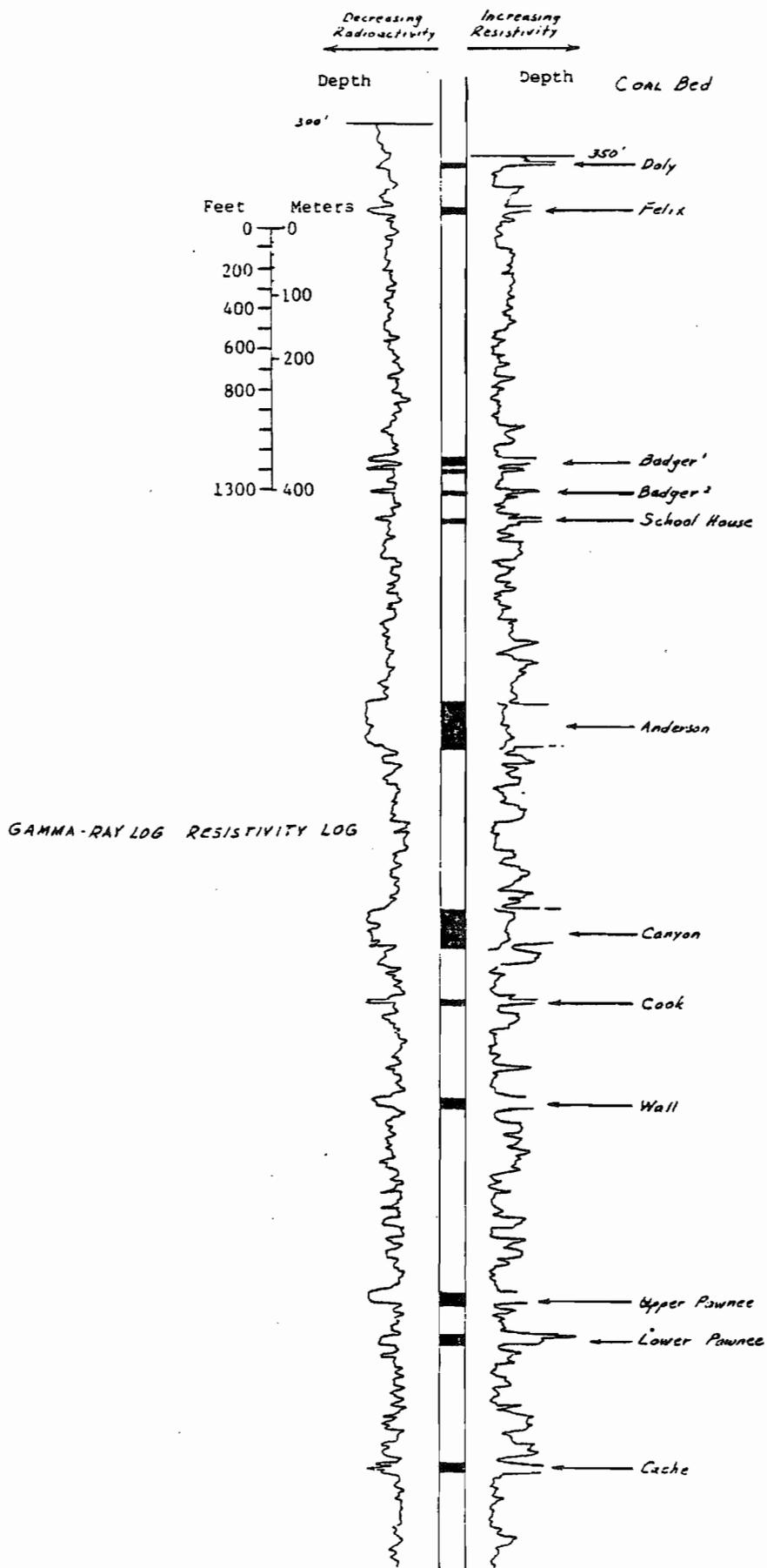


Figure 4-11 Typical Log Response of Some Coal Beds in the Eastern Portion of Powder River Basin (from Denson, Dover, and Osmonson, 1978).

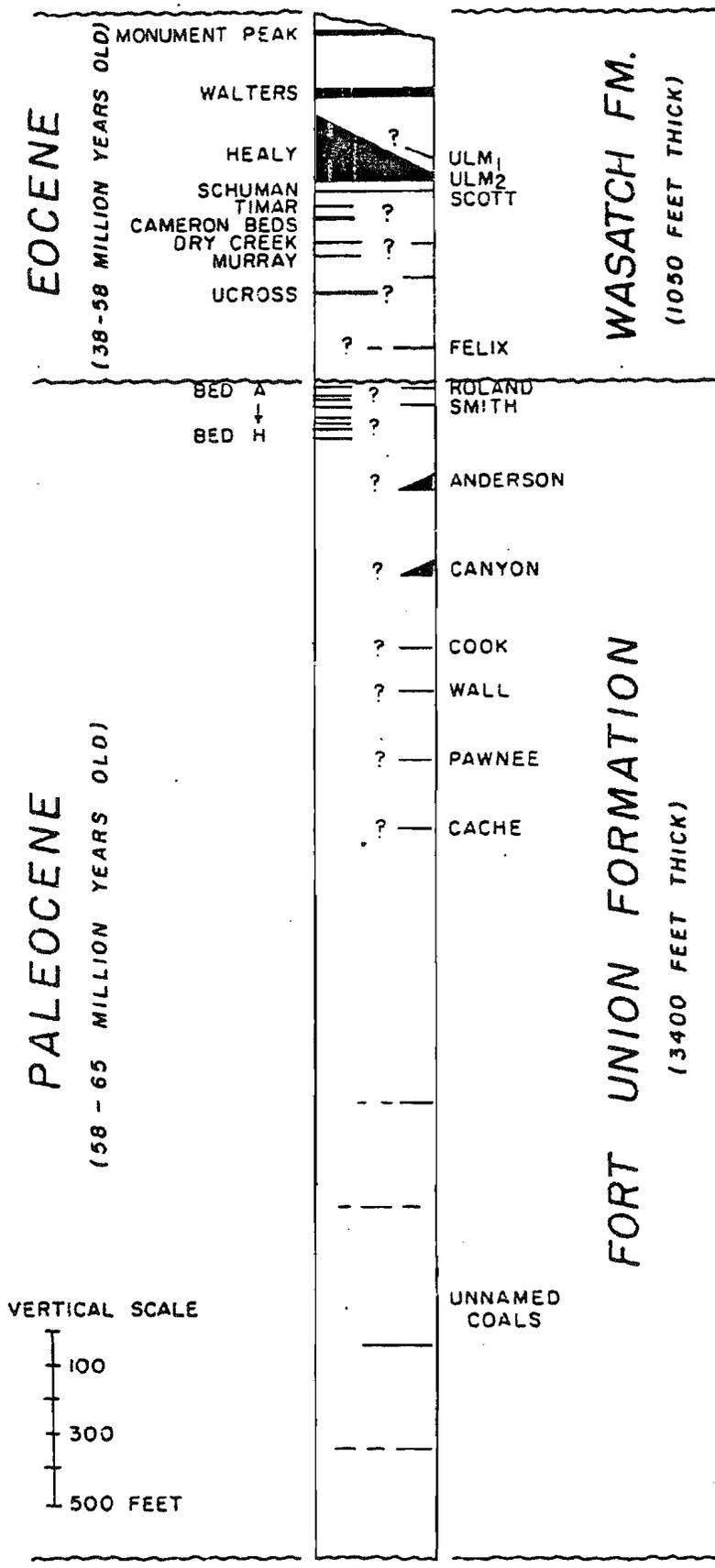
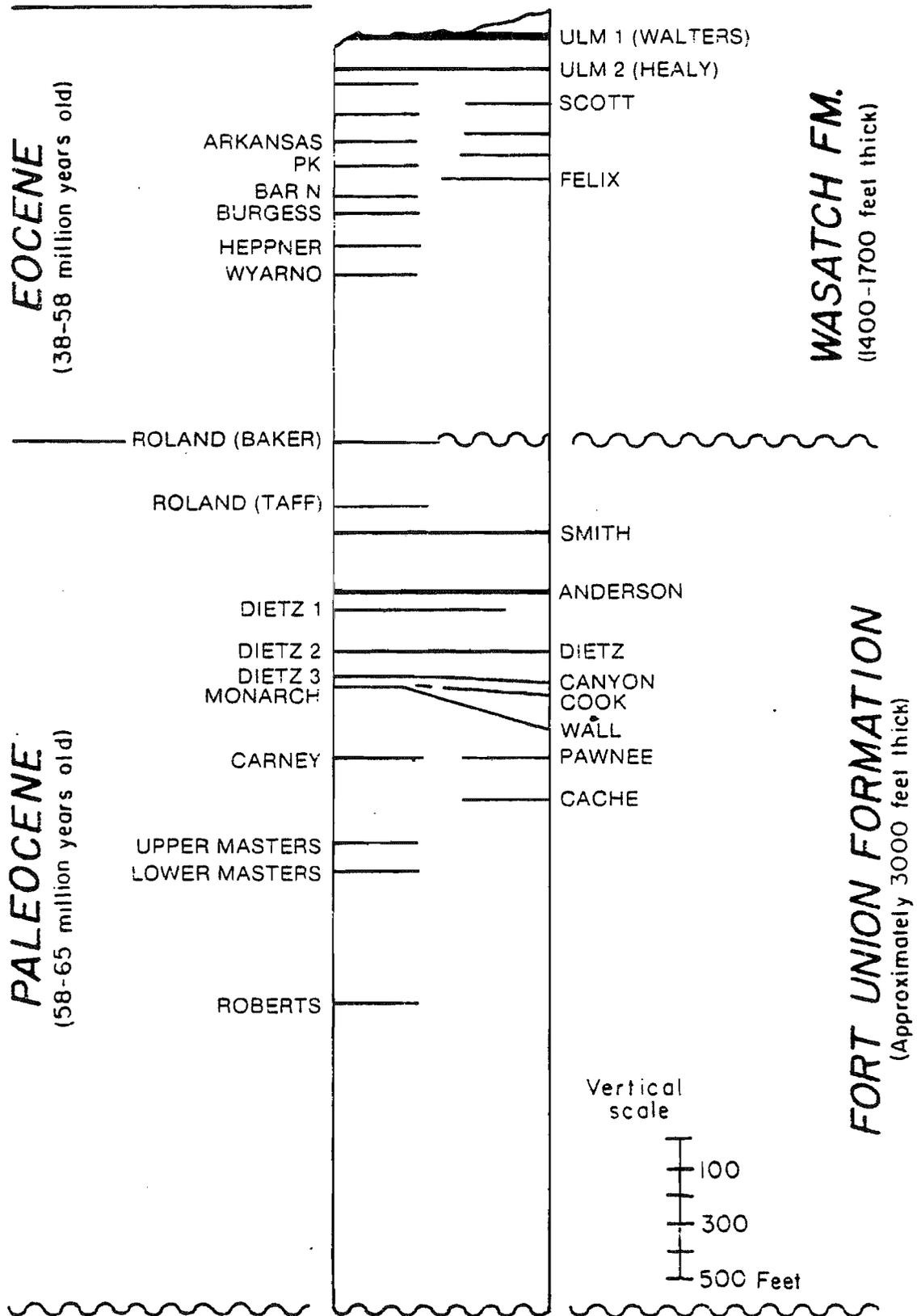


Figure 4-12 Stratigraphic Column Showing Coal Beds in Johnson County, Wyoming (Wendell, et al, 1976)



NOTE Coal beds are not drawn to scale.

Figure 4-13 Stratigraphic Column Showing Coal Beds in Sheridan County, Wyoming (Lageson, et al, 1978)

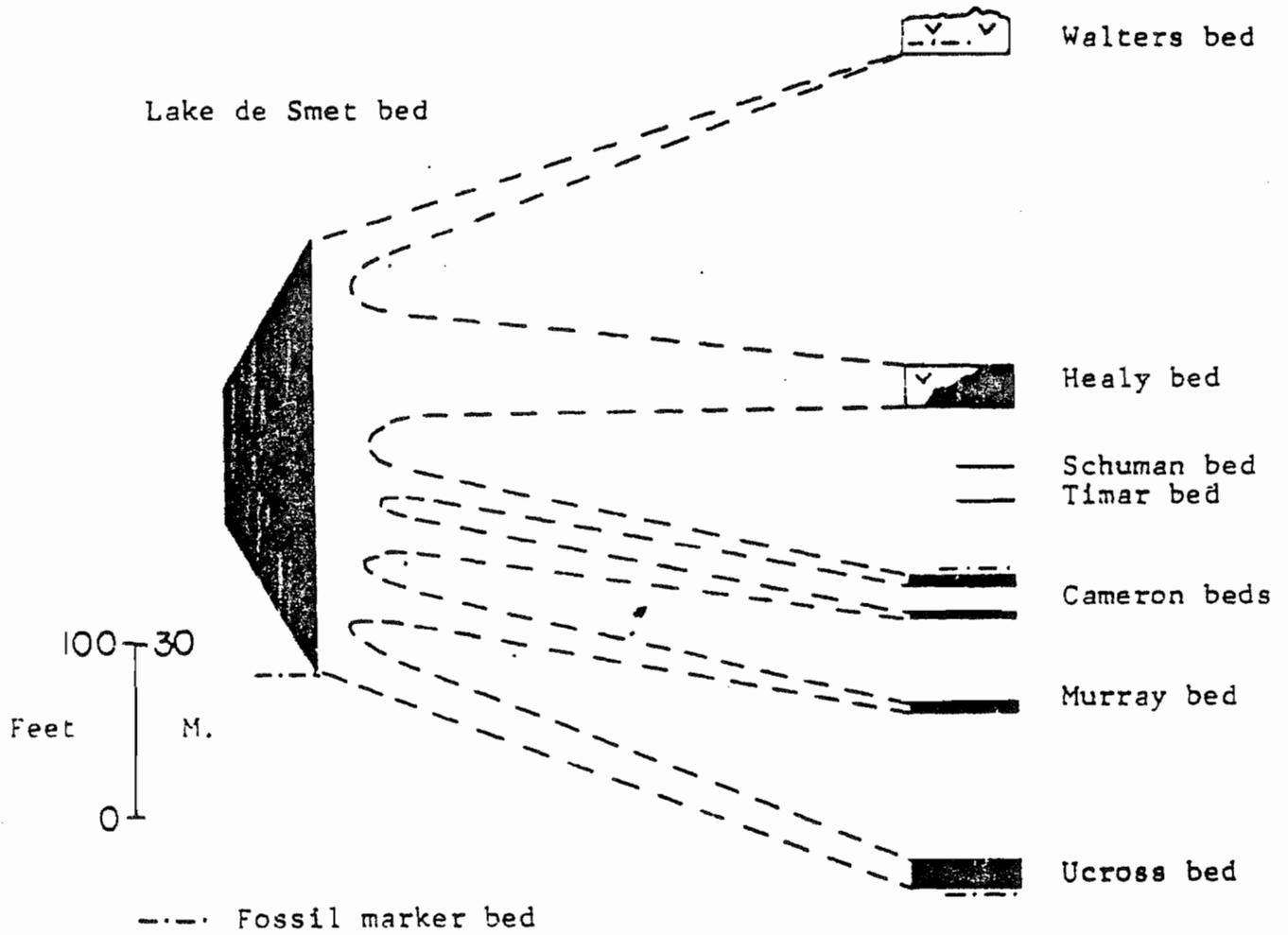
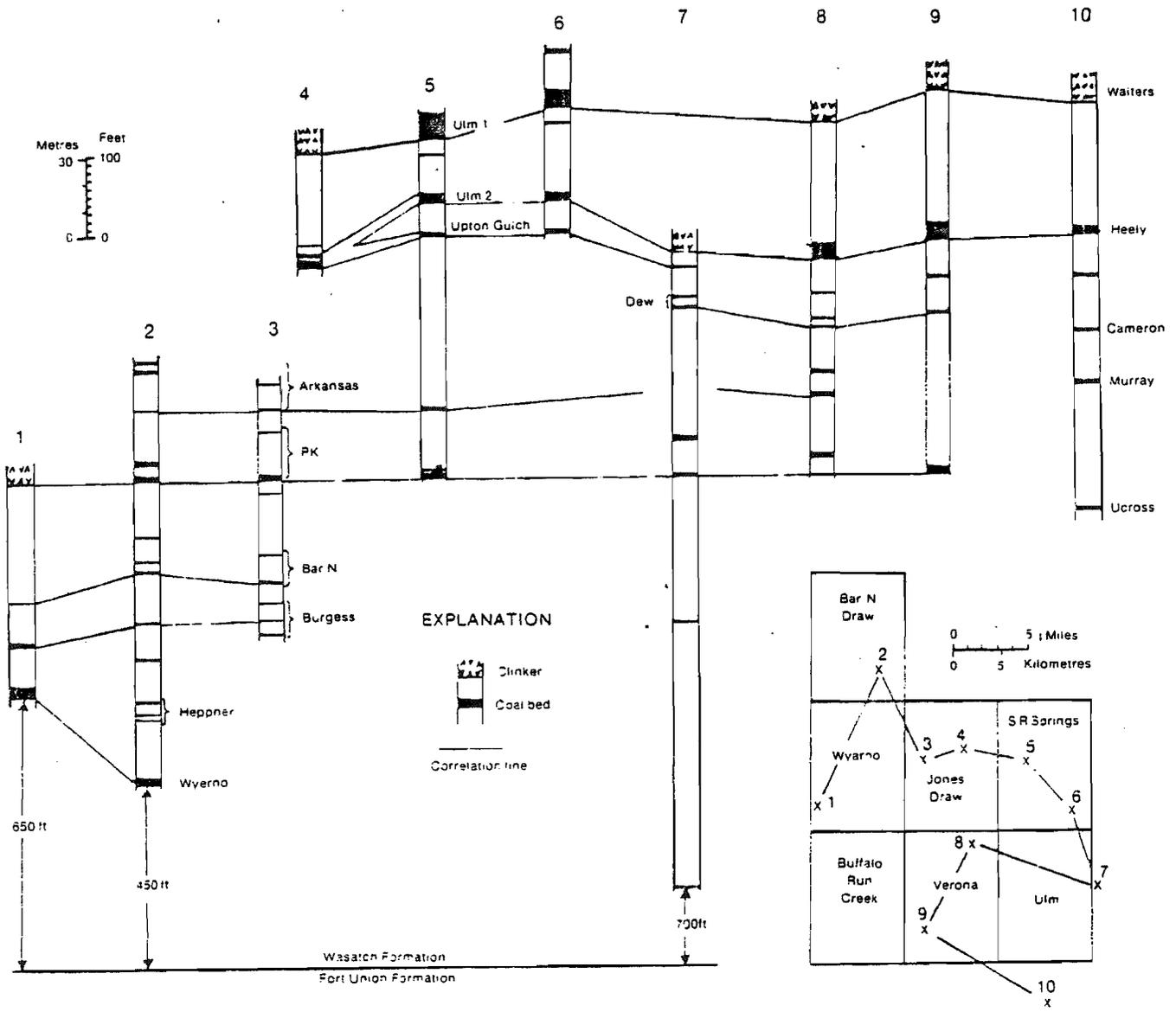


Figure 4-14 Diagram of the Lake de Smet Coal Bed Showing its Relationship to the Major Coal Beds to the East (Obernyer, 1978).



**Figure 4-15** Stratigraphic Sections Showing Coal Beds and Zones of the Upper Part of the Wasatch Formation East of Sheridan, Wyoming, and their Relation to Coal Beds in the Buffalo-Lake De Smet Area (Section 10). All Sections are from Outcrop Measurements, Except No. 7, which is from the Gamma Ray Log of the Anshutz-Moncrief-Sohio 1 Faddis Kennedy Well (Culbertson and Maple, 1976).



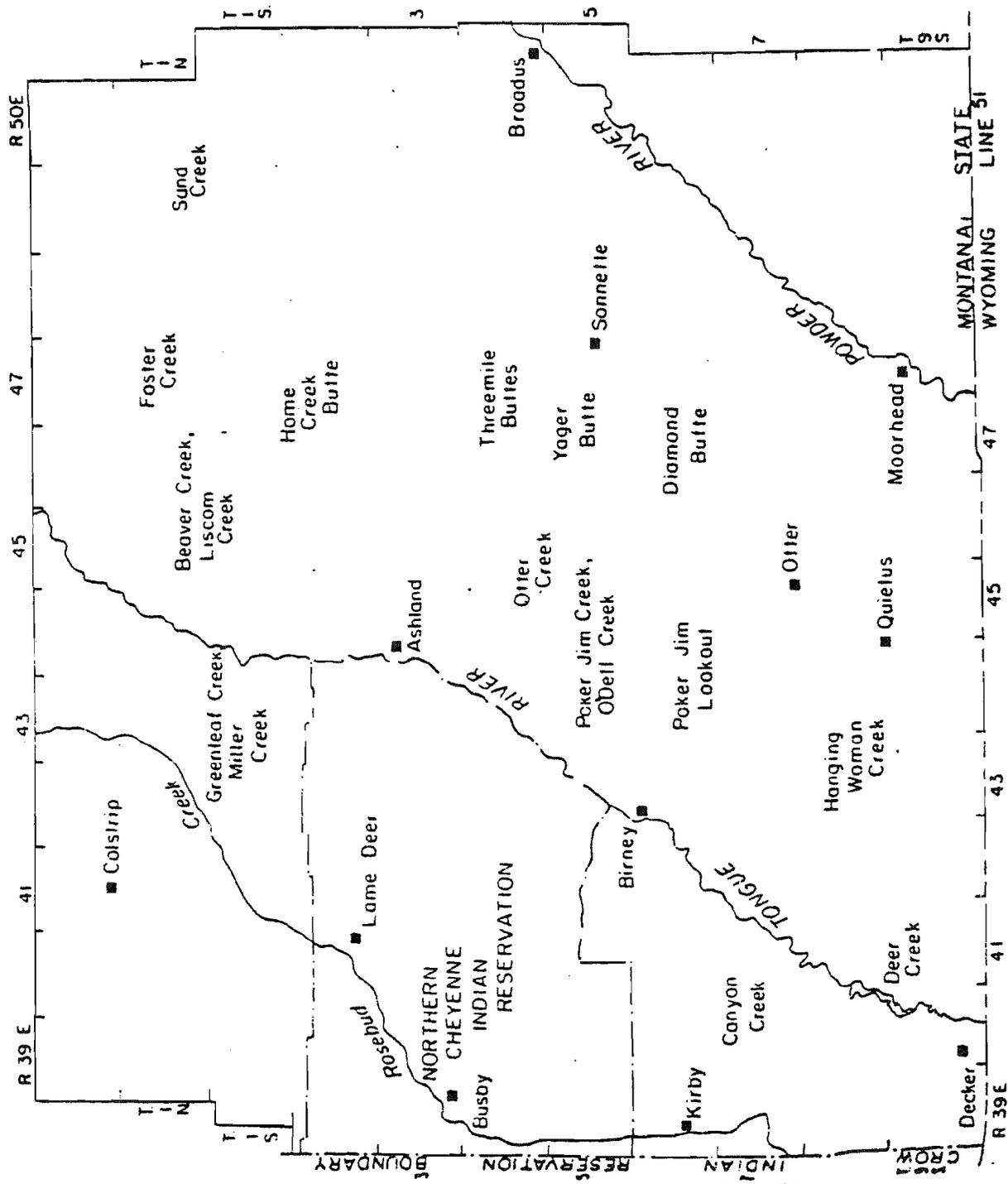


Figure 4-17 Location Map Showing Some of the Coal Deposits of the Northern Powder River Basin, Montana (Matson and Pinchock, 1976).

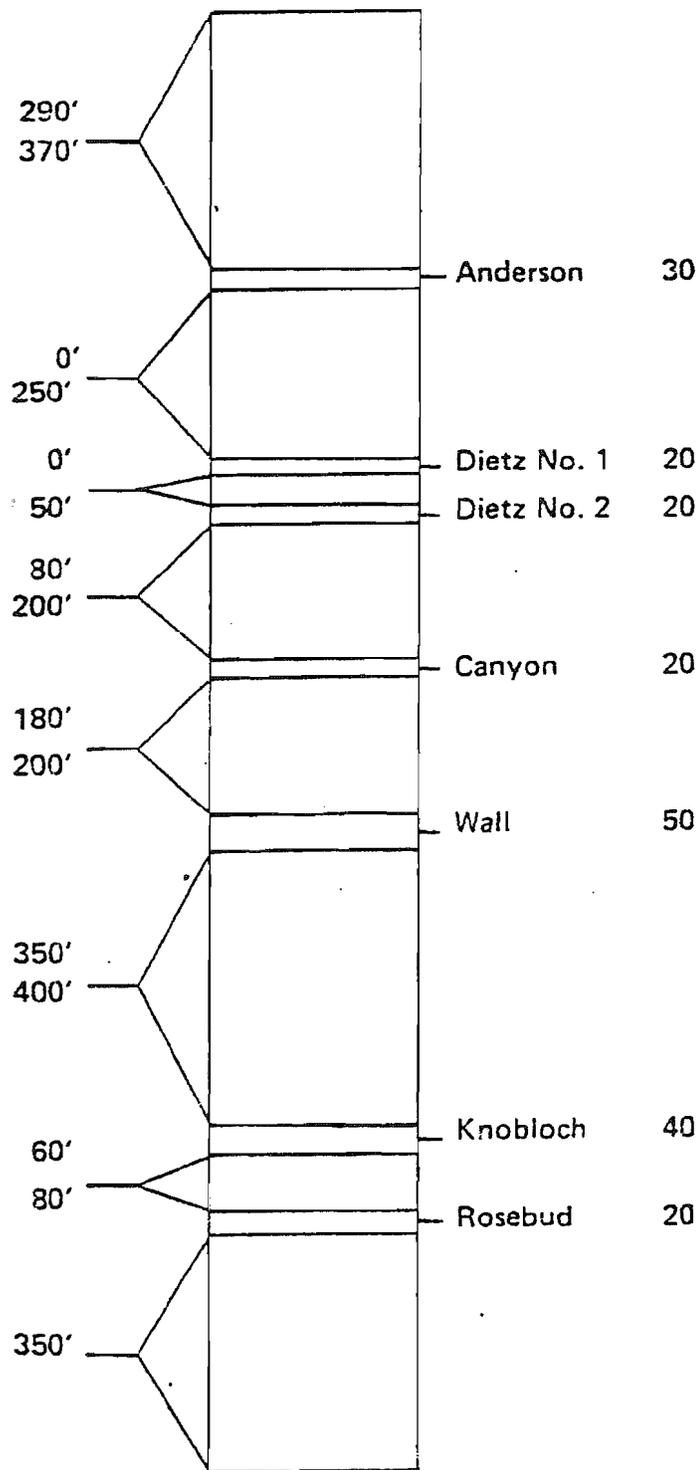


Figure 4-18 Stratigraphic Diagram Showing Distribution and Thickness of the Important Coal Beds in the Tongue River Member, Northern Powder River Basin, Montana (Matson and Pinchock, 1976).

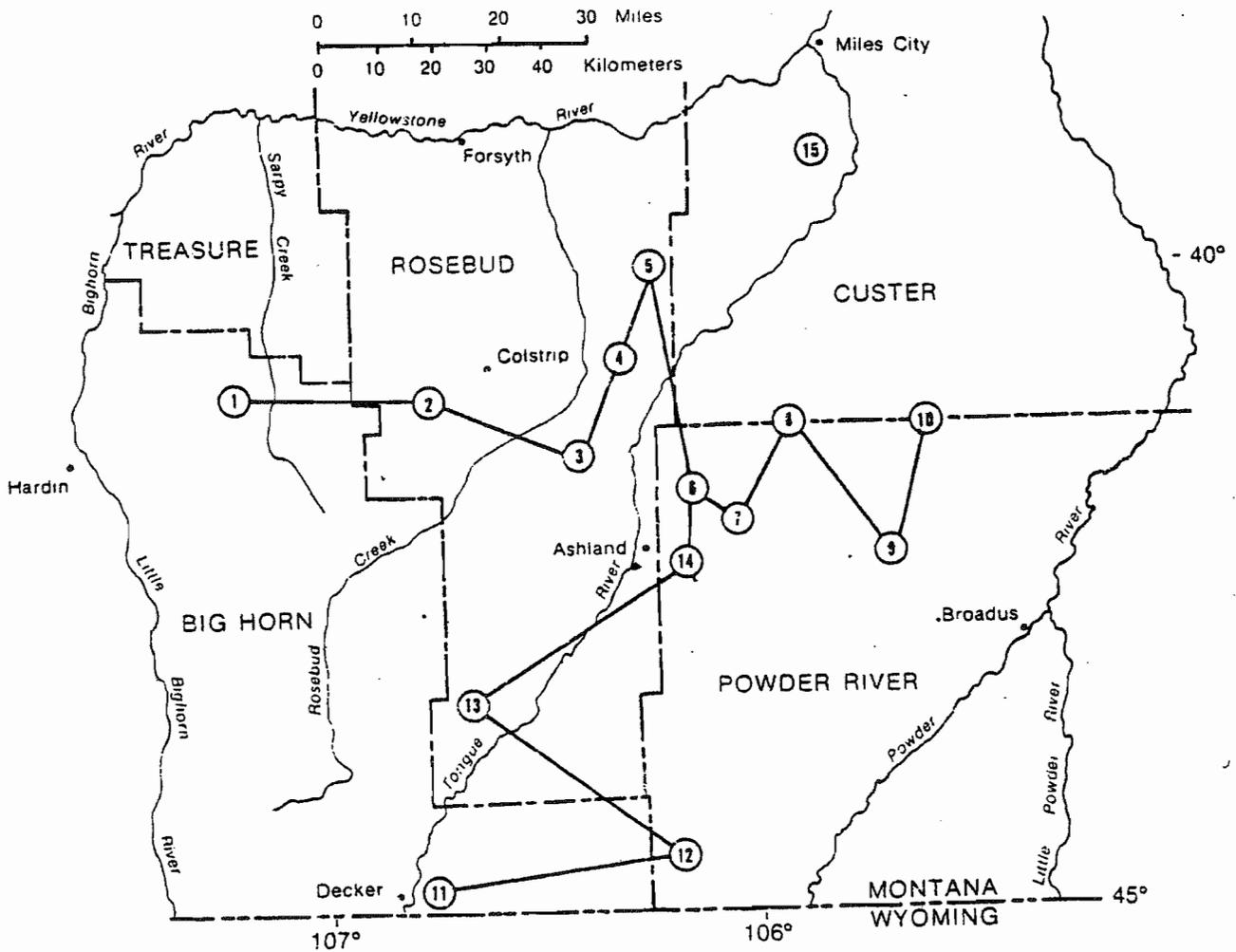


Figure 4-19 Location of Stratigraphic Sections Shown in Figures 4-20 and 4-21 (Maple and Swanson, 1977, p20)



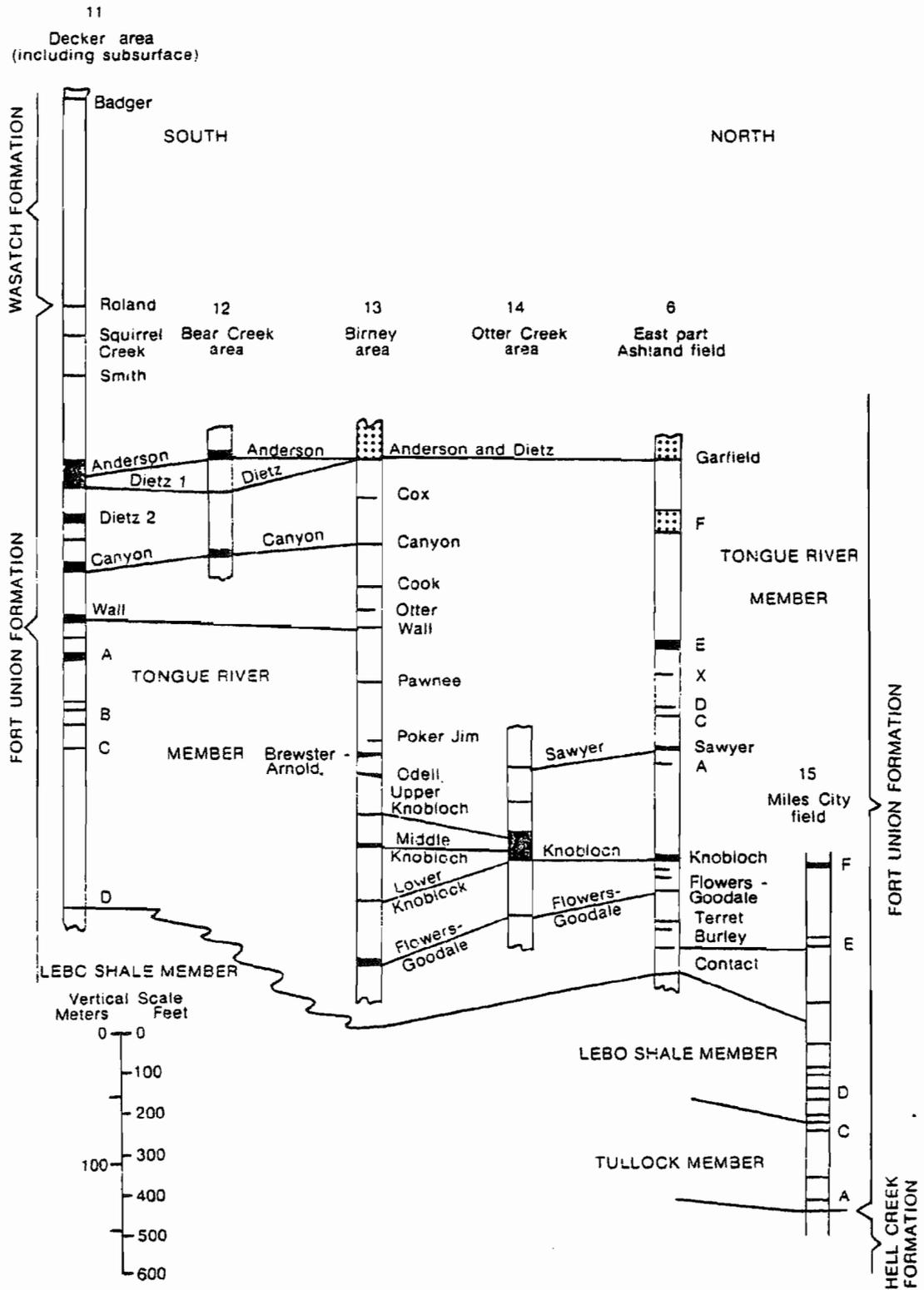
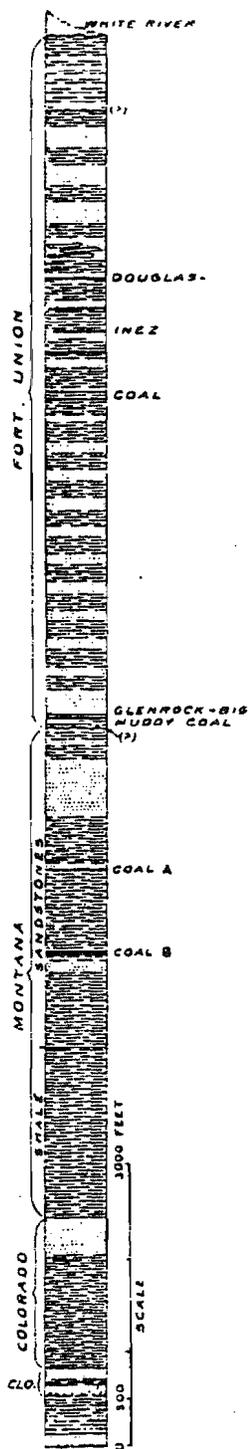


Figure 4-21 North-South Correlation of Coal Beds Northern Powder River Basin, Montana (Mapel and Swanson, 1977, p. 18).



**Figure 4-22** Stratigraphic Column of the Glenrock Coal Field (Shaw, 1909, p. 155). Though Nomenclature in Above Stratigraphic Section is not Current, Relative Stratigraphic Position and Lithology are Representative.

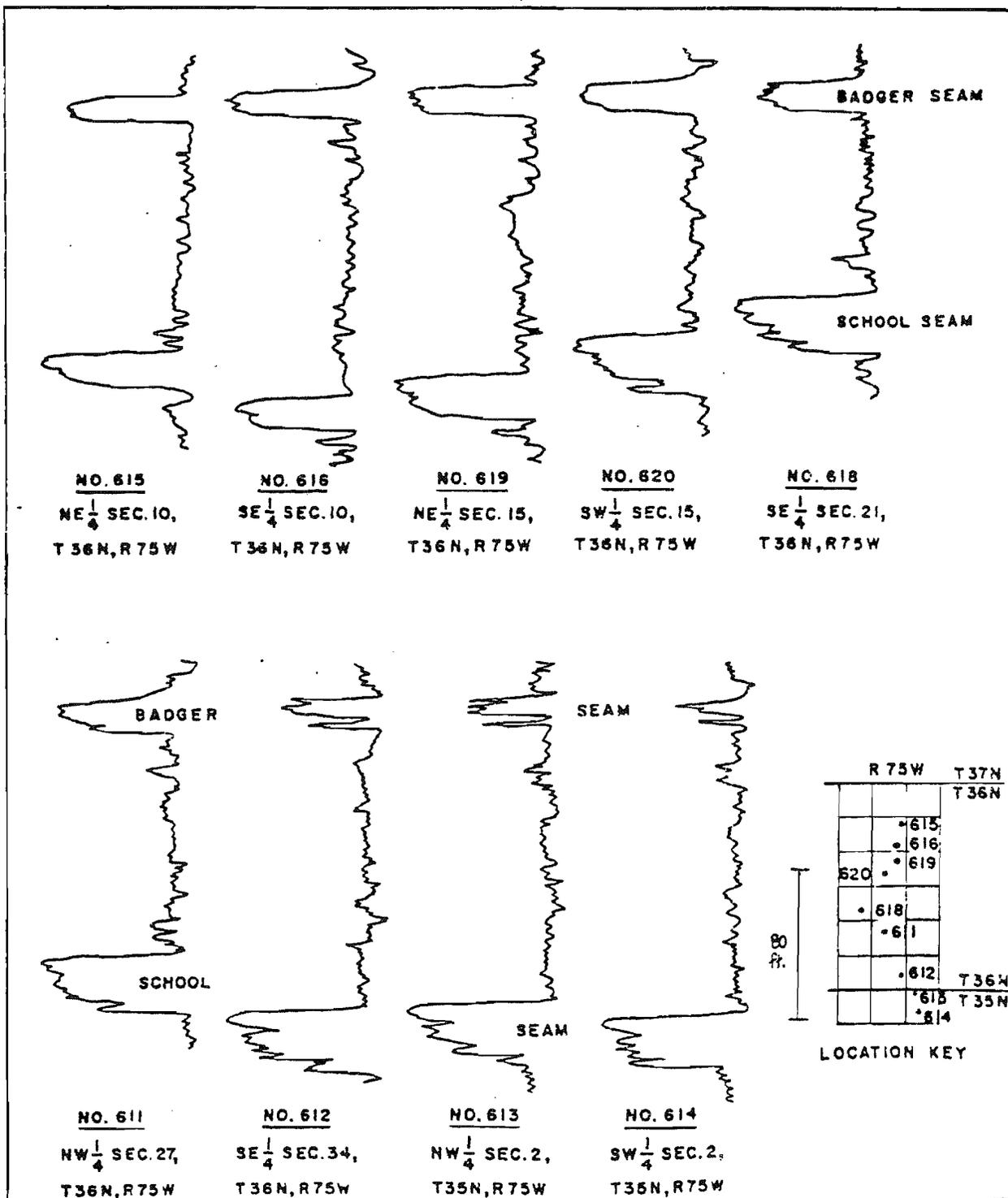


Figure 4-23 Gamma Ray Logs from Drill Holes in the Dave Johnston Coal Deposit (From: Duell, 1969).

Strippable Deposit	Coal Bed(s) (Average thickness in feet)	Acreage Estimate	Original Estimated Reserves to Jan. 1, 1978	Production and Mining Losses Since Jan. 1, 1969	Remaining Strippable Reserves to Jan. 1, 1978
Acme-Kleenburn*	Monarch and Dietz No. 3 (23')	2,029.0	39,300,000	12,000,000	27,300,000
Clear Creek	Canyon (11.2')	9,337.6	184,900,000	--	184,900,000
Dave	School (38')	2,418.0	126,200,000		
Johnston	Badger (16')	390.0	9,500,000	26,900,000	108,800,000
Dry	F (7.6')	13,260.8	179,500,000	--	179,500,000
Cheyenne					
Lake DeSmet	Healy (163')	3,520.0	1,000,000,000	--	1,000,000,000
Spotted	Felix (12.5')		480,700,000	--	480,700,000
Horse	Smith (10.0')	36,736.0	178,000,000	--	178,000,000
	Local (10.0')		58,300,000	--	58,300,000
Sussex	Wasatch Fm. coal (11.8')	651.0	13,600,000	--	13,600,000
Wyarno-	PK (11')	?	200,000,000	--	200,000,000
Verona*	Ulm 2 (20')	?	990,000,000	--	990,000,000
	Ulm 1 (30')	?	543,000,000	--	543,000,000
	Other Wasatch coals (10'+)	?	67,000,000	--	67,000,000
Wyodak	Wyodak-Anderson (71'); Anderson (D) and Canyon (E)	115,282.0	19,000,000,000	45,300,000	18,954,700,000
Subtotal		223,624.4+	23,070,000,000	84,200,000	22,985,800,000

Table 4-1 Strippable Coal Reserve Base Wyoming Portion of Powder River Basin Remaining as of January 1, 1978 (from Glass, 1978)

Deposit	Anderson	Dietz	Canyon	Wall	Knobloch	Rosebud
Decker	2239.99					
Deer Creek	410.47					
Kirby	216.52	834.35	158.53	473.69		
Canyon Creek				1884.25		
Poker Jim Lookout	872.65					
Hanging Woman Creek	1583.29	1120.96				
West Moorhead	883.74	347.49	690.19			
Poker Jim Creek-O'dell Creek					938.07	
Otter Creek					2075.55	
Ashland					2696.20	
Coistrip						1439.26
Foster Creek					708.13	
Diamond Butte			418.02			
Yager Butte				496.34		
Threemile Buttes			191.28			
Home Creek Butte			14.61			
Sand Creek					267.34	
Beaver Creek-Liscom Creek					491.62	
Greenleaf Creek-Miller Creek					325.00	76.14

Table 4-2 Reserves of Strippable Coal by Deposit and Coal Bed, Northern Powder River Basin, Montana (Matson and Pinchock, 1976).

Average As Received Basis	Wasatch										Fort Union			
	15 analyses	142 cores	15 analyses	13 analyses	single core	10 analyses	14 analyses	5 analyses	analysis	19 cores	159 analyses	1703 analyses	10 analyses	2 analyses
Moisture (%)	30.2	28.0	27.4	27.2	31.8	27.5	27.5	27.7	19.1	29.6	29.8	27.5	27.4	27.9
Volatile Matter (%)	31.2	31.7	31.1	31.9	28.7	30.6	30.4	33.0	14.8	30.7	30.7	34.5	36.9	31.9
Fixed Carbon (%)	34.3	32.5	31.4	30.5	34.8	33.2	33.9	36.5	41.7	34.6	33.5	39.6	34.0	31.5
Ash (%)	4.3	7.8	7.9	11.4	4.1	6.2	6.5	6.6	4.4	5.1	6.0	4.4	9.8	9.0
Sulfur (%)	1.5	0.6	0.35	0.6	0.63	0.49	0.57	0.54	0.5	0.34	0.5	0.4	0.66	0.71
Btu pound	8,060	7,884	7,971	8,183	7,943	8,100	8,038	8,210-8,300	9,310	8,385	8,244	9,000	8,311	8,434

Most of these weathered outcrop samples  
except where noted to be core samples  
from U.S. Geological Survey Drilling 1973-74

Table 4-3 Average Coal Analyses for Some of the Major Coal Beds in the Powder River Basin (data from several sources, compiled by Glass, 1978).

Author	Study area	Major sets
Stone and Snoeberger (1976).	Southwest of Gillette (Felix coal).	N. 24° W. N. 78° E.
Glass (1975)	Gillette area (Anderson Canyon coal).	N. 10° W.-N. 5° E. N. 85° E.-S. 88° E. N. 56°-70° E. N. 26°-38° E. N. 30° W. N. 70°-82° W. N. 50°-60° W.
Lee, Smith and Savage (1976).	Sheridan-Decker coal field.	N. 45° W. N. 37° E. N. 13° E.
Henkle, Muhn & DeBuyl (1977).	15 mi northwest of Gillette.	N. 35°-45° W. N. 45°-55° E. N. 5° W.-N. 5° E. N. 75° E.-S. 85° E.

Table 4-4 Summary of Fracture and Cleat Orientations as Determined in Four Studies of Coal-Bearing Rocks of the Powder River Basin (Henkle, Muhn, DeBuyl, 1978).



		WASATCH FORMATION							
		ULM <sub>2</sub> (3) <sup>1</sup>		SCOTT (3)		FELIX (42)		UNSPECIFIED (6)	
As-received		Range	Average	Range	Average	Range	Average	Range	Average
PROXIMATE	MOISTURE (%)	28.1-29.7	28.9	25.0-32.2	29.1	17.8-33.5	28.0	23.7-29.6	27.6
	VOLATILE MATTER (%)	31.6-33.2	32.2	29.7-30.9	30.2	29.1-36.4	31.7	26.9-30.9	29.2
	FIXED CARBON (%)	30.8-33.2	32.4	27.5-29.8	28.8	28.4-39.4	32.5	25.4-33.3	29.9
	ASH (%)	5.6-7.6	6.5	8.2-15.8	11.9	4.5-14.9	7.8	6.2-23.2	13.3
	SULFUR (%)	0.60-1.24	0.94	0.87-2.22	1.75	0.32-3.26	0.89	1.07-4.16	2.19
	HEAT VALUE (BTU/POUND)	7901-8029	7965	7241-7425	7330	7180-9535	8053	6501-8215	7418
		FORT UNION FORMATION							
		SMITH (1)		ANDERSON (23)		CANYON (9)		WYODAK (53)	
PROXIMATE	MOISTURE (%)	-	31.8	24.9-34.1	29.5	26.5-31.5	29.6	23.4-36.9	29.8
	VOLATILE MATTER (%)	-	28.7	26.5-34.5	30.1	28.7-33.3	30.7	26.5-32.7	30.7
	FIXED CARBON (%)	-	34.8	29.0-38.0	33.9	31.8-36.4	34.6	29.6-41.4	33.5
	ASH (%)	-	4.7	3.5-12.2	6.5	3.1-7.4	5.1	2.9-12.2	6.0
	SULFUR (%)	-	0.63	0.17-1.13	0.52	0.14-0.92	0.34	0.20-1.20	0.50
	HEAT VALUE (BTU/POUND)	-	7991	7128-8737	7979	7537-8609	8286	7420-9306	8224

<sup>1</sup>Number of samples averaged. (Table compiled from analyses published by the U. S. Geological Survey and the U. S. Bureau of Mines.)

Table 4-6 Averaged Analyses of Coal Beds in the Fort Union and Wasatch Formations of Campbell County (Breckenridge, et al. (1974).

	CROFTON MF - 826	TRUMAN CRAW MF - 817	WILDCAT MF - 735	(CROFTON 1 SW) HOMESTEAD CRAW MF - 544	RECLUSE MF - 732	(TOWNSEND SPRING) ORIVA NW MF 545	GILLETTE WEST MF - 974
ANDERSON	33 26 - 36 Thin Parting	29 24 - 39 2 beds	33 25 - 44 1 - 5 beds "Swartz-Anderson"	24 18 - 40	20 8 - 34 "Swartz-Anderson" 1-3 beds	33 5 - 42	
DIETZ	9 7 - 10	10 6 - 17 1 - 2 beds	22 12 - 46 combined w/Canyon at 3 wells 65-70' thick	28 10 - 40	24 12 37 1 - 4 beds thin parting	30 3 - 32	Wyodak bed
CANYON	49 32 - 60 Parting	29 4 - 53 2 - 4 beds	27 17 - 35 combined w/Dietz at 3 wells 65-70' thick	10 10 - 33	24 10 - 30 1 - 4 beds thin partings	45 11 - 98	87 67 - 108 1 - 4 beds
COOK	34 25 - 45	20 12 - 28 1 - 2 beds	8 3 - 13 1 bed	14 5 - 30 2 beds	6 4 - 12 feet 1 - 2 beds	7 3 - 21 2 beds	
WALL		38 10 - 66 1 - 4 beds	26 14 - 45	20 10 - 33	25 13 - 37 1 - 3 beds		9 3 - 12 1 bed
UPPER PAWNEE	32 19 - 38 1 - 2 beds	14 4 - 25 1 - 2 beds	8 5 - 10	11 4 - 19	23 11 - 36 1 - 2 beds		10 2 - 17
LOWER PAWNEE			11 7 - 14	7 3 - 11			8 3 - 17
CACHE	13 4 - 20	12 4 - 26 1 bed	11 8 - 19	11 3 - 17	9 4 - 16 1 - 2 beds		24 20 - 33 1 - 3 beds
NOTES	At least 3 unnamed beds in 250' section below Cache, each being 2 - 13' thick	25' of coal in 1500' section in hole T-6 (18 beds) At least 4 - 6 unnamed beds in 400' section below Cache, each being 3 - 12' thick	At least 3 beds below Cache 3 - 12 feet thick in 200' section		1 - 5 unnamed beds in 300' section below Cache, 3 - 14' thick		204 feet of coal in well 25 sec 27 Anshutz - 1 Federal 048

Compiled from: Law, 1978; McLaughlin and Hayes, 1973; Hayes, 1973; Kent, 1976 a and b; Haddock, Kent and Boher, 1976; Kent, Haddock and Boher, 1977.

25 arithmetic average of recorded thickness over 3 feet, excluding partings  
5 - 30 range of recorded thickness over 3 feet.

**Table 4-7 Range and Average Thickness of Some Fort Union Coal Beds From Seven Recent Quadrangle Maps in the Eastern Powder River Basin**

		WASATCH FORMATION				FORT UNION FORMATION			
		HEALY (12) <sup>1</sup>		LOWER CAMERON (5) <sup>1</sup>		BED E <sup>3</sup> (2) <sup>1</sup>		BED B <sup>4</sup>	LOWERMOST BED <sup>5</sup>
As received		Range	Average	Range	Average	Range	Average	Single Analysis	Single Analysis
PROXIMATE	MOISTURE (%)	23.6-31.2	29.1	26.8-31.1	28.8	18.8-23.5	21.1	28.8	23.6
	VOLATILE MATTER (%)	26.6-33.1	30.5	28.7-32.8	29.8	35.7-35.6	35.6		
	FIXED CARBON (%)	35.4-32.3	34.2	34.7-27.9	31.7	37.9-35.7	36.8		
	ASH (%)	2.2-9.7	6.3	7.2-12.5	9.6	5.2-14.6	6.5		
ULTIMATE <sup>2</sup>	HYDROGEN (%)	6.1-6.7	6.5	6.0-6.6	6.4	6.5	6.5	6.7	7.8
	CARBON (%)	45.4-48.3	46.6	42.7-44.6	43.6	51.2	51.2		
	NITROGEN (%)	0.7-1.0	0.8	0.5-0.8	0.6	.7	.7		
	OXYGEN (%)	34.2-40.6	38.8	37.5-40.7	39.1	35.9	35.9		
	SULFUR (%)	0.3-1.0	0.6	0.4-1.4	0.9	0.5-0.6	0.5	0.6	0.7
HEAT VALUE (BTU/POUND)		7515-8270	7910	7344-7627	7492	7980-9157	8729	7931	8446

<sup>1</sup>Number of samples averaged for proximate analysis.

<sup>2</sup>Ultimate analysis does not add up to 100% because fewer analyses were averaged.

<sup>3</sup>Bed E of Wegemann (1912) in Coal Basin No. 2 of the Sussex Field.

<sup>4</sup>Bed B of Wegemann (1912) or Bed E of Hose (1955) in Coal Basin No. 2 of the Sussex Field.

<sup>5</sup>Lowermost bed of Wegemann (1912) in Coal Basin No. 4 of the Sussex Field.

(Table compiled from channel, tippie or core samples analyzed by the U. S. Bureau of Mines. Only a few of the analyses represent the full thickness of a given bed. Also with the exception of one tippie sample, noncoaly partings and dirty (dony) coal were removed from each sample before analysis. Considerable core loss was noted in 8 core samples of the Healy coal).

Table 4-8 Coal Analyses from Johnson County, Wyoming (Wendell, et al, 1976).

FORT UNION FORMATION																			
		CARNEY			DIETZ NO. 1	DIETZ NO. 2			DIETZ NO. 3			MASTERS <sup>1</sup>			MONARCH			ROL-AND <sup>2</sup>	SMITH
AS RECEIVED		RANGE	AVER.	AVER.		RANGE	AVER.	AVER.	RANGE	AVER.	AVER.	RANGE	AVER.	AVER.	RANGE	AVER.	AVER.		
NUMBER OF ANALYSES		46 <sup>3</sup> (13) <sup>4</sup>	46	13	1	14 <sup>3</sup> (4) <sup>4</sup>	14	4	11 <sup>3</sup> (2) <sup>4</sup>	11	2	6 <sup>3</sup> (2) <sup>4</sup>	6	2	76 <sup>3</sup> (18) <sup>4</sup>	76	18	1	1
PROXIMATE	MOISTURE(%)	21.2-25.8	24.1	23.6	24.7	21.3-23.6	22.4	22.4	19.1-25.7	23.8	21.8	22.7-25.8	24.0	23.3	19.8-25.0	23.0	22.8	23.5	23.9
	VOLATILE MATTER(%)	29.5-35.8	32.0	32.3	37.6	31.3-34.1	33.2	32.8	30.0-34.8	31.6	33.0	32.4-34.8	33.9	34.5	31.2-38.3	33.9	33.4	34.5	35.8
	FIXED CARBON(%)	34.9-43.7	40.3	40.3	33.0	35.5-40.2	37.8	38.1	33.9-41.7	39.5	40.7	35.6-38.2	37.5	37.4	33.1-42.1	38.8	39.2	37.2	34.3
	ASH(%)	2.6-8.6	3.7	3.8	4.7	5.0-9.5	6.7	6.8	3.5-8.6	5.2	4.6	3.8-5.9	4.7	4.9	1.1-2.8	4.4	4.6	4.8	5.1
ULTIMATE	HYDROGEN(%)	5.8-6.5		6.3	6.2	6.1-6.4		6.3	6.1-6.3		6.2	6.1-6.3		6.2	5.8-6.9		6.4		6.5
	CARBON(%)	52.3-55.3		53.8	51.5	50.6-53.6		52.2	52.6-56.6		54.5	52.7-55.7		53.1	49.2-55.3		53.9		51.0
	NITROGEN(%)	0.9-1.2		1.1	1.1	1.2-1.3		1.2	1.1-1.4		1.3	1.0-1.2		1.1	1.0-1.3		1.1		1.1
	OXYGEN(%)	32.5-36.1		34.7	36.1	31.7-33.1		32.5	31.3-34.7		33.0	34.1-34.8		34.5	30.4-35.0		33.3		34.6
	SULFUR(%)	0.3-0.8	0.4	0.4	0.4	0.7-1.3	1.0	1.1	0.3-0.6	0.5	0.5	0.3-0.7	0.5	0.3	0.2-1.2	0.5	0.6	1.4	0.8
	HEAT VALUE BTU/POUND	8910-9720	9240	9260	8903	9000-9430	9200	9200	8730-9710	9060	9360	9010-9360	9230	9250	8450-9820	9350	9410	9010	8820

<sup>1</sup> Indifferentiated Upper and Lower Masters    <sup>2</sup> Roland or Tall    <sup>3</sup> Number of analyses used to determine range for proximate analysis, sulfur, and heat value  
<sup>4</sup> Number of analyses used to determine range for hydrogen, carbon, nitrogen, and oxygen    (Table compiled from channel, staple, or delivered samples analyzed by the U.S. Bureau of Mines. Only few analyses represent the full thickness of a given bed. Manually sortings and dirty (ony) top were removed from channel samples)

Table 4-9 Coal Analyses of Fort Union Coals from Sheridan County, Wyoming (Lageson, et al, 1978)

Sample No.	Location			Form of analysis	Moisture	Volatile matter	Fixed carbon	Ash	Heating value (Btu)	Sulfur	Forms of sulfur		
	Sec.	T.	R.								Sulfate	Pyritic	Organic
Ulm 1 bed													
D169078	26	56N.	81W.	A	35.9	30.1	28.4	5.6	6,290	1.2	0.06	0.34	0.65
				B	—	46.9	44.4	8.7	9,820	2.0	.09	.53	1.32
				C	—	51.4	48.6	—	10,760	2.1	.10	.59	1.45
D169770	17	54N.	80W.	A	34.6	32.1	27.9	5.4	6,190	0.5	0.19	0.03	0.30
				B	—	49.1	42.7	8.2	9,470	.8	.29	.05	.46
				C	—	53.5	46.5	—	10,320	.9	.32	.05	.509
D169771	17	54N.	80W.	A	37.1	32.2	22.3	7.4	5,290	0.8	0.28	0.06	0.42
				B	—	51.2	37.0	11.8	8,400	1.2	.44	.10	.67
				C	—	58.0	42.0	—	9,530	1.4	.50	.11	.76
Ulm 2 bed													
D169079	26	56N.	81W.	A	32.1	33.2	31.8	2.9	7,880	1.9	0.21	0.49	1.17
				B	—	48.9	46.8	4.3	11,590	2.8	.31	.71	1.73
				C	—	51.1	48.9	—	12,120	2.9	.33	.75	1.81
D169071	26	55N.	82W.	A	36.5	30.6	27.7	5.2	5,960	0.4	0.01	0.03	0.38
				B	—	48.2	43.6	8.2	9,380	.6	.01	.05	.59
				C	—	52.5	47.5	—	10,210	.7	.01	.05	.64
D50515	1	53N.	82W.	A	30.7	29.8	34.4	5.1	7,900	0.4	—	—	—
				B	—	43.0	49.7	7.3	11,400	.5	—	—	—
				C	—	46.4	53.6	—	12,300	.5	—	—	—
PK bed													
D165047	8	56N.	82W.	A	27.4	31.9	38.4	2.3	8,320	3.2	0.37	0.97	1.90
				B	—	43.9	52.9	3.2	11,460	4.5	.51	1.33	2.62
				C	—	45.4	54.6	—	11,840	4.6	.53	1.38	2.71
D169073	22	55N.	82W.	A	37.1	31.7	26.3	4.9	4,810	0.8	0.21	0.02	0.61
				B	—	50.4	41.7	7.9	9,240	1.3	.33	.04	.97
				C	—	54.7	45.3	—	10,030	1.4	.35	.04	1.05

Table 4-10 Analyses of Coal Samples from three Beds in the Wasatch Formation, Sheridan Coal Field. All Samples are from Outcrops Except D50515, Which was a Fresh Sample from a Mine in the Healy Bed in the Buffalo-Lake De Smet Area (from Culbertson and Maple, 1976).

Deposit	No. of samples	Moisture	Volatile matter	Fixed carbon	Ash	Sulfur	Btu/lb.
<b>ANDERSON COAL BED</b>							
Decker	8	23.728	29.856	39.634	4.310	.291	9236
Deer Creek	3	23.197	28.705	36.640	11.459	.630	8340
Poker Jim Lookout	8	29.626	30.013	35.084	5.277	.375	7926
Hanging Woman Creek	56	25.990	29.850	38.642	5.133	.293	8503
Kirby	11	26.716	28.085	38.471	4.295	.321	8328
West Moorhead	3	26.233	31.133	37.300	5.333	.367	8297
Decker Mine	Tipple	23.0	34.000	39.300	3.7	.400	9600
(Combined Anderspn-Dietz)							
<b>DIETZ COAL BED</b>							
Decker	4	23.612	25.562	36.563	11.764	.349	8367
Deer Creek	3	23.197	28.705	36.640	11.459	.630	8340
Hanging Woman Creek	4	27.423	29.622	36.811	5.507	.337	8078
Kirby	15	26.780	27.783	37.426	5.870	.590	8442
West Moorhead	4	31.333	29.717	34.823	4.127	.418	7990
<b>CANYON COAL BED</b>							
Decker	3	22.863	29.856	39.737	7.544	.418	9104
Poker Jim Lookout	3	30.483	29.466	35.050	5.002	.371	8201
Hanging Woman Creek	4	25.155	29.940	38.542	6.365	.407	8428
Kirby	3	23.780	29.637	40.770	5.817	.240	8789
West Moorhead	12	28.327	29.779	36.550	5.343	.420	8055
Canyon Creek	7	26.829	26.970	35.870	10.328	.786	8192
Diamond Butte	5	35.128	27.921	33.033	3.918	.307	7395
Sonneté	1	36.960	26.709	30.054	6.277	.955	6904
Threemile Buttes	7	37.339	26.378	30.696	5.587	.942	6867
<b>WALL COAL BED</b>							
Canyon Creek	42	24.346	30.571	40.429	4.629	.305	9088
Yager Butte	89	32.663	28.03	34.391	4.916	.320	7552
<b>KNOBLOCH COAL BED</b>							
Ashland	27	27.664	28.824	37.633	4.828	.153	8420
Otter Creek	28	28.233	29.915	36.712	4.710	.367	8468
Poker Jim Creek-O'dell Creek	6	24.165	30.036	40.695	5.104	.226	8846
Greenleaf Creek-Miller Creek	8	27.405	28.498	37.672	6.424	.540	8580
Beaver Creek-Liscom Creek	12	31.435	28.487	34.532	7.962	.492	8015
Foster Creek	3	31.113	27.740	33.257	7.89	.767	7573
Sand Creek	2	31.835	28.055	33.435	6.675	.300	7340
<b>ROSEBUD COAL BED</b>							
Colstrip	16	21.168	29.107	38.852	9.541	.823	8836
Greenleaf Creek-Miller Creek	4	27.175	26.743	37.491	8.592	1.169	8376
Sarpy Creek Mine	Tipple	25.000	29.000	37.000	9.000	.330	8450
Peabody Mine	Tipple	26.300	28.600	34.700	10.400	.750	8450
Western Energy Mine	Tipple	25.500	27.720	38.330	3.450	.800	8750

Table 4-11 Typical Coal Analyses from Fort Union Coal Beds in the Northern Powder River Basin, Montana (Matson and Pinchock, 1976)

	Location				Laboratory No.	Air-drying loss	Form of analysis	Moisture	Volatile matter	Fixed carbon	Ash	Sulphur	Heating value	
	Quarter	Sec.	T. N. R. W.	Calories									British thermal units	
Location 42 (Bed B) .....	SE. ¼	3	46	74	22973	21.7	A	31.0	30.5	28.4	10.1	1.4	4,022	7,240
							B	11.8	39.0	36.2	12.9	1.8	5,136	9,248
							C	44.2	41.1	14.7	2.1	5,827	10,489	
							D	51.8	48.2	-----	2.4	6,828	12,290	
Location 15 (Bed D) .....	NE. ¼	17	44	73	22904	25.3	A	35.5	30.5	29.7	6.2	1.2	4,082	7,348
							B	11.0	40.9	39.8	8.3	1.6	6,464	9,535
							C	45.9	44.8	9.3	1.8	6,141	11,954	
							D	50.7	49.3	-----	1.9	6,772	12,190	
Location 23 (Bed E) .....	NE. ¼	21	45	73	22955	20.3	A	29.0	32.0	31.1	7.8	1.4	4,564	8,215
							B	10.9	40.2	39.1	9.8	1.7	5,728	10,310
							C	45.1	43.9	11.0	2.0	6,428	11,570	
							D	50.7	42.3	-----	2.2	7,225	13,005	
Composite analysis of 5 samples of Roland coal bed at Peerless mines, 3½ miles east of Gillette.					A2965	17.9	A	33.0	29.7	31.5	5.8	.5	4,311	7,760
							B	18.4	36.1	38.5	7.0	.6	5,244	9,440
							C	44.3	47.1	8.6	.8	5,433	11,580	
							D	48.4	51.6	-----	.8	7,033	12,360	
Average of 20 samples from Sheridan Field .....						10.4	A	23.3	32.2	41.1	3.5	.3	5,194	9,350
							B	14.3	33.9	45.9	3.9	.4	5,801	10,442
							C	41.9	53.6	1.6	.5	6,771	12,188	
							D	43.9	56.1	-----	.5	7,091	12,756	
Average of 5 samples from Douglas Field .....						11.0	A	26.8	28.6	33.7	8.8	.9	4,377	7,676
							B	16.9	32.5	40.6	10.0	1.0	4,972	8,970
							C	39.1	48.3	12.0	1.3	5,986	10,774	
							D	44.2	55.6	-----	1.4	6,806	12,254	

Table 4-12 Analyses of Coal Samples from the Pumpkin Buttes Coalfield, Dry Cheyenne, and Nearby Fields (Wegeman, Howell, and Dobin, 1928, p. 10).

Geologic formation . . . .	Fort Union (?).								Montana.		
Name of coal zone . . . . .	Douglas-Incz.				Glenrock-Big Muddy.				Resistant sandstone.	Low-est.	
Laboratory No. . . . .	<sup>a</sup> 5318	<sup>a</sup> 5317	<sup>a</sup> 5321	<sup>a</sup> 5422	5325	5326	5330	5322	<sup>a</sup> 5320	<sup>a</sup> 5323	<sup>a</sup> 5319
<b>Sample as received:</b>											
Prox. Moisture . . . . .	22.92	20.44	37.86	35.01	22.87	22.87	21.90	19.92	15.58	19.17	19.83
Prox. Volatile matter . . . . .	42.62	30.49	29.08	28.46	48.03	33.89	34.05	49.25	23.28	26.17	41.39
Prox. Fixed carbon . . . . .	22.25	18.68	22.37	28.82	20.54	36.71	37.38	20.25	22.68	17.54	26.21
Prox. Ash . . . . .	12.21	30.39	10.69	7.71	8.56	6.53	6.67	10.58	38.46	37.12	12.57
Prox. Sulphur . . . . .	.58	.43	.35	.28	.52	.97	.86	.68	1.17	.52	.72
Ult. Hydrogen . . . . .								5.39		3.85	
Ult. Carbon . . . . .								51.96		30.68	
Ult. Nitrogen . . . . .								.60		.56	
Ult. Oxygen . . . . .								30.79		27.27	
Calories . . . . .	4,071	3,136	2,861	3,295	4,679	4,956	5,040	4,851	2,941	2,718	4,581
British thermal units	7,328	5,645	5,150	5,931	8,422	8,921	9,072	8,732	5,294	4,892	8,246
Loss of moisture on air drying . . . . .	4.30	5.30	21.40	23.30	4.40	4.20	3.30	1.50	2.40	5.30	2.00
<b>Air-dried sample:</b>											
Prox. Moisture . . . . .	19.46	15.99	20.94	15.27	19.32	19.40	19.23	18.70	13.50	14.65	18.19
Prox. Volatile matter . . . . .	44.53	32.19	37.00	37.11	50.24	35.37	35.21	50.00	23.85	27.63	42.23
Prox. Fixed carbon . . . . .	23.25	19.72	28.46	37.57	21.49	38.32	38.06	20.56	23.24	18.52	26.75
Prox. Ash . . . . .	12.76	32.10	13.60	10.05	8.95	6.82	6.90	10.74	39.41	39.20	12.83
Prox. Sulphur . . . . .	.61	.45	.45	.37	.54	1.01	.89	.69	1.20	.55	.73
Ult. Hydrogen . . . . .								5.30		3.44	
Ult. Carbon . . . . .								52.75		32.40	
Ult. Nitrogen . . . . .								.61		.59	
Ult. Oxygen . . . . .								29.91		23.82	
Calories . . . . .	4,254	3,312	3,640	4,296	4,894	5,173	5,212	4,925	3,013	2,870	4,675
British thermal units	7,657	5,961	6,552	7,733	8,810	9,312	9,382	8,865	5,424	5,166	8,414
Thickness of coal bed . . . . .	<i>Ft. in.</i> 1 10	<i>Ft. in.</i> 4 2	<i>Ft. in.</i> 1 8	<i>Ft. in.</i> 2 6	<i>Ft. in.</i> 3 6	<i>Ft. in.</i> 4 8	<i>Ft. in.</i> 5 6	<i>Feet.</i> 6	<i>Feet.</i> 3	<i>Ft. in.</i> 1 10	<i>Feet.</i> 3

<sup>a</sup> Weathered sample.

Table 4-13 Analyses of Coal Samples from the Glenrock Coal Field, Wyoming (Shaw, 1909, p. 162).

*Badger coal bed:*

As Received basis	Range (5 analyses)	Average
Moisture (%)	22.7-29.3	27.4
Volatile Matter (%)	31.7-34.5	33.3
Fixed Carbon (%)	28.5-32.6	31.4
Ash (%)	6.6- 9.8	7.9
Sulfur (%)	0.4- 0.5	0.45
Btu/pound	7,606-8,290	7,951

*School coal bed:*

As received basis	Range (3 analyses)	Average
Moisture (%)	19.5-26.4	22.2
Volatile Matter (%)	34.4-38.1	35.9
Fixed Carbon (%)	28.3-33.6	30.5
Ash (%)	8.8-15.7	11.4
Sulfur (%)	0.5- 0.7	0.6
Btu/pound	7,830-8,870	8,183

*Glenrock-Big Muddy Zone coals:*

As received basis	Range (10 analyses)	Average
Moisture (%)	19.9-27.2	23.4
Volatile Matter (%)	29.7-49.3	35.9
Fixed Carbon (%)	20.3-41.3	34.0
Ash (%)	4.8-10.6	6.8
Sulfur (%)	0.40-0.97	0.66
Btu/pound	7,695-9,270	8,742

Table 4-14 Analyses of Coal Samples from the Glenrock Coal Field (Glass, 1976).

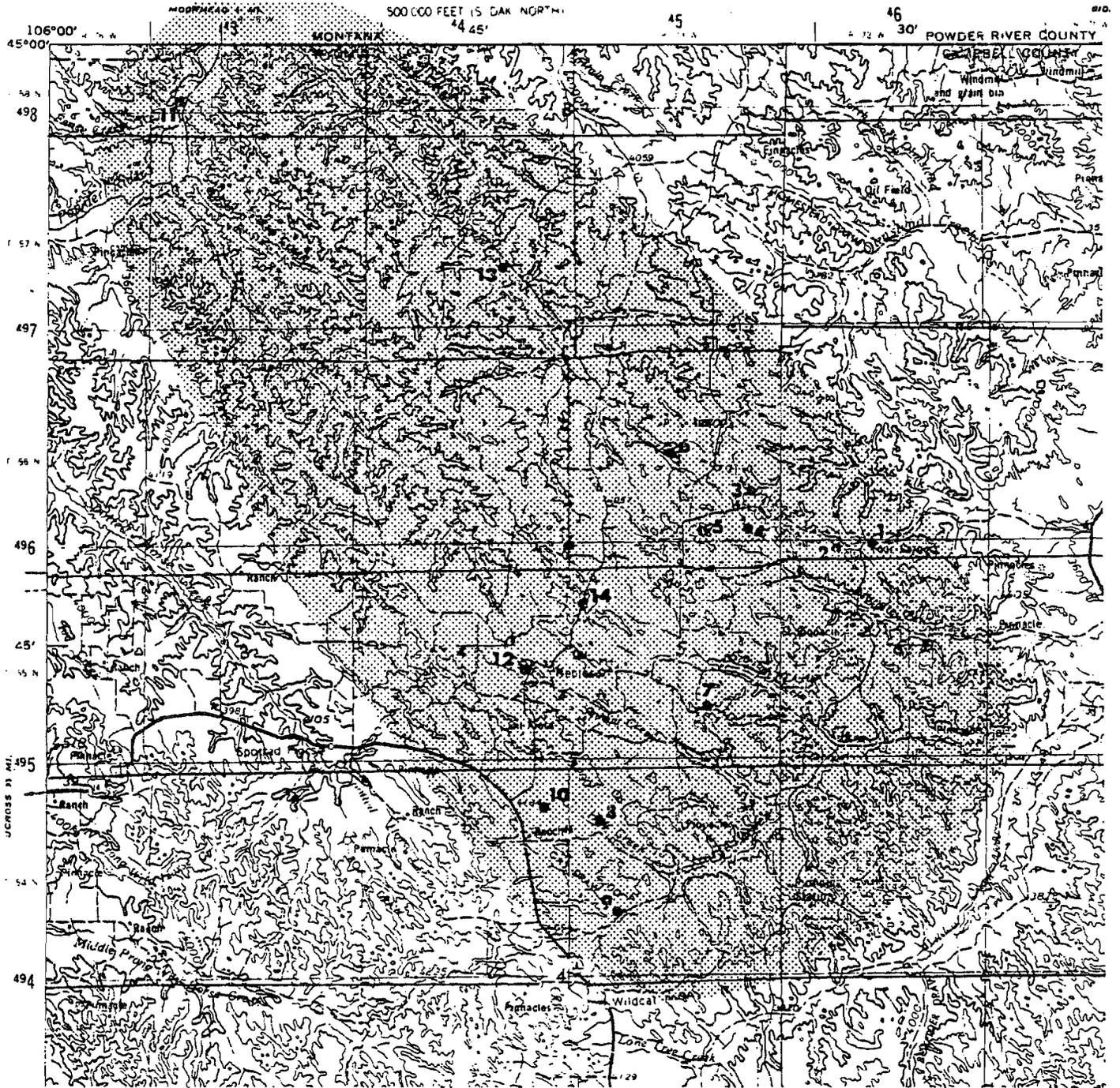
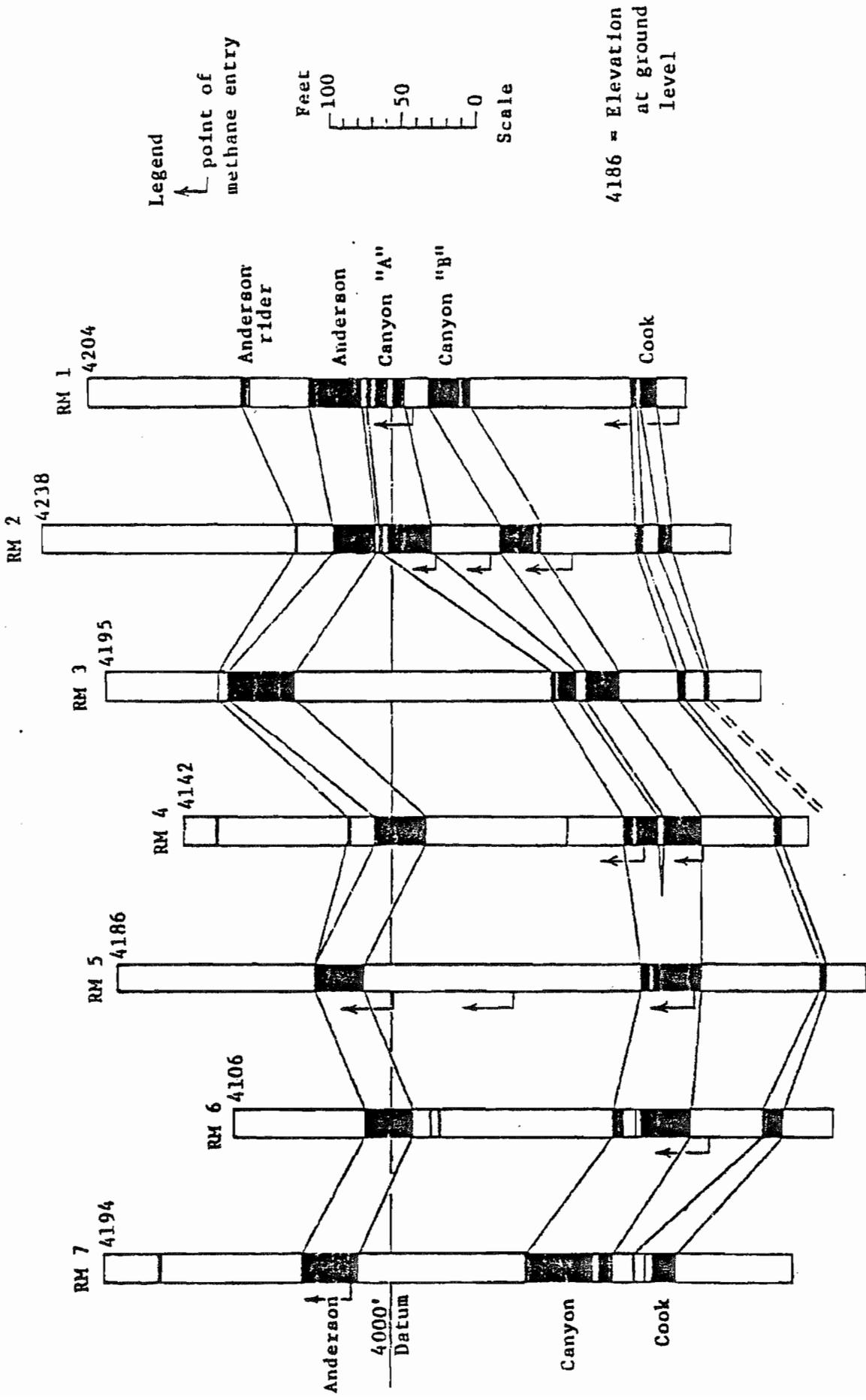


Figure 5-1 Shallow wells in the Recluse area, Campbell County, Wyoming, with anomalously large concentrations of methane gas (base, NE corner of USGS 1:250,000 Gillette topographic map)



**Figure 5-2** Section Showing Relationships of Coal Beds and Methane Entry in U.S. Geological Survey 1975 Test Holes in the Recluse Area, Campbell County, Wyoming (Hobbs, 1978).

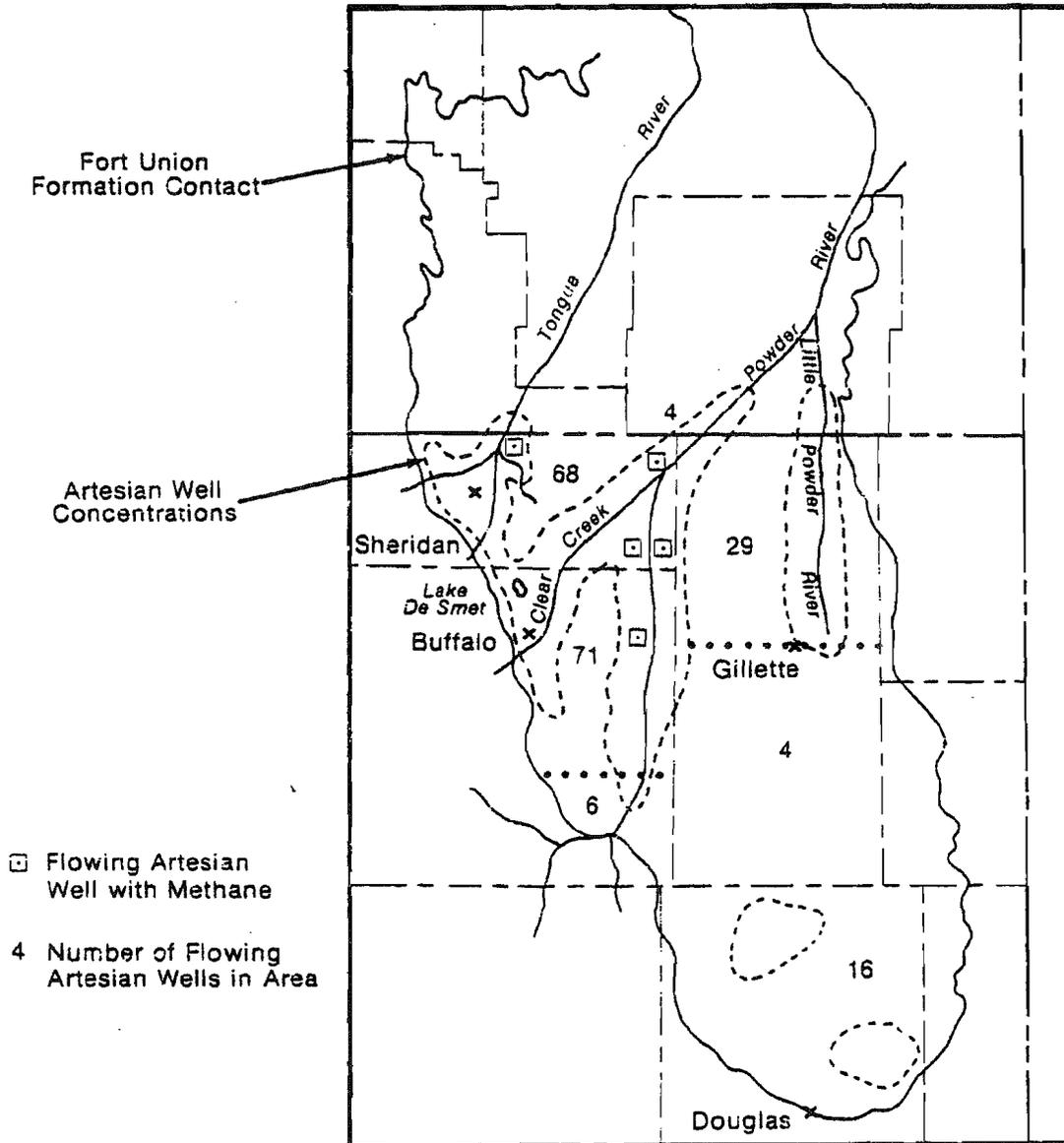
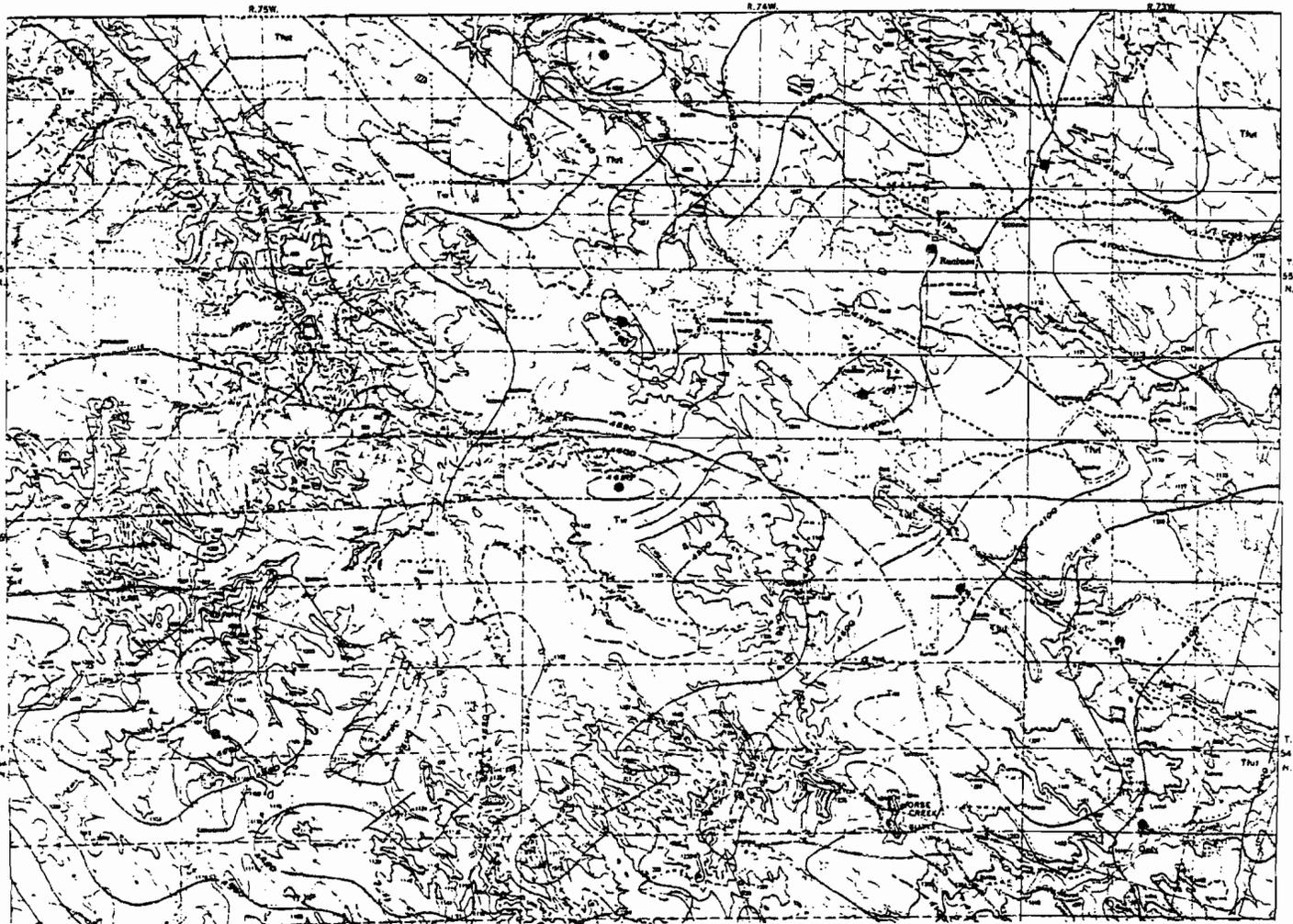
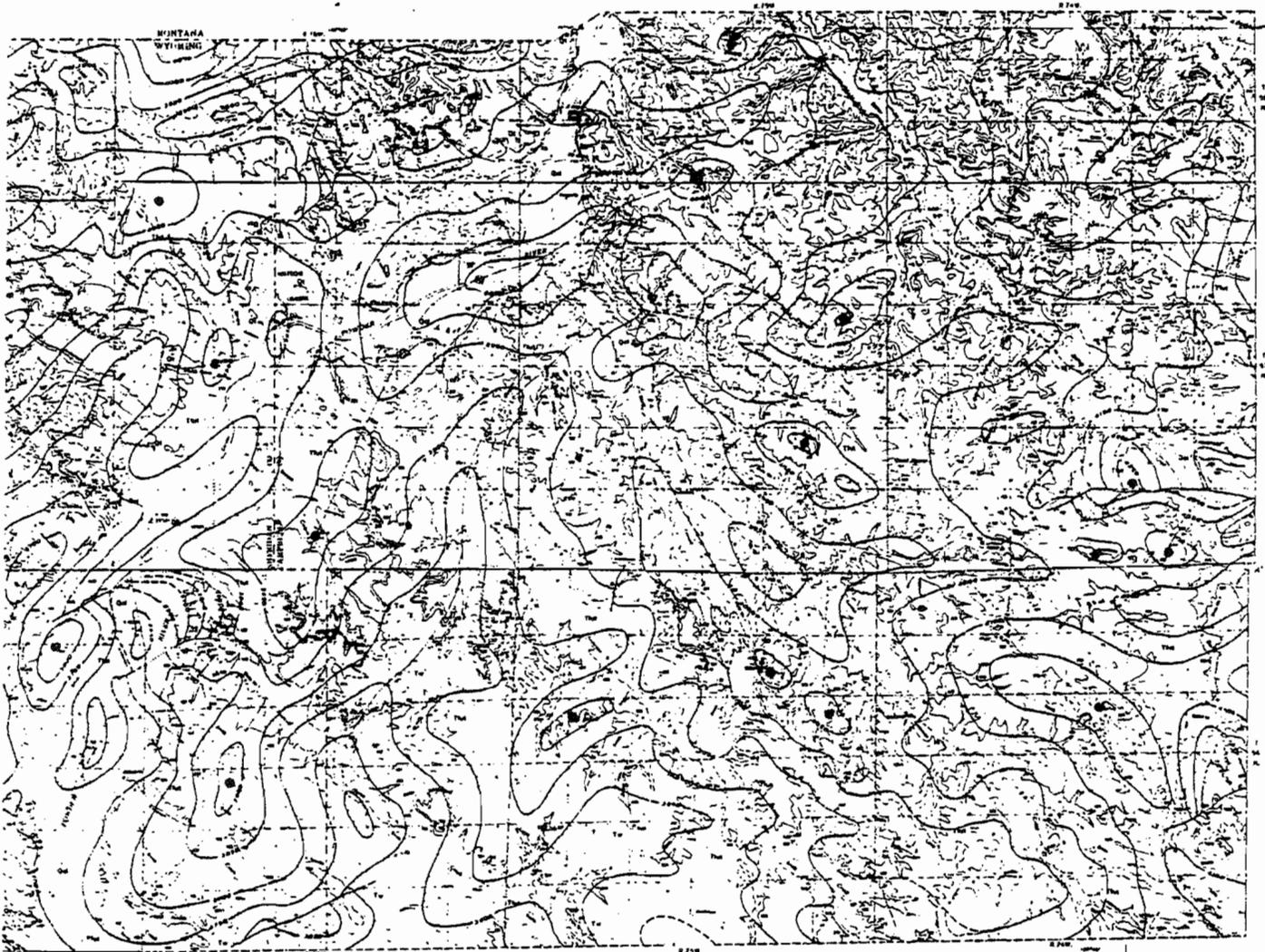


Figure 5-3 Map Showing Distribution of Flowing Artesian Wells Within the Powder River Basin Area Underlain by the Fort Union Formation.



**Figure 5-4** Geologic Map of Recluse Area Showing Structural Highs and Possible Methane Drilling Targets (Map after Olive, 1957) Locations of Five Shallow Drill Holes with Anomalously Large Methane Content are also Shown (see Section 5.1.1; Holes 8, 9, 10, 12, and 14).



**Figure 5-5** Geologic Map Showing Numerous Anticlinal Highs and Possible Methane Drilling Targets in Northwestern Campbell and Northeastern Sheridan Counties (Map after Olive, 1957). The Dobreny Ranch Water Well Which has Produced Methane Since 1916 is by the Powder River, Near the Montana Border



Figure 5-6 Geologic Map of a Representative Portion of the Clear Creek Area Just East of Methane Drilling Targets (Map after Mapel, 1959).



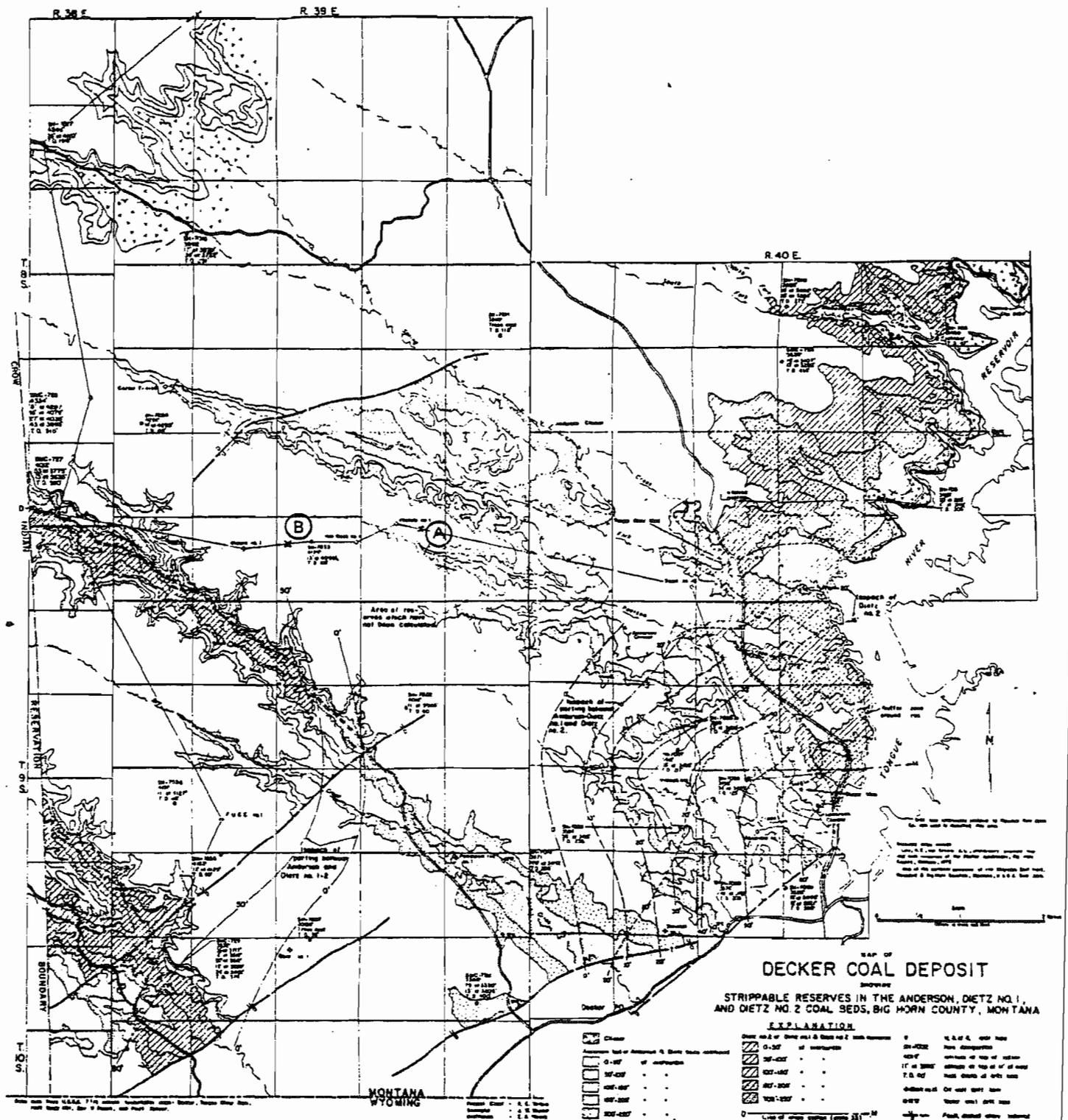


Figure 5-8 Geologic Map of Decker Mine Area Showing Locations of Possible Methane Drilling Targets of Figure 5-7. (Map after Matson and Blumer, 1977).

Well	Date	Gas-water ratio <sup>1</sup> (at 25° C and atmospheric pressure)	Percentage composition (by volume)						
			Oxygen (O <sub>2</sub> )	Nitrogen (N <sub>2</sub> )	Carbon dioxide (CO <sub>2</sub> )	Methane (CH <sub>4</sub> )	Ethane (C <sub>2</sub> H <sub>6</sub> )	Propane (C <sub>3</sub> H <sub>8</sub> )	Isobutane (C <sub>4</sub> H <sub>10</sub> ) and higher paraffin hydrocarbons
54-76-5ac .....	Aug. 29, 1961	( <sup>2</sup> )	0.14	8.87	0.31	90.66	0.02	Trace	Trace.
54-77-5db .....	Aug. 30, 1961	0.5	.63	8.69	.47	90.10	.08	0.03	Trace.
57-76-20bd .....	.....do.....	.3	4.82	23.13	.78	71.18	.07	.02	Trace
58-82-30aa .....	Mar. 21, 1962	2.2	1.03	6.14	.94	91.82	.07	.....	
51-77-20cc .....			0.56	11.56	0.47	87.38	.03		

<sup>1</sup> Gas-volume discharge (liters)/water-volume discharge (liters).

<sup>2</sup> Water discharge not measurable.

<sup>3</sup> Well identification code: 54-76-5ac = SW<sup>1</sup>/<sub>4</sub>, NE<sup>1</sup>/<sub>4</sub>, Sec. 5, T54N, R76E

**Table 5-1** Analyses Showing Methane Content in Gas Samples Obtained from Four Flowing Artesian Wells in Sheridan County and One Well in Johnson County (Lowry & Cummings, 1966; Whitcomb, et al., 1966).

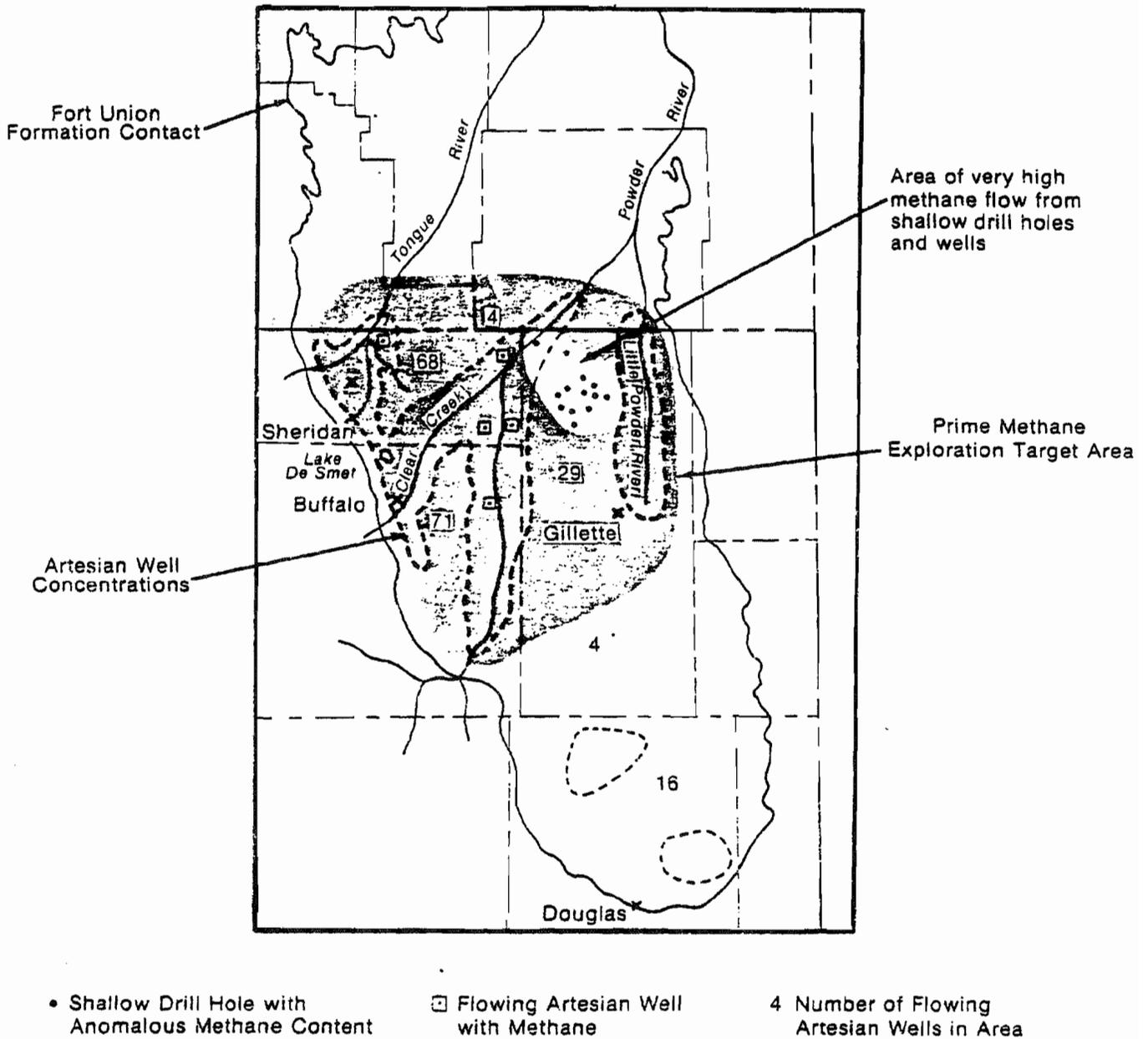


Figure 6-1 Methane Exploration Target Area in Tongue River Member of the Fort Union Formation, Central Powder River Basin.