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GEOLOGIC OVERVIEW, COAL, AND COALBED METHANE RESOURCES OF THE WIND RIVER BASIN, WYOMING

By

Herman H. Rieke

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Morgantown, West Virginia 26505

TRW, INC.
ENERGY ENGINEERING DIVISION
MCLEAN, VIRGINIA 22102

FOREWORD

The report was prepared by TRW for the Department of Energy (DOE) under DOE Contract No. De-AC21-78MC08089. This contract is administered by the Morgantown Energy Technology Center (METC) under the direction of the DOE Methane Recovery from Coalbeds Project Manager, John Duda, and the Technical Project Officer, Dr. Harold Shoemaker, in Morgantown, West Virginia.

This report, compiled from on-site investigations, publications, open-file reports, and personal communications with persons familiar with the area, is intended to be a current, comprehensive handbook of the geology, coal, and coalbed methane resources of the area. The maps, figures, tables, and format of this document provide the reader with a tool for office use or to be taken along as a part of the field investigation. As with any document, information gathered from subsequent investigations may alter the facts, ideas, and conclusions reached in this report. It is the intent of DOE/METC that this document be updated as appropriate.

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1. SUMMARY

This report on the Wind River Coal Basin compiles available data needed to determine its coalbed methane resource and to provide a framework for the DOE/METC/TRW Methane Recovery from Coalbeds Project (MRCP) resource delineation effort in that basin. A primary target area of about 1,500 square miles has been designated, having the highest potential for coalbed methane production and covering Fremont County and the western part of Natrona County, Wyoming (Figure 1-1). This target was determined by evaluating desorption data obtained by TRW from the U.S. Geological Survey (USGS) coal cores from the Wind River Indian Reservation and integrating the data with coalbed geology. On the basis of this information, an estimated range of 5.2 to 2,225 billion cubic feet of gas may be contained in the Wind River Basin. Ranges for the expected inplace methane resource have been established for the coal fields of the Wind River Basin, based on available data.

The Wind River Basin is an east-west trending intermontane asymmetrical syncline located in the Wyoming Basin. Covering an estimated 8,100 square miles in central Wyoming, it lies within a semiarid region where vegetation is sparse, and the topography generally is rugged because of erosional dissection. The Wind River flows northward and is the principal waterway draining the basin. Semiarid climate, sparse vegetation, and rugged topography have restricted the area's population to concentrations in a few major towns. Transportation routes include a limited number of major highways, secondary roads, rail lines, and pipelines.

The Wind River Basin contains comparatively minor structural deformation in the form of folding and faulting. Structurally, the surrounding area is more complex, with major thrust fault zones traversing northwest to southeast over the region.

Sedimentary deposition in the area occurred from late Precambrian to Quaternary. The basement Precambrian rocks are composed of a thick sequence of granitic, gneissic, and migmatitic rocks. With the exception of a hiatus during Silurian time, the basin was a stable peneplain with

continuous deposition from Cambrian to Pennsylvanian. The Tertiary Age was marked by the deposition of shales, sandstones, conglomerates, and lenticular coalbeds. Pleistocene glacial drift covered the northern edge of the basin, and alluvium was deposited along streams and river channels.

Major coal-bearing strata of the Wind River Basin are contained in the Upper Cretaceous Mesaverde Formation. The area is divided into seven coal fields and regions: Muddy Creek coal field; Pilot Butte coal field; Hudson (Lander) coal field; Beaver Creek coal field; Big Sand Draw coal field; Alkali Butte coal field; and Arminto (Powder River) coal field. Their major coal deposits are found in the Mesaverde and Meeteetse Formations, along the basin perimeter. The Alkali Butte coal field contains three coalbeds greater than 4 feet thick, the most important being the Signor, Beaver, and Shipton coals, with a rank of subbituminous C. The Hudson coal field contains the Signor coalbed or zone which has been traced some 22 miles from the Alkali Butte coal field to the east. Coal contained within this zone is ranked as subbituminous. The remaining five coal fields have not been extensively developed. Thin and split coalbeds are prevalent in a few of these fields, and in many instances top-quality coals are scattered, making it difficult to justify development. Little is known about the basin's coal resource at depth.

In addition to its coal resources, the basin contains significant oil and gas resources in Paleozoic, Mesozoic, and Cenozoic rocks. The Paleozoic Tensleep, and Phosphoria Formations, Mesozoic Lakota, and Muddy Formations have been extensively developed for oil production. Gas is being produced from the Permian Phosphoic Formation; Jurassic, Sundance, and Morrison Formations; Cretaceous Lakota, Frontier, Cody, and Mesaverde Formations; and the Paleocene Fort Union Formation.

The basin's potential methane resource has been estimated using existing MRCP desorption and geological data. There is no supportive data from the USBM and MSHA on mine emissions available for mines emitting gas. The area considered the prime methane resource target within the Wind River

Basin is discussed below. It includes the majority of Fremont and parts of Natrona Counties in Wyoming. The reasons for its selection are:

- Existence of overpressured zones
- Reports of thick coalbeds lying in the interval between 3,000 and 14,000 feet
- Presence of gas and oil in great quantities
- Continuity of major coal-bearing zones.

A program for investigating the methane recovery potential of the Wind River Basin should include the following additional activities:

- Obtain geophysical logs and gas information from oil and gas wells penetrating coal-bearing zones in the basin.
- Continue to cooperate with the USGS, other surveys, and private organizations to collect coal core, coal chip, and gas samples to perform methane desorption tests and analyses.
- Collect other pertinent information through logs, personal contacts, reports, and mine data, and from personnel working within the basin area.
- Cooperate with the local oil industry on deep (>3,000 feet) tests.
- Participate in a detailed study of the target area to help pinpoint test sites for methane exploration.
- Perform drilling, logging, sampling, and flow testing of test sites chosen by the detailed study.

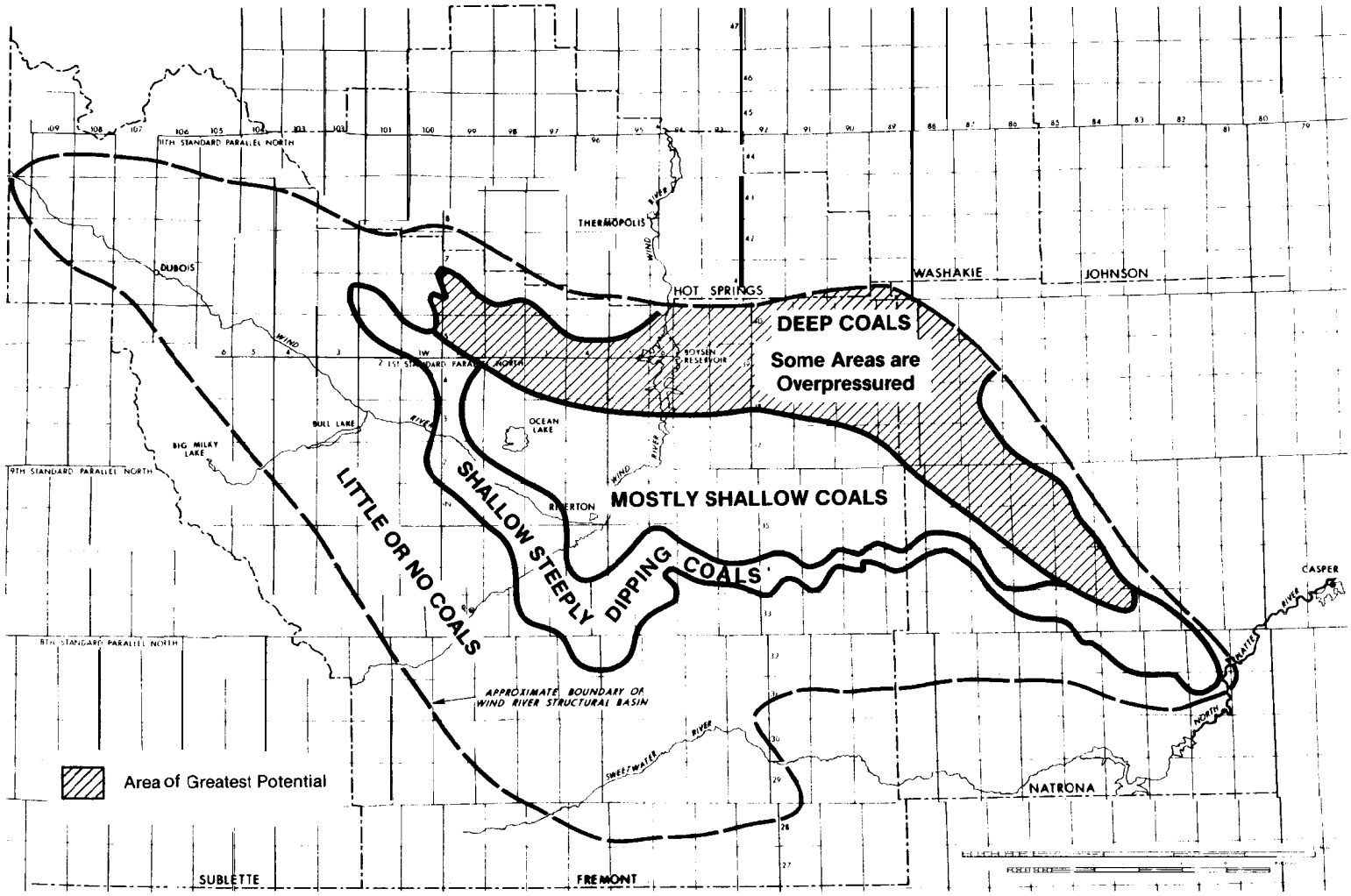


Figure 1-1. Primary Target Areas in the Wind River Basin

2. INTRODUCTION

Methane, the major component of natural gas, is generated during the natural process of coal formation and frequently is trapped in the coal and associated strata. The total magnitude of the U.S. coal-associated methane resource has been estimated to be as much as 700 trillion cubic feet. Given current and conservatively projected economic and technological factors, the recovery of a substantial part of this natural gas resource appears feasible.

The objective of this report is to provide a data base on what is presently known about the coalbed methane resource in the Wind River Basin of Wyoming. Various sections of the report detail the basin's general geographic, cultural, and geologic settings, and give an overview of its coal resources and associated coalbed methane.

The work was performed under DOE's MRCP. The MRCP consists of a planned sequence of resource characterization, research and development, and technology systems tests, designed to evaluate and test technical and economical extraction and utilization of gas associated with coalbeds. Resource delineation of the methane content of the nation's coalbeds has been done on a very limited basis, mostly in conjunction with active mining. Previous work includes only a very small percentage of the coal resource and does not provide the knowledge needed to locate recovery and utilization projects in the coalbeds with the greatest potential for methane production.

An area of approximately 8,100 square miles of the Wind River Basin has been selected out of the 59,000 square miles of the Rocky Mountain Coal Province as having the probability of early commercialization. The target area was selected on the basis of the following general criteria:

- Physical and chemical characteristics of coal
- Seam depth (greater than 700 feet)
- Total effective coal thickness (greater than or equal to 30 feet)
- Individual seam thickness (greater than or equal to 5 feet)
- Areal extent of the seams.

The information gathered in conjunction with this report provides a basis for defining the Wind River target area and for recommending additional coring and well testing efforts in the newly defined targets.

The Wind River Basin's geographic/physiographic, cultural, and geologic settings are presented in Sections 3.1 through 3.3. Section 3.4 (Geology) includes discussions of the geologic history, depositional environments, basin stratigraphy, and structural framework. Appropriate maps are included with these discussions.

The coal resources of the Wind River Basin are reviewed in Section 4. Coal type (rank and quality), areal extent, stratigraphic position, and chemical characteristics are discussed. Subsections discuss individual coalbeds in more detail and provide correlations across the basin.

Section 5 deals with the basin's potential methane resource and presents tables and figures summarizing pertinent data. This section includes a discussion of three shallow, coal-exploratory well tests in Fremont County, Wyoming. Conclusions and recommendations, made in Section 6, include a definition of the areas with highest probability of early commercialization and a suggested exploration program. A rationale for proposing high coalbed methane contents at great burial depths in abnormally high fluid pressure environments is presented.

Cited references are listed in Section 7. Supplemental references, applicable to the region but not cited, appear in Section 8. The Appendices provide supporting information such as maps, map indices, and publication lists.

3. WIND RIVER BASIN

The Wind River Basin, an asymmetrical intermontane syncline encompassing an area of about 8,100 square miles in west-central Wyoming (Figure 3-1), is named after the northward-flowing Wind River, a tributary of the Big Horn River. The coal-bearing area generally coincides with the topographic and structural basin; however, the Wind River coal basin is limited to that portion of the basin underlain by Mesaverde age or younger rocks. Glass and Roberts (1978) chose this definition because the Mesaverde Formation is the oldest important coal-bearing unit in the basin.

The economic base for this region is mineral resources and ranching. Principal mineral resources being recovered include uranium, trona, natural gas, oil, bentonite, and coal. The coalbeds are thought to be lenticular with no individual lens covering a large area. The original coal resource for the basin was estimated by Campbell (1917) to be on the order of 17 billion tons. Presence of an active and growing oil, gas, and coal industry in the region, along with supporting industries and transportation systems, should contribute to commercialization of the potential coalbed methane resource.

3.1 GEOGRAPHY

The Wind River topographic basin extends for approximately 180 miles in a southeasterly to northeasterly direction and is located entirely in Fremont County and the western part of Natrona County, Wyoming (Figure 3-1). This teardrop-shaped basin is about 75 miles wide from north to south, bounded along its southwestern side by the granitic Wind River Mountains, and on its south side by the Granite Mountains (Figure 3-2). It is the third-largest coal-bearing basin in the state, outranked only by the Green River and Powder River Basins. The approximate dimensions of the area underlain by coal are 125 miles long and 45 miles wide (Figure 3-2). The deepest part of the basin is located in the northeastern section close to the Owl Creek Mountains and the Casper Arch. The sedimentary column in this area has a maximum thickness of 33,000 feet. Paleozoic and Mesozic rocks, with the exception of the Silurian, are present. Three-fourths of the basin's area is covered by Tertiary-age rocks (Paape, 1968) which conceal, for the most part, the important coal-bearing Upper Cretaceous

Formations outcropping along the southern boundary of the basin near the town of Lander. The basin is bordered on the north by the Owl Creek and Absaroka Mountains and the Casper Arch, as shown in Figure 3-2. An estimated 39,000 cubic miles of sedimentary rock (Cambrian to Eocene) fill this basin.

3.2 PHYSIOGRAPHY

The Wind River Basin is part of the larger Wyoming Basin and, as such, represents a major break in the continuity of the Rocky Mountains (Figure 3-3). The Wyoming Basin is an extension of Great Plains topography and geology through a gap between the Bighorn and Laramie Mountains separating the southern and middle Rocky Mountains and connecting the Great Plains with the Colorado Plateau. Altitudes in the Wyoming Basin are mostly between 6,000 to 8,000 feet, and average about 7,000 feet (Hunt, 1974). Altitudes range from about 4,400 feet at the north end of the Wind River Canyon in the basin to more than 13,000 feet on the crest of the Wind River Mountains which lie along the southwest boundary of the basin. The climate, soils, and vegetation do not differ greatly among the coal regions of the Wyoming Basin. Keefer (1970) discusses the bounding physiographic provinces, as shown in Figure 3-2.

Generally, the Wind River region is a gently undulating plain, sloping toward the interior from the surrounding barrier. Woodruff and Winchester (1912) present detailed topographic descriptions for each coal field in the basin. The Wind River Basin can be subdivided generally into the following physiographic areas: Washakie Range, Sweetwater Plateau, Hiland-Clarkson Hill Area, Rattlesnake Hills, and Wind River topographic basin (Figure 3-4).

3.2.1 Washakie Range

The Washakie Range, at the northwest corner of the Wind River Basin, is a series of faulted folds in Precambrian, Paleozoic, and lower Mesozoic rocks that were completely buried by volcanic debris of the Absaroka Range during post-early Eocene time (Keefer, 1970). This uplift reaches altitudes of more than 10,000 feet. The range extends 70 miles northwest of the western end of the Owl Creek Mountains, and ends with the western flank of Buffalo Fork Mountain west of Togwotee Pass. The structures have now

been partly exhumed along the major drainages. A continuous reverse fault probably separates the steep south flank of the range from the adjacent northwest margin of the basin.

3.2.2 Sweetwater Plateau

The Sweetwater Plateau is a relatively flat and undissected area in the southeastern part of the basin (Figure 3-4).

3.2.3 Hiland-Clarkson Hill Area

This area includes parts of the Wind River, Powder River, and North Platte River drainage systems, all in the Missouri River watershed (Rich, 1962). Maximum relief in the area is about 2,140 feet. Altitude ranges from around 5,200 feet above sea level along the North Platte River to about 7,340 feet on top of Horse Heaven Mesa at the eastern end of the Rattlesnake Hills. The Hiland-Clarkson Hill Area is etched out of tilted and horizontal Tertiary rocks.

3.2.4 Rattlesnake Hills

The Rattlesnake Hills occupy approximately 150 square miles in western Natrona County, Wyoming, 15 miles southeast of the geographic center of Wyoming (Pekarek, 1978). The hills rise to a maximum altitude of about 9,300 feet (Rich, 1962). Topographically, the Rattlesnake Hills result from the erosion of the northwest-plunging Rattlesnake anticline of Laramide age. In middle and late Eocene time, volcanic debris (that is subsequently being eroded) was ejected upon the eroded anticline. At least 42 volcanic vents and intrusive bodies occur in the Rattlesnake Hills and the immediately adjacent area to the southwest. Precambrian rocks are exposed in the core of the anticline.

3.2.5 Wind River Topographic Basin

In most of the central part of the basin, altitude ranges between 4,800 and 7,000 feet. Upturned rocks of Paleozoic and Mesozoic age form distinct cuestas and hogbacks along the mountain fronts, and nearly horizontal rocks of Tertiary age form generally broad valleys and prominent gravel-capped mesas and buttes in the central part of the basin (McGreevy, et al., 1969). The Wind River Valley is relatively deep compared to most other stream valleys in the basin, and high bluffs border the river in many

places. Mesas and buttes form drainage divides between the smaller streams. Along the flanks of the Wind River Basin, where older strata dip rather steeply, the topography is marked by conspicuous strike valleys with intervening sandstone ridges. In the basin's interior portion where younger, more gently dipping rocks rest with angular unconformity upon older rocks, the terrain is generally a rolling, less rugged plain. Occasionally, however, erosion has turned these rolling plains into rugged badlands (Glass and Roberts, 1978). The topography of the northern part is very irregular owing to the alternating succession of resistant and nonresistant rocks. This area erodes rapidly during flash floods.

3.3 CULTURAL FEATURES

Lander and Riverton are the main towns in the Wind River Basin. The basin's largest city is Riverton, with a population of about 9,569; Lander has a population of about 7,943; and other basin towns have several hundred or fewer residents. The remaining populace of the basin live on ranches or within the Indian reservation. Several towns in the Wyoming Basin arose along the Union Pacific Railroad: Laramie, Rawlins, and Rock Springs. Casper, an oil and gas center, developed on the North Platte River.

3.3.1 Land and Mineral Ownership

Land ownership in the Wind River Basin has evolved from historical events discussed in Duntsch (1965), Gerharz (1949), U.S. Bureau of Indian Affairs (1962), and U.S. Bureau of Reclamation (1950). Gallivan (1957) stated that at least 85 percent of the land is controlled by either the federal government or the Indian tribes, ownership being about equal in their respective areas.

Mineral land leases in the Wind River Basin are vested in five major classes of owners (Gallivan, 1957):

- Private ownership
- Federal government ownership
- State ownership
- Indian tribal ownership
- Individual Indian allotments.

That portion of the land lying outside the Wind River Indian Reservation contains approximately 1,220,000 acres. Of that amount, approximately 1,048,000 acres, or about 86 percent of the area are

federally owned. The State of Wyoming owns an additional 91,000 acres, or about 7.5 percent of the total. A mere 81,000 acres, or 6.5 percent, are privately owned. The small percentage of private ownership becomes even more significant in light of the fact that over 24,000 acres of the private land are concentrated in only two townships (T32N, R99W and T33N, R100W) (Figure 3-5). Out of 50 full and nine partial townships, only three have over 5,000 acres of private land; nine have over 2,000 acres; 22 have 320 acres or less; and six have no private land (Gallivan, 1957).

Federal lands, therefore, have an important position in the Wind River Basin. A series of maps in the Appendices shows the extent of federal land holdings, marketing facilities, and resource development for this coal area.

3.3.2 Base Map

A base map of the Wind River Basin has been constructed showing major political boundaries, large lakes and rivers, important towns, and township and range boundaries (Figure 3-5). Geologic and coalbed gas information is displayed in a manner suitable to the preservation of all data recorded in this base map.

Indices showing topographic maps for both the 2° (scale 1:250,000) and 6° (scale 1:1,000,000) quadrangle units are included as Enclosures A-1 and A-2 (Appendix A). The complete basin has been topographically mapped in 7-1/2-minute quadrangle units. Indices to the available topographic and geologic maps for Wyoming are included (Enclosures A-3 and B-1).

3.3.3 Political Boundaries

A large percentage of the Wind River Basin population lives on ranches and in small trading communities. Although there has been a relatively long history of commercial mineral extraction, some important political and societal issues are associated with these natural resources. These arise from the:

- Extraction of minerals on federal and state lands
- Wind River Indian Reservation
- Ranchers versus mining development enterprises.

3.3.4 Marketing Facilities

Access to the potential methane resource and delivery of gas from the basin to market is facilitated by pipelines and utilities within the State of Wyoming. Routes of existing natural gas transmission lines are shown in Figure 3-6.

3.3.4.1 Transportation Systems

The Burlington Northern Railroad runs east-west across the northern flank of the basin, swinging north to Thermopolis at Bonneville, slightly more than halfway across the basin. The Chicago and Northwestern Railroad runs southwest from Bonneville, through Hudson to Lander (Glass and Roberts, 1978).

The main east-west transportation corridor through the basin is U.S. Route 26. U.S. Route 287 provides access from Rawlins to the south, and U.S. Route 16 exits the basin to the north. Transportation systems and nearby population centers are shown in the 2° topographic quadrangles in Appendix A (Enclosures A-4 and A-5).

3.3.5 Resource Development

The Wind River Basin has much of the same character as the neighboring Bighorn Basin, except that late Tertiary age formations in most parts of the basin conceal the coal-bearing rocks. Coal, however, is only one of the important minerals known to exist in this basin. Phosphate, bentonite, gypsum, trona, uranium deposits, and oil and natural gas are other mineral commodities either being produced or possibly considered as prospects for future mining ventures.

Future cooperative agreements with mineral operators will provide the MRCP an opportunity to sample and test encountered coalbeds during exploratory and developmental drilling operations. This is the most cost-effective method for obtaining coalbed methane content data and reservoir production characteristics. Oil and gas operators now working in the basin will aid in sampling and testing of the coalbeds and in the potential production and transmission of coalbed methane. A review of current mining and petroleum activities in Fremont and Natrona Counties, Wyoming, will help in planning MRCP resource test operations.

3.3.5.1 Previous Investigations

The Wind River Basin has been known to contain coal of commercial value since some of the earlier explorers examined coalbeds along the Popo Agie River (Figure 3-5). Data from early (prior to 1910) mineral investigations have been used extensively and repeatedly in subsequent reports. The following geologists have contributed greatly to understanding the region.

In 1859 and 1860, Hayden made a geologic reconnaissance study of a large part of Wyoming that included parts of the basin. Comstock (1875) and Eldridge (1894) delineated the geology in the northern part of Fremont County. Knight (1895) prepared for the USGS a summary of the coal fields in the state, that included analyses of coal from mines near Lander. The Lander coal field was reported on in detail by Woodruff (1907). Darton (1908) studied the stratigraphy of the Paleozoic and Mesozoic rocks of central Wyoming. Woodruff and Winchester (1912) made a comprehensive investigation of the Cretaceous and Tertiary coal resources of the Wind River Basin.

Graduate geology students from the University of Wyoming have been very active in preparing theses on small areas in the basin. Authors, names, and theses titles may be obtained from the Geological Society of Wyoming, P. O. Box 3008, University Station, Laramie, WY 82070. Additional map references (non-university) are provided by Enclosure B-1 (Appendix B).

3.3.5.2 Mining History

Glass and Roberts (1978) noted that although commercial mining in the Wind River Basin has more than a 100-year history, production was small, even in its best years, when compared to the state as a whole. The record annual production for the basin was set in 1920 when the combined tonnage from two mines reached 290,495 tons. Even then, mines in the Wind River coal basin accounted for only three percent of Wyoming's total annual production. Currently, the basin has no operational coal mines.

3.3.5.2.1 Coal

Recorded coal mining in the Wind River coal basin dates back to 1870 with the opening of the Wyoming Central underground mine just south of

Hudson. Since 1870, no fewer than 58 coal mines have been opened in the Wind River coal fields. Of these, 52 have been located by Wyoming's Geological Survey (Figure 3-7). Production in the 1800s seldom exceeded a few thousand tons per year, and came from no more than three or four mines in the Hudson area (Glass and Roberts, 1978). All this early coal was marketed to ranchers or nearby communities for heating purposes.

In 1906 the Chicago and Northwestern Railroad completed a line from Casper to Lander. Markets for coal mined in the Hudson coal field expanded as the railroad and towns along the railroad's route bought the coal. As existing mines increased, production and new mines opened, and production from the Hudson coal field gradually increased to almost 95,000 tons per year by 1910. Annual production fluctuated between 95,000 and almost 290,000 tons for the next 18 years, with the basin's record production set in 1920 (Glass and Roberts, 1978).

Annual production gradually declined after 1927. This decline was not slowed by the demands of World War I I as in other coal mining areas of Wyoming, but because of the remoteness of the Wind River Basin and competition from larger Wyoming coal fields. By 1950, there were five operating coal mines in the basin with a combined tonnage of only 3,692 tons. The only two operational mines in the basin produced 1,534 tons by 1960. The last mine, the George mine, closed in 1966. A small strip mine, the Muddy Creek strip, accounted for the only coal mined after 1966, producing 85 tons in 1973 (Glass and Roberts, 1978).

3.3.5.2.2 Uranium

In the Wind River Basin uranium mineralization is found in rocks of practically every geologic age, including the crystalline rocks of adjacent Precambrian uplifts (Hansel and Holden, 1978). Uranium is being mined at the Crooks Gap area (Sections 8, 9, 16, 17, 20, 21, 28, 29, T28N, R92W) in Fremont County (Figure 3-5). The mineralized bodies appear to be localized along axes of shallow synclinal troughs, which may be sedimentary channels, that are superimposed at right angles to and situated on the flanks of a northerly trending anticline (Wilson, 1966). Open-pit mining operations have been intermittent. The Gas Hills area (NW 1/4 T32N, R90W; NE 1/4 T32N, R91W; T33N N, Rs 89, 90 W; SE 1/4 T33N, R91W) in Fremont and Natrona Counties contains uranium deposits in Mesozoic and Eocene Formations

(Figure 3-5). Wilson (1966) reported that early Eocene normal faults probably acted as barriers to the flow of uranium-bearing ground water solutions.

Knowledge about the occurrence of uranium is important because uraniferous coal and carbonaceous shales have been reported in the Powder River Basin to the northeast and in the Red Desert area to the south. Uranium in coal can affect the ability to identify coalbeds from gamma-ray and gamma-ray spectral logs, in addition to possible safety problems.

3.3.5.2.3 Phosphate

Phosphate rock is found in the Permian Phosphoria Formation in west-central and western Wyoming (Wilson, 1966). The bulk of the phosphate rock in Wyoming is on public lands which have been withdrawn from entry. The phosphate land withdrawals, as of July 31, 1927, amounted to 996,539 acres (Wilson, 1966). Extensive deposits are known to exist in Fremont County, Wyoming. Uraniferous phosphate deposits are known to occur in the Wagon Bed Formation (Eocene age) in the Beaver Divide area of Fremont County. Although close to transportation centers, these deposits are currently of marginal grade (Hansel and Holden, 1978). Leasing of phosphate lands is under the jurisdiction of the Bureau of Land Management (BLM).

3.3.5.3 Oil and Natural Gas

More than 60 oil and gas fields which have been discovered in the Wind River Basin produce from 17 different formations--the majority from structural closures (Figure 3-8). Knowledge about location and depth of these reservoirs and the origin and occurrence of natural gas will provide insight to the establishment of the potential of the basin's coalbeds. Despite a long drilling history and great production performance, there are still many areas to be explored in this basin. Primary reservoirs are the Pennsylvanian Tensleep Sandstone, the Madison Limestone, the Permian Phosphoria Formation, the Cretaceous Lakota, and the Muddy Frontier and Cody Sandstones. Keefer (1969) has pointed out that exploratory drilling has not tested the Frontier and older Mesozoic rocks in the 3,500 square miles of the central, structurally deep part of the Wind River Basin, and that in 4,500 square miles, Paleozoic rocks remain, for the most part, untested. The Frontier, Mesozoic, and Paleozoic reservoirs are at depths

of less than 15,000 feet in 2,000 square miles within these untested areas (Keefer, 1969). To date, identification and evaluation of deep-lying coal resources has not been attempted using well logging data from these wells. Shapurji (1978) reported that detailed geologic investigation and examination of drillholes, especially in the basin's western and southwestern portions, indicate that the Mesaverde section contains potentially minable quantities of coal. In the deeper part of the basin, Tertiary formations are still relatively untested (McCaslin, 1978), but deep drilling is presently underway.

3.4 GEOLOGY

Shelton and Ross (1971) catalogued the significant geologic features of the Wind River Basin and compared them with the Bighorn and Powder River Basins (Figure 3-9). Their study involved graphic analysis of the basin's physiography, sedimentology, structure, igneous activity, and stratigraphic framework with respect to geologic time. All these factors are important when delineating the quantity and quality of the basin's coalbed methane resources.

Recognition of the stratigraphic position of marine transgressions within the Wind River Basin is important in correlating and subdividing strata into significant intervals. Sedimentary rocks in the basin can be divided into two general depositional environments. The Paleozoic/Mesozoic age sediments are predominantly of marine origin and contain continuous coalbeds in the Upper Cretaceous sequence, whereas the Cenozoic-to-recent deposits are predominantly continental in origin. The nature of the restricted Cenozoic depositional environments is one of the more important factors in the formation of coal and coalbed methane.

Numerous detailed stratigraphic studies of the Paleozoic, Mesozoic, and Cenozoic formations have been published (e.g., Keefer and Van Lieu, 1966; Thomas, 1948). Figure 3-10 presents a generalized stratigraphic nomenclature chart for the State of Wyoming and the Denver Basin.

3.4.1 Geologic History

Figure 3-9 shows the overall similarity between the Wind River, Big Horn, and Powder River Basins. Close similarity exists with regard to basin evolution, tectonism, and structural style. Each of these basins has

experienced a long cratonic history and a relatively brief period of transverse basin development, which preceded separation into smaller zeugotaphrogeosynclines. The Laramide orogeny resulted in bounding tilted fault blocks that formed in response to differential vertical uplift along upthrusts (Shelton and Ross, 1971). Volcanic activity and epeirogeny were post-Laramide structural events.

Common restricted depositional conditions are recognized in all three basins. These environments are represented by the Lower Cretaceous dark gray shale, coaliferous Cretaceous and Tertiary strata, Tertiary organic lacustrine shale, and uranium-bearing sediments. The phosphatic shale of the Permian Phosphoria Formation in the Wind River and Big Horn Basins intertongues eastward with red shale and evaporite beds of the Powder River Basin (Figure 3-10). Rapid lateral facies changes within the basin have a pronounced effect upon the development of potential coalbed reservoirs.

3.4.1.1 Depositional Environments

The Wind River Basin was part of the stable shelf that lay east of the Cordilleran geosyncline during Paleozoic and much of Mesozoic time (Keefer, 1965). Sediments representing all geologic periods, with the possible exception of the Silurian, were deposited across the region during repeated epicontinental marine transgressions. Stratigraphic sequences are thicker and more complete in the western part of the basin than in the eastern, where they are thin and discontinuous. Some units disappear eastward because of truncation or non-deposition (Figure 3-10). The depositional environments were influenced locally by slight fluctuations in sea-level and by tectonic movements. These movements were limited to broad upwarps and downwarps which show little direct relation to the later developed Laramide structural trends.

At the close of the Jurassic, highlands began to form in the geosynclinal area west of Wyoming, and the major sites of deposition were shifted eastward. During Late Cretaceous time the non-marine deposits accumulated across the Wind River Basin area. The latest Cretaceous marine invasion (represented by the Lewis Shale) covered only the eastern part of the basin (Figure 3-11). Paape (1968) noted that the thickness of the Upper Cretaceous rocks in the basin is much greater than the thickness of all the older strata combined.

Laramide deformation began in latest Cretaceous time with downwarping of the basin trough and broad-doming of parts of the peripheral areas. The intensity of movement increased through the Paleocene, and culminated in earliest Eocene time in high mountains that were uplifted along reverse faults. A complete record of orogenic events is preserved in the more than 20,000 feet of fluviatile, paludal, and lacustrine strata that accumulated in the areas of greatest subsidence.

Basin subsidence and mountain uplift had virtually ceased by the end of early Eocene time. Clastic debris eroded from the mountains, augmented by volcanic debris, continued to fill the basin during the later stages of Tertiary time. Near the close of the Tertiary, the entire region was elevated several thousand feet above its previous level, and the present cycle of erosion was initiated. Normal faulting, perhaps concomitant with regional uplift, locally modified the older structural features (Keefer, 1965).

Hyne et al. (1979) reported that stratigraphic rock column resulting from the deposition of an intermontane, lacustrine delta, such as the Catatumbo river delta in Venezuela, is similar to that deposited in many oceanic deltas, with subtle differences. These types of basins, however, probably lack the tidal areas (plain, flats, channels, and shelf) of deposition. Slump deposits at the base of the prodelta sediments, overbank splay, interdistributary bay, crevasse splay, and marsh deposits overlying beach deposits are for the most part absent in the intermontane lacustrine delta sequences. This data will help in the geologic interpretation of geophysical well logs.

3.4.1.1.1 Paleozoic Era

Deposition took place mainly in shallow seas, so that slight changes in base level commonly resulted in widespread unconformities and changes in sedimentation patterns. Crustal stability persisted throughout the Paleozoic Era in the Wind River Basin. Lower Paleozoic rocks are mainly carbonates and some shales, with the shales being confined mainly to the Lower Cambrian. Lower Carboniferous strata are represented by two marine depositional sequences separated by a period of epeirogenic uplift and erosion. Extensive carbonate deposits were laid down during Early Mississippian time (Keefer, 1965). At the end of the carbonate deposition

(Madison Limestone) all of central Wyoming emerged and was eroded. The Pennsylvanian Period represented a time for an alternating deposition of limestone, shale, and sandstone under marine conditions. Coalbeds are not known to have developed in this continental shelf environment. Evidence for the lack of coal is derived from outcrop studies and subsurface well log data.

Permian rocks are complex owing to the restrictive nature of the depositional environments of this period. Major facies studies by McKelvey (1959) showed the distribution of sediments across the basin. Red beds, shale, and gypsum were deposited in the eastern part of Fremont and Natrona Counties, Wyoming. The central portion of the basin in Fremont County was restricted to carbonates, mudstone, chert, and phosphate along the basin's western edge. The Phosphoria Formation was deposited on the edge of the Continental Shelf in a bay of the Cordilleran seaway (Claypool, et al., 1978). Some sandstone was deposited at the northwestern corner. At the end of the Permian the westward dip of the Precambrian surface was about 15 feet per mile across central Wyoming (Keefer, 1965).

3.4.1.1.2 Mesozoic Era

Red bed deposition dominated during Triassic time. In earliest Triassic time, siltstones and carbonates were deposited in a marine environment in the central and western parts of the basin. A westward shift in the red bed depositional environment resulted in nearly a thousand feet of red shale, siltstone, and sandstone over the basin. Uniform deposition took place on broad alluvial, deltaic, and littoral plains and mud flats (Keefer, 1965). There is little evidence for tectonic activity in or near the basin.

The Jurassic of central Wyoming also represents a complex depositional system with diverse types of sediments and widespread unconformities (Keefer, 1965). The pattern of unconformities within this rock sequence indicates considerable tectonic activity. Early Jurassic time was characterized by continental conditions, whereas in the Middle Jurassic Series a marine environment persisted.

Upper Jurassic sediments are characterized by several hundred feet of sandstone and variegated shale of the Morrison Formation. Owing to

lithologic similarity of uppermost Jurassic and lowermost Cretaceous rocks, the position of the Jurassic Cretaceous boundary is uncertain in many places (Keefer, 1965). Locally, a series of lenticular conglomerates near the middle of the sedimentary sequence may mark the systemic boundary.

During Early Cretaceous time there were shallow marine depositional areas, as evidenced by black marine shales. The oil-producing Muddy Sandstone shows characteristics of having both marine and nonmarine origins. Keefer (1965) suggests that low islands existed, with fresh water streams and abundant vegetation. Widespread bentonite beds in the Muddy Sandstone reflect volcanic activity.

Upper Cretaceous rocks show a complex history of transgression and regression. Vast amounts of clastic debris were shed into the basin from the west. As the marine environment shifted eastward in early Late Cretaceous time, an extensive regressive sandstone (basal Frontier Formation) was deposited across the Mowry black marine shale. A period of continental sedimentation ensued with swamps, lagoons, and marine embayments dominating the depositional environments.

A major marine transgression followed Frontier deposition. More than 2,000 feet of marine shale were deposited in the Cody sea. Maximum transgression was reached in middle Niobrara time, followed by a long period of regression. Another 2,000 feet of marine sediments accumulated, mostly very fine-grained shaly sandstone. The final regressive deposit is the basal sandstone of the Mesaverde Formation (Keefer, 1965).

Much intertonguing takes place between the Cody and Mesaverde Formations. In the western part of the Wind River Basin, the transition from shallow offshore sedimentation took place during Eagle time when another 2,000 feet of marine shaly, sandy sediments accumulated.

Both the Mesaverde and Meeteetsee Formations are a result of sedimentation in flood plain, coastal swamp, and lagoonal environments. The land surface sloped gently eastward and existing highlands in eastern Idaho continued to furnish large amounts of clastic debris to eastward-flowing rivers. Volcanic ash also was deposited.

Commencing with the deposition of the Lance Formation (Upper Cretaceous), Laramide tectonic movements began within and around the basin. These movements had a significant influence on the sedimentation pattern up to Eocene time. Keefer (1965) suggested that the upper surface of the Meeteetsee/Lewis be considered a place of "zero" deformation (Figure 3-11). At the beginning of Lance deposition, broad upwarps began to form in the areas now occupied by the Granite Mountains along the basin's southern edge, and by the Washakie Range. The major structural features of the basin were defined by latest Cretaceous time (Paape, 1968).

3.4.1.1.3 Cenozoic Era

The Wind River Mountains began to rise along the western side of the Wind River Basin at the beginning of the Paleocene. Both the Granite and Washakie Mountains continued to rise, and anticlinal folding took place in some of the marginal areas of the basin.

The basin trough continued to subside during all of Paleocene time and, during the latter part of the Paleocene, it was flooded by a large body of water known as Waltman Lake. Hyne et al. (1979) noted that Waltman and Modern Lakes are similar in size. The sediments deposited consist of organic black shales. These shales are thought to be the source rock for much of the oil and gas found in the lower Tertiary formations of the northeastern part of the basin.

During early Eocene time, folding and uplifts were accelerated. Large-scale reverse faulting took place in the northwestern part of the basin. Alluvial fans formed in front of the rising highlands. The southern Big Horn Mountains and the Casper Arch also were uplifted along extensive reverse faults. The Wind River Basin was filling internally with up to 8,000 feet of lower Eocene sediments.

Basin subsidence and the tectonic activity of the Laramide orogeny ended by the close of early Eocene time. Renewed folding and faulting of existing structural features took place after the Wind River Formation was deposited. Small lakes formed in low areas. Large-side normal faulting was probably related to a large regional orogenic uplift that occurred in late Tertiary time. Keefer (1965) reported that in many places this faulting resulted in the collapse of major Laramide uplifts along former

reverse faults. Regional tilting and normal faulting continued into the Miocene.

The sedimentary history of the basin during middle and late Tertiary times is one of nearly continuous aggradation. The Oligocene, Miocene, and Pliocene rocks are predominantly volcanic, which is in sharp contrast to the predominantly non-volcanic, locally derived clastic material of lower Eocene age.

By Pliocene time, the entire region, except for the highest mountain peaks, was buried. During late Pliocene this area was uplifted 3,000 to 4,000 feet and a long period of degradation set in. Keefer (1965) noted that this is continuing today and that the structural and physiographic features present are not too different from those of early Eocene time.

3.4.2 Stratigraphy

Wind River Basin rock unit descriptions, from many published papers, have been condensed for this report. For further details the reader is referred to the following publications: (1) Precambrian rocks--Smithson and Ebens, 1971; (2) Paleozoic rocks--Keefer and Van Lieu, 1966; (3) Mesozoic rocks--Love et al. (1945 a, b, c); Yenne and Pipiringos (1954); and Keefer and Rich (1957); and (4) Tertiary rocks--Love (1939), and Keefer (1965). A generalized columnar stratigraphic section for the basin is presented in Figure 3-12.

3.4.2.1 Precambrian Rocks

Igneous and metamorphic rocks of Precambrian age comprise the core of the mountain ranges and underlie sedimentary rocks within the basin (McGreevy, et al., 1969). Smithson and Ebens (1971) reported that the Wind River Range is composed mostly of Precambrian granite gneisses, augen gneisses, and migmatites which are metamorphic or ultrametamorphic rocks typical of old shield areas. The Precambrian rocks of the Owl Creek Mountains cover only about 50 square miles and consist of granite and granite gneiss.

In the Washakie Range, just west of the Indian reservation, the Precambrian rocks consist of gray and pink granite and granite gneiss cut by thin pegmatite dikes and quartz veins. Schistose rocks are common (Keefer, 1957). The Precambrian and Paleozoic rocks are of interest only

in those areas where they have been thrust over the Mesozoic coal-bearing formations. The Immigrant Trail, Dubois, and Big Sandy areas of the basin contain such thrusts (see Section 3.4.3.2).

3.4.2.2 Paleozoic Formations

The Paleozoic sequence of sedimentary rocks is thicker and more complete in the western part of the Wind River Basin (Figure 3-13). Marked changes in the thickness and lithology of nearly all formations take place from west to east across the basin. Some units disappear eastward owing to truncation or nondeposition (Keefer and Van Lieu, 1966). Maximum thickness of Paleozoic rocks is about 3,400 feet (Paape, 1968).

The Cambrian rocks are represented by a marine sandstone, shale, and limestone sequence. The most generally accepted nomenclature for this sequence is, from the base upward: Flathead Sandstone, Gros Ventre Formation, and Gallatin Limestone. These units thin eastward from about 1,025 feet in the Wind River Range to about 775 feet in the Wind River Canyon. In the Wind River Range the Flathead is about 200 feet thick, the Gros Ventre Formation, about 750, and the Gallatin Limestone ranges in thickness from 265 to 365 feet. These rocks lie unconformably on Precambrian igneous and metamorphic rocks and were deposited during Middle and Late Cambrian time.

- Flathead Sandstone--The Flathead is reddish brown, light-brown, and gray fine- to coarse-grained sandstone. The basal beds are commonly conglomeratic and arkosic. The upper beds are shaly.

- Gros Ventre Formation--The Gros Ventre Formation in the Wind River Range can be divided into three units: a lower shale and shaly sandstone unit; a middle limestone unit; and an upper shale and limestone unit. In the Owl Creek Mountains, the Gros Ventre Formation is an easily weathered unit of shale, sandstone, and siltstone with some limestone in the upper part.

- Gallatin Limestone--The Late Cambrian Gallatin Limestone consists of upper and lower limestone units separated by a thin shale unit. Ordovician rocks of the Wind River Reservation are represented only by the Bighorn Dolomite which, because of its resistant nature, is probably the most conspicuous Paleozoic unit in the Owl Creek, Washakie, and Wind River Mountains (Figure 3-2). In outcrop, the Bighorn is 125 to 250 feet thick, but it thins to the southeast and is absent in the southeast corner of the basin.

- Bighorn Dolomite--The basal Lander Sandstone Member is less than five feet thick and occurs only at Trout Creek west of Lander, and at Windy Gap, north of Dubois. The middle and upper members of the Bighorn Dolomite have a combined thickness of 200 to 300 feet. The unnamed middle member is a cliff-forming, buff to light-gray, massive, granular dolomite. The member thins southward and eastward because of the erosional unconformity at the top of the Bighorn Dolomite. The upper member, named the Leigh Dolomite, is a chalky white weathering dolomite that thins southward from 85 feet at the northwest end of the Wind River Range. Devonian rocks in the Wind River Basin include all strata lying between the Bighorn Dolomite and Madison Limestone (Keefer and Van Lieu, 1966).

- Darby Formation--The Darby Formation consists of thin- to thick-bedded dolomite in the lower part, and siltstone, shale, and sandstone interbedded with limestone and dolomite in the upper part. It is thickest--about 175 feet--in the northwest part of the basin. It thins to the southeast and is absent east of the line between Thermopolis and Fort Washakie.

  Silurian age rocks have not been recognized in the basin. Figure 3-14 shows the approximate time intervals represented by Mississippian, Pennsylvanian, and Permian Formations in central and western Wyoming.

  Mississippian time is represented by the Madison Limestone, named for the Madison Range in the Three Forks region of southwestern Montana.

- Madison Limestone--It consists of massive gray limestone and dolomitic limestone with chert beds and nodules. Highly fractured and brecciated zones are conspicuous in the upper part. The Madison Limestone is separated from the overlying Amsden Formation by a conspicuous erosional unconformity.

  Pennsylvanian rocks are represented by two formations representing Early and Middle Pennsylvanian time. No coal is known to occur in the Carboniferous rocks of the Wind River Basin.

- Amsden Formation--The Early Pennsylvanian Amsden Formation ranges in thickness from 210 to 355 feet. The lower 100 feet of cliff-forming, white-to-light brown, cross- to thin-bedded sandstone is the Darwin Sandstone Member, which has been referred to in part as being Late Mississippian age. The upper part of the Amsden is a nonresistant sequence of dolomite, shale, sandstone, and limestone that produces characteristic reddish and yellowish soils. Contact with the overlying cliff-forming Tensleep Sandstone is topographically abrupt, but locally is lithologically gradational.

- Tensleep Sandstone--The Tensleep Sandstone of Middle Pennsylvanian age is lithologically similar to, and can be confused with, the Darwin Sandstone Member of the Amsden Formation. It is a light brown to white, massive to cross-bedded sandstone. Many outcrops weather brown or reddish brown and from a distance appear nearly

black. Thickness of the Tensleep ranges from about 200 to about 400 feet. The formation is mostly of marine origin but vertebrate tracks have been reported in it near Lander, Wyoming, suggesting at least temporary subaerial conditions. A conspicuous erosional unconformity separates the Pennsylvanian Tensleep Sandstone from the overlying Permian rocks (Keefer and Van Lieu, 1966).

- Park City Formation--McKelvey (1959) suggested that the Permian sequence be divided into four major rock groups: red beds; carbonate; mudstone, chert, and phosphorite; and sandstone (Figure 3-10). Respectively, these are then assigned to the Goose Egg Formation, Park City Formation, Phosphoria Formation, and Shedhorn Sandstone. Because of the non-diagnostic nature of Phosphoria fossils and diverse facies interrelationship, detailed correlations within the Phosphoria are difficult. (Lane (1973) discusses this nomenclature with respect to subsurface data.) The name Park City Formation is commonly used because the Permian in the western part of the Wind River Basin consists primarily of carbonate rocks.

  The Park City Formation in the western Wind River Basin consists of 200 to 300 feet of limestone, dolomite, dolomitic siltstone, shale, and chert. The shales and siltstones are locally phosphatic. The phosphatic rocks form two distinct zones on the east flank of the Wind River Range near Lander and have been referred to as the lower and upper phosphate zones by King (1947) and as units B and D by Sheldon (1957). The zones are one to two feet thick and contain from 15.2 to 29.7 percent P_2O_5. The stratigraphic relationship of the Permian Phosphoria Formation and related rocks is summarized in Figure 3-15.

  Organic matter in the black shale members of the Phosphoria exhibits maximum conversion to petroleum hydrocarbons at temperatures corresponding to a 1.5- to 2.8-mile range of burial depth (Claypool, et al., 1978). This has a profound effect on targeting of the coalbed methane resources.

3.4.2.3 Mesozoic Formations

Triassic rocks are underlain by the Permian age beds throughout west-central Wyoming (Picard, 1978). Marine Permian rocks (Phosphoria Formation) in the western part of the Wind River Basin intertongue eastward and southeastward with red beds (Goose Egg Formation) that are difficult to distinguish from red beds of Triassic age.

- Dinwoody Formation--The Dinwoody Formation is a marine Early Triassic unit that consists of a 25- to 50-foot basal unit of silty limestone, gray crystalline limestone, and greenish-brown-to-gray shales; and an upper unit of as much as 100 feet of calcareous siltstone, silty limestone, crystalline limestone, and some shale. The Dinwoody is 50 to 150 feet thick in the area and thins eastward (Figure 3-10).

- Red Peak Formation--The Red Peak Formation (Chugwater Group) of thin-bedded red siltstone, red shale, and red silty sandstone is a continental red bed unit deposited after retreat of the Dinwoody sea. The Red Peak is 800 to 1,000 feet thick in the western part of the basin.

- Alcova Limestone--The Alcova Limestone (Chugwater Group) is pink-to-gray, finely crystalline limestone from five to 15 feet thick, although it is absent in the extreme northern part of the area.

- Crow Mountain Sandstone--The Crow Mountain Sandstone (Chugwater Group) is cross-bedded, light brownish-red-to-gray, fine- to medium-grained sandstone that generally contains rounded, frosted sand grains.

- Popo Agie Formation--The Popo Agie Formation (Chugwater Group) consists of red sandstone, shale, and siltstone. Abundant analcite and thin beds and lenses of conglomerate composed of granules and pebbles of limestone, claystone, and marlstone pebbles, and reptilian bone fragments occur in the upper part. Many workers cannot agree on which is the basal unit of the Jurassic Period in the Wind River Basin. The age of the Nugget Sandstone in west-central Wyoming is uncertain. Picard (1978) stated that a Late Triassic age for the Nugget Sandstone cannot be eliminated as a possibility; consideration of the time required to fold and truncate the Popo Agie Formation suggests that the Nugget Sandstone is Jurassic in age (Figures 3-10 and 3-12).

- Nugget Sandstone--The Lower Jurassic Nugget Sandstone consists of pinkish-white, fine- to very fine-grained, large-scale cross-bedded sandstone. A thin siltstone or shale is present at the base. The formation is as thick as 300 feet, thins to the northeast, and is absent in the northern part of the basin.

- Gypsum Spring Formation--The upper part of the Middle Jurassic Gypsum Spring Formation consists of interbedded red siltstone and gray limestone. The lower half of the unit is mainly white, thick-bedded gypsum and anhydrite.

- Sundance Formation--The Late Jurassic Sundance Formation contains interbedded sandstone, shale, and limestone deposited in a marine environment. Sandstone that is fine- to medium-grained, cross-bedded, and glauconitic is more abundant in the upper part. The lower part has more abundant gray-to-green shale. Oolitic limestone is found throughout the unit. The Sundance thickens westward and reaches a thickness of 500 feet.

- Morrison Formation--The Morrison Formation is a series of fluvial siltstone, claystones, shales, and sandstones. The proportion of sandstone decreases from greater than 50 percent, and the proportion of varicolored shale increases to greater than 80 percent from southeast to northwest across the western part of the basin. The Morrison contains many of the well-known dinosaur-bearing beds of the Rocky Mountain region.

Throughout much of the Wind River Basin, rocks assigned to the Morrison and Cloverly Formations have been mapped as a single unit because no consistent regional basis for subdivision has yet been found (Figure 3-10). However, a major lithologic break that occurs from 100 to 200 feet above the base of the unit in the northern part of the Wind River Basin may mark the contact between the two formations (Love, et al., 1945). Keefer and Troyer (1964) reported that this break is regionally marked by a change from lenticular dull earthy, silty sandstone, and dully variegated silty claystone below to sparkly, clean, porous, and conglomeratic sandstone and brightly variegated claystone above. Nonmarine Jurassic fossils have been found below the break, but nonmarine Cretaceous fossils have been found in beds above the break. Paape (1968) assigned the name Lakota to this conglomerate (Figure 3-12).

- Cloverly Formation--The Early Cretaceous Cloverly Formation consists of light brown to brown sandstone ("rusty beds") at the top, pale purple and light green claystone in the middle, and a chert pebble conglomerate at the base. The thickness of the unit ranges from 250 to 450 feet. The "rusty beds" were deposited in coastal plain and shoreline environments. The remainder of the unit was deposited in an environment that was entirely continental. The contact between the rusty beds and the overlying Thermopolis Shale is marked by a change from chiefly gray sandstone and shale below to chiefly black fissile shale above (Keefer and Troyer, 1964).

- Thermopolis Shale--The Early Cretaceous Thermopolis Shale consists of unnamed upper and lower black shales and a named medial member, the Muddy Sandstone--a gray thin-bedded sandstone. The upper black shale member grades into the overlying siliceous Mowry Shale. The unit ranges in thickness from 320 to 450 feet.

- Muddy Sandstone--The Muddy Sandstone is a very persistent unit of fine- to medium-grained sandstone interbedded with varied amounts of gray-to-black shale (Gopinanth, 1976). In the basin it represents a series of prograding deltaic and interdeltaic shoreline environments. No coal is known to occur.

- Mowry Shale--The Mowry Shale consists of hard black siliceous shale with a few sandy beds, and many thin bentonite beds. The Mowry is the uppermost unit of the Early Cretaceous.

- Frontier Formation--The Late Cretaceous Frontier Formation is an important oil- and gas-producing formation in many Wyoming fields. It consists of alternating gray to black shale and gray sandstone with a few thin tuff and bentonite beds, and ranges in thickness from 600 to 1,000 feet. The unit is resistant to weathering and usually crops out as ridges. Thick coalbeds occur near the top of the formation (Windolph, 1981, personal communication).

- Cody Shale--The Late Cretaceous Cody Shale can be divided into a lower shaly member and an upper sandy member. The Cody is easily weathered, in contrast to the underlying and overlying formations,

and commonly forms broad, flat, soil-covered valleys. The lower member consists of gray-to-black silty shale that becomes coarser toward the top. The upper member consists of thin-bedded calcareous sandstone and siltstone interbedded with minor amounts of gray-to-black fissile shale (Figure 3-16). The Cody Shale ranges widely in thickness, from 2,500 to 5,000 feet, partly because its plastic nature permits tectonic thinning and thickening.

- Mesaverde Formation--In most places the Mesaverde Formation can be divided into a basal sandstone of beach origin, and an overlying terrestrial unit of variable lithology and thickness including sandstone, siltstone, shale, carbonaceous shale, and coal (Figure 3-16). Individual beds are commonly lenticular and not more than a few feet thick. The upper member is a white sandstone commonly forming cliffs and ledges. Where present, the Mesaverde ranges in thickness from 1,000 to 2,000 feet, but it is absent in the southwest part of the basin.

- Meeteetse Formation--The Meeteetse Formation of Late Cretaceous age can be divided into a lower banded unit and an upper massive lenticular sandstone unit. The lower part of the Meeteetse is interbedded sandstone, siltstone, shale, and coal. Large, spherical concretions up to three feet in diameter weather out of the lower sandstone unit. Some of the coalbeds are of minable thickness. Plant remains and dinosaur bones are found in the Meeteetse. The upper part of the Meeteetse is a massive lenticular sandstone unit ranging in thickness from 0 to 300 feet. The formation is absent in the western and southern parts of the area; elsewhere it is as much as 1,400 feet thick.

- Lance Formation--The Lance Formation of latest Cretaceous age consists of a basal sandstone with lenses and thin beds of conglomerate overlain by gray-to-black claystone and shale. The upper unit contains sandstone and conglomerate beds, and a few thin partings of coal. The Lance attains a maximum thickness of 1,200 feet. It thins from north to south, and is absent in the western and southwestern parts of the basin.

3.4.2.4 Tertiary Formations

On the margins of the Wind River Basin, the Tertiary age Fort Union Formation lies unconformably over the Lance Formation. The unconformity extends only a short distance into the subsurface of the basin. In the central part of the basin deposition was continuous from Late Cretaceous to Paleocene times.

- Fort Union Formation--The Fort Union can be divided into two parts: a lower sequence of interbedded sandstone conglomerate, shale, and carbonaceous shale of fluviatile origin and an upper sequence of shale, siltstone, claystone, and sandstone. Keefer (1961) divided the upper part of the Fort Union into the Waltman Shale and the

Shotgun Butte Members. Figure 3-17 provides an interpretation of the uppermost Cretaceous and lower Paleocene stratigraphic relationship in the basin.

- Indian Meadows Formation--Of earliest Eocene age, the Indian Meadows Formation crops out on the northern margin of the Wind River Basin, and is impossible to distinguish from the overlying Wind River Formation in the subsurface (Figure 3-10). The Indian Meadows consists of banded red, gray, and tan clays and silts, plus coarse conglomerates that originated as stream channel and alluvial fan deposits. Masses of Paleozoic rock, more than one-quarter mile long, are found within the formation and may be landslide deposits or remnants of thrust sheets formed during uplift of the Owl Creek and Washakie Ranges. The Indian Meadows is absent along the southwest side of the basin but may be several thousand or more feet thick in the subsurface along the north side of the basin.

- Wind River Formation--The Wind River Formation of early Eocene age is exposed over a greater part of the surface area of the Wind River Indian Reservation than any other geologic unit. The Wind River Formation originated during the period following uplift of the Wind River, Washakie, and Owl Creek Ranges in earliest Eocene and is composed of debris deposited in alluvial fans near the mountains, stream channels, flood plains, lakes, and swamps farther out in the basin (Soister, 1968). Rock types include alternations of red and green siltstone, claystones, sandstone, and conglomerate. The Wind River conglomerates contain abundant Precambrian rock fragments that record exposure of the igneous and metamorphic cores of the ranges bordering the basin. These conglomerates are in contrast to those of the formations which contain conglomerate derived from Mesozoic rocks. Conglomerate in the upper part of the Indian Meadows is coarse and consists of fragments of Paleozoic rocks. Figure 3-18 illustrates the complexity of the stratigraphy of the Wind River Formation. The thickness of the Wind River ranges from a few feet at the basin margin to at least 6,000 feet in the northern part of the Wind River Indian Reservation.

- Aycross Formation--The Aycross Formation, a middle Eocene unit found in the northwest corner of the reservation south of the Washakie Range, unconformably overlies the Wind River Formation (Figure 3-10). The Aycross is composed of tuff, claystone, shale, and sandstone. Conglomerates composed of volcanic clasts are conspicuous locally. Lateral changes in lithology and thickness are rapid.

- Tepee Trail Formation--The Tepee Trail Formation of middle and late Eocene age unconformably overlies the Aycross Formation in the southern Absaroka Mountains and consists of greenish andesitic volcanic conglomerates, sandstones, shales, tuffs, flows, and thin carbonaceous beds. The unit is about 2,000 feet thick.

- Unnamed Tuff--In the northeast part of the reservation on the south flank of the Owl Creek Mountains, an unnamed middle and late Eocene unit of tuff and volcanic conglomerate with some limestone has been

mapped. The unit is, in part, the same age as the Tepee Trail Formation.

- Wiggins Formation--The Wiggins Formation of Oligocene age overlies the Tepee Trail Formation and forms the spectacular cliffs and peaks, such as the Ramshorn, on the southern margin of the Absaroka Mountains. It is about 1,000 feet thick and is composed of volcanic conglomerate and breccia interbedded with tuffs. The conglomerates thicken and the size of the clasts increases toward the north and northwest indicating that the vents which produced the volcanic detritus lay to the north (Love, 1939). Quaternary age deposits are derived from the surrounding rocks.

- White River Formation--The White River Formation of late Oligocene age in places overlies the Wiggins Formation (Rich, 1962). In the eastern part of the Wind River Basin, the lower 12 to 50 feet of the White River Formation are a massive-to-poorly bedded conglomerate containing granite boulders as much as 20 feet in diameter, rounded pebbles and cobbles of Paleozoic sandstone, brownish-gray quartzite, basic igneous rock, and pale-green Precambrian quartzite. The matrix consists of coarse-grained arkosic sandstone.

  Many of the conglomerate beds contain pale-brown to medium-dark-gray pebbles of chert or chalecdony that are coated with a dull white porcelain-like material. The white coating is probably the result of leaching or hydration of the silica within the pebble itself or of the siliceous cement surrounding the pebble. Rich (1962) stated that while these chert pebbles are common in both the White River Formation and the overlying Miocene rocks, the white coating seems to be found only on the pebbles in the White River Formation.

  The rest of the White River Formation is characterized by light-gray, pinkish-gray, tan, and white tuffaceous siltstone and claystone interbedded with light- to dark-gray tuff and conglomeratic sandstone. The individual beds are lenticular and can be traced only short distances along the strike. The upper 50 to 100 feet is predominantly white to light-gray tuff interbedded with pinkish-gray tuffaceous siltstone. The tuff beds are lenticular and range in thickness from 0 to about 20 feet (Rich, 1962).

  Carbonaceous layers are scarce in the White River Formation; however, a radioactive carbonaceous zone about 20 feet thick and about 1,000 feet long was found approximately 300 feet above the base of the White River Formation in Sec. 4, T31N, R83W. It consists of two lenticular beds of carbonaceous sandy siltstone separated by a thin coarse-grained sandstone. The carbonaceous zone is overlain and underlain by white poorly indurated sandstone (Rich, 1962).

- Split Rock Formation--The Split Rock Formation is of early and middle Miocene in age. The lower 150 to 400 feet of the lower and middle Miocene rocks is made up of alternate white lenticular

conglomeratic sandstone and light-gray to pinkish-gray sandy siltstone, all tuffaceous.

Overlying the basal beds is a predominantly tuffaceous sandstone sequence with intercalated beds of thin to thick tuff and lenticular conglomerate. The sandstone beds are white to light gray, fine- to medium-grained, moderately well sorted, and massive to crossbedded.

- Pleistocene glacial deposits--Pleistocene till and outwash gravel representing five glacial advances are present in the southwest part of the area along the northeast flanks of the Wind River range. The oldest glaciation is indicated only by pebble, cobble, and boulder gravel. The younger glaciations are represented by both outwash gravel and progressively better developed morainal forms consisting of compact stony, silty sand.

- Holocene deposits--Holocene sediments include unconsolidated pebble, cobble, and boulder gravel; sand, silt, and clay deposited on flood plains as slope wash, terrace, pediment, landslide, and colluvial deposits.

3.4.3 Structure

The Wind River Basin in central Wyoming is typical of the large sedimentary and structural basins that formed in the Rocky Mountain region during Laramide deformation (Figure 3-1) (Keefer, 1970). Since it is an integral part of the Rocky Mountain structural complex of folded and faulted sedimentary rocks, the tectonic history of the basin generally will parallel that of the whole system (Figure 3-19). The results of tectonic activity in the Wind River, Bighorn, and Powder River Basins are summarized in Figure 3-19. Flat-lying lower Eocene strata, part of the thick sequence of basin-fill sediments that accumulated during the major phases of tectonism in latest Cretaceous and early Tertiary times, occupy the central part of the basin. Broad belts of folded and faulted Precambrian, Paleozoic, and Mesozoic rocks, forming the flanks and cores of the adjacent mountain range and anticlinal complexes, completely surround it. Paape (1968) noted that the basin's shape appears to be a result of the complex compressional forces which caused extensive reverse faulting along all flanks of the basin during the Laramide orogeny.

Thomas (1971) stated that the regional tectonic history appears to be the result of a basement plate framework defined by basement weakness zones activated laterally by orogenic forces. The basement weakness zones are expressed as lineaments. This lateral reactivation produces simple shear

on the weakness zones and plate couple in the areas between them. The plate couple may produce cross-plate normal faults, horsts, or grabens, and drag folds oriented at right angles to the tensional effects (Figure 3-19). Plate drag folds of a positive or negative variety and the tensional faults, horsts, and grabens in turn control paleotopography which controls depositional conditions (Thomas, 1971).

During Paleozoic and much of Mesozoic time, central Wyoming was part of the foreland bordering the Cordilleran geosyncline on the east. Tectonic activity was limited to broad upwarping and downwarping of low amplitude along trends which in many places did not coincide with the trends of later Laramide structures (Keefer, 1970). In Cretaceous time, the seaways shifted eastward into eastern Wyoming in response to uplift in southeastern Idaho, and a thick sequence of alternating marine and nonmarine deposits accumulated in the Wind River Basin area.

Laramide deformation in central Wyoming began in latest Cretaceous time with downwarping of the basin trough and broad doming of parts of the peripheral areas. The intensity of movement increased through the Paleocene and culminated in earliest Eocene time in high mountains that were uplifted along reverse faults. A complete record of orogenic events is preserved in the more than 18,000 feet of fluviatile and lacustrine sediments that accumulated in the areas of greatest subsidence.

Laramide mountain building and basin subsidence had virtually ceased by the end of early Eocene time. Near the close of the Tertiary, the entire region, mountains and basin alike, was elevated about 5,000 feet above its previous level, and the present cycle of erosion was initiated. Normal faulting, perhaps concomitant with epeirogenic uplift, resulted in the partial collapse of some Laramide uplifts (Keefer, 1970).

An understanding of this basin's structural development will aid in the exploration for coalbed methane. Figure 3-20 shows major structural features of the Wind River Basin. Basin structures are discussed with respect to the west, east, north, and south margins of the basin.

3.4.3.1 Folding

The Wind River Basin is markedly asymmetric; the structurally deepest parts are close to the Owl Creek and Bighorn Mountains on the north and the

Casper arch on the east (Figure 3-2). The main trough of the basin lies three to five miles south of these mountains and appears to intersect the north end of the Casper arch at a right angle. Asymmetry toward the southwest and a pronounced northwest alignment (N. 40° W.) of individual folds and faults dominate the structural pattern across the entire region (Keefer, 1970). The present Wind River Basin is composed of two distinct synclinal areas; one trending east-west along the northern flank of the basin which hereafter is referred to as the main northern basin syncline; the other, a secondary synclinal area extending along the southeastern margin of the basin, which hereafter is referred to as the minor southeastern basin syncline (Paape, 1961).

The structures of the Precambrian granitic and metasedimentary core rocks of the Wind River range have been little studied, but faults, shear zones, dikes, and folds generally have northwest, north, or northeast trends. Keefer (1970) states that the latest movements on northwest-trending structures may be of Laramide age and that east- and northeast-trending structures may have been produced by Precambrian deformations.

Along the east flank of the Wind River Range, Paleozoic and Mesozoic strata form a linear outcrop belt with uniform northeastward (basinward) dips of 12° to 15°. The monoclinal continuity is interrupted by a series of sharply folded northwest-trending anticlines which extend along the west margin of the basin for 90 miles (Figure 3-20). The 13 individual folds that occur along this trend have structural closures ranging from 500 to 4,000 feet (Keefer, 1970).

The Owl Creek Mountains along the north margin of the Wind River Basin include a complex group of structures showing diverse trends and structural behavior. West of Mexican Pass the range is partitioned into several horst-like blocks of Precambrian rocks flanked by Paleozoic rocks. Individual blocks, trending northwest, are almost completely surrounded by reverse faults or monoclinal flexures. The adjacent basin margin is also intensely deformed into sharply folded asymmetric anticlines and synclines. East of Mexican Pass the structure of the range is virtually that of a single broad anticlinal arch with a gently dipping (12° to 15°) north flank

bordering the Bighorn Basin and a steep-to-overturned south flank that overrode the north margin of the Wind River Basin along a continuous reverse fault zone (South Owl Creek Mountains fault).

The plunging southwest end of the Bighorn Mountains forms the northeast margin of the Wind River Basin. Paleozoic and Mesozoic strata, which dip 15° to 25° basinward, have been faulted over the basin margin along the buried South Owl Creek Mountains faults. Structural relief here probably also exceeds 30,000 feet in places.

The Casper arch is a major, but not deeply eroded, structural upwarp whose steep-to-overturned west limb coincides with the east margin of the Wind River Basin (Figure 3-4). A nearly continuous northwest-trending series of subsidiary anticlines is superimposed along the west edge of the major arch.

The Granite Mountains, along the south edge of the Wind River Basin, were uplifted several thousand feet and were deeply eroded during Laramide deformation. Then, owing to extensive downfaulting and downfolding in post-early Eocene time, the central Precambrian core collapsed and was buried by middle and upper Tertiary sediments. Erosion has now exposed part of the basement complex (Keefer, 1970).

The south margin of the Wind River Basin is interrupted by a series of northwest-plunging anticlines which from west to east include Beaver Creek, Sand Draw, Alkali Butte, Conant Creek, Muskrat, Dutton Basin, and the Rattlesnake Hills (Blackstone, 1948) (Figures 3-8 and 3-20). Older rocks exposed in these folds extend beneath the unconformable Eocene Wind River sediments and structural detail cannot be observed (Brenner, 1972). A somewhat similar situation exists in the northwest part of the basin where the Dry Mountain-Sheldon trend and the Circle Ridge, Maverick Springs, Little Dome line of folding extends basinward beneath the Wind River Formation. Blackstone (1948) stated that geophysical data do not show these folds continuing across the central part of the basin between the northern and southern margins.

3.4.3.2 Faulting

As shown by Figure 3-20, many of the folds are associated with faults, especially the northeastern and western parts of the basin. Primary fault

types are high angle reverse, normal, and thrusts. Schilt et al. (1979) developed a composite seismic section running transversely across the Wind River Basin, Wind River Mountains, and the Green River Basin (Figure 3-21).

The Laramide uplifts have exposed Precambrian basement at the surface next to deep sedimentary basins with relief on the basement of the order of 6.2 miles (10 km). Many of these uplifts are flanked by moderate- to-low-angle thrust faults, with crystalline rocks thrust over sediments. It has long been argued whether these faults steepen and become nearly vertical within the crust, maintain a shallow dip well into the crust, or flatten out at shallow depths without significantly penetrating the crust.

A fault steepening to vertical would imply a principal compressive stress essentially vertical, while a shallow dipping fault would indicate a horizontal principal compressive stress. If movements were largely a result of gravity sliding, one might expect the fault to flatten without extending very deep into the crust. Schilt et al. (1979) discovereda fault plane dipping 30° to 35° penetrating to a depth of at least 15.5 miles (25 km) (Figure 3-21). This fault geometry demonstrates a compressional stress regime at the time of faulting. It implies that vertical and horizontal displacements occurred in the area of at least 8 and 13 miles, respectively (Schilt, et al.,1979).

The continuity of the fault plane to nearly the base of the crust (and perhaps deeper) implies that the crust fractured essentially as a rigid plate (Figure 3-21). As the fault approaches the base of the crust, it may flatten to parallel the Mohorovicic Discontinuity, or if it were offset initially, it may have since re-equilibriated to a uniform depth (Schilt, et al., 1979).

Both the north and south margins of the range are bounded by normal faults along which there was late Tertiary movement that caused the mountain block to be downdropped with respect to the adjacent basin areas. The west end of the range overrode the southwestern arm of the Wind River Basin along the buried Emigrant Trail reverse fault of Laramide origin. Paleozoic and Mesozoic strata dip10° to 15° north off the north flank of the Granite Mountains, but along the basin margin these rocks were folded into several large north- and northwest-trending anticlines that project far into the interior of the basin (Keefer,1970).

The implications of Precambrian igneous rocks being thrust over coal-bearing rocks would be important in the exploration for coalbed methane (Figure 3-22). The characteristics of these thrusts are:

- Folded Precambrian crystalline rocks
- Variable low angle dip steepening with depth
- Overturned and deformed sequence of Paleozoic rocks underlying the Precambrian thrust mass
- Cretaceous age rocks below the thrust (Figure 3-23).

Such thrusts imply small movements along a large number of closely spaced joints in the more competent igneous rocks (Berg, 1961).

The northern boundary of the basin is complex and difficult to interpret due to masking of older structure by the Wind River Formation at the foot of the Owl Creek Mountain uplift. The basin margin is overthrust. Maximum horizontal displacement of six miles is postulated south of the canyon of the Big Horn River where Eocene rocks overlap the fault trace (Brenner, 1972).

Figure 3-24 shows the relationship of lineaments with respect to oil and gas fields in southwestern Wyoming and northern Colorado. There appears to be some relationship in some places in the Wind River Basin between lineaments and producing fields.

3.4.4 Basin Hydrology

The Wind River Basin lies entirely in the Missouri Basin ground water region (Figure 3-25). The Missouri Basin region is located in the north-central part of the contiguous United States and southern Canada; it includes small parts of Alberta and Saskatchewan Provinces, parts of Montana, Wyoming, North Dakota, South Dakota, Minnesota, Iowa, Colorado, Kansas, Missouri, and all of Nebraska. The area includes about 519,000 square miles (about one-sixth) of the United States and about 9,700 square miles of Canada.

3.4.4.1 Climate/Vegetation

McGreevy et al. (1969) reported that the climate ranges from humid in the Wind River and Owl Creek Mountains to arid in the central part of the basin. Mean annual temperature at Riverton for the period 1931 to 1960 was

43.5°F. Wide ranges in seasonal temperatures are common, with winter temperatures commonly dropping far below 0°F and summer temperatures frequently exceeding 100°F. Mean annual precipitation at Riverton for the period 1931 to 1960 was 8.79 inches. Annual precipitation ranged from 4.85 to 14.74 inches. Mean annual precipitation at Lander (Figure 3-5), at the edge of the Wind River Mountains, is 13.58 inches (Figure 3-25). The lower parts of the basin receive an average annual rainfall of about 10 inches. The gaging stations of the U.S. Weather Bureau, located in or near the Hiland-Clarkson Hill area, record an average annual precipitation ranging from 6.8 inches at Arminto to 14.2 inches at Casper, Wyoming (Figure 3-25). More than half the annual precipitation falls during April through July. The precipitation is inadequate for farming, and cultivation of crops is successful only where additional water is supplied by irrigation (Rich, 1962). The generalized areal distribution of mean annual precipitation in the basin has been mapped and is shown in Figure 3-25. At Pavillion, the length of the growing season averaged 142 days during the period from 1940 to 1950. The last killing frost (28°F or below) in the spring occurs about mid-May, and the earliest killing frost in the fall usually occurs between September 15 and October 15. The average annual temperature for the years 1924 to 1950 was 44.8°F.

Vegetation in the basin consists mainly of sagebrush, prickly-pear, rabbitbrush, and some grass and weeds. Wherever precipitation is somewhat greater, grasses are more abundant. There are few trees in the topographically lower parts of the basin.

The valleys support some grass, sagebrush, and cactus, and a few willows and cottonwoods grow along the stream channels. The western slopes of the hills are commonly very steep and sparsely vegetated; the eastern slopes have a scanty sagebrush cover and a few scrub pine trees. The pine trees are generally concentrated along outcrop belts of massive porous sandstone, such as those sandstones in the Frontier Formation, the White Sandstone member of the Mesaverde Formation, and the lower part of the Fort Union Formation. Nonirrigated parts of the area are used mostly as winter grazing lands for cattle and sheep. Summer grazing is limited, for the most part, to grassland areas in the Owl Creek Mountains.

3.4.4.2 Surface Water Hydrology

Appendix C, Water-Resources Investigations in Wyoming (USGS, 1977), provides information on surface water in the Wind River Basin. The Wind River is the master stream in the area, originating in the Absaroka Mountains in the northwest corner of the Wind River Basin (Figure 3-2). The Wind River flows southeastward parallel to the Wind River Mountains to its confluence with the Little Wind River near Riverton where it turns northward, eventually flowing through the Wind River Canyon into the Bighorn Basin where it is called the Bighorn River. The larger tributaries to the Wind River head in the Wind River and Absaroka Mountains. Some principal tributaries in the western part of the basin are Bull Lake Creek, the Little Wind River, and the Popo Agie River in the southern part; Crow Creek in the northwestern part; and Fivemile and Muddy Creeks in the central part.

The eastern portion of the basin contains tributaries of the Wind, Powder, and North Platte Rivers' drainage systems, all in the Missouri River watershed. The central part of the northeastern part of the basin is drained by the South Fork of the Powder River, which flows northeastward into the Powder and Yellowstone Rivers. In the eastern and southern parts of the basin, the Rattlesnake Hills separate the northward-flowing tributaries of the North Platte River from the southward-flowing tributaries of the Sweetwater River. The Sweetwater River joins the North Platte River at the Pathfinder Reservoir.

The North Platte River, which flows northward along the eastern edge of the mapped area, flows eastward near Casper, Wyoming, and eventually reaches the Missouri by way of the Platte River.

Surface water supplies are stored in the Wind River Basin in on-channel reservoirs, off-channel reservoirs, and lakes, such as Bull Lake, Boysen Reservoir, Shoshone Lake, and others. Average water evaporation is high. Ocean Lake was created by ground water seepage from the irrigated areas in the Riverton Irrigation Project withdrawal area.

3.4.4.3 Ground Water Hydrology

Whitcomb and Lowry (1967) stated that ground water occurs under both artesian and water table conditions. Artesian conditions are prevalent in

the Wind River Formation and in older sedimentary rocks. These older formations, except for the massive sandstone and limestone that occur near the base of the sequence, consist largely of nearly impermeable shale and siltstone interbedded with relatively permeable sandstone. Water in an unconfined (water table) condition occurs in the outcrop areas of artesian aquifers, in the Arikaree Formation, and in alluvial and windblown sand deposits. Major aquifers in the basin are listed in Table 3-1.

The physical and water-bearing characteristics of the geologic formations in the project area are summarized in Appendix C. There has been little development of ground water in the older rocks because of their considerable depth below land surface in most of the basin. Conclusions regarding the older rocks are based principally on data from other areas. In Table 3-1 the comparative terms "small", "moderate", and "large", as applied to quantities of water, are given arbitrary gpm values of less than 50, 50 to 300, and more than 300, respectively (Whitcomb and Lowry, 1967).

Additional information on the ground water hydrology of the Wind River Basin is presented in Water-Resources Investigations of Wyoming (USGS, 1977), Appendix C.

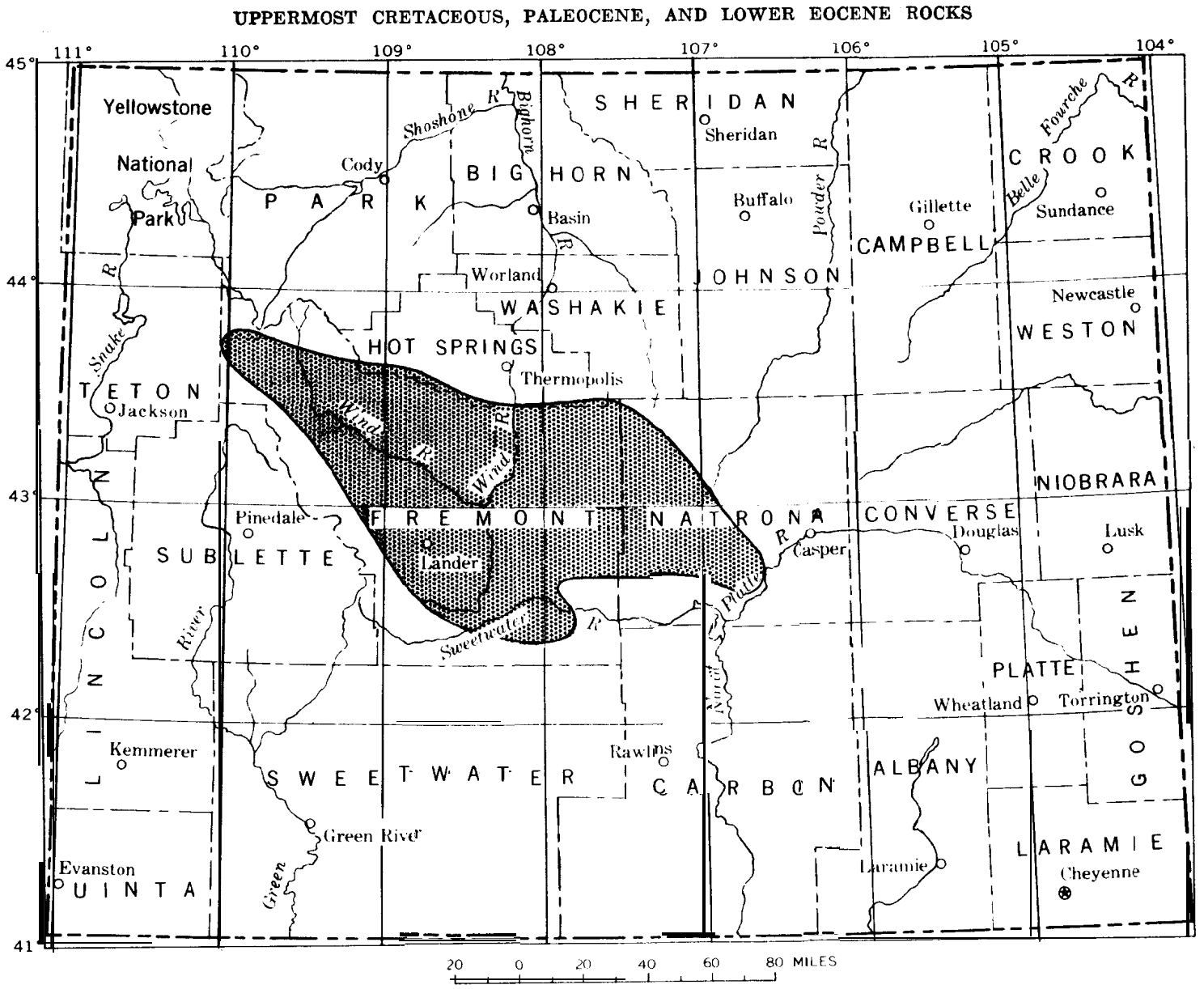


Figure 3-1. Location of the Wind River Structural Basin in Wyoming (Keefer and Van Lieu, 1966)

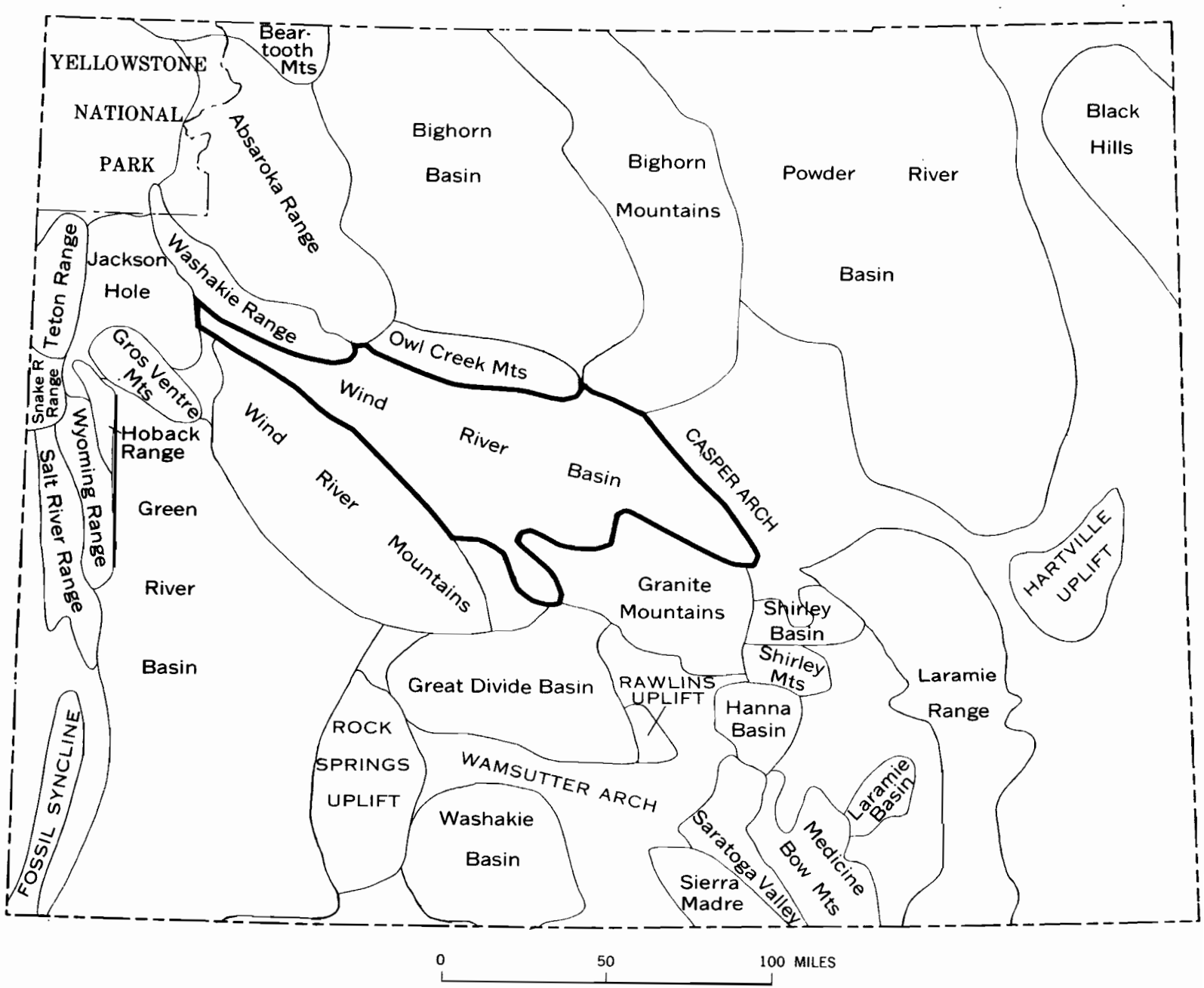


Figure 3-2. Geographical Features and Physiographical Provinces of Wyoming (Love, 1964)

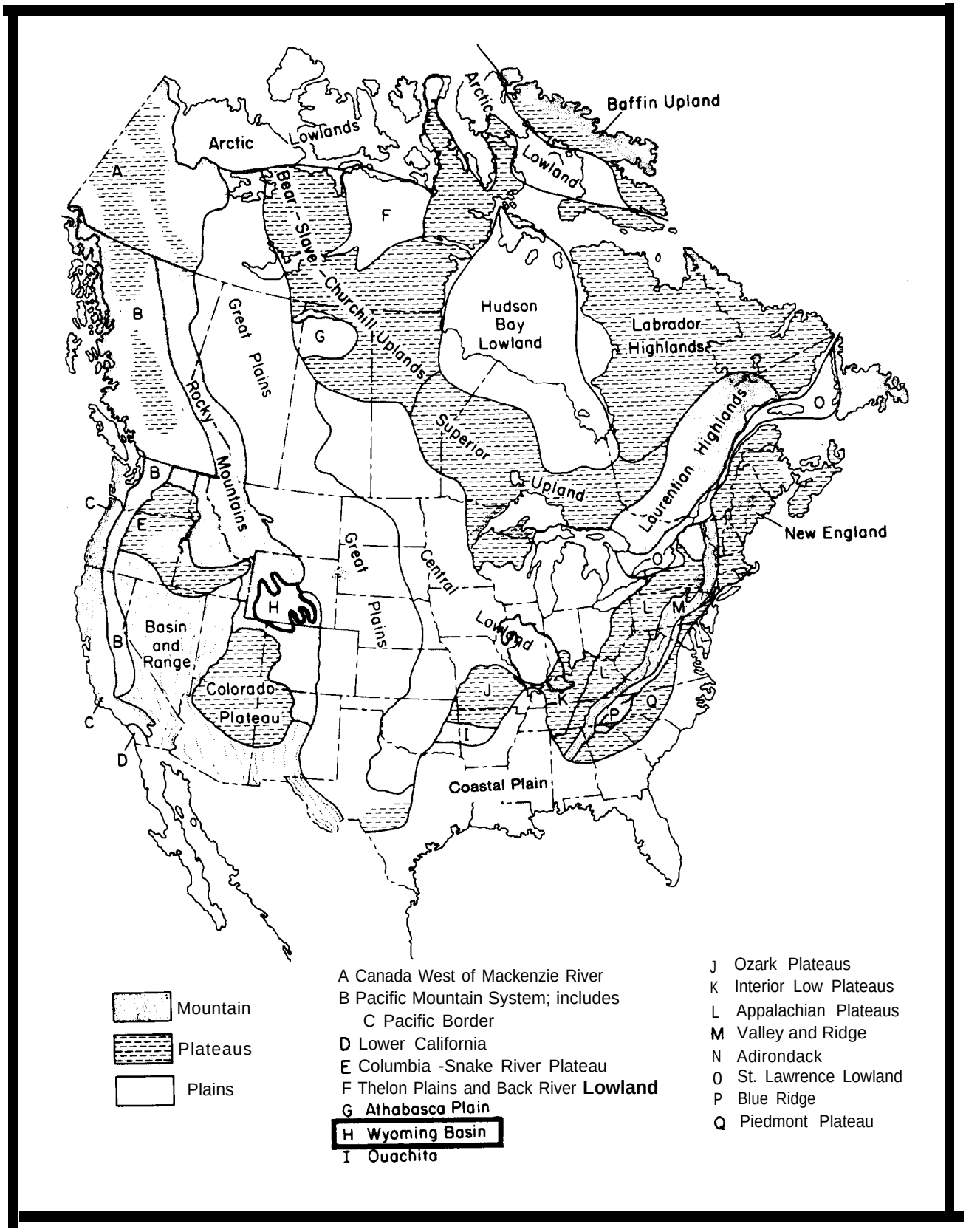


Figure 3-3. Physiographic Regions of the United States and Canada and Their Dominant Landforms (Hunt, 1974) (Courtesy of Freeman and Co.)

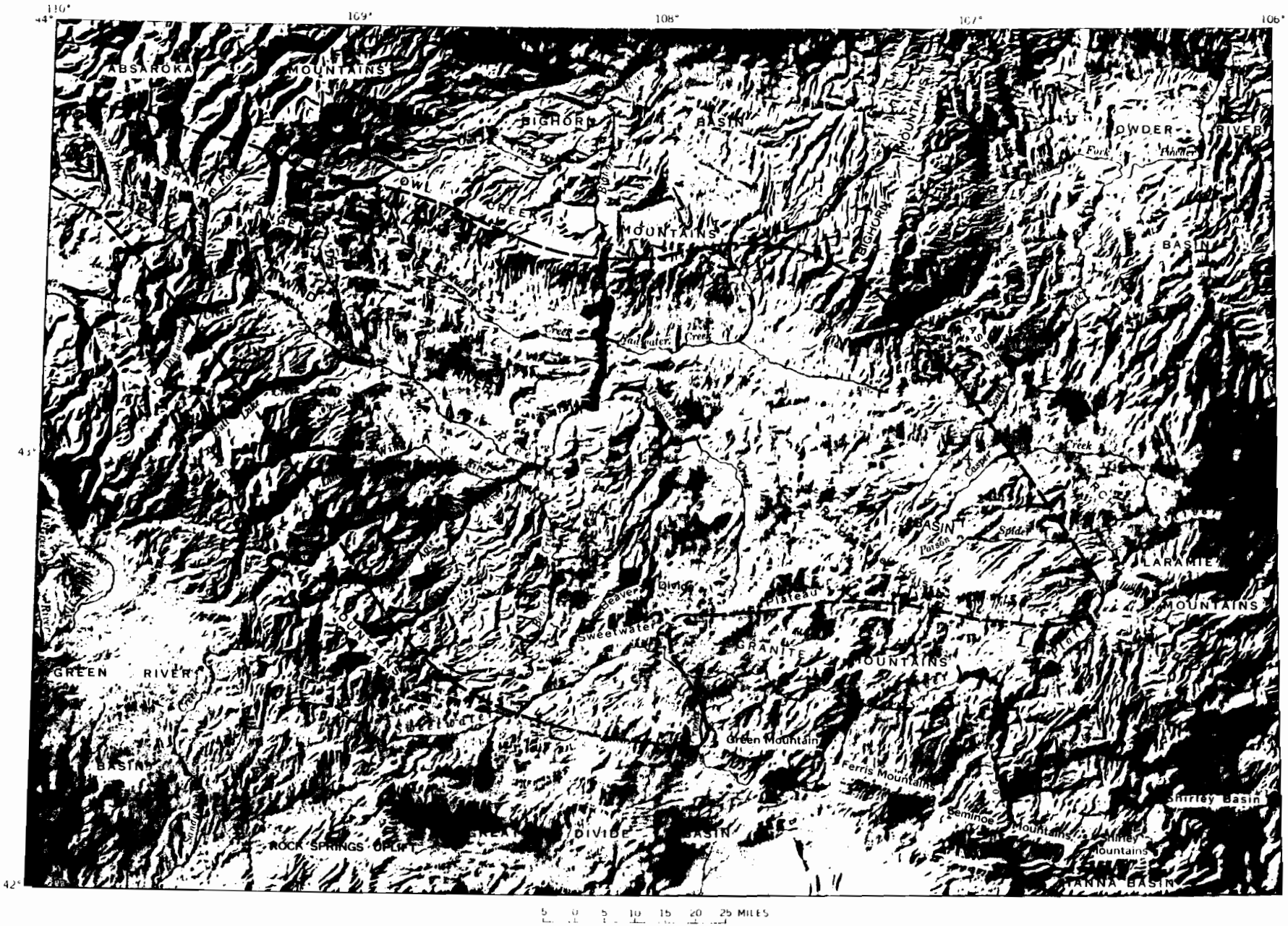


Figure 3-4. Major Physiographic Features in the Wind River Basin, Fremont and Natrona Counties, Wyoming. Dashed line indicates approximate outline of the structural basin (Keefer, 1970)

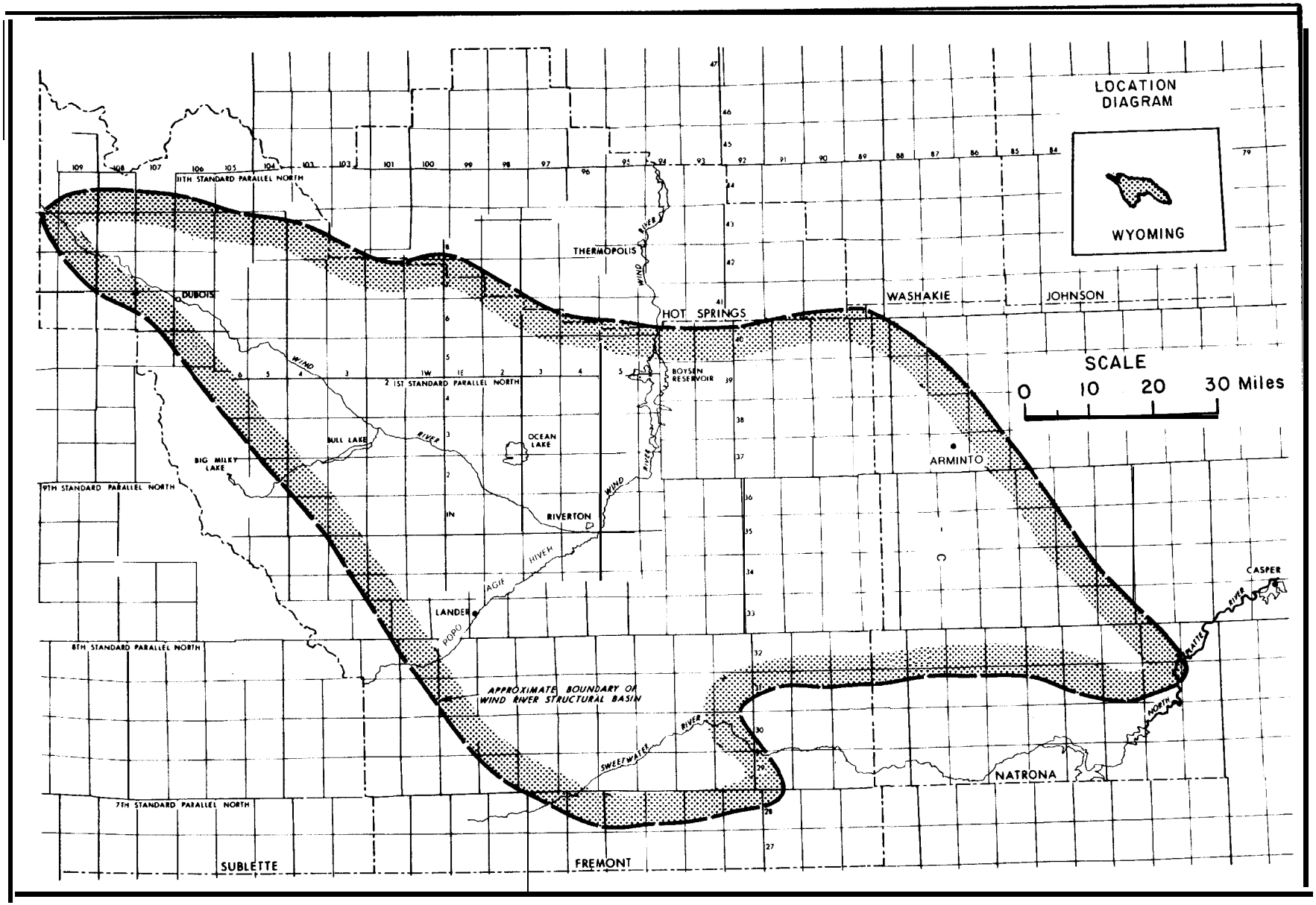


Figure 3-5. Base Map, Wind River Basin, Wyoming (Keefer, 1970)

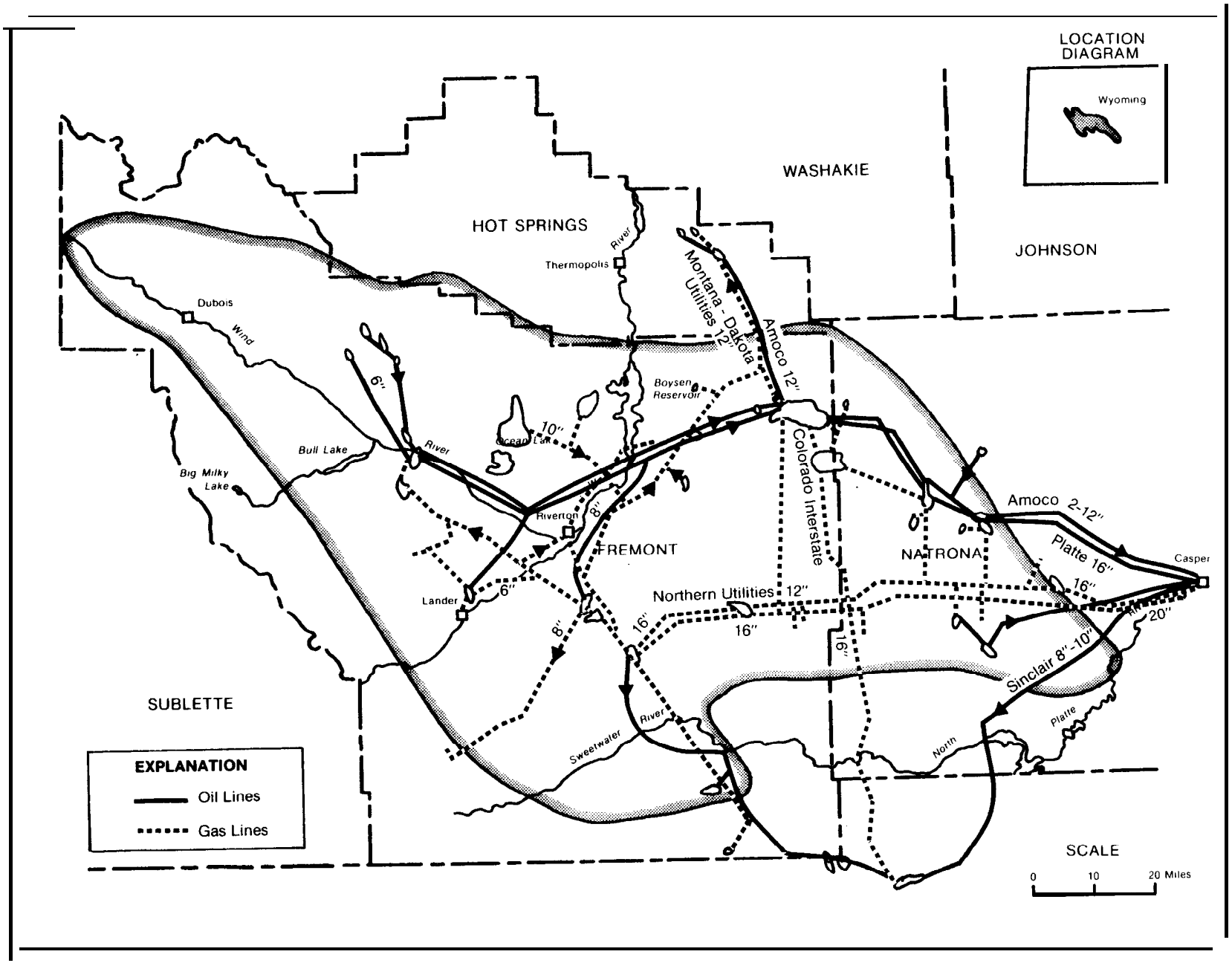


Figure 3-6. **Routes of Major Natural Gas Pipelines in Wyoming (Courtesy of the Penn Well Publ. Co.)**

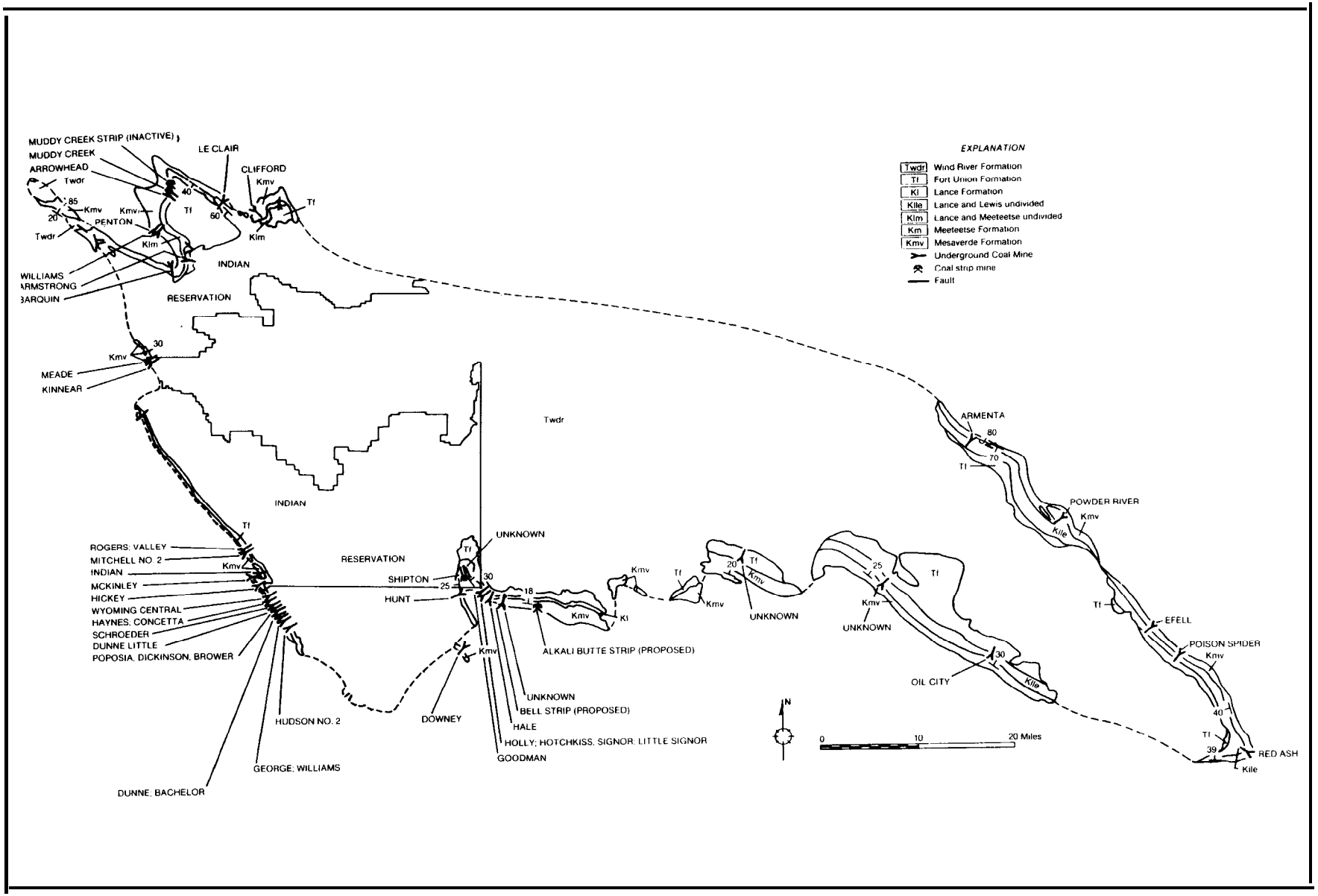


Figure **3-7. Mine Locations and Geologic Map of the Wind River Coal Basin (Glass and Roberts, 1978) (Courtesy of the Wyoming Geological Association)**

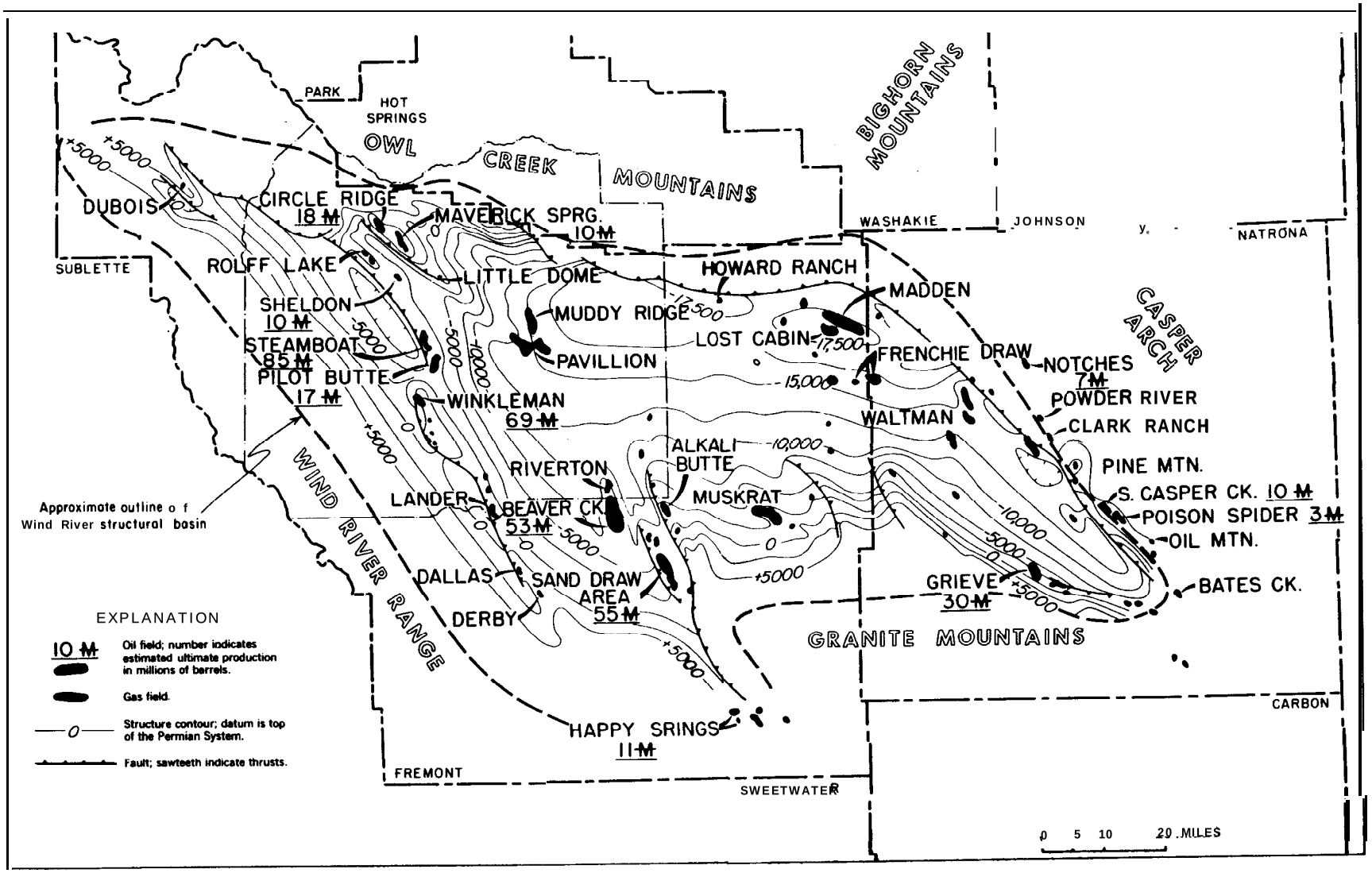


Figure 3-8. Oil and Gas Fields of the Wind River Basin (Brenner, 1974) (Courtesy of the Rocky Mountain Assoc. of Geologists)

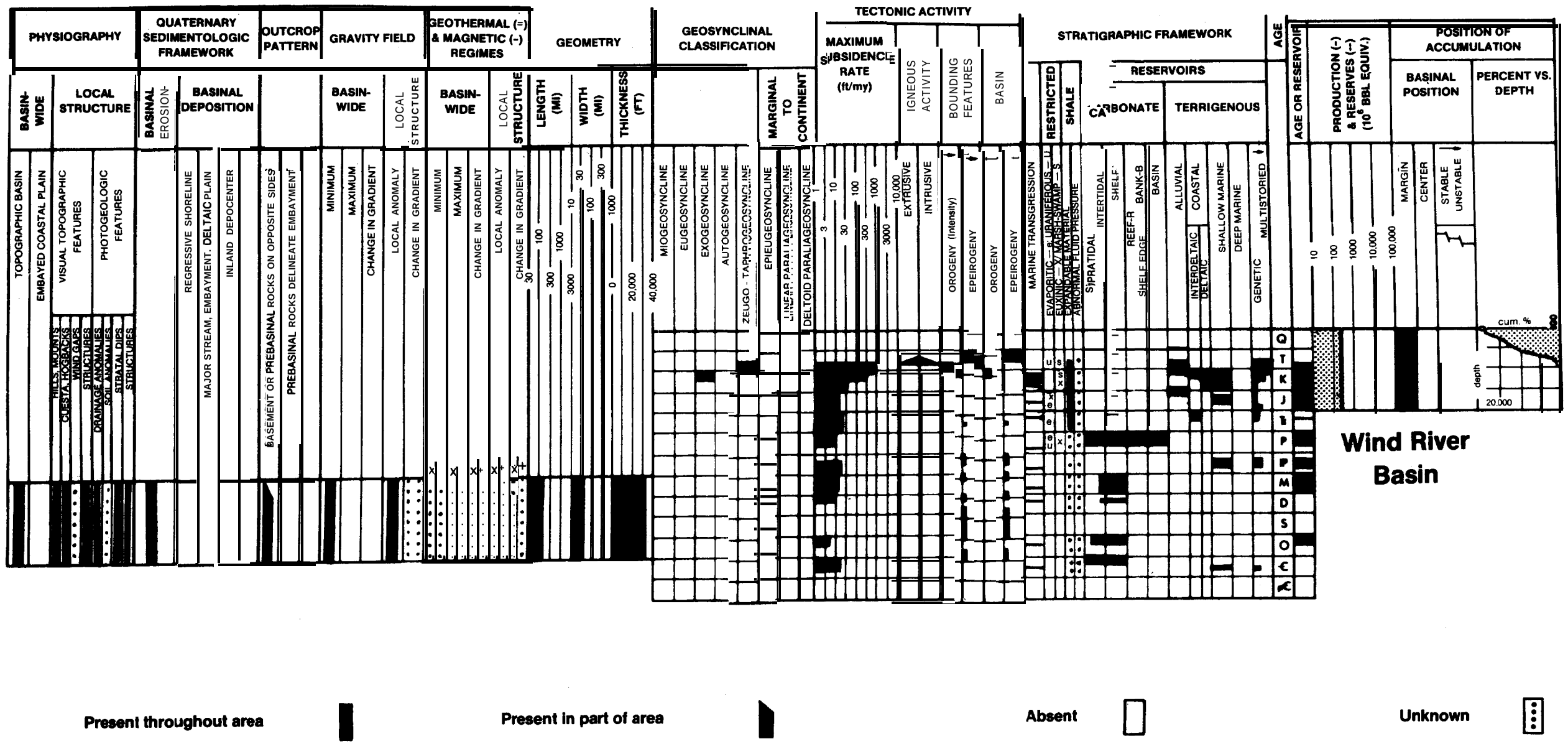


Figure 3-9. Geologic Comparison of the Wind River, Big Horn, and Powder River Basins of Wyoming (Shelton and Ross, 1971) (Courtesy of The Mountain Geologist)

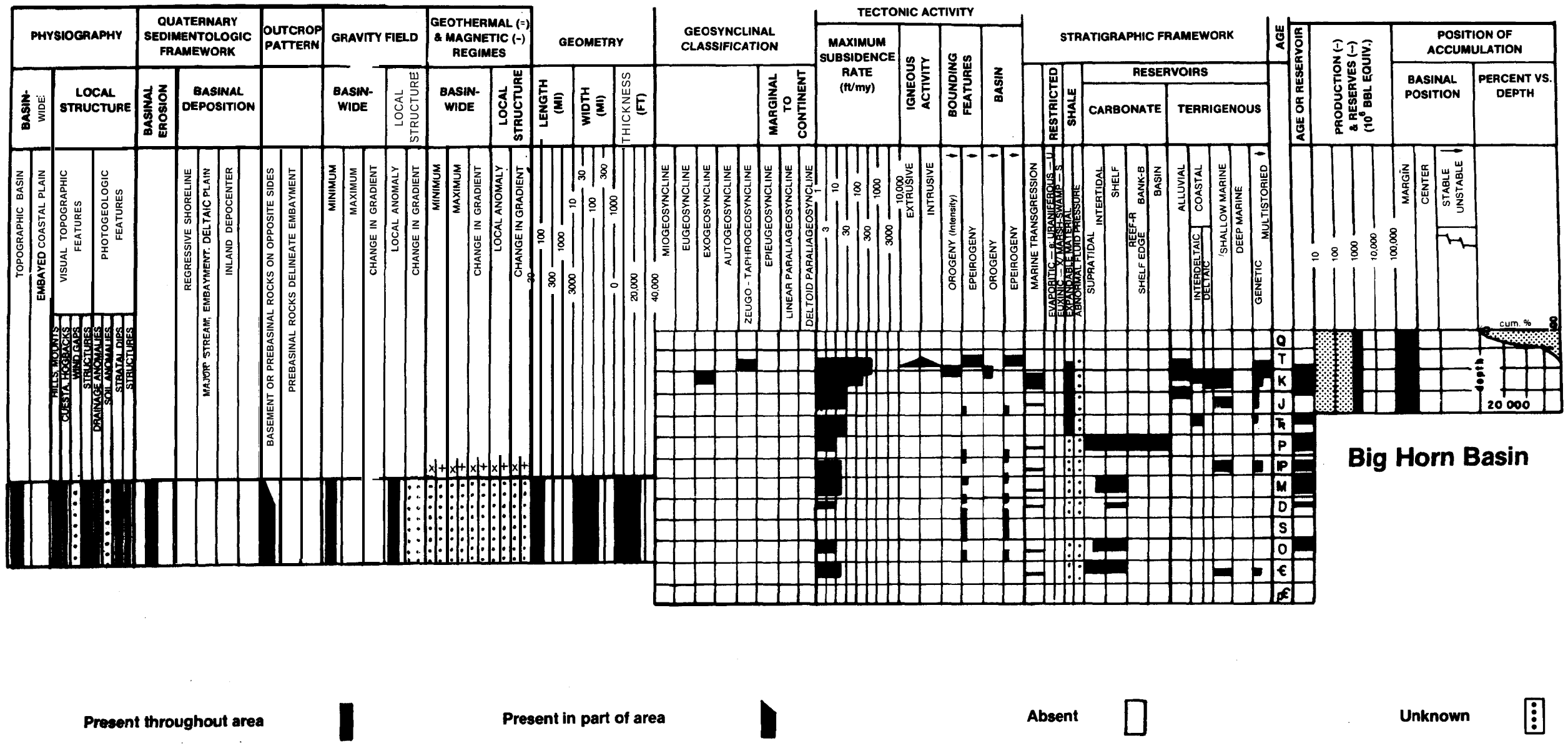


Figure 3-9. Geologic Comparison of the Wind River, Big Horn, and Powder River Basins of Wyoming (Shelton and Ross, 1971) (Courtesy of The Mountain Geologist) (Continued)

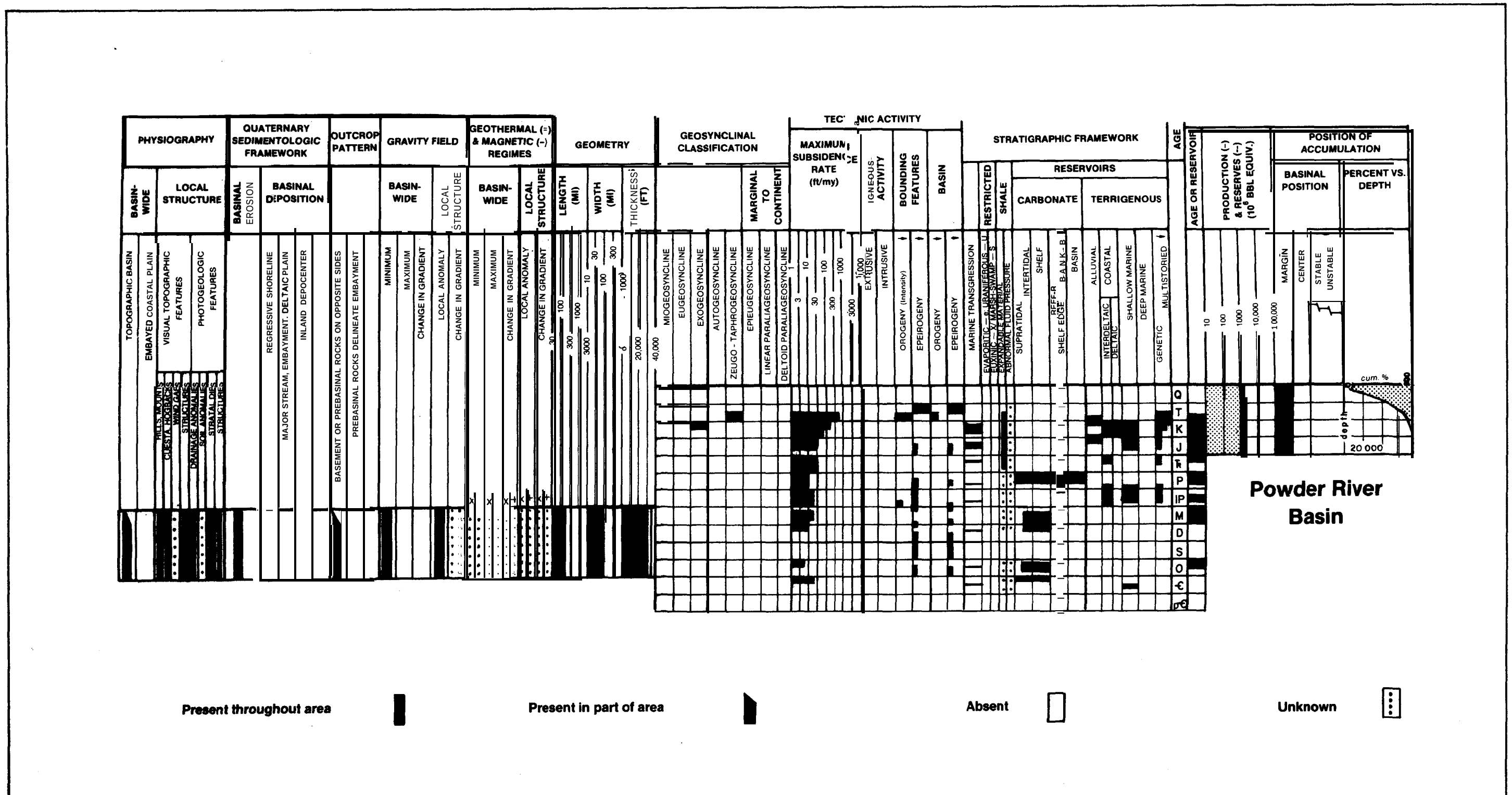


Figure 3-9. Geologic Comparison of the Wind River, Big Horn, and Powder River Basins of Wyoming (Shelton and Ross, 1971) (Courtesy of The Mountain Geologist) (Continued)

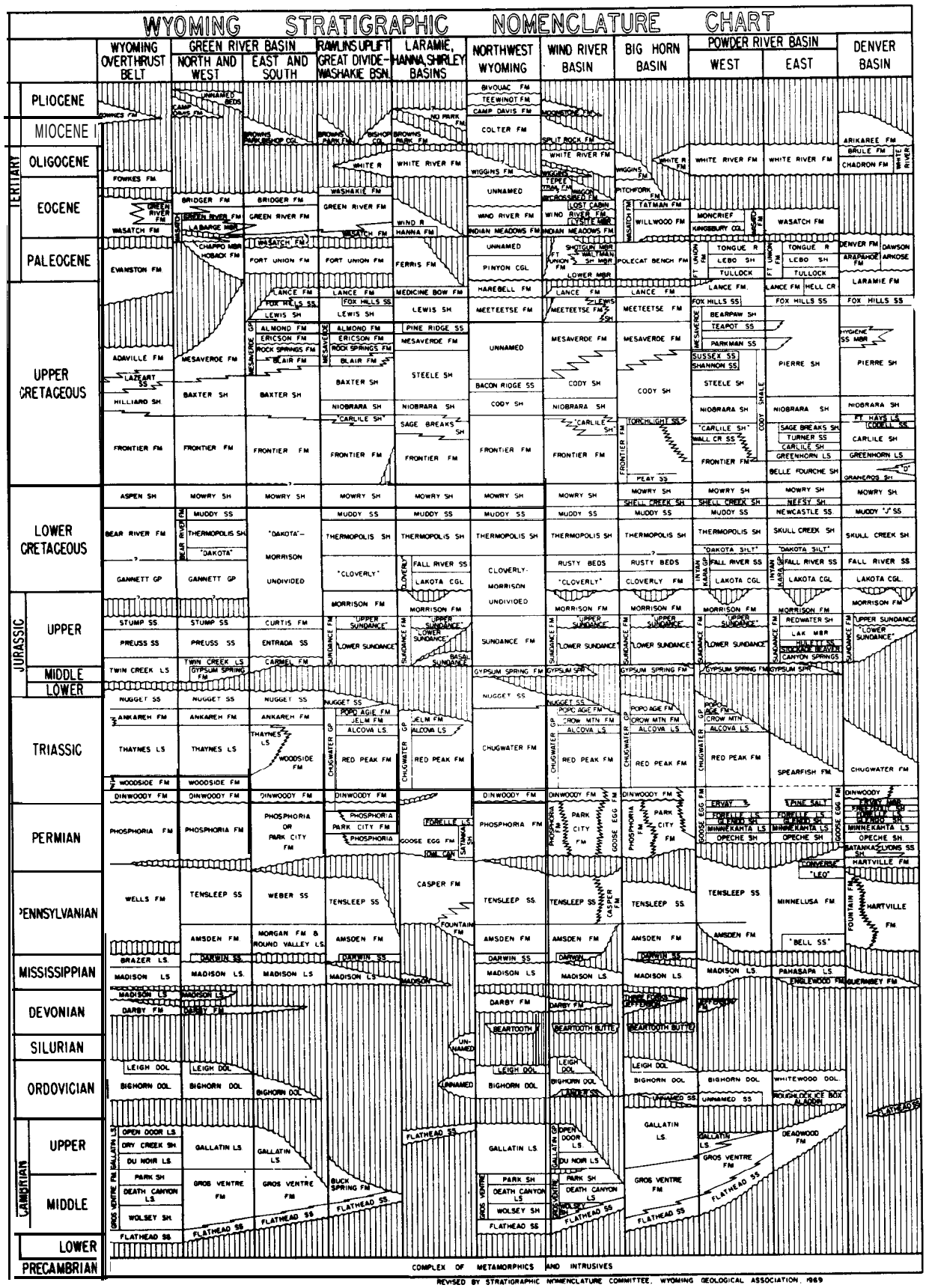


Figure **3-10.** Stratigraphic Correlations for Wyoming and the Denver Basin (Courtesy of the Wyoming Geological Association)

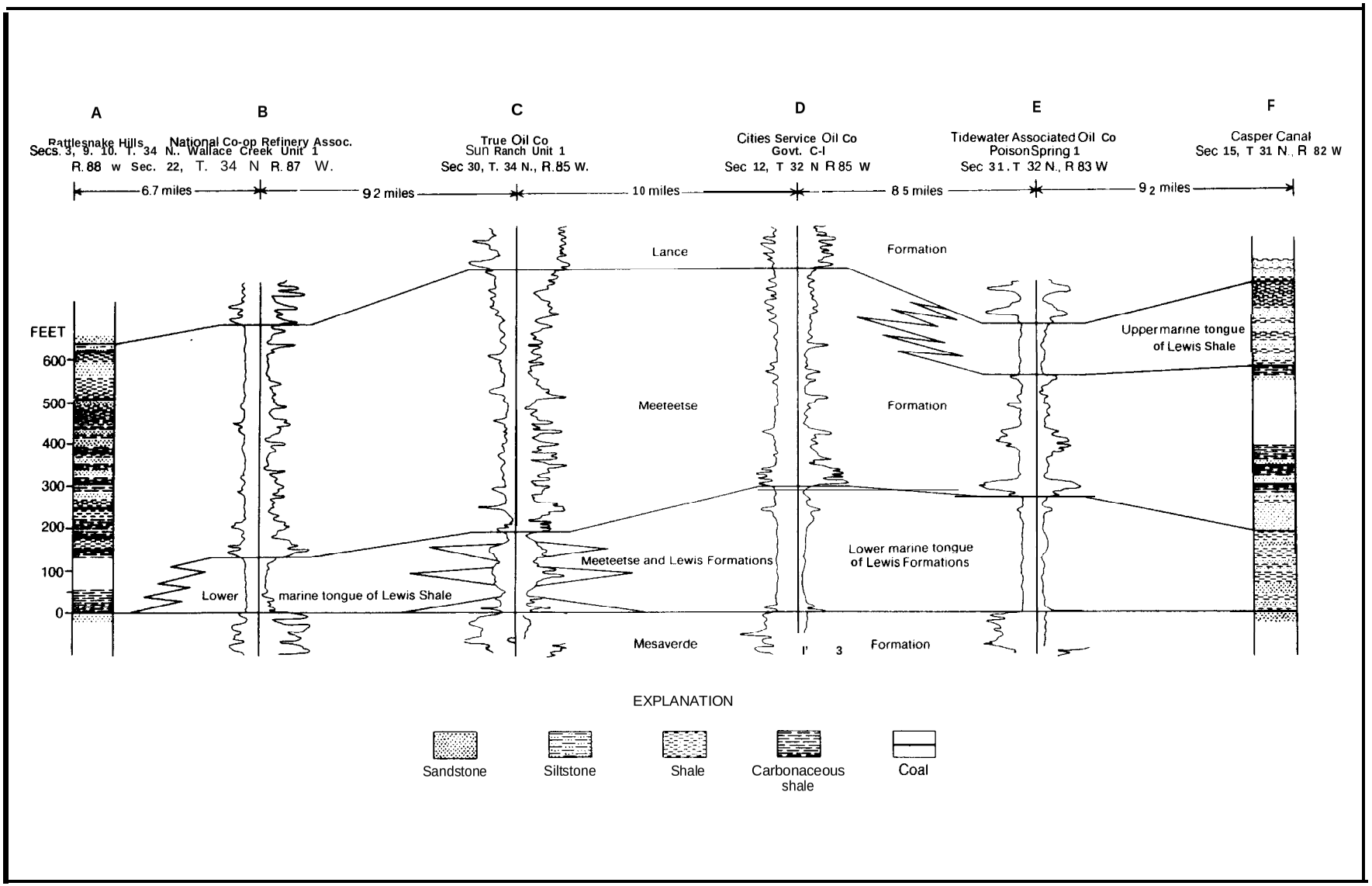


Figure 3-11. Facies Changes and Continuity of Coalbeds in the Meeteetse Formation (Upper Cretaceous) in the Southeastern Part of the Wind River Basin (see Figure 3-5). For each well, resistivity log on right, self-potential log on left.

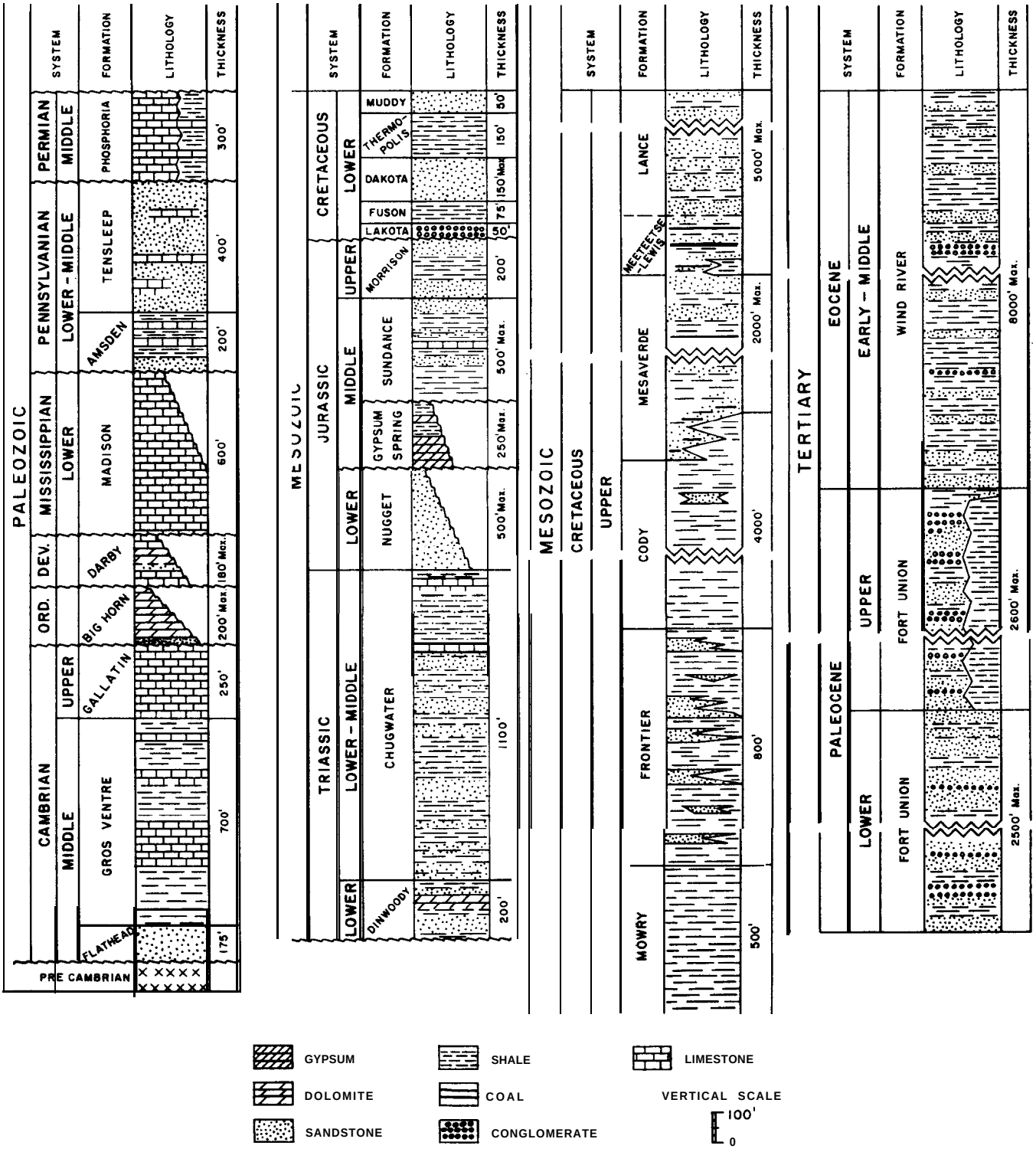


Figure 3-12. A Composite Columnar Stratigraphic Section Providing Total Maximum Thickness of Sediments in the Wind River Basin (Paape, 1968) (Courtesy of the American Association of Petroleum Geologists)

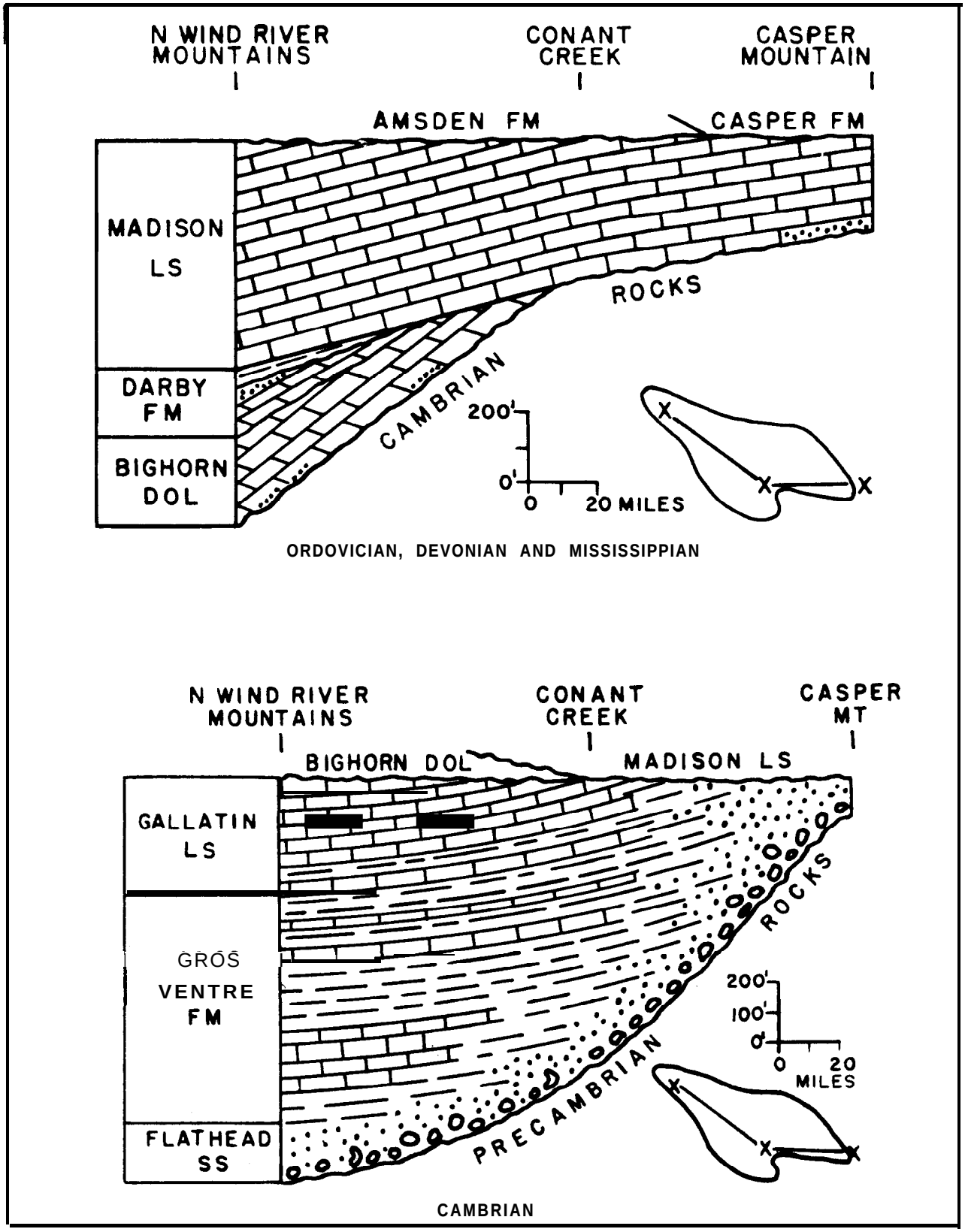


Figure 3-13. Stratigraphic Diagrams and Thickness of Cambrian Rocks, and Ordovician, Devonian, and Mississippian Rocks in the Wind River Basin (Keefer, 1965) (Courtesy of the American Association of Petroleum Geologists)

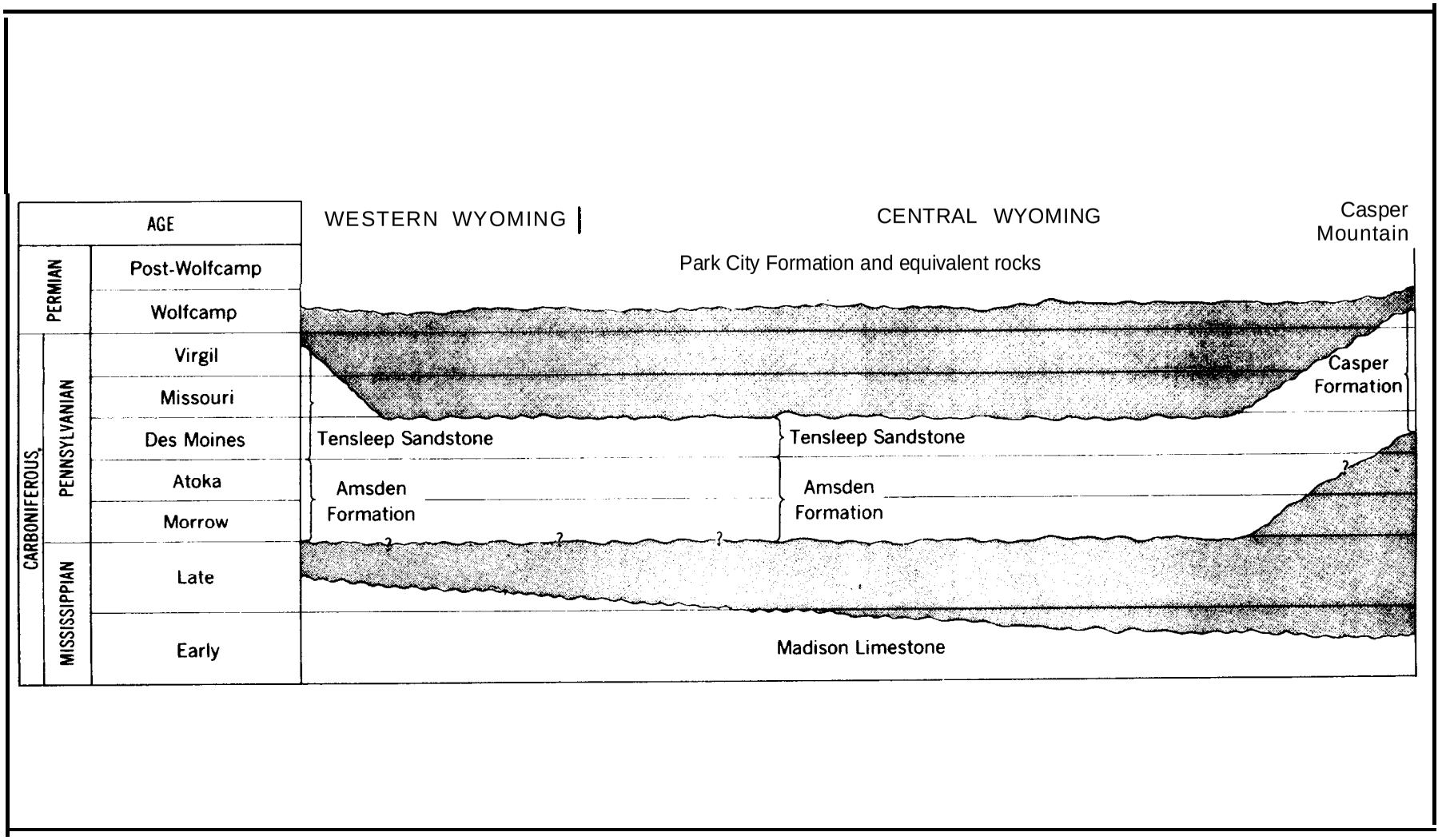


Figure 3-14. Schematic Diagram Showing Approximate Time Intervals of Permian and Carboniferous Formations (Keefer and Van Lieu, 1966)

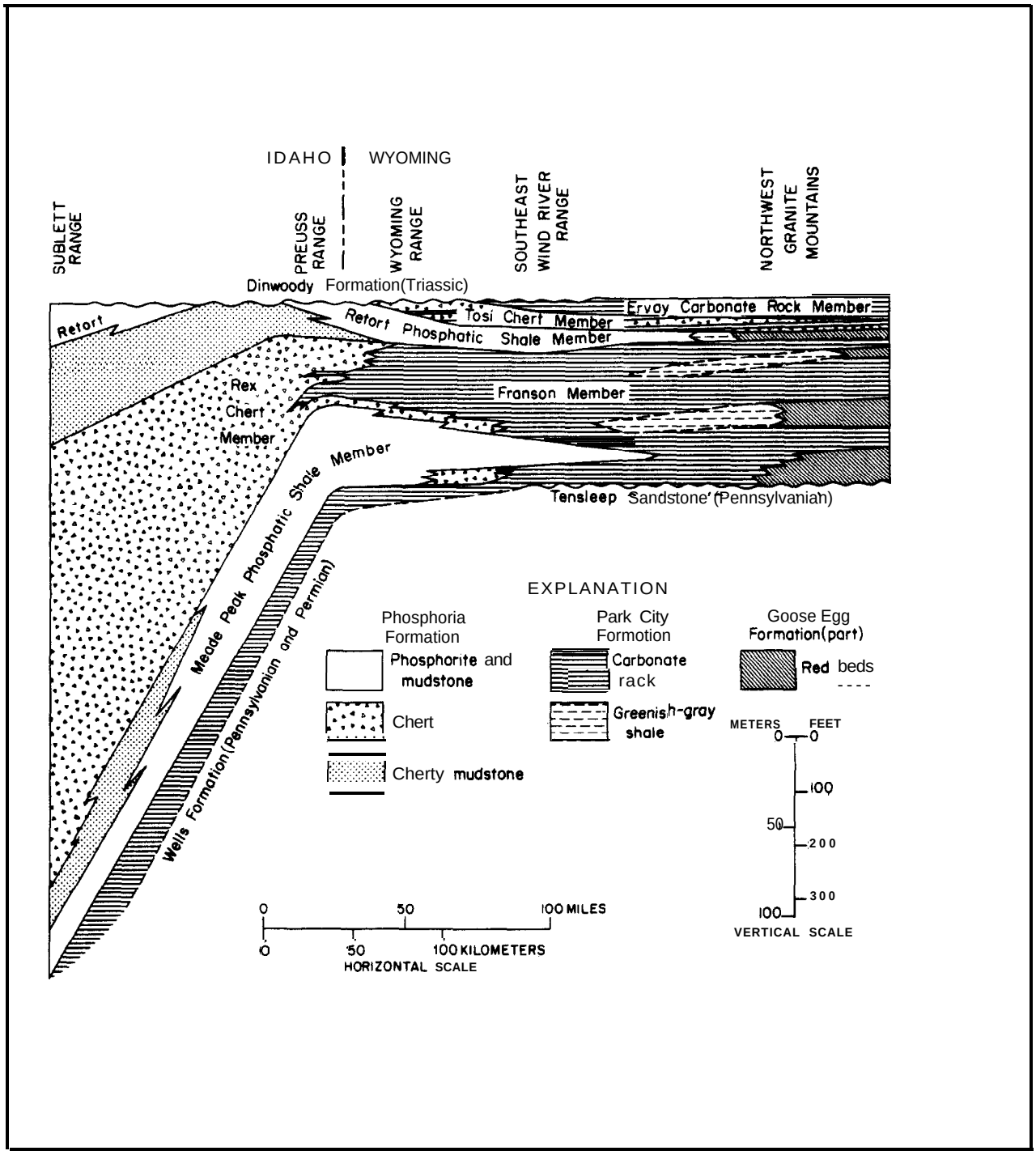


Figure 3-15. Cross Section Showing Stratigraphic Relations of Permian Rocks in Wyoming and Idaho (Claypool, et al., 1978) (Courtesy of the American Association of Petroleum Geologists)

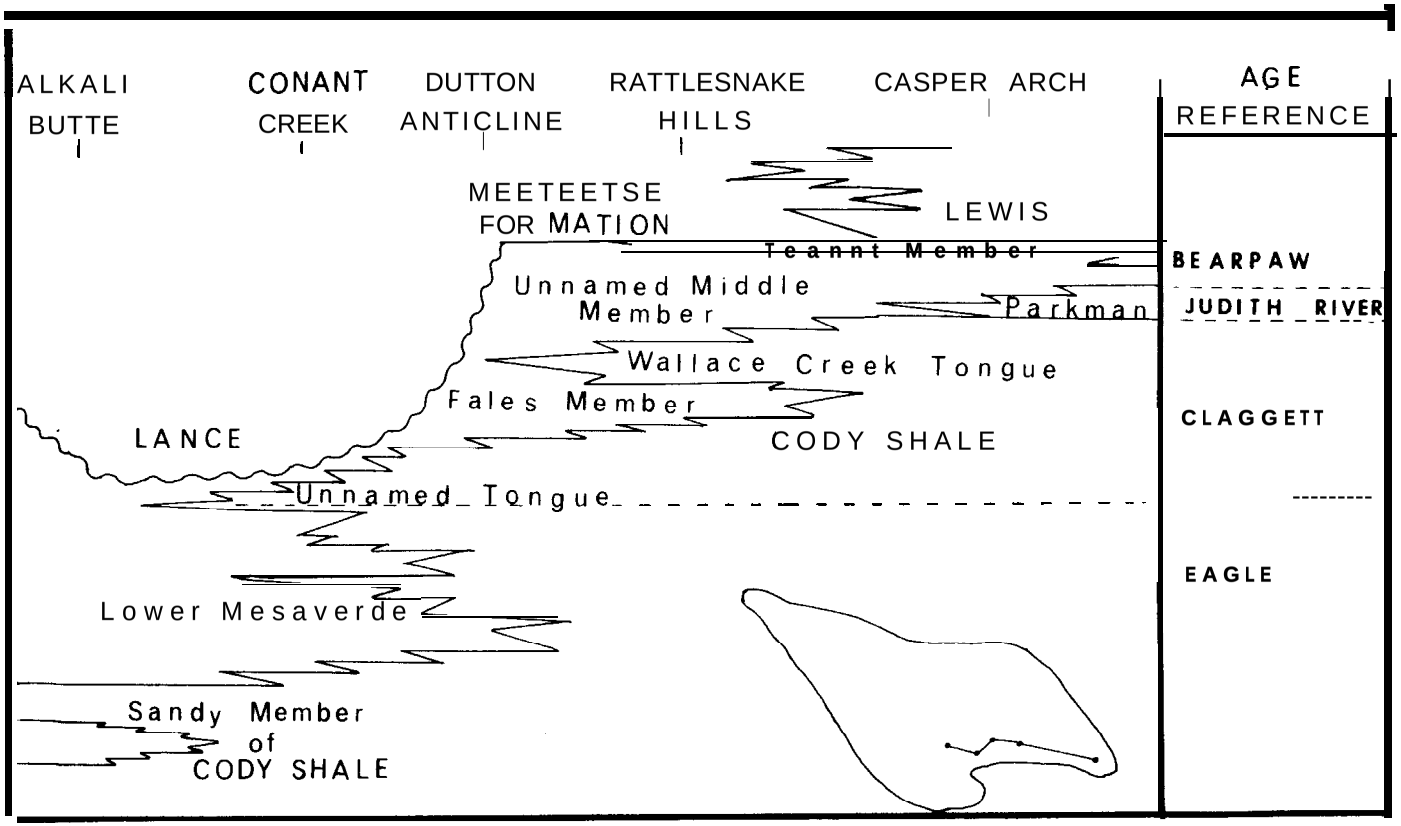


Figure 3-16. Diagrammatic Cross Section Showing Age and Intertonguing of Mesaverde Formation and Cody Shale, Southern Flank of the Wind River Basin (Shapurji, 1978)

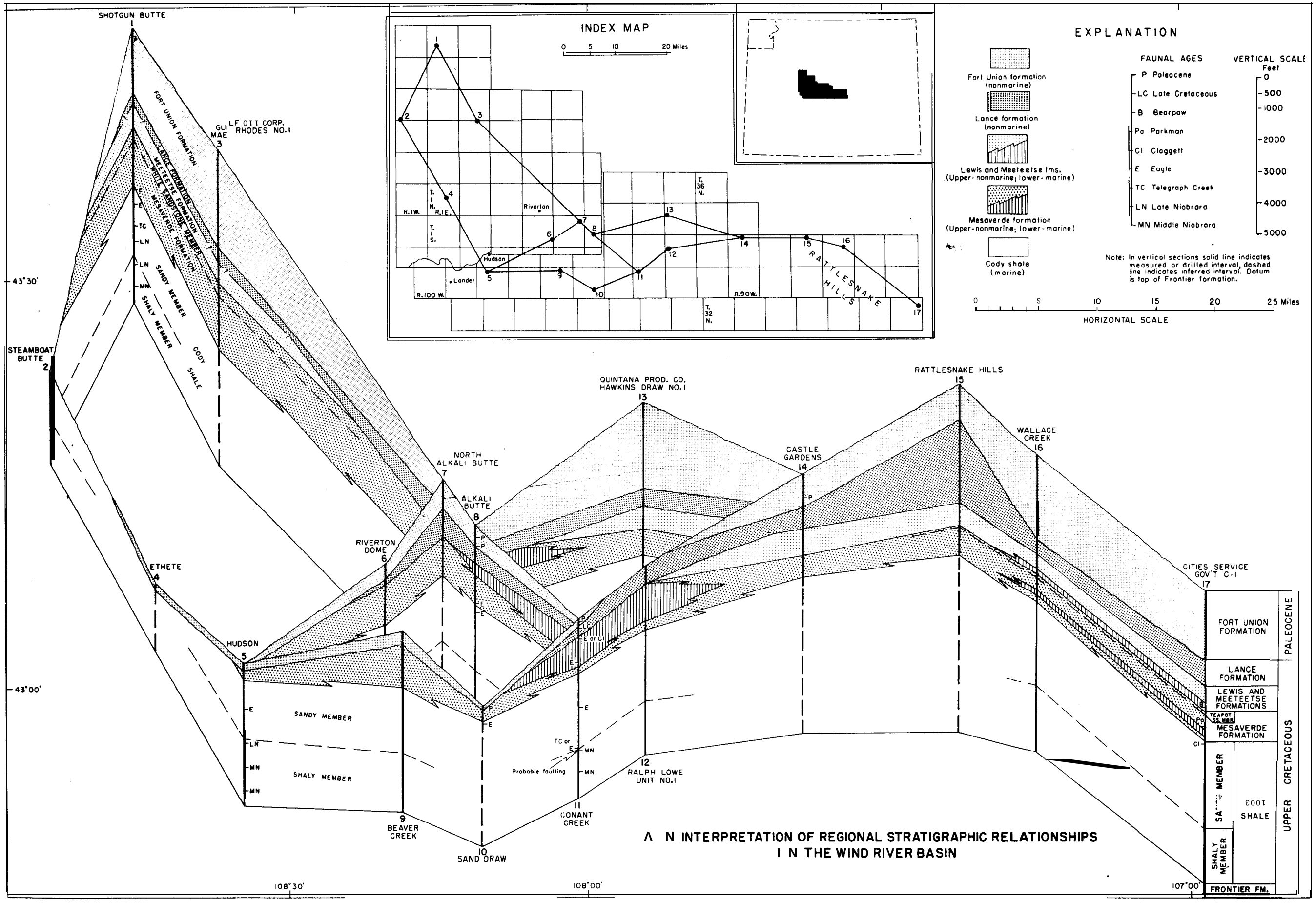


Figure 3-17. Regional Stratigraphy of the Upper Cretaceous and Paleocene Formations in the Wind River Basin (Keefer and Rich, 1957)

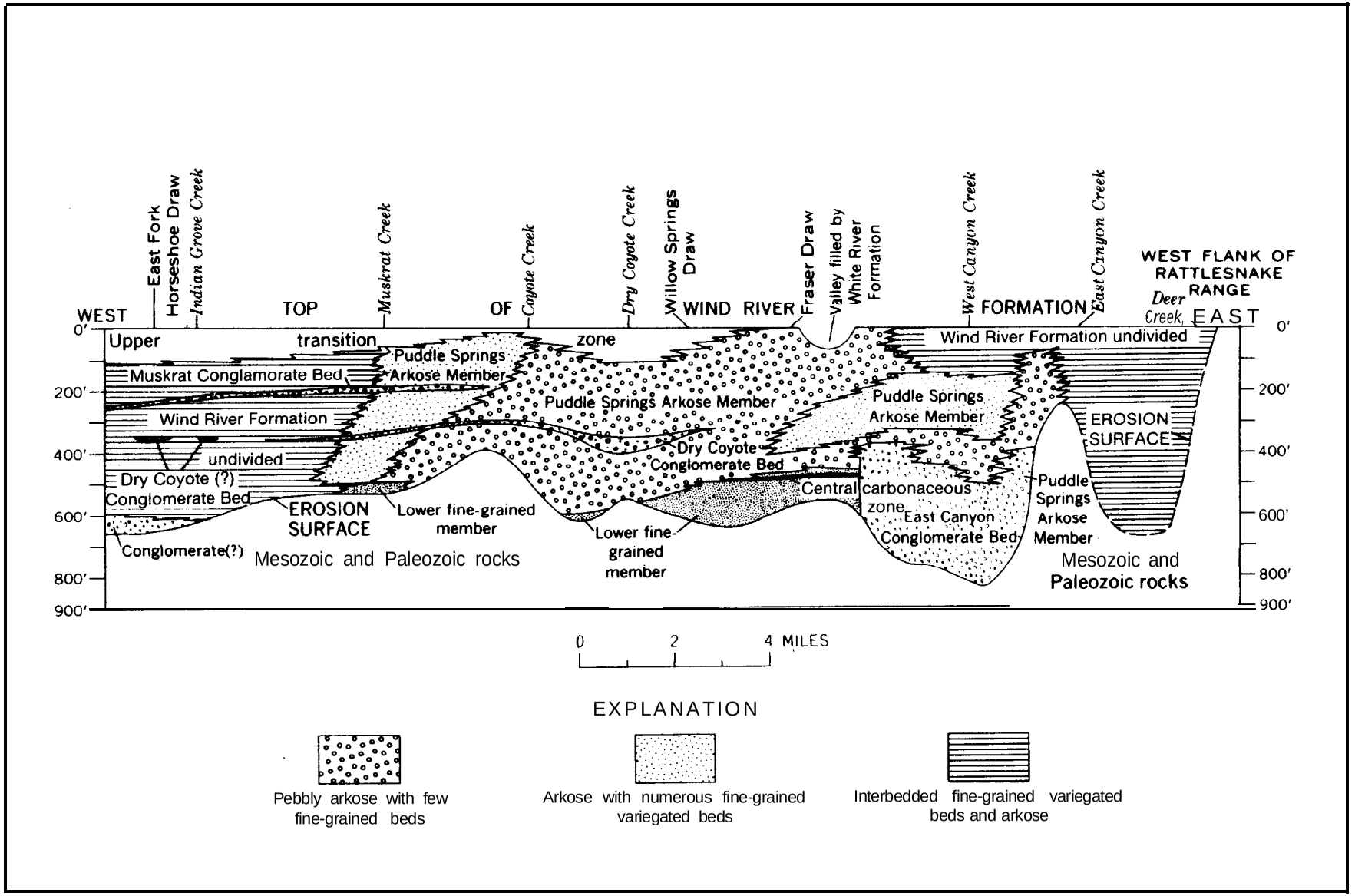


Figure 3-18. Diagrammatic Stratigraphic Section of the Wind River Formation Near the South-Central Edge of the Wind River Basin, Illustrating Lithologic Units and Facies Changes (Soister, 1968)

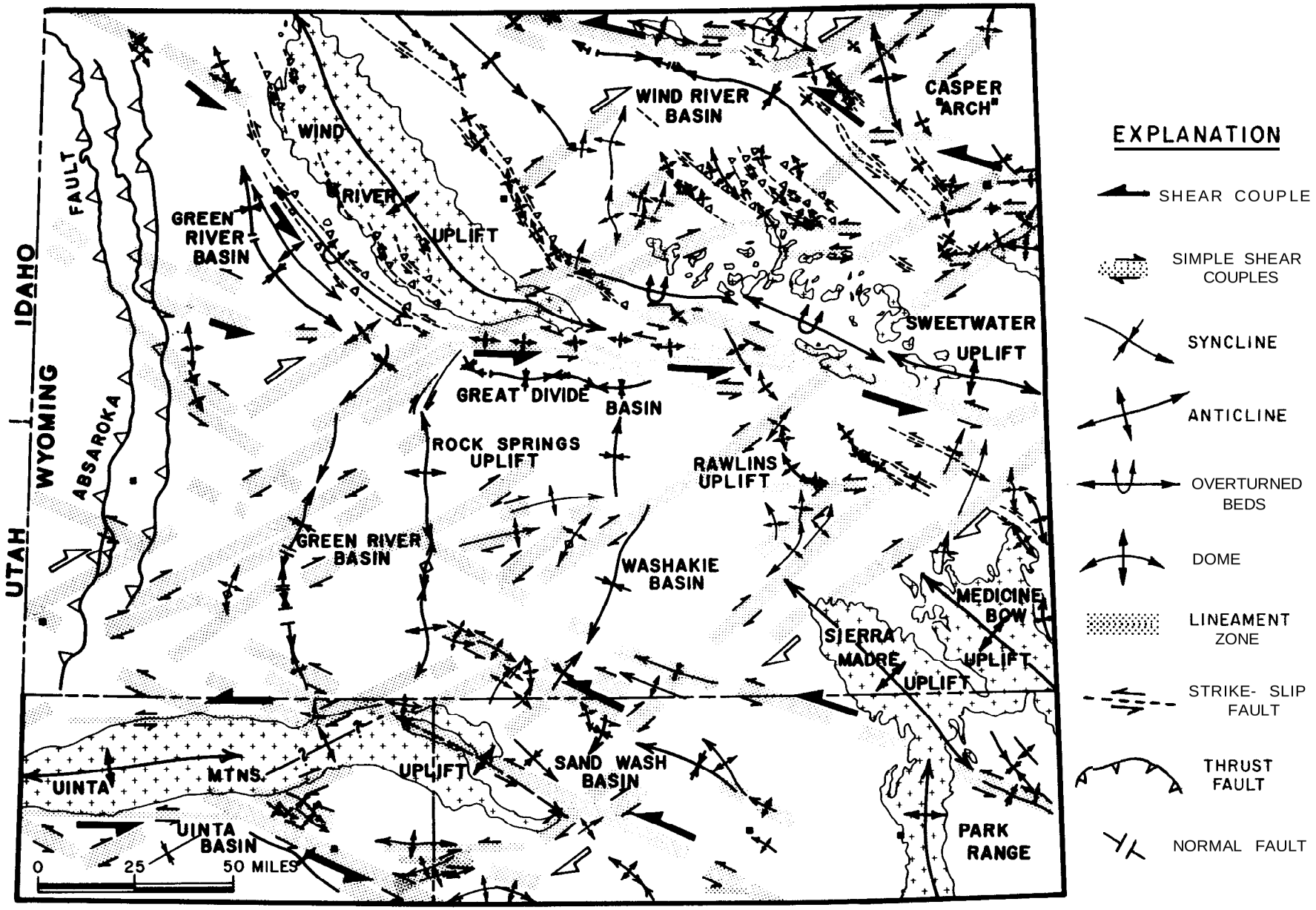
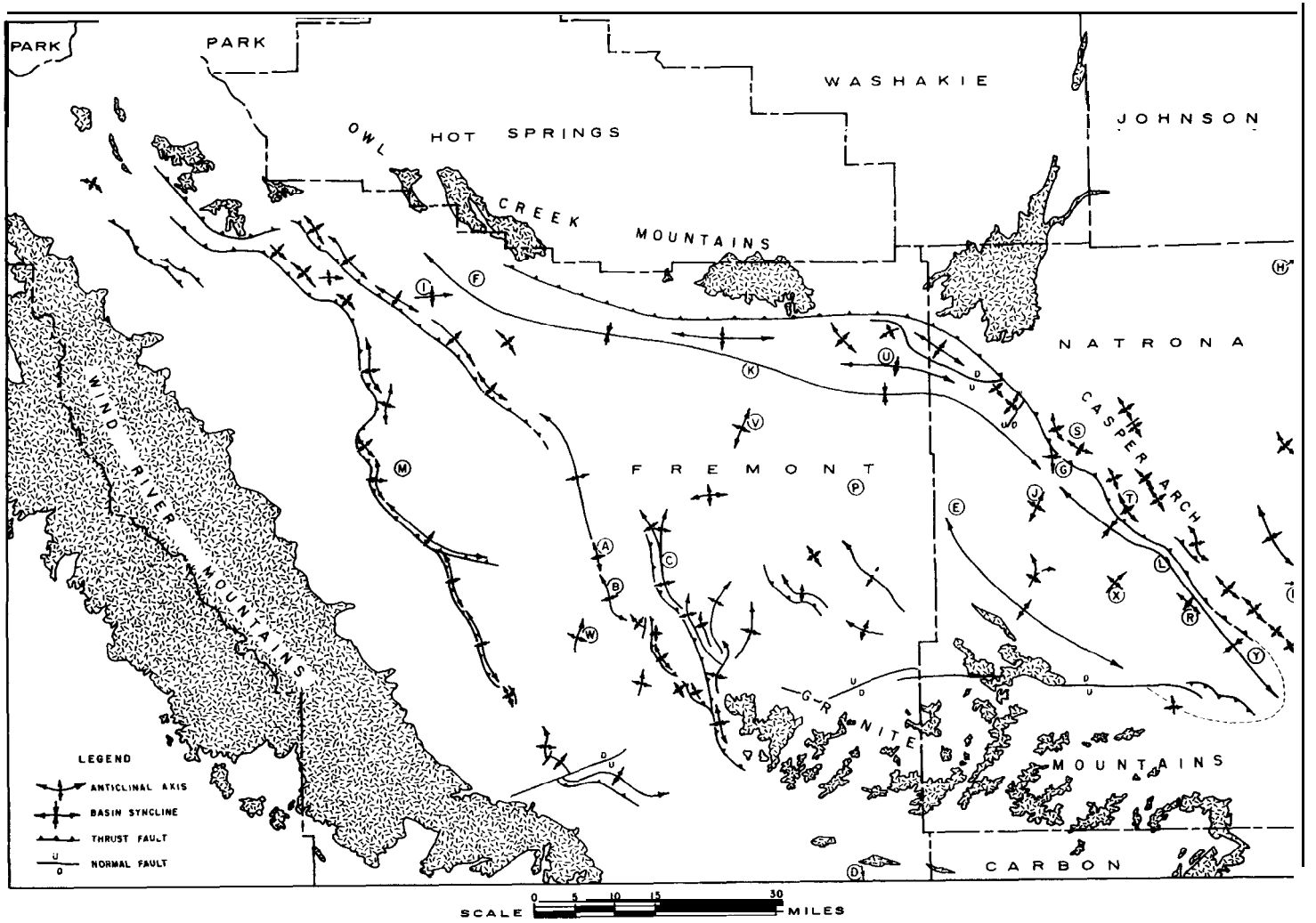


Figure 3-19. Regional Structure and Simple Shear Zones for Southwest Wyoming and Northern Colorado (Thomas, 1971) (Courtesy of the Wyoming Geological Association)



A. River-ton Dome
B. Beaver Creek anticline
C. Alkali Butte anticline
D. Southeast Wind River Mountain — Lost Soldier area
E. Raderville area
F. Shotgun Butte area
G. Waltman area
H. Sussex-Meadow Creek area
I. Little Dome anticline
J. Cooper Reservoir anticline
K. Northern major basin syncline
L. Southeastern minor basin syncline
M. Steamboat Butte-Sage Creek trend
N. Glenrock area
P. Squaw Butte unit area
R. West Poison Spider anticline
S. Lox-Arminto anticlines
T. Boone Dome
U. Lost Cabin anticline
V. Poison Creek anticline
W. Nine Mile anticline
X. Sun Ranch anticline
Y. Poison Spring Creek area

Figure 3-20. Major Structural Features of the Wind River Basin (Paape, 1968) (Courtesy of the American Association of Petroleum Geologists)

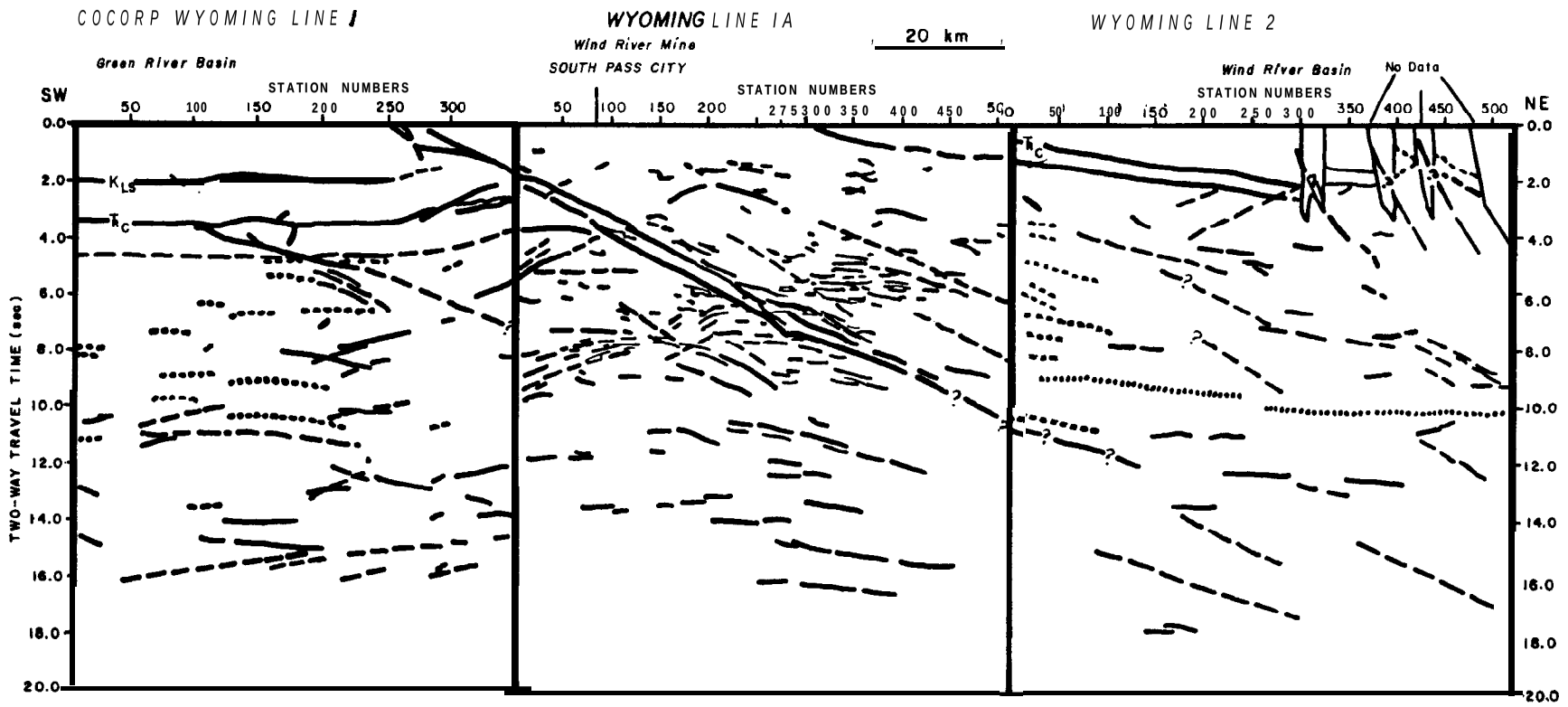


Figure **3-21.** COCORP Seismic Data in Southwestern Wyoming. Profile Runs Transversely Across the Wind River Basin, Wind River Mountains into the Eastern Part of the Green River Basin (Schilt, et al., 1979). Deep Reflections Beneath the Wind River Basin may correspond to the Moho (11.0 and 15.0 sec.)

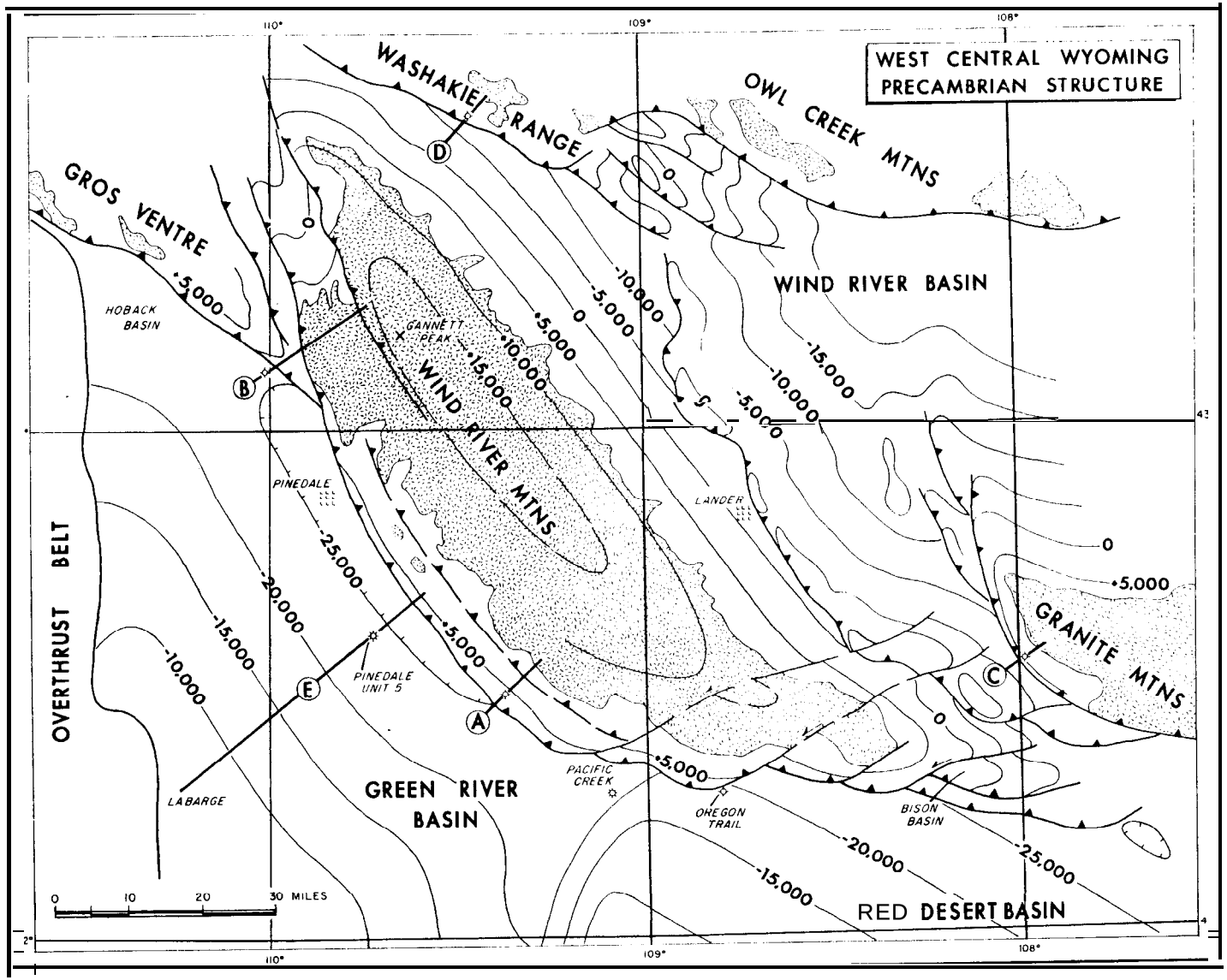


Figure 3-22. Generalized Precambrian Structure of West Central Wyoming Showing Location of Cross Sections: A-Big Sandy Area, B-New Fork Area, C-Immigrant Train Area, D-Dubois Area, and E-Stratigraphic Section (Berg, 1961) (Courtesy of the Wyoming Geological Association)

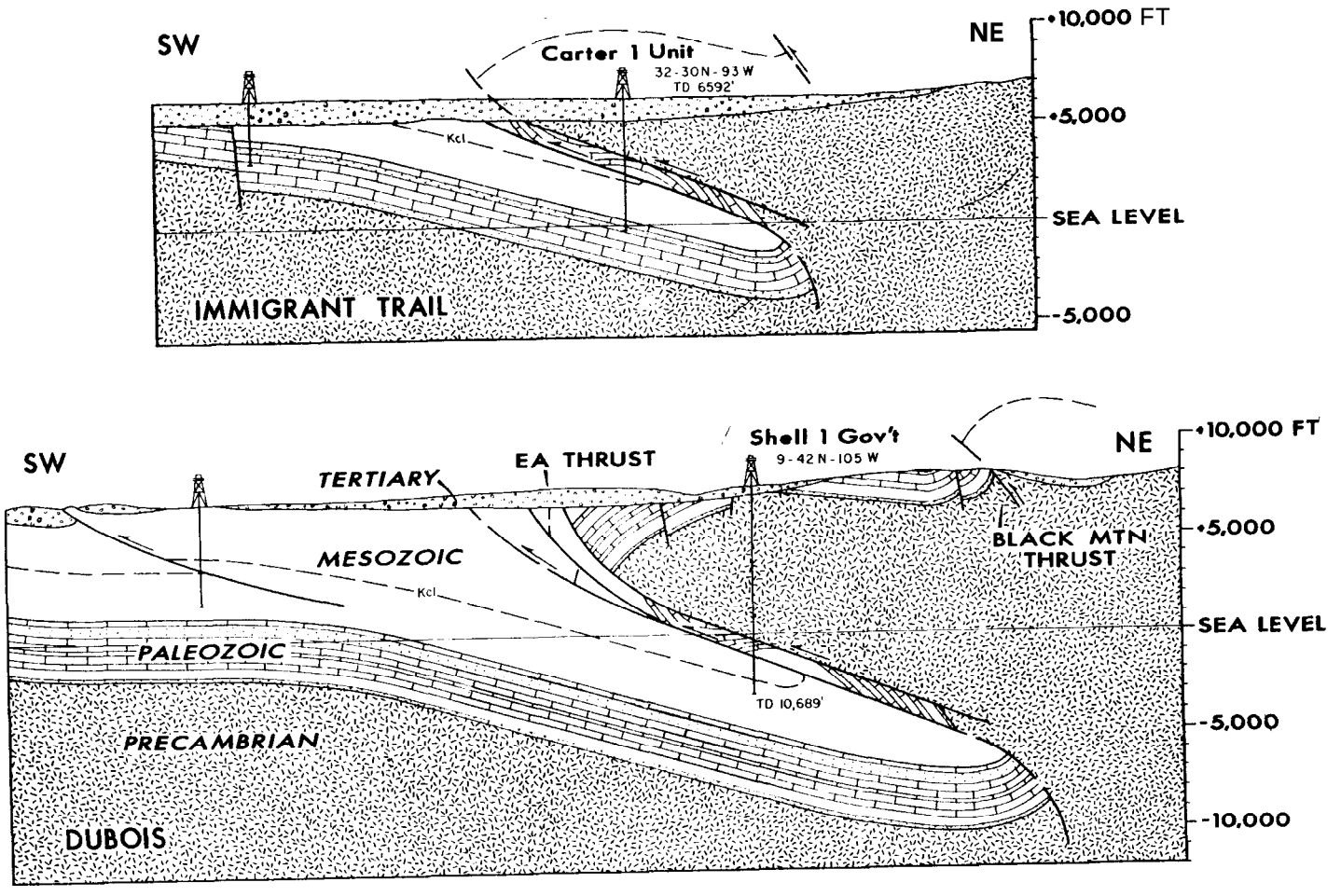


Figure 3-23. Structure Sections of Immigrant Trail and Dubois Areas. Surface Geology in Dubois Section, from Love (1939). "Kcl" horizon is Lower Cretaceous Cloverly Sandstone. (Berg, 1961) (Courtesy of the Wyoming Geological Association)

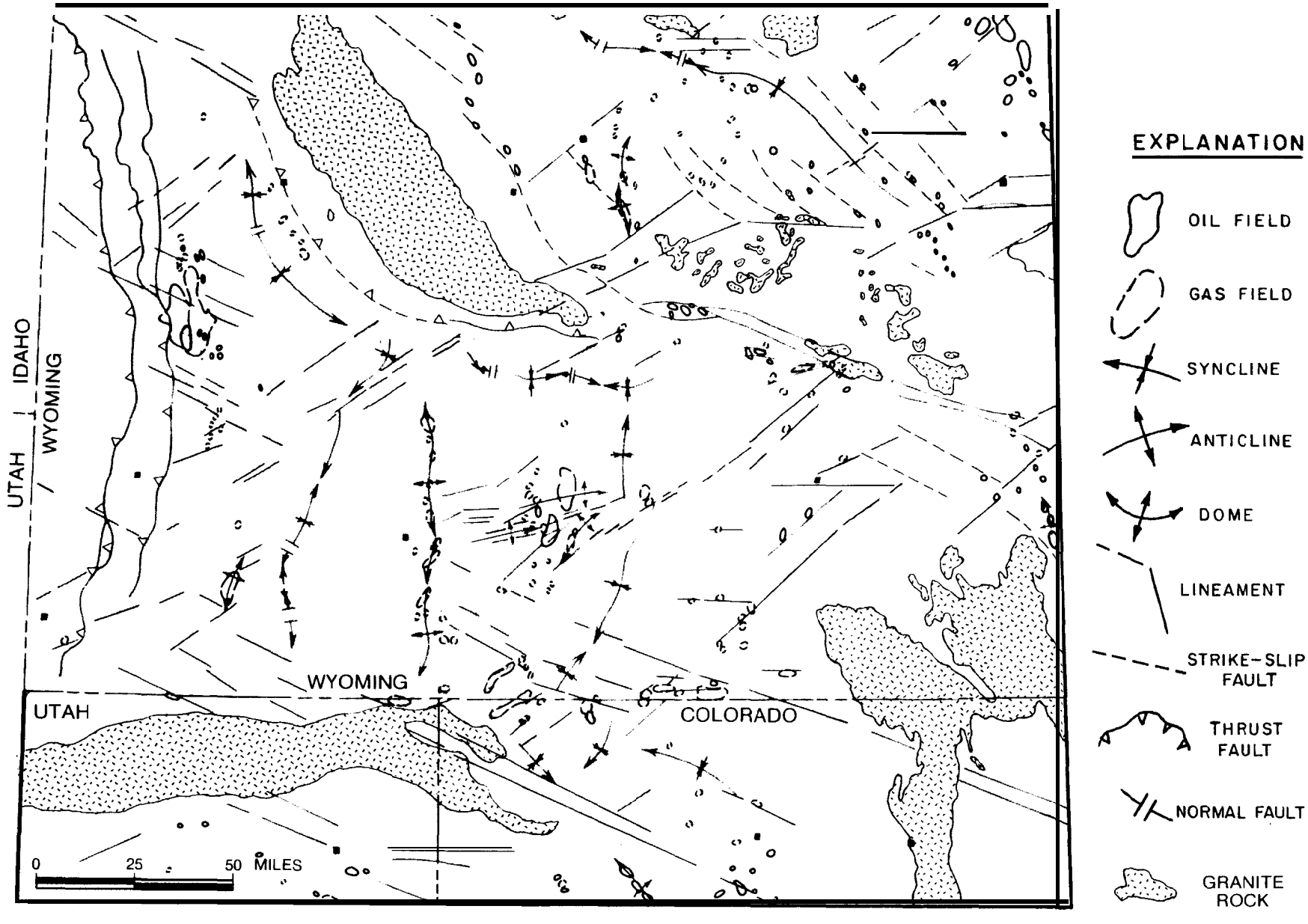


Figure 3-24. A Comparison Between Lineaments (Basement Weakness Zones) and Oil and Gas Production in Southwestern Wyoming and Northern Colorado (Thomas, 1971) (Courtesy of the Wyoming Geological Association)

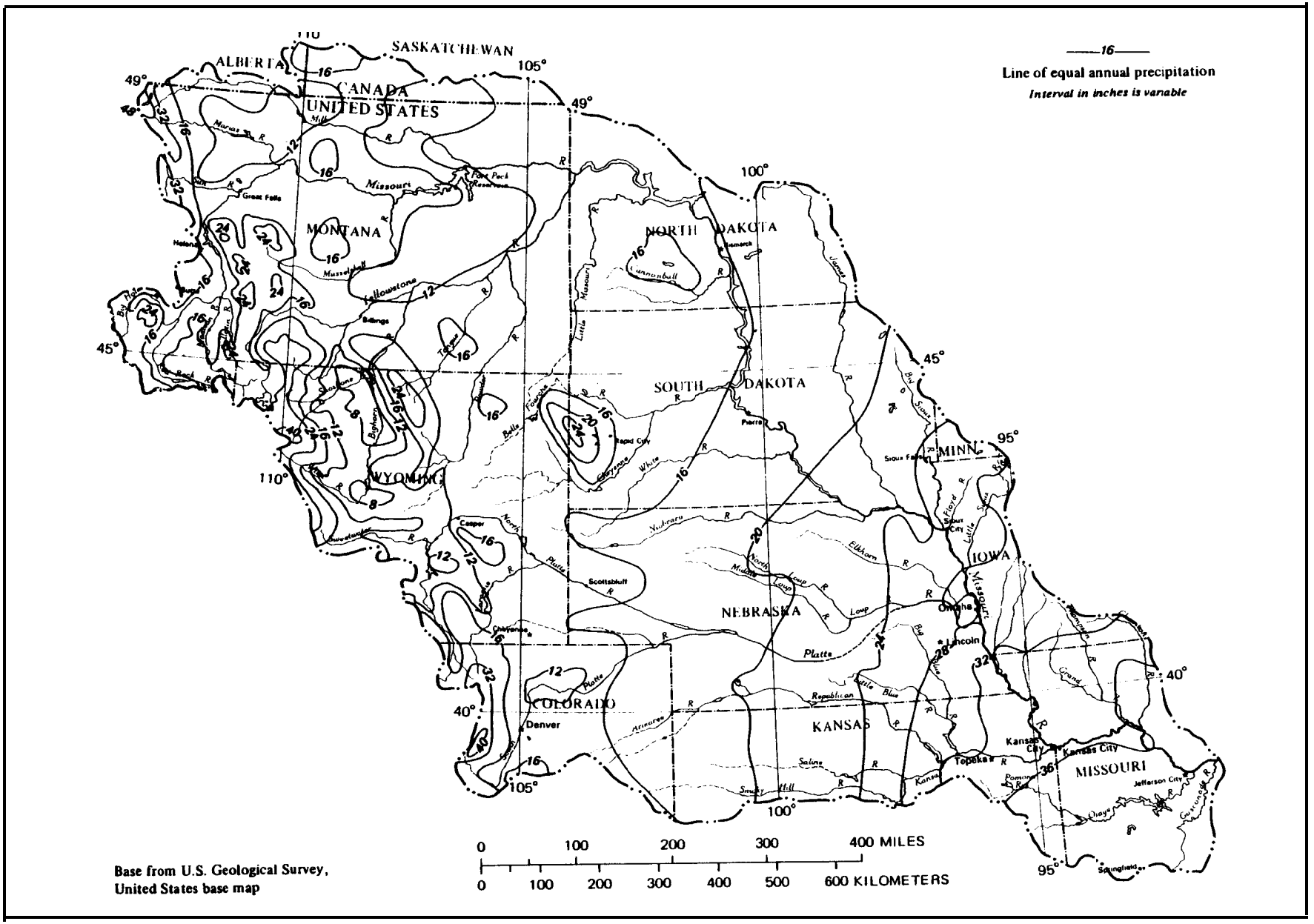


Figure 3-25. Normal Annual Precipitation (1931-1960) in the Missouri Basin Region (Taylor, 1968)

Table 3-l. Principal Aquifers in the Wind River Basin, Wyoming, Their Geologic Ages and Maximum Thicknesses (Modified from Taylor, 1978; Whitcomb and Lowry, 1968)

AQUIFER NAME	GEOLOGIC AGE	MAXIMUM THICKNESS (FT.)	MAXIMUM THICKNESS (M)	YIELD	TYPE
1. Arikaree Formation (Split Rock and Moonstone Formations)	Miocene	2,700	820	Small to Large	Bicarbonate
2. White River Formation	Oligocene	650	200	Unknown	Bicarbonate
3. Wagon Bed Formation	Eocene	700	210	Unknown	Magnesium Calcium Sulfate
4. Battle Spring, Wind River, and Indian Meadows Formations	Eocene	8,000	2,400	Large	Sodium and Calcium Sulfate and Bicarbonate
5. Tensleep Formation Amsden Formation	Pennsylvanian Pennsylvanian	900	270	Large	Sodium and Calcium Sulfate and Bicarbonate

4. COAL RESOURCE

The Wind River coal region in west-central Wyoming could contain substantial coal resources which extend from outcrop along the rim of the basin to depths greater than 14,000 feet near the synclinal axis in the deep northeastern part of the basin (Figure 4-l). Coalbed methane resources associated with these deeply buried coalbeds could be potentially very substantial. Methane characterization data, however, are limited to only certain widely-scattered locations where shallow subbituminous Messaverde coals have been sampled. Although these coals are of low ASTM rank, which normally indicates small amounts of adsorbed methane per unit volume of coal, the beds are continuous and thicken locally. These conditions usually are conducive to having large volumes of methane contained per unit area of coalbed. Also, there are areas in the Wind River Basin which contain numerous thick coalbeds associated with sandstones and carbonaceous shales that can be intercepted by a single well (Figure 4-Z). This small, limited sample is only the first step in the development of an exploration rationale required to characterize overall distribution of the coalbed methane in the Wind River Basin.

4.1 REGIONAL SETTING

Glass (1978) reported that Wyoming's coals occur in rock sequences deposited during either the Cretaceous Period (66 to 135 million years ago) or the young Tertiary Period (38 to 66 million years ago). During both periods, depositional environments and climates were at least periodically well-suited to the development of densely vegetated swamps. Peats that accumulated in these swamps were transformed into the nearly trillion tons of coal that still underlie 41 percent of the state of Wyoming (Glass, 1978).

Wyoming's coal fields are situated in two coal-bearing provinces. As shown in Figure 4-3, coals in northeastern Wyoming are within the Northern Great Plains Province, whereas the other coal basins and regions are in the Rocky Mountain Province. The major coal-bearing areas in Wyoming are:

- Powder River coal basin
- Green River coal basin
- Hams Fork coal region
- Hanna coal field

- Wind River coal basin
- Bighorn coal basin
- Rock Creek coal field
- Jackson Hole coal field
- Black Hills coal region
- Goshen Hole coal field.

Wyoming is designated as coal-producing District 19 by the U.S. Bureau of Mines. The state's coal areas are divided into 10 major regions, basins, or fields covering approximately 40,000 square miles. Twenty-four percent of the nation's coal resources lie under less than 6,000 feet of overburden in the state.

The formations that contain coalbeds characteristically are thick, usually ranging from 700 to 7,000 feet. Thicknesses of the various Tertiary formations vary from basin to basin, whereas the Cretaceous formations normally exhibit gradual regional thickening or thinning across Wyoming.

The most widespread coal-bearing rocks in Wyoming are Cretaceous in age and usually crop out as narrow bands of upturned rock around the margins of the larger structural basins and uplifted areas in the state. The Wind River Basin is subdivided into seven individual coal fields (Figure 4-4), so distributed along the edge of the basin (Woodruff and Winchester, 1912):

- Muddy Creek Field
- Pilot Butte Field
- Hudson (Lander) Field
- Beaver Creek Field
- Big Sand Draw Field
- Alkali Butte Field
- Arminto (Powder River) Field.

All coal-bearing formations crop out along the flanks of the Wind River Basin. Coalbeds also crop out as irregularly exposed, linear bands in the thrust belt of western Wyoming. On the other hand, relatively flat-lying, generally non-coal-bearing Tertiary rocks occupy the central portions of most of the coal-bearing areas where they overlie older Cretaceous rocks. Even Tertiary rocks often exhibit steeper dips as they approach the margins of the coal-bearing basins and regions (Glass, 1978).

The coal-bearing formations contain numerous coals separated from one another by as little as a few inches of shale or claystone to hundreds of feet of rock that may vary from coarse sandstone or conglomerate to siltstones, claystones, and shales (Figure 4-2). Although the Cretaceous coals interspersed in these rocks generally are less than 10 feet thick, a few Cretaceous coals are 30 to 100 feet thick in westernmost Wyoming (Glass, 1978).

Coalbeds of resource thickness (>14 inches) occur in the Frontier, Mesaverde, Meeteetse, and Lance Formations of Cretaceous age, and in the Fort Union and Wind River Formations of Tertiary age (Windolph, et al., 1980).

The Wind River Basin coal resource is large, and most of it is contained in thick beds lying at great depths (11,000 feet) within the basin. Most earlier coal resource calculations were restricted to outcrop areas along strike of the coalbeds, and for relatively short distances downdip (Woodruff and Winchester, 1912; Berryhill, et al., 1950; Thompson and White, 1952; Averitt, 1975; Glass, 1975). Until recently, little was known of the extent of Wind River coalbeds downdip to the center of the basin. For that reason, early calculations of coal resources grossly understate the amount of coal that certainly exists in the center of the basin.

At the request of the U.S. Bureau of Indian Affairs, the U.S. Geological Survey initiated a coal-exploratory drilling program during the Fall of 1978 to obtain fresh coal samples, core samples, and electric logs. Mr. John F. Windolph, Jr. (USGS, Reston, Virginia) is the project geologist in charge. Data from these shallow drill holes (< 1,200 feet), together with data from geologic field mapping and numerously measured sections, will be used to evaluate the coal resources of the Wind River Indian Reservation (Figure 4-5).

4.1.1 Rank

Wyoming coal ranges in rank from lignite to high-volatile A bituminous. These lignites, however, are restricted to a small area in the northeastern corner of the Powder River Basin. Some occurrences of lignites have been reported from the Wind River Basin (Unfer, 1951)

representing a southern extension of the Tertiary lignite deposits of Montana and North Dakota.

Subbituminous coals, all either Tertiary or Late Cretaceous in age, are found in all Wyoming coal-bearing areas except the Black Hills Region (Figure 4-3). Subbituminous coals usually occupy the more central parts of the coal basins. Glass and Roberts (1978) stated that the ASTM rank of the Wind River coals was subbituminous C.

Older coalbeds in any given Wyoming coal field generally are higher in rank than the younger beds. Rank of individual beds in a field 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 (Unfer, 1951).

4.1.2 Chemical Composition

Moisture, volatile matter, and fixed carbon contents of Wyoming coals vary widely across the state in response to variations in rank. The bituminous and high-rank subbituminous Cretaceous and Tertiary coals are very similar on an as-received basis. Moisture contents are less than 15 percent, volatile matter contents are between 30 and 40 percent, and fixed carbon contents are greater than 40 percent. In contrast, the lower-ranked subbituminous Tertiary coals of the Green River Region and the Powder River Basin have as-received moisture contents between 20 and 30 percent and about equal volatile matter and fixed carbon contents.

Ash and sulfur contents are characteristically low and related to depositional histories of the coals rather than to any differences in rank (Glass, 1978). Consequently, variation in ash content, in particular, is quite irregular. As-received ash content ranges from a few percent to more than 50 percent in response to the volume of inorganic debris entering the original peat swamp. However, published analyses of various coals sampled across the state suggest that a typical, persistent Wyoming coal of minable thickness contains less than 10 percent ash (Table 4-l).

More than 99 percent of Wyoming's total known coal resources contains less than 1 percent sulfur, and about half of that is less than 0.7 percent. Forty percent of Wyoming's reserve base contains less than 0.7 percent sulfur (Hamilton, et al., 1975).

The state's highest sulfur coals occur in the Green River Coal Region. Although these Wasatch Formation coals are not being mined, exploration has shown sulfur contents as high as 7 percent. However, on an as-received basis, published analyses of Wyoming's Cretaceous coals usually show 0.9 to 2.0 percent sulfur compared to 0.3 to 0.9 percent sulfur in the state's Tertiary coals. Because of contract demands, the sulfur contents of mined coals average 0.5 percent and rarely exceed 1.0 percent (Table 4-l).

Most of the sulfur in Wyoming's coal is in organic form. The sulfate form of sulfur averages less than 0.03 percent (3 to 5 percent of the total sulfur); the pyritic form averages less than 0.2 percent (25 to 29 percent of the total sulfur); the organic form averages less than 0.47 percent (70 to 72 percent of the total sulfur) (Walker and Hartner, 1966). Proximate analyses for Wind River coals are given in Tables 4-2 and 4-3.

4.1.2.1 Major and Minor Elements

Major elements in Wyoming coals which constitute more than 0.1 percent of the coal are: silicon, calcium, aluminum, iron, and magnesium--usually in that order of abundance (Glass, 1978). Common minor elements accounting for less than 0.1 percent of a coal are potassium, sodium, titanium, phosphorous, chlorine, and manganese--in that order (Table 4-4).

Silicon, aluminum, calcium, and iron all can be present in concentrations greater than 2 percent; silicon concentrations have exceeded 5 percent in some samples. The minor elements rarely exceed 0.1 percent and are best described in parts per million (Glass, 1978).

Based on recent analyses, Wyoming's Cretaceous and Tertiary coals show similar concentrations of all the major and minor elements except calcium and sodium. Concentrations of calcium and sodium in the Tertiary coals usually are four to five times the concentrations normally reported in the Cretaceous coals of Wyoming.

4.1.2.2 Trace Elements

Of the 30 trace elements recognized in some 48 analyses of Wyoming coals, concentrations of the various elements range from a high of 1,000 ppm to a low of 0.004 ppm. If these elements are grouped according to their average concentrations of a whole-coal basis, six elements average less than 1 ppm, 12 elements range between 1 and 5 ppm, 11 elements range

between 5 and 100 ppm, and one element--barium--averages more than 300 ppm (Table 4-5).

With the exception of zinc, which averages 17.9 ppm, the more common metals--copper, cobalt, nickel, and lead--all occur in concentrations ranging from 1 to 5 ppm. While the potentially dangerous elements, arsenic and molybdenum, also average 1 to 5 ppm, selenium, cadmium, and mercury normally occur in concentrations of less than one part per million.

Based on these 48 published analyses, Tertiary coals in Wyoming appear to contain higher concentrations of 26 of these trace elements than do the Cretaceous coals. Only boron, beryllium, fluorine, and germanium are higher in the Cretaceous coals (Glass, 1975).

4.1.2.3 Heating Value

Heat values of currently mined coals, like moisture contents, vary widely across Wyoming. In the southern half of the state, as-received heat values average 10,500 Btu/lb and typically range between 9,270 and 11,700 Btu/lb. Some younger coals, mined at the Jim Bridger strip mine in southwestern Wyoming (Green River Basin), account for the lower heat values, averaging only 9,350 Btu/lb. While heat values of coals mined in western Wyoming average 9,600 Btu/lb, heat values in northeastern Wyoming are much lower. Although heat values in northeastern Wyoming coals (Powder River Basin) range from 9,300 Btu/lb in the Sheridan area to 7,550 Btu/lb in Converse County, they average only 8,300 Btu/lb.

Heat values of Wyoming coals are commensurate with their rank. On a moist-mineral-matter-free basis, the bituminous coals range between 11,000 and 14,400 Btu/lb, while the subbituminous coals range between 8,400 and 13,000 Btu/lb.

Unfer (1951) reported that heat values increase noticeably under greater increments of overburden for the subbituminous coals. An increase of 300 Btu/lb per 110-foot increase in overburden has been reported in the Hanna Field.

4.2 COALBED STRATIGRAPHY

Accurate coalbed correlation is an essential prerequisite to the determination of coal resources and reserves, especially those which are

particularly gassy. The subbituminous coals of the Wind River Basin have not been effectively correlated except within individual coal fields. Coalbeds are shown in generalized geologic columns for each field in the Wind River Basin. Figure 4-6 provides a pro forma geologic column showing key coalbeds or coal-bearing zones and major beds in the Wind River Basin. Correlation of individual coals across most of the coal-bearing areas or even across a coal field is seldom documented. For this reason, correlation of a coal from one coal-bearing area to another is not yet possible. In fact, correlation of some coal-bearing formations from one basin or region to another is speculative. In the author's opinion, some of the coals can be effectively projected and correlated to those coalbeds in the Bighorn Basin just north of the Wind River Basin. Campbell (1917) pointed out that the Wind River Basin has much the same character as the Bighorn Basin, except that the late Tertiary formations more nearly conceal the coal-bearing rocks. For this reason less is known regarding the coalbeds, which have been mined in only a small way. The coal is subbituminous and compares favorably with coals of the same rank in adjacent Wind River fields.

Although coals are reported in the Frontier, Cody, Lance, Fort Union, and Wind River Formations, the thicker and more important coals are limited to the Upper Cretaceous Mesaverde Formations (Glass, 1978).

Stratigraphic details of the coal-bearing formations in the Wind River coal fields are presented in order from oldest to youngest. This is also the order of importance from the best coal and the greatest amount to the poorest coal of the least amount (Thompson and White, 1952).

4.2.1 Frontier Formation

According to Keefer and Troyer (1964) the Frontier Formation in the Wind River Basin is a resistant sequence of sandstone and shale overlain by the Cody Shale and underlain by the Mowry Shale. It is an important oil- and gas-producing formation in many fields in the Wind River Basin. A detailed surface and subsurface study of the formation in the basin has been made by Thompson et al. (1949).

The Frontier Formation consists for the most part of alternating gray to black shale, gray fine- to medium-grained, massive- to thin-bedded sandstone, and a few thin beds of tuff and bentonite. Chert pebbles as much as one-fourth-inch in diameter are present in the upper 30 feet. Abundant marine fossils of early Niobrara age occur in the upper part. The contact between the Frontier Formation and the overlying Cody Shale is generally well-marked by a lithologic and topographic change from ledgy sandstone below to soft, weathered shale above (Keefer and Troyer, 1964).

However, owing to facies changes and the transitional nature of the rock within the contact zones, the formation boundaries are not consistent over long distances. Keefer (1972) reported that as a result of this condition the thickness of the Frontier varies considerably from place to place (Figure 4-7).

4.2.1.1 Nomenclature

Keefer (1972) noted that despite the above-mentioned facies changes and the lenticularity of many individual strata, several discrete stratigraphic intervals occur in the Frontier Formation (Figure 4-8).

Interval A is the lowermost subdivision of the Frontier Formation in the Wind River Basin (Keefer, 1972). This interval is a shale throughout much of the basin, except in the western part, where it is a sandstone. The lower boundary is marked by a sharply defined electric-log kick. The kick probably corresponds to a thin bentonite bed.

Interval B is mainly a shale zone 50 to 150 thick. There are some interbedded sandstones at many localities (Figure 4-7).

Interval C contains the lowermost regionally persistent sandstone within the formation. Keefer (1972) reported that across the basin this interval consists of two fairly well-defined sandstone units separated by a shale unit (Figure 4-7). This is the third Wall Creek sand that is very petroliferous. Thickness ranges from 100 to 500 feet for the interval.

Interval D is a dual unit consisting of shale and shaly sandstone, 40 to 125 feet thick, and an overlying sandstone, 25 to 130 feet thick (Keefer, 1972).

Interval E is composed of interbedded sandstone and shale ranging in thickness from 70 to about 250 feet. The Torchlight Sandstone forms the top of the interval (Keefer, 1972).

Interval F is a well-developed sandstone ranging from 80 to 140 feet thick. This sand sequence contains thin beds of carbonaceous shale and coal. Oil and gas field terminology refer to this as the First Wall Creek Sandstone.

Interval G is predominantly a shale and shaly sandstone sequence in the eastern part of the basin, which grades westward into a sandstone interbedded with minor amounts of shale (Keefer, 1972). Thickness of the interval ranges from 125 to 300 feet.

As shown in Figure 4-7 the top of interval G is marked in nearly all subsurface sections by a rather easily recognized change on electric logs from more expanded resistivity curves below to less expanded curves above. This difference in curve characteristics apparently reflects an upward decrease in sand content of the strata which span the contact.

Interval H is 100 to 200 feet thick and is almost entirely a shale or sandy shale. It is sometimes assigned to the Cody Shale (Keefer, 1972). The top of the interval is marked in all subsurface sections by one of the most easily recognized electric-log markers within the Upper Cretaceous sequence of this region. This marker has been referred to as the "chalk kick" (Thompson, et al., 1949) and it forms an excellent reference horizon, along with the marker at the base of interval A, for bracketing all the rocks either assigned to the Frontier Formation in one place or another or otherwise included in the closely related stratigraphic units both above and below the Frontier.

The Cody Shale is discussed only briefly in conjunction with the Mesaverde Formation.

4.2.1.2 Frontier Coalbed Stratigraphy

Very little is known about the extent of the coals in the Frontier Formation. Windolph (1981, personal communication) noted that the upper Frontier coals were mined on the Wind River Indian Reservation in an area covered by the Blue Hole quadrangle. Two coalbeds are present--one three feet thick; the other two feet thick--and are separated by a six-foot

split. The coal is about 150 feet below the Cody Shale and is positioned on the top of the First Wall Creek sand.

4.2.2 Mesaverde Formation

The lithology of the Mesaverde Formation of the Wind River Basin bears little resemblance to that of the formation at its type section. The Mesaverde consists of light to dark gray sandstone interbedded with shale, siltstone, ironstone, and coal. Tonsteins appear for the first time in the coalbeds (Windolph, 1981, personal communication). Thompson and White (1952) reported that the sandstones are more massive, more resistant, and much cleaner than those of the underlying Cody Shale. The units are highly lenticular; most beds can be traced less than five miles, and several for only a few hundred feet. Perhaps the most persistent bed within the formation is a fine-grained white to light-gray sandstone averaging about 50 feet in thickness, considered to be the basal bed of the formation throughout most of the area (Thompson and White, 1952).

The Mesaverde Formation appears to overlie conformably the Cody Shale and is overlain unconformably by the Lance, Fort Union, or Wind River Formations (Figure 3-17).

The western sections are thinnest where the overlap is by rocks of the Fort Union or the Wind River Formations, and in the eastern part of the area the formation is thicker where overlain unconformably by the Lance Formation (Thompson and White, 1952). The maximum angular unconformity observed between rocks of the Mesaverde and Lance Formations is about 5 degrees; between the Mesaverde Formation and rocks of the Fort Union Formation, it is 30 degrees; and between rocks of the Mesaverde and Wind River Formations, about 40 degrees (Thompson and White, 1952).

4.2.2.1 Nomenclature

Shapurji (1978) pointed out that nomenclature of the Mesaverde Formation in the Wind River Basin presents one of the most difficult problems owing to the complex intertonguing of marine, transitional, and nonmarine deposits. The sedimentation is characterized by facies changes and variations in thickness over relatively short distances. Several workers have proposed various nomenclatures for the Mesaverde section in the Wind River Basin and adjoining areas (Figure 4-9). The Mesaverde

stratigraphic discussion is presented in two parts: the Eastern and Western Areas. The dividing line between the two lies approximately between the western flank of the Rattlesnake Hills and the Dutton Anticline (Castle Gardens No. 14) (Figure 3-17). The approach of this report relates the surface-observed stratigraphy to subsurface data from geophysical well logs.

4.2.2.2 Eastern Area

The Mesaverde Formation in the eastern area is composed of several distinctively recognizable units intertongued with the Cody Shale. In the eastern and southeastern part of the Wind River Basin, the Mesaverde Formation is now generally subdivided into three members (Barwin, 1961). In ascending order, these are the Phayles (Fales) Member, an unnamed middle member, and the Teapot Sandstone Member.

The Phayles Member occupies a position between the top of the Cody Shale and the base of the Wallace Creek tongue of the Cody Shale (Figure 3-18). The type section of the Phayles Member is on the west flank of the Rattlesnake Hills in SW 1/4 Sec. 4, T33N, R78W (Barwin, 1961, p. 174). Gill et al. (1970) reexamined the type area and adopted the spelling of "Phayles" as indicated on the Garfield Peak 7-1/2-minute quadrangle map (Shapurji, 1978).

Rich (1962) and Shapurji (1978) both recognized that a tongue of the Parkman Sandstone extends westward into the basin from the Casper Arch. Figure 4-10 shows this relationship. The Parkman Member appears to be stratigraphically younger than the Phayles Member and is in conformable contact with the Wallace Creek tongue of the Cody Shale. Shapurji (1978) believes that the Parkman Member occupies a position above the Wallace Creek tongue of Cody Shale and below the unnamed middle member (Figure 3-16). This member thins considerably to the west and pinches out between the east flank of the Rattlesnake Hills and the West Poison Spider field (Shapurji, 1978).

4.2.2.3 Western Area

The western part of the basin bears a simpler Mesaverde nomenclature. Figure 3-16 shows that the Mesaverde Formation is represented by the lower Mesaverde section, including all deposits between the base of the unnamed

tongue of Cody Shale and the lower sandy member of Cody Shale. The lower Mesaverde is composed of a basal sandstone overlain by a unit of interbedded sandstone, siltstone, shale, and coal. The basal sandstone unit of the lower Mesaverde intertongues with the sandy member of Cody Shale resulting in great variation in thickness. Shapurji (1978) stated that the thickness ranges from about 350 to 1,800 feet, thinning and intertonguing with the Cody Shale to the east. The upper part of the lower Mesaverde is missing at some localities, due to either nondeposition or post-Mesaverde erosion (Keefer and Rich, 1957).

In the extreme northwest part of the basin, a distinctive unit composed of very light-gray sandstone is recognized. This sandstone unit is referred to as the White Sandstone Member of Mesaverde Formation (Troyer and Keefer, 1955) (Figure 3-17).

The White Sandstone Member overlies the lower Mesaverde and is overlain by the Meeteetse Formation. The contact between the lower Mesaverde and the White Sandstone Member may be disconformable. The White Sandstone Member ranges in thickness from 225 to 435 feet in the Shotgun Butte area (Keefer and Troyer, 1964). Keefer and Rich (1957) stated that the White Member is identical to and occupies the same stratigraphic position as the Teapot Sandstone Member; but a direct correlation between these members is uncertain due to erosion of the section in the central part of the basin (Shapurji, 1978).

The Phayles Member can be subdivided into three distinctive lithologic units: a basal sandstone unit, a middle carbonaceous shale, and an upper unit of interbedded sandstone, siltstone, and shale. When typically developed, the units within the Phayles Member can be recognized on electric logs (Figure 4-11). At the type locality the Phayles Member attains a maximum thickness of 250 feet. The member thins eastward and interfingers with the Cody Shale (Figure 4-12). The Phayles Member is conformably overlain by the Wallace Creek tongue of the Cody Shale.

The unnamed middle member includes all rocks above the Wallace Creek tongue of Cody Shale and below the Teapot Sandstone. This member consists of a basal very fine- to medium-grained sandstone, overlain by a unit of sandstone, shale, and carbonaceous shale; ranges in thickness from 300 to 600 feet; and thins toward the west (Shapurji, 1978). The upper contact

between the unnamed middle member and the Teapot Sandstone appears to be slightly disconfonnable.

The Teapot Sandstone Member represents the uppermost unit of the Mesaverde Formation. The top of the Teapot Sandstone is in conformable contact with the marine tongue of Lewis Shale. This conformity persists in the eastern part of the study area. Towards the eastern edge of the Rattlesnake Hills, marine tongues of the Lewis Shale interfinger with nonmarine tongues of the Meeteetse Formation (Figures 3-11 and 4-10). Consequently, the Teapot Member is overlain by the Meeteetse Formation toward the west. In the subsurface, the Teapot Sandstone member attains a maximum thickness of about 175 feet (Shapurji, 1978).

4.2.2.4 Mesaverde Depositional Environment

Mesaverde lithology was deposited as a result of transgressive and regressive events, described in considerable detail by Keefer and Rich (1957), Barwin (1961), Weimer (1961), and Rich (1958). Weimer (1961) proposed that a large delta, called the Rawlins delta, was deposited in northwest Colorado and south-central Wyoming during Late Cretaceous time.

Deposition of the lower Mesaverde Formation in the western area of the basin indicates a widespread eastward regression of the Late Cretaceous seas resulting in thick accumulations of sediments in nearshore marine, brackish water, fluvial, and swampy environments containing widespread peat deposits. Minor oscillations of the shoreline resulted in interfingering of littoral and offshore marine deposits as indicated by the Mesaverde-Cody contact (Shapurji, 1978). Figure 4-13 is a generalized lithofacies map delineating the nonmarine (swamp, lagoonal, fluvial, deltaic) from marine facies. Shapurji (1978) characterized the Mesaverde depositional environments based on facies lithologies (Table 4-2). Future MRCP interpretative correlations in the basin should be formulated using the following criteria: geophysical well log signatures, similarities in depositional environments, and surface geology information.

The Phayles Member of the Mesaverde Formation shows evidence of littoral, nearshore marine, coastal-swamp, and lagoonal environments which contain lenticular coalbeds. Deposition of the Phayles Member was influenced by a major eastward regression of the Late Cretaceous sea, followed

by a period during which the shoreline was relatively stable (Barwin, 1961). The end of Phayles deposition was marked by a readvance of the sea, and subsequent deposition of marine shale of the Wallace Creek tongue (Figure 4-11). The offshore marine sedimentation of the Wallace Creek tongue was terminated by another eastward regression event, interrupted by minor oscillations of the shoreline, resulting in the deposition of the unnamed middle member (Figure 4-12). The unnamed middle member was deposited in a variety of environmental conditions (Shapurji, 1978). The upper part of the member is characterized by lagoonal, coastal-swamp, and fluvial deposits. The basal sandstone of the unnamed middle member reflects a littoral and nearshore marine depositional environment. As regression continued eastward, the Teapot Sandstone Member was deposited. This member has characteristics reflecting coastal-swamp, lagoonal, and fluvial environments of deposition and has no coalbeds.

Deposition of the Teapot Sandstone Member was followed by a major westward transgressive phase, and on lap of the lower marine tongue of the Lewis Shale (Shapurji, 1978).

4.2.2.5 Mesaverde Coalbed Stratigraphy

As a rule, coalbeds in the western portion of the Hams Fork Coal Region are geologically older than those in the Wind River Basin (Figure 4-14) (McCord, 1980). Green River coals are thought to be the same age as the Wind River Mesaverde coals, whereas the youngest Mesaverde age coals occur in the southwestern part of the Powder River Basin (Figure 4-15). The Bighorn Basin directly to the north of the Wind River Basin contains persistent Mesaverde coals in the southern and southwestern parts (Glass, 1978).

Where basal nonmarine Mesaverde environments existed in the southwestern part of the basin, a basal coalbed exists just above the Cody Shale. Examination of outcrops near the top of the Cody Shale in the western area of the basin by Windolph's USGS group showed a coarsening upward of grain sizes and intertonguing with the basal sand units of the Mesaverde Formation. The coarsening upward and intertonguing may indicate a regression of the Cretaceous sea. Sedimentary structures characteristic of mouth bars, point bars,' and distributary channel fillings were observed in the lower part of the Mesaverde Formation. These sedimentary structures

also indicate regression of the sea and an emerging environment. During the emergence, protective barriers and widespread swampy platforms formed; vegetation accumulated on these platforms and was preserved to form coal (Figure 4-7). Thin, discontinuous coalbeds which rapidly grade into carbonaceous shale formed in a marsh in proximity to barrier islands. Thin to thick, laterally extensive Mesaverde coals that grade laterally into carbonaceous shale formed in the marsh on emergent levee, overbank, and bayfill deposits at the landward side of the lagoon. Deposition of the above detrital deposits, as well as tidal-creek channel sandstones, caused splitting and merging of the coalbeds. Figure 4-16 illustrates similar types of coal depositional environments known to have existed in the upper part of the Almond Formation (Upper Mesaverde) (Figure 3-10). Most coal-beds formed in this zonal sequence are thick, lenticular, and of irregular distribution, and are probably related to crevasse splay and distributary channels (Windolph, et al., 1980). A thicker and more widespread sheet-like coalbed (Signor coal) overlies this zone and may have been deposited under more stable conditions found in the back-bay swamp of a lower delta plain environment.

An upper delta plain environment is suggested by the next higher sedimentary sequence. This sequence consists of approximately 1,000 feet of interbedded lenticular sandstone, siltstone, gray shale, carbonaceous shale, thick to thin coalbeds commonly discontinuous laterally, and thin freshwater limestone beds.

The uppermost unit of the Mesaverde Formation is a white, coarse- to medium-grained blanket sandstone containing several thin carbonaceous shale beds. It appears to be in unconformable contact with the underlying sequence and is interpreted as having been deposited on an alluvial plain. The basal shale units of the overlying Meeteetse Formation record a trans-gression of the Cretaceous sea (Windolph, et al., 1980).

Downey Coalbed

Windolph (1981, personal communication) has revealed through detailed measured stratigraphic sections that the Downey coalbed in the Big Sand Draw coal field is the same as the Signor coalbed in the Alkali Butte coal field. The Downey coalbed was thought to be the lowest commercial coal

occurring in the Mesaverde Formation. This coalbed was typically 28 feet thick where it was mined in the Big Sand Draw coal field (Thompson and White, 1952).

Signor Coalbed

The Signor coalbed probably is the most persistent Mesaverde coal yet identified in the southwestern part of the Wind River Coal Basin (Figure 4-17). The Signor bed is traceable for more than 10 miles in the Alkali Butte Coal Field. Its maximum reported thickness is 16.5 feet. Although it is 7 to 10 feet thick over much of its outcrop, it does thin in places to less than 2. The coal has been deep-mined, and dips at 13 to 31 degrees. Windolph et al. (1980) tentatively correlated a coalbed measuring 7 feet thick in the Hudson quadrangle with the Signor bed some 22 miles toward the east in the Alkali Butte coal field (Figure 4-13).

The coalbeds delineated in the classical Hudson stratigraphic section are not associated with the Signor coalbed. These coals are lower stratigraphically and are not present in the Alkali Butte area, but they do appear in the Stanolind Oil and Gas Company well (SE 1/4 SE 1/4, 3, 33N, 96W) (Figure 4-2). In the Hudson coal field the Signor coalbed is cut out by dual unconformities (Windolph, 1981, personal communications). Most of the Mesaverde Formation is removed by the Fort Union and right above (20 to 30 feet). The Wind River Formation cuts out the Fort Union Formation.

Lord et al. (1913) published an analysis of a single channel sample of the Signor coalbed from the Alkali Butte coal field (Table 4-3). Only the lower 4.2 feet of the 7.9-foot-thick coal were analyzed. Glass (1978) summarized the analyses of the Lander coalbed from the Hudson coal field (Table 4-3).

Kinnear Coalbed

This thin Mesaverde coal crops out for about one mile in the Pilot Butte coal field in the northwestern part of the basin where it was once deep-mined (Glass, 1978). The Kinnear coal has a maximum reported thickness of 2.8 feet although 2 feet is a better average thickness (Woodruff and Winchester, 1912). The bed dips 29 to 30 degrees northeast, and is the only coal identified in the Pilot Butte coal field. Inasmuch as this coalbed lies about 280 feet above the Mesaverde/Cody contact, it could be

equivalent to the Signor coalbed (Figure 4-7). Table 4-6 provides a single analysis of a channel sample of this coal (Lord, et al., 1913). Where sampled, the coal was 2.8 feet thick.

Unnamed Coalbeds

Between the Signor and Beaver coalbeds are numerous discontinuous beds as much as 15 feet thick (Figure 4-7). These coals were formed in an upper delta plain environment (Windolph, et al., 1980).

Beaver Coalbed

The Beaver coalbed is a subbituminous Mesaverde coal that crops out in the Alkali Butte coal field. This is a fairly persistent coal, occurring about 430 feet above the Signor bed (Glass, 1978). The coal maintains a thickness of 3 feet for more than a mile along its outcrop. There are no analyses of this coalbed. All calculated resources of this coal lie within the Wind River Indian Reservation.

Shioton Coalbed

The Shipton coalbed is a fairly persistent Mesaverde coal in the Alkali Butte coal field. It overlies the Beaver coal by about 65 feet, and the Signor coalbed by about 495 feet. It crops out for more than 3 miles with a maximum thickness of 9.5 feet. It averages close to 5 feet thick and has been deep-mined. It dips 18 to 25 degrees to the north or west.

A single analysis of a channel sample from an underground mine (Shipton Mine) was published by Lord et al. (1913) (Table 4-6). Only 5.5 feet of a 7.5-foot-thick expression of the coal were included in the analysis.

4.2.3 Meeteetse Formation

The Upper Cretaceous Meeteetse Formation is recognized only in the Muddy Creek coal field in the northwestern corner of the basin. Meeteetse coals common to that area are nearly as well developed as the Mesaverde coals of the Alkali Butte field. Meeteetse coals are reportedly up to 16 feet thick, although they average less than 4 feet (Woodruff and Winchester, 1912). The thickest expressions of Meeteetse coals occur in persistent shaly carbonaceous zones where numerous thin coals coalesce into interbedded shale and coal units (Keefer and Troyer, 1964). Because these

carbonaceous units contain several thin coalbeds separated by shale partings or contain one or two relatively clean coalbeds of greater thickness, it is difficult to calculate and classify the coal reserves in them without a large number of measurements along each coal zone.

4.2.3.1 Nomenclature

The Meeteetse Formation has a similar relationship to the Lewis Shale, as does the Mesaverde Formation to the Cody Shale. The name Lewis Shale is restricted to marine strata overlying the Mesaverde Formation and underlying the Lance Formation.

In the eastern part of the basin the Lewis Shale is separated into upper and lower tongues by an eastward projecting tongue of the Meeteetse Formation (Rich, 1962). The base of the lower tongue of the Lewis Shale is generally well exposed, and the contact with the underlying Teapot Sandstone is marked by a change from white sandstone below, to dark- and olive-gray shale and thin-bedded sandstone above.

Figures 3-17 and 4-15 show that toward the southwestern part of the Wind River Basin the Meeteetse is cut out between the Dutton anticline and the Conant Creek anticline.

4.2.3.2 Eastern Area

The Meeteetse Formation in the Hiland-Clarkson Hill area in Natrona County, Wyoming, is overlain and underlain by tongues of the Lewis Shale. The basal beds of the Meeteetse Formation consist of thin to thick beds of light-gray friable sandstone and dark-gray carbonaceous shale. In some exposures the sandstone beds are soft and friable, whereas in others they are relatively well indurated (Rich, 1962).

The formation is characterized by a succession of alternating sandstone, siltstone, shale, tuffaceous siltstone or mudstone, carbonaceous shale, and lenticular coalbeds. Where surface exposures are good, the unit has a gray, black, yellowish-gray, and brown-banded appearance unlike any other Upper Cretaceous formation in the area. Locally, as at Meadow and Aspirin Creeks, sane of the lower sandstone beds weather into "cannonball" concretionary masses (Rich, 1962).

4.2.3.3 Western Area

The Meeteetse Formation in the Shotgun Butte area is 656 to 1,335 feet thick, and can be divided into a lower banded unit of alternating lithologies and an upper massive lenticular sandstone unit (Keefer and Troyer, 1964).

The lower part of the Meeteetse Formation is an interbedded sequence of sandstone, siltstone, shale, carbonaceous shale, and coal ranging in thickness from 650 to 1,080 feet.

Keefer and Troyer (1964) reported that, where well exposed, the strata present a distinctive gray-, black-, yellow-, and brown-banded appearance unlike that of any other Upper Cretaceous sequence in the region. The sandstone in the lower unit is mostly gray and buff, thin-bedded to massive, fine- to medium-grained, soft, porous, friable, and in part bentonitic; it weathers to smooth, rounded hills. A distinguishing feature are the spherical cannonball-like calcareous sandstone concretions, as much as 3 feet in diameter, that weather out profusely on the slopes. Near the base of the formation are sporadic, large brown ferruginous sandstone masses similar to those in the underlying Mesaverde Formation.

Easily eroded shale, siltstone, and claystone comprise the rest of the lower part of the Meeteetse. Some beds are bentonitic and weather distinctly tan or yellowish gray. Coalbeds are present throughout the unit and several are of minable thickness. The thickest coalbeds are near the top of the sequence in the vicinity of Welton Mine, Sec. 20, T6N, R1E (Keefer and Troyer, 1964).

The upper part of the Meeteetse Formation is a massive lenticular sandstone unit ranging in thickness from 0 to about 300 feet. Individual sandstone beds are locally as much as 120 feet thick. The sandstone is buff and gray, fine- to coarse-grained, massive, moderately porous and friable, and contains sporadic concretion-like masses of brown ferruginous sandstone as much as 10 to 15 feet in diameter. A few thin beds of gray shale are interbedded with the sandstone, but no coalbeds were seen (Keefer and Troyer, 1964).

Figure 3-17 illustrates both the conformable and unconformable natures of the Meeteetse Formation in the western area of the basin.

4.2.3.4 Meeteetse Depositional Environment

According to Keefer (1965), the Meeteetse Formation was deposited in widespread swamps, broad flood plains, and lagoons that lay along the west edge of the Late Cretaceous sea. The thin tongues of marine shale and sandstone of the Lewis Shale represent minor readvances of the sea into the eastern part of the Wind River Basin. There is little evidence of local tectonic activity during the deposition of the Meeteetse and Lewis, except possibly a little downfolding of the major trough area along the present north margin of the basin. The Meeteetse Formation is easily distinguished from the Fort Union Formation by its lack of conglomerate beds.

4.2.3.5 Meeteetse Coalbed Stratigraphy

The Meeteetse coalbeds are lenticular and in a few places in the Muddy Creek field (Figure 3-8) extend at minable thickness for more than a mile (Figure 4-18) (Berryhill, et al., 1950). Because the boundaries of the Meeteetse Formation cannot be traced reliably into the subsurface, the Meeteetse and the overlying Lance Formation commonly are grouped for mapping purposes (Figure 4-19) (Paape, 1968). The Meeteetse Formation is overturned in the northern portion of the basin (Windolph, 1981, personal communication).

Welton Coalbed

The Welton coalbed is the thickest Meeteetse coal described in the Wind River coal basin (Figure 4-18). It is up to 16.5 feet thick, although a thin shale parting commonly separates the basal two feet of the bed from the upper part (Keefer and Troyer, 1964). The coal crops out for more than two miles where it dips eastward at 19 to 28 degrees. It apparently splits and thins northward. It has been deep-mined in the past (Glass, 1978).

In 1913, an analysis of a single channel sample of the Welton coal was made. Only 3.8 feet of a 12.2-foot-thick expression of the coal, however, were analyzed (Lord, et al., 1913) (Table 4-6).

4.2.4 Lance Formation

The Lance Formation is a conspicuous blue-weathering sequence of gray, medium-grained sandstones and chocolate-brown, carbonaceous shales and coals. It is the uppermost Cretaceous formation in the basin and although

sparsely fossiliferous, it yields a diagnostic plant, Sequoia reichenbachi, which can be used to distinguish the formation from overlying Paleocene or younger strata (Thompson and White, 1952).

The Lance Formation overlaps the Mesaverde with as much as 5 degrees angular unconformity from the Alkali Butte anticline eastward to Conant Creek. On the west side of the Alkali Butte anticline the Lance Formation is overlapped and cut out entirely by the Fort Union Formation, which rests on older strata with as much as 30 degrees angular discordance (Figure 3-17). Paape (1968) stated that the Lance Formation ranges in thickness from 4,500 feet along the northern flank of the basin to a wedge edge along the southwestern flank. This thinning is partly erosional, but mostly depositional. In areas where the Lance Formation is thickest, sandstone generally predominates in the lower part and shale and claystone, in the upper part.

4.2.4.1 Nomenclature

The Lance Formation crops out extensively along the south and east margins of the Wind River Basin. It is absent along the west margin of the basin, but occurs in limited outcrops in the Shotgun Butte area (Keefer, 1965). The formation also is widespread in the subsurface where it has been wholly or partly penetrated by many wells. This formation has not been subdivided into individual units in the Wind River Basin.

4.2.4.2 Eastern Area

In the vicinity of Castle Gardens, the Lance is chiefly white to light-gray, massive crossbedded sandstone containing thin beds of carbonaceous shale. Correlations are more uncertain farther west, but in outcrops extending from Muskrat Creek westward to Alkali Butte, the formation is believed represented by a heterogeneous unit of white to gray sandstone, carbonaceous shale that weathers dark bluish gray, and thin reddish-brown ironstone beds. The ironstone beds locally contain siliceous shale fragments, rounded polished chert pebbles, and abundant fresh water mollusks (Keefer, 1965). The sequence seems bounded at both the top and bottom by unconformities; intrafonnational unconformities also may occur locally.

4.2.4.3 Western Area

In the Shotgun Butte area, where the Lance Formation has a maximum thickness of 1,150 feet, the lower half of the formation consists of thin gray sandstones weathering to a conspicuous blue-gray and containing numerous dark mineral grains, interbedded with chocolate-brown shales and coalbeds as much as 6 feet thick. A white to light-gray sandstone about 15 feet thick commonly marks the base of the formation. It is overlain by a chocolate-brown carbonaceous shale which, in places where the soft basal sandstone is covered, is the lowermost unit visible above the unconformity. In the lower part of the formation a bluish-weathering coal is present. The upper half of the Lance Formation contains more sandstone in somewhat thicker beds, averaging from 15 to 30 feet. The upper sandstones are more ferruginous and rarely contain dark mineral grains. The lighter gray sandstones also weather blue-gray. In the Conant Creek area, a porous, coarse-grained sandstone as much as 4 feet thick contains fresh water mollusks and sporadic, well-rounded, and polished pebbles of black and green chert occur near the top of the formation. Similar thin conglomerates of the pebble-granule type are also present at other horizons. These conglomerates contain, in places, angular fragments of white siliceous Mowry Shale. No fragments of pre-Cambrian rock were observed (Thompson and White, 1952). The upper part of the Lance Formation in the Shotgun Butte area is predominantly shale and claystone similar to that in thicker sections elsewhere in the basin.

4.2.4.4 Lance Depositional Environment

Keefer (1965) proposed that the sedimentary pattern during the deposition of the Lance Formation was significantly influenced by local tectonic movements representing the start of basin growth. This is in contrast to the depositional history of earlier Cretaceous time.

Probably the most prominent feature was an extensive downwarp along the present north margin of the Wind River Basin. As much as 6,000 feet of fine-grained clastic strata accumulated in this area during Lance time (Figure 4-20). Although most of these strata seem to have been deposited in broad river flood plains and in swamps, sane of the thick noncarbonaceous gray shale and claystone beds in the upper part of the formation may have originated in large lakes.

4.2.4.5 Lance Coalbed Stratigraphy

Coals are documented in the Upper Cretaceous Lance Formation only in the Shotgun Butte area and the Alkali Butte coal field. The most persistent coal in the Alkali Butte coal field is about 62 feet above the unconformable contact between the Mesaverde and Lance formations (Figure 4-18). Most of these coals are very thin and shaley. Glass (1978) stated that because of the lack of recent detailed mapping in the Arminto coal field of the easternmost Wind River Basin, some coals identified as Mesaverde in that field could be Lance coals. To date, this has not been confirmed.

Only one potentially minable Lance coal has been identified in the Alkali Butte coal field. Thompson and White (1952) noted that a Lance coal, 3 to 6 feet thick, extended for more than 2 miles along its outcrop.

4.2.5 Fort Union Formation

The Paleocene age Fort Union Formation is thought to be a minor coal-bearing formation in the Wind River Coal Basin. Fort Union coals are documented only in the south-central and eastern portions of the basin. Even in those areas, Fort Union coals are uncommon and thin, seldom reaching 3 feet in thickness. The Fort Union is divisible into "three" parts (Figure 4-21). This formation ranges in thickness from a wedge edge to possibly 8,000 feet in the subsurface along the north flank of the basin (Figure 4-22).

There is a marked angular unconformity both above and below the Fort Union Formation which somewhat facilitates surface field identification on the basis of structural relationships.

4.2.5.1 Nomenclature

The Shotgun Butte area contains one of the thickest and most complete sections of Paleocene rocks exposed in central Wyoming (Figure 4-18) (Keefer and Troyer, 1964). These rocks are assigned to the Fort Union Formation, which is the term used to designate all Paleocene strata in the Wind River Basin. Regionally the formation can be divided into two general sequences. The lower part consists of interbedded sandstone, conglomerate, shale, and carbonaceous shale deposited in and adjacent to an extensive body of water (Keefer, 1961). The upper part, in turn, contains two distinct rock types deposited contemporaneously in the marginal and

offshore areas, respectively, of the Paleocene lake or sea. The marginal unit, consisting chiefly of drab-colored shale, siltstone, claystone, and sandstone, has been named the Shotgun Member--from exposures in the Shotgun Butte area. The offshore unit, consisting of homogeneous dark-brown to black silty micaceous shale, has been named the Waltman Shale Member from outcrops near the town of Waltman, Wyoming, along the east margin of the Wind River Basin, approximately 80 miles east of the Shotgun Butte area. Keefer and Troyer (1964) noted that the Waltman Shale Member thins progressively westward and wedges out a few miles east of the Shotgun Butte area (Figure 4-16).

4.2.5.2 Eastern Area

Keefer (1965) stated that the lower part of the Fort Union Formation is characterized by white to gray, fine- to coarse-grained, massive to crossbedded sandstone, interbedded with dark-gray to black shale, claystone, siltstone, and brown carbonaceous shale. Some of the uppermost sandstone beds are highly glauconitic. Abundant thin, brown-weathering ironstone beds are present in most places, and lenticular coalbeds occur locally. The sequence on electric logs produces a more expanded series of resistivity and self-potential curves than the overlying or underlying strata (Figure 4-20).

In the north and northeastern parts of the basin, the lower part of the Fort Union Formation predominantly consists of fine-grained sandstone, siltstone, shale, and claystone. Very little coarse debris is present (Keefer, 1965). A typical section is given by the California Co. Madden 1 in Figure 4-23.

The contact between the lower part of the Fort Union Formation and the overlying Waltman Shale Member is sharp and well defined on electric logs (Figure 4-23). Lithologically, however, most subsurface sections show a thin transitional zone of interbedded sandstone, black micaceous shale, carbonaceous shale, and thin coalbeds at the top of the lower part that represents deposits laid down during the beginning episodes of the development of Waltman Lake (Keefer, 1965).

The Waltman Shale Member of the Fort Union Formation is widespread in the subsurface of the Wind River Basin, underlying more than 1,000 square miles. Thickness ranges from zero in wells near the south and west margins of the basin to more than 3,000 feet in wells near the northeastern margin on the basin. In both lithologic and electric log characteristics, the member is the most easily recognized unit in the entire Tertiary sequence of this region. The dark-brown to black color and its almost lustrous, uniformly silty, and micaceous character is a particularly diagnostic feature of the shale in well cuttings. The shale is generally fissile in the subsurface. On electric logs the member is characterized by low self-potential and resistivity curves that have nearly monotonous signatures (Figure 4-23). Individual units, as shown in Figure 4-23, are easily identified in sections that are several miles apart. Keefer (1965) stated that the cause of the characteristic marker peaks is not readily apparent from sample studies, but these studies may reflect slight yet significant changes in the matrices of seemingly uniform rocks.

The contact between the Waltman Shale Member and the overlying Shotgun Member is transitional, and thin beds of black shale alternate with fine-grained sandstone, carbonaceous shale, and coal (Keefer, 1965). The contact is generally placed at the top of the main shale mass, although on this basis some sandstone beds are inevitably included in the Waltman Shale Member and black shale beds in the Shotgun Member. The transitional contact is likewise apparent on many electric logs (Figure 4-23).

The Shotgun Member is widespread in the subsurface of the Wind River Basin, where it forms the series of sandstone, shale, and carbonaceous beds which overlie the Waltman Shale Member and were deposited during the withdrawal of Waltman Lake. Thickness ranges from 0 to as much as 1,100 feet in wells along the south margin of the basin and from 150 to more than 2,200 feet in wells along the north margin (Keefer, 1965). Considerable local variation in thickness is the result of erosion of the crests of anticlines rising during the close of Paleocene and the beginning of Eocene deposition.

4.2.5.3 Western Area

Because the Waltman Shale Member is absent, the Fort Union Formation is not readily divisible into individual members in the western, southern,

and southeastern parts of the Wind River Basin (Figure 4-18). In these regions the formation is largely a series of interbedded white, gray, tan, buff, and brown sandstone, conglomerate, shale, and siltstone. The base is usually marked by a conspicuous light-colored conglomerate composed almost entirely of well-rounded pebbles and cobbles of noncalcareous Paleozoic rocks. Pre-Cambrian igneous material is extremely rare, but in the eastern part of the basin some graphic granite and other deeply weathered granite fragments are present. The size of the fragments decreases eastward and in some areas the conglomerate is absent. The exposed lower part of the Fort Union Formation in the Shotgun Butte area ranges in thickness from 520 to about 1,200 feet. This unit is comprised predominantly of sandstone and conglomerate and its thickness ranges from 210 feet in the Ethete section to about 1,000 feet at the north end of Alkali Butte anticline.

The overlying Shotgun Member of the Fort Union Formation is 1,190 to 2,830 feet thick. It forms a wide belt of outcrops surrounding Shotgun Butte and extends southward toward Little Dome anticline (Figure 3-20). The lower part is also present and well exposed in the vicinity of Twin Buttes.

The Shotgun Member, in contrast to the lower part of the Fort Union Formation, is a remarkably even-bedded sequence of soft, easily eroded claystone, siltstone, shale, and sandstone.

Keefer and Troyer (1964) reported that in the Armstrong mine section, the upper 217 feet of the Shotgun Member are entirely sandstone and contain lenses of granules and pebbles of chert, quartzite, and siliceous shale or porcelanite similar to the conglomerate in the lower part of the Fort Union Formation (Figure 4-18).

The contact between the Shotgun Member and the lower part of the Fort Union Formation is conformable and marked by a sharp lithologic and topographic change from resistant sandstone and conglomerate below to soft, very fine-grained strata above. The contact of the Shotgun Member and the overlying Indian Meadows Formation seems to be conformable at Shotgun Butte, but in other parts of the basin there is an unconformity of considerable angular discordance and erosional relief (Figure 3-17). The contact is generally marked by a conspicuous change from drab-colored strata below to red above (Keefer and Troyer, 1964).

4.2.5.4 Fort Union Deoositional Environment

Hyne et al. (1979) suggested that the Paleocene Waltman Lake and Fort Union Formation are an ancient analog of Lake Maracaibo and the Catatambo River delta. The Catatumbo River delta displays a coarsening-upward sequence; however, it lacks the slurry deposits near the base of the column and the tidal deposits near the top that are comnon in oceanic deltas. The three recognizable members of the Fort Union Formation correspond to a lower fluvial environment (lower unnamed member), lacustrine (Waltman Shale), and the fluvial deltaic environment (Shotgun Member).

The tectonic movements which began in latest Cretaceous time in the Wind River Basin continued through the Paleocene Epoch and continued to influence the pattern of sedimentation. The Fort Union Formation was deposited during a time of uplift of the surrounding mountain and subsidence of the Wind River Basin, resulting in the deposition of thick fluvial and extensive lacustrine deposits. As the late Paleocene Waltman Lake spread westward and southward, the quiet-water Waltman Shale was deposited. The Shotgun and Waltman Shale Members intertongue extensively, and the Shotgun Member is, in part, deltaic in origin (Hyne, et al., 1979). Deltas were prograding into a fresh- to brackish-water lake which could have drained into an eastward-flowing river.

Topography and sediment infill determined the configuration of the lake (Paape, 1961). Sediments filling the basin were transported to the east from the north, west, and south sources (Owl Creek, Washakie, Wind River, and Granite Mountains) (Figure 3-2).

Concomitant downwarping along the present northeast margin of the basin resulted in the accumulation of a thick sequence of fine-grained fluviatile sediments in the major basin trough area during early Paleocene time and of several thousand feet of lacustrine or marine deposits in middle and late Paleocene time (Keefer, 1965).

The shoreline of Walbnan Lake migrated east to west across the Wind River Basin, and apparently the water body extended eastward (and perhaps northeastward) beyond the present limits of the basin. Sedimentation occurred largely under quiet-water conditions, and this environment prevailed for a long time. By the end of Paleocene time the lake had

largely disappeared, although vestiges probably remained in the central part of the basin.

4.2.5.5 Fort Union Coalbed Stratigraphy

Several coalbeds in the lowest part of the formation are present in the subsurface sections but are either incompletely exposed on the surface or are represented by a brown carbonaceous shale (Figure 4-23). Although coal is not present in exposed rocks of the Fort Union Formation at Big Sand Draw or Alkali Butte, it is present in the subsurface in the Beaver Creek coal field, in Atlantic's wells on Riverton Dome, and Stanolind's well on North Alkali Butte (Figure 3-20). In the southernmost part of the Beaver Creek Field, drill holes show as many as three coals in the Fort Union Formation, but they are only 2 to 3 feet thick (Thompson and White, 1952). One prospect in the Arminto field exposed 4.5 feet of Paleocene coal (Woodruff and Winchester, 1912). About 25 miles east of Alkali Butte, coal has been mined in the Castle Gardens area in rocks of the Fort Union Formation.

4.2.6 Wind River Formation

The Wind River Formation is a variegated sequence of continental beds of early Eocene age exposed at the surface throughout most of the Wind River Basin. Within the mapped area, the formation nearly always is present in the synclines and, in places, covers older rocks on the anticlines. More frequently it has been eroded from their tops and crops out only around the flanks.

The Eocene Wind River Formation is also a minor coal-bearing formation in the Wind River Basin (Glass, 1978). Drilling in the southernmost part of the Beaver Creek coal field, however, documents a few 2- to 3-foot thick coals (Thompson and White, 1952). Most Wind River coals are only a few inches thick, of little economic value, and of no value to the MRCP.

4.2.6.1 Nomenclature

According to Soister (1968) the Wind River Formation is divided into: (1) the lower fine-grained member, 0 to 130 feet thick; (2) the Puddle Springs Arkose Member, generally 400 to 800 feet thick; and (3) the upper transition zone, generally 50 to 100 feet (Figure 3-18). Two persistent conglomerate beds have been mapped in the Puddle Springs and have been

designated the Dry Coyote and the Muskrat Conglomerate beds. Another persistent unit, the East Canyon Conglomerate bed, was traced mostly in the subsurface by Soister (1968). A prominent carbonaceous shale and impure coal zone at the top of the lower fine-grained member was traced by logs of drill holes and is informally known as the central carbonaceous zone (Figure 4-24).

The Wind River Formation on the north side of the Wind River Basin is divided into two members: the Lysite, overlain by the Lost Cabin.

4.2.6.2 Description

The Wind River Formation is composed chiefly of variegated red, white, pink, and brown to greenish-gray claystones and siltstones which commonly form spectacular badlands, and thick zones of lensing, coarse-grained, brown arkosic sandstones. Locally, conglomerates are present and these are characterized by an abundance of igneous rocks of pre-Cambrian age, many of which are partly decomposed. The lowest of several widespread zones is a light-gray acidic tuff which averages about 20 feet in thickness in the area around Hudson.

Above the typical variegated beds of the Wind River Formation is a zone of variable thickness (as much as 185 feet) without red layers. This zone appears transitional between typical variegated beds of the Wind River below and the lower part of the overlying middle and upper Eocene rocks (Thompson and White, 1952).

The Wind River Formation lies unconformably upon rocks of the Cody, Mesaverde, Lance, or Fort Union Formations. The angularity of this unconformity is very pronounced in some areas, such as along the west side of the Alkali Butte anticline where it is 40° between the Wind River and Mesaverde Formations. In places where Wind River rocks lie on the Fort Union Formation, the angularity is usually 5° to 10°. The Wind River Formation is conformably overlain by middle and upper Eocene rocks, exposed along the Beaver Divide.

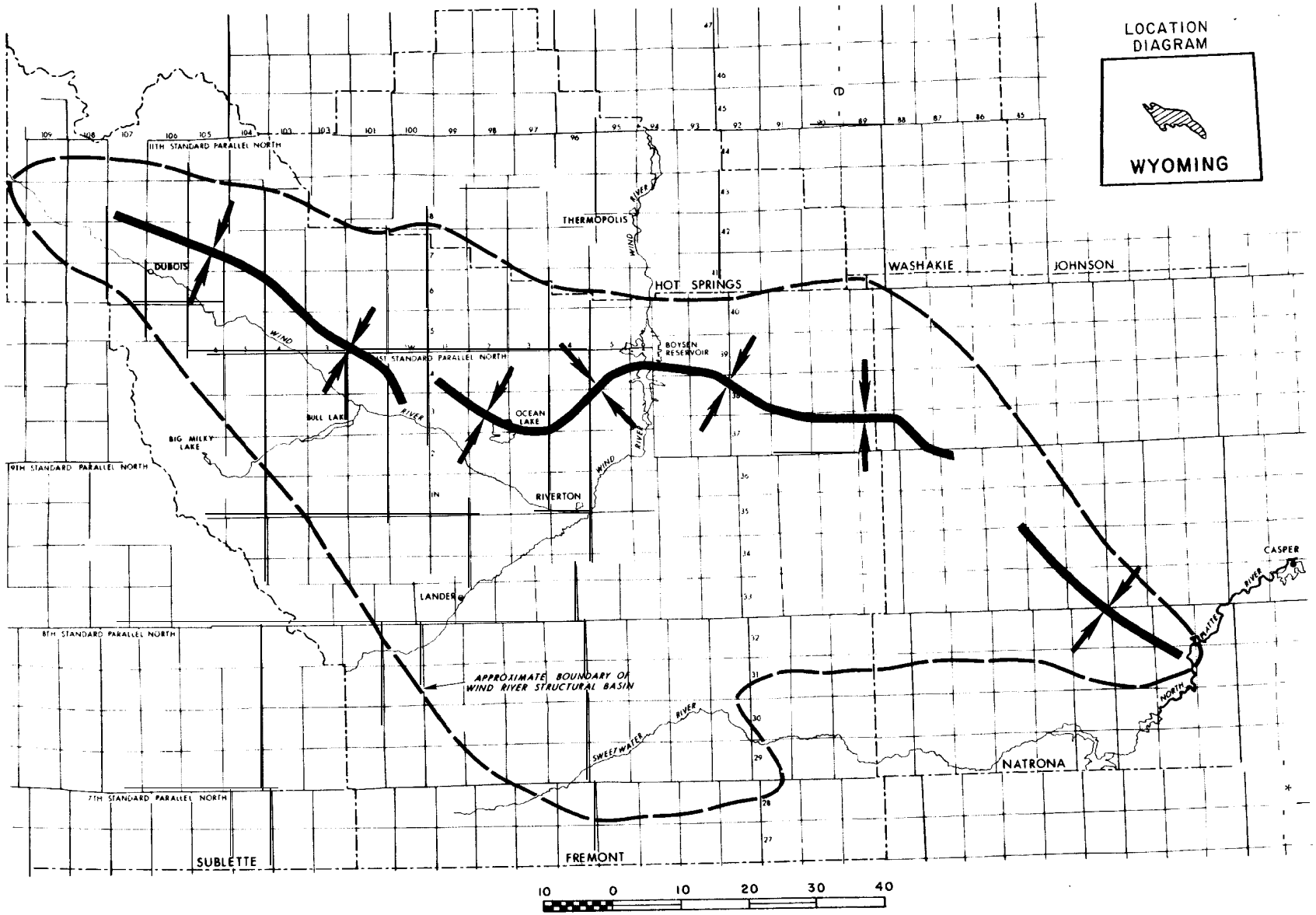


Figure 4-.1 Synclinal Axis of the Wind River Basin, Wyoming

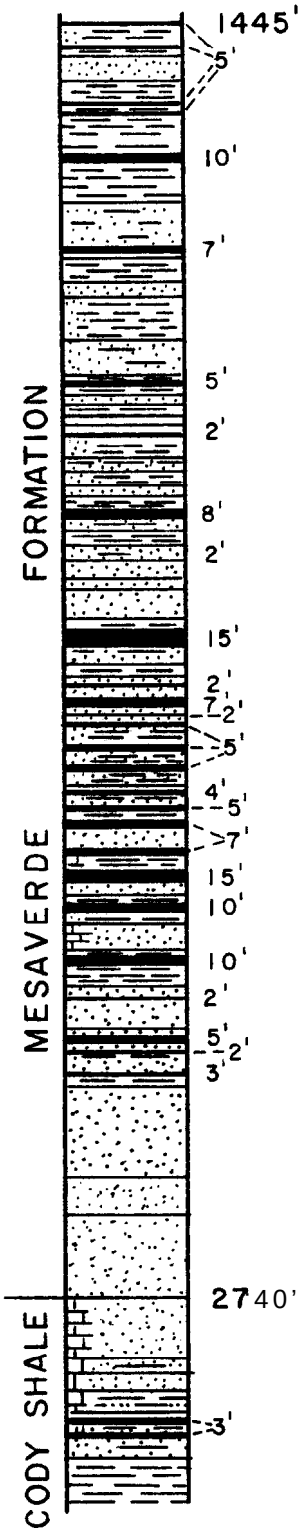


Figure 4-2. Twenty-nine Mesaverde Coalbeds Greater than 2-feet Thick Were Documented in the Stanolind Oil and Gas Co., Johnson No. 1 Well (SE ¼ SE ¼, 3, 33N, 96W), Beaver Creek Coal Field, Fremont County, Wyoming (Thompson and White, 1952)

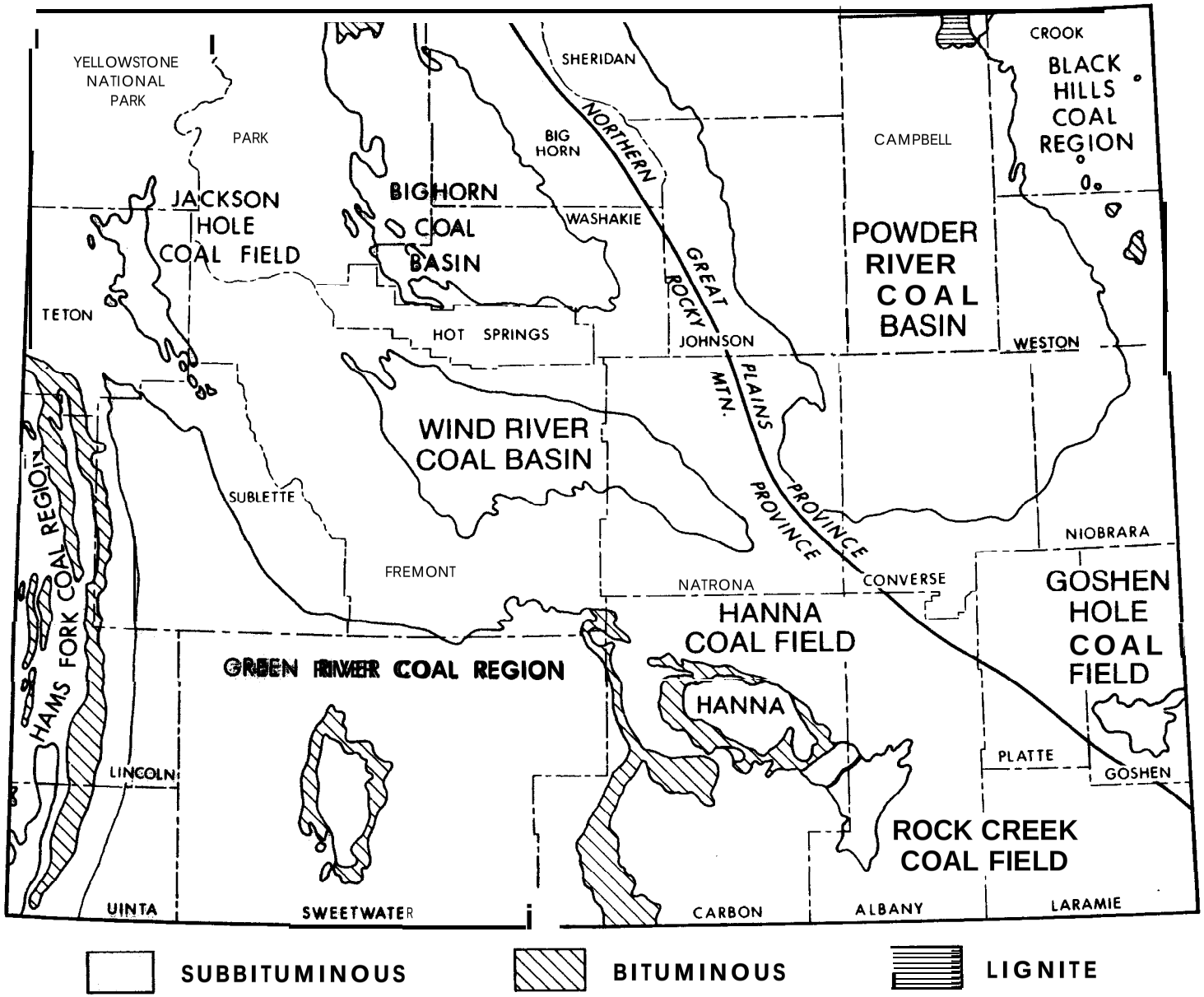


Figure 4-3. Wyoming Coal-Bearing Areas (Modified after Glass, 1980) (Courtesy of McGraw-Hill)

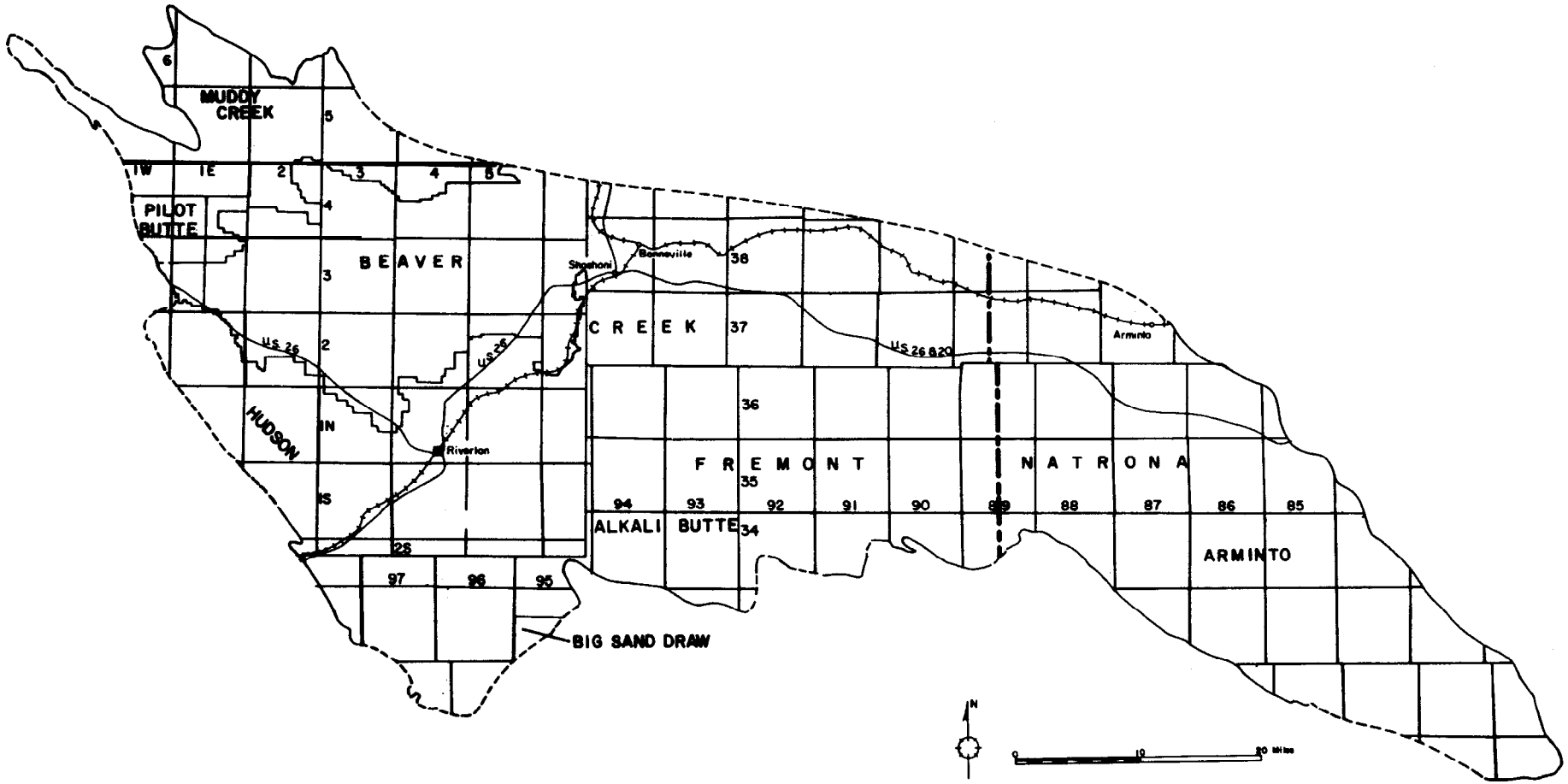


Figure 4-4. Individual Coal Fields in the Wind River Coal Basin (Glass and Roberts) (Courtesy of the Wyoming Geological Association)

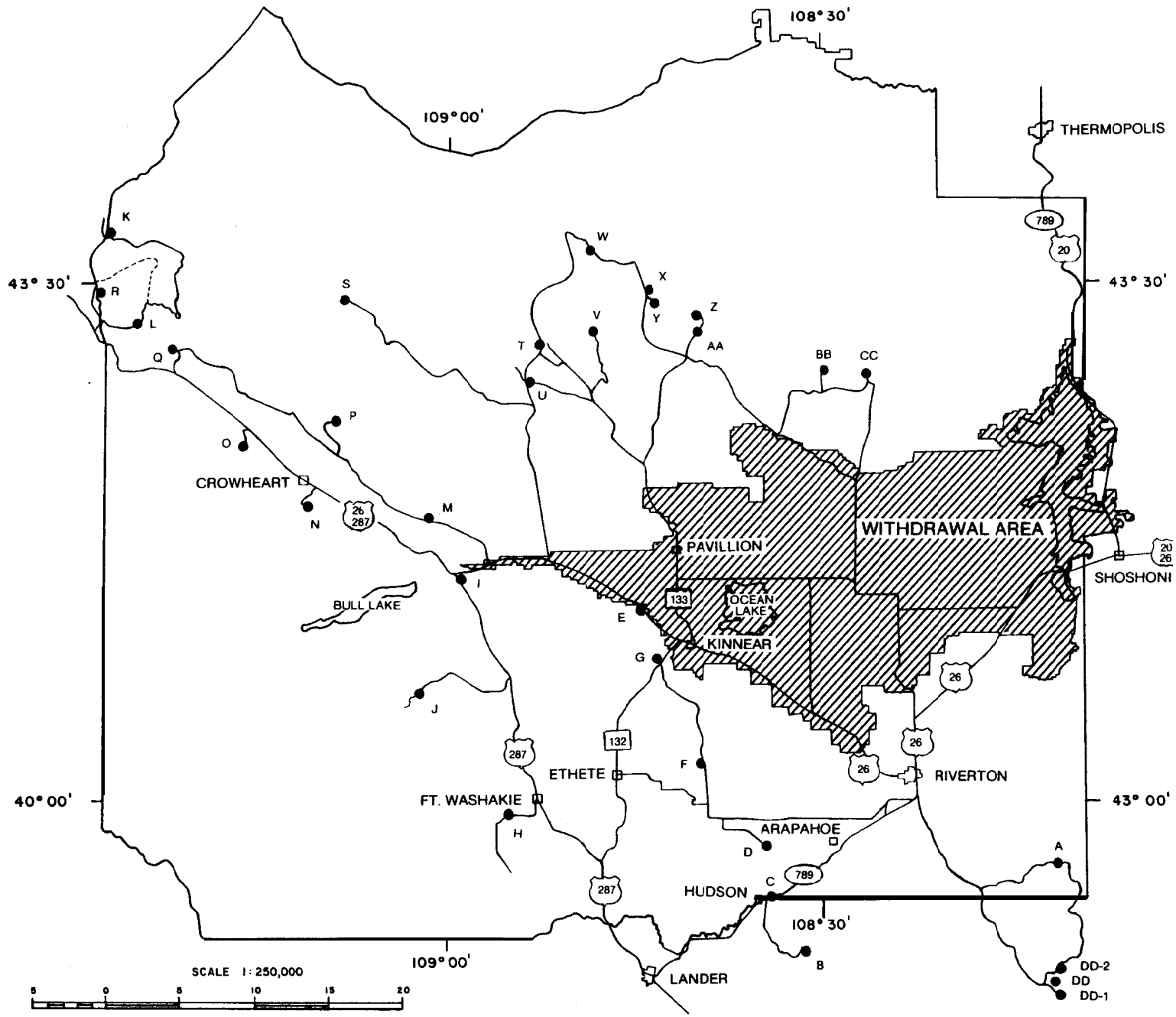


Figure 4-5. USGS Drilling Sites on the Wind River Reservation (Windolph, et al., 1980)

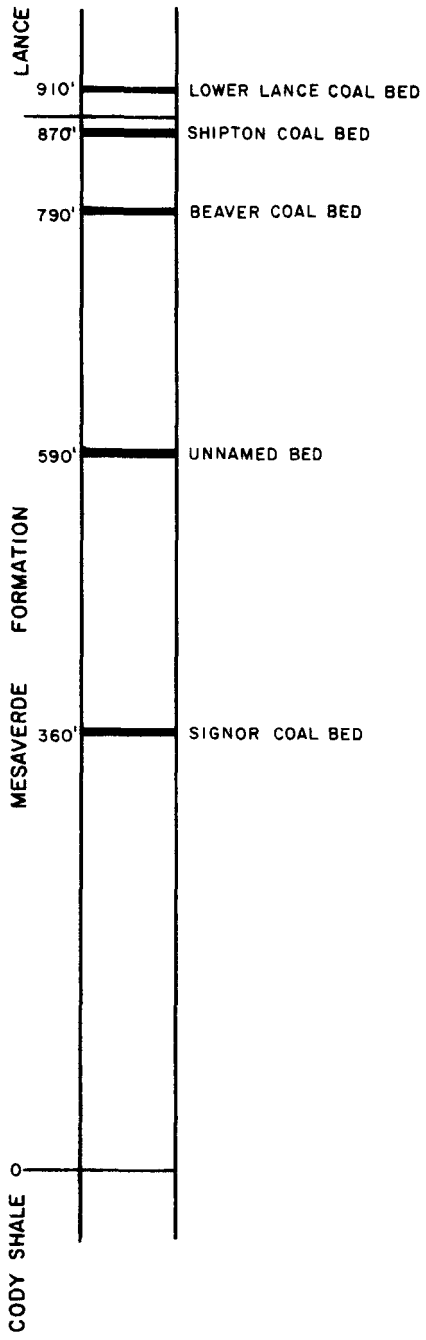


Figure 4-6. Generalized Stratigraphic Relationship of the Key Coalbeds or Coal-Bearing Zones in the Wind River Basin

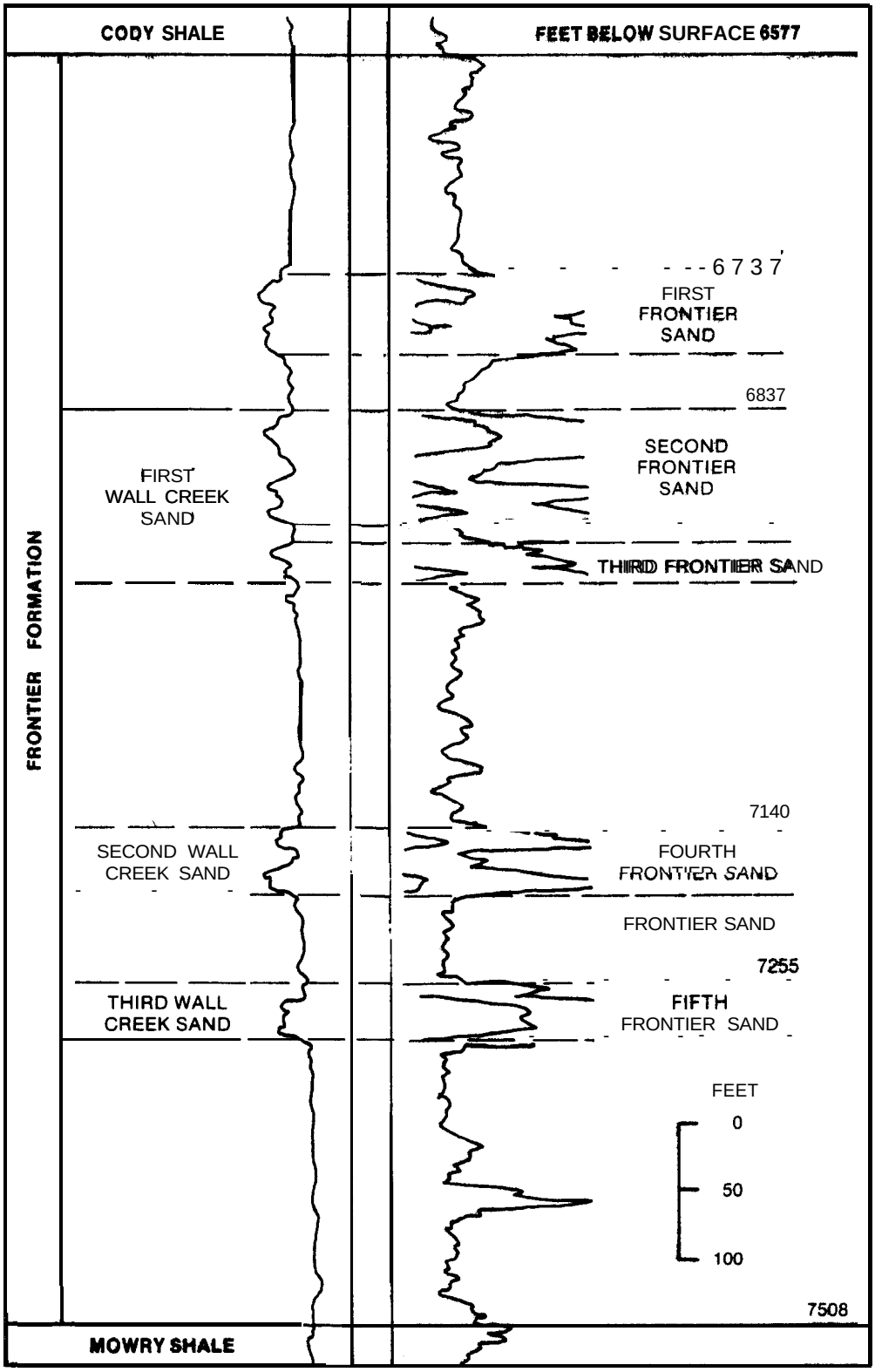


Figure 4-8. Electric Log of Stanolind Oil and Gas Co. Johnson No. 1, Sec. 3, T33N, R96W, in Beaver Creek Field, Showing Common Subdivisions of Frontier Formation (Keefer, 1969)

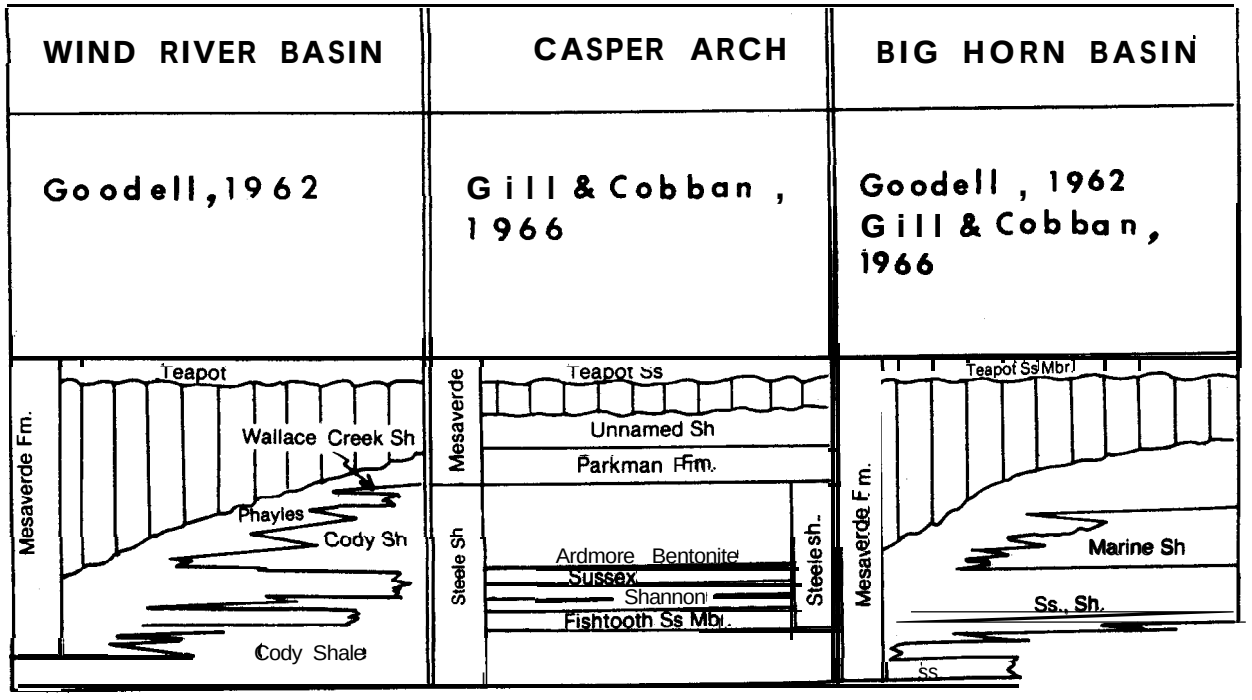


Figure 4-9. Stratigraphy Nomenclature Chart of Mesaverde Formation in Wind River Basin and Adjoining Areas (Shapurji, 1978) (Courtesy of the Wyoming Geological Association)

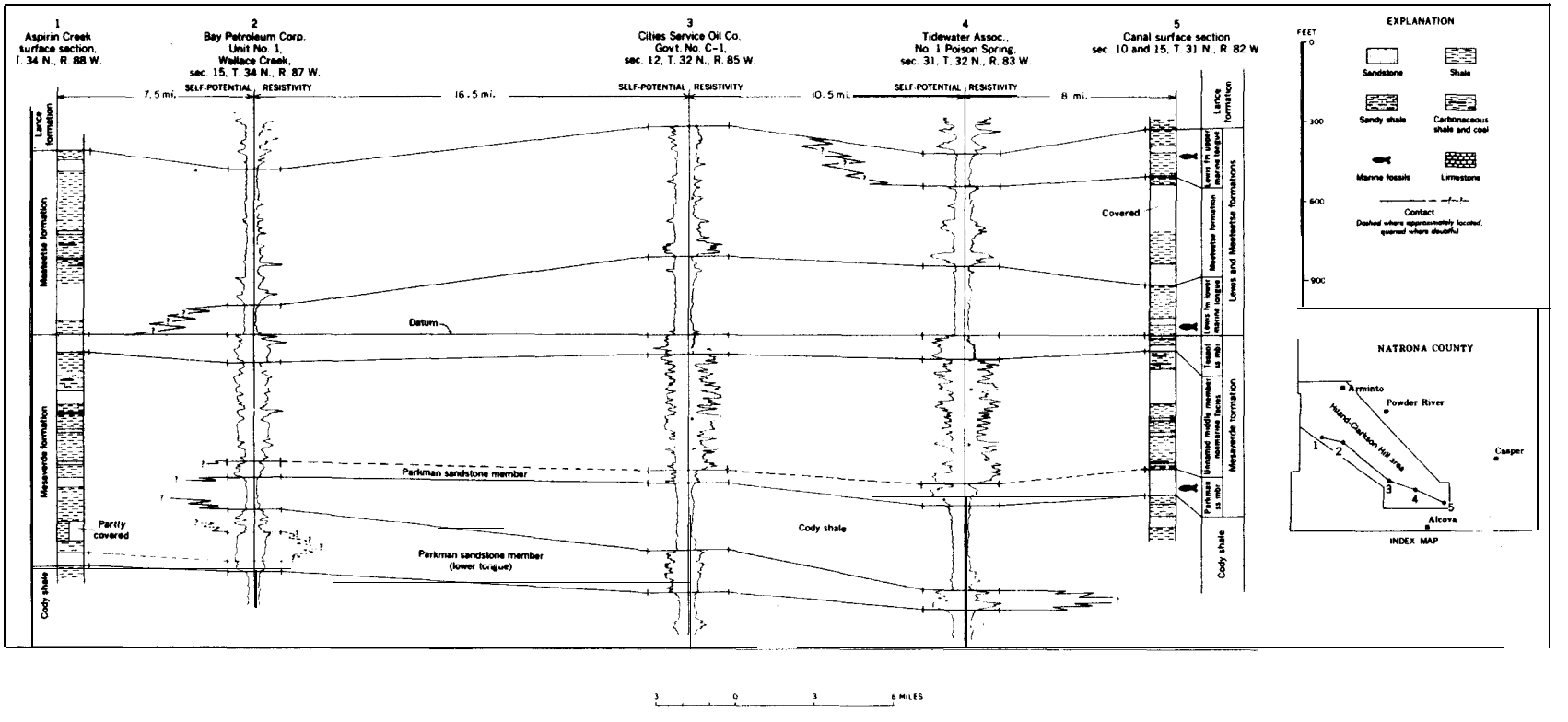


Figure 4-10. Mesaverde Subsurface Correlations in the Hiland-Clarkson Hill Area, Wyoming (Rich, 1962)

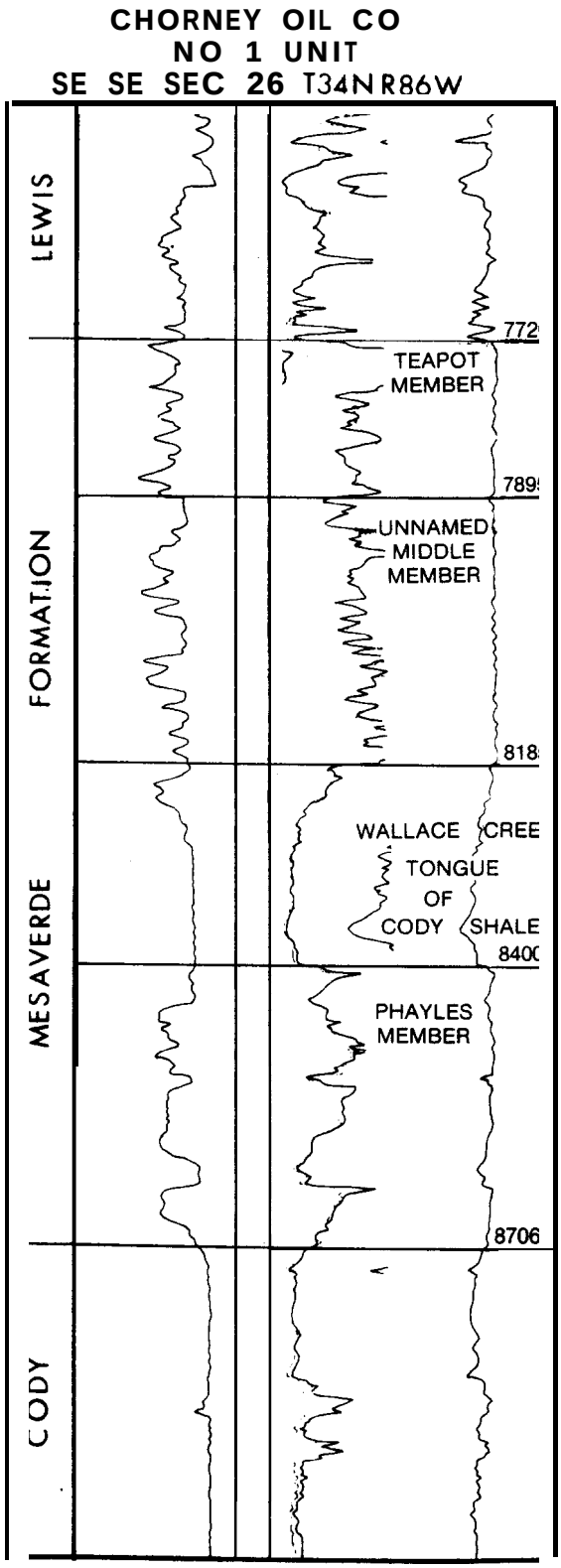


Figure 4-11. Type Electric Log Showing the SP and Resistivity Signatures for the Subsurface Stratigraphic Divisions of the Mesaverde Formation, Southeastern Wind River Basin (Shapurji, 1978) (Courtesy of the Wyoming Geological Association)

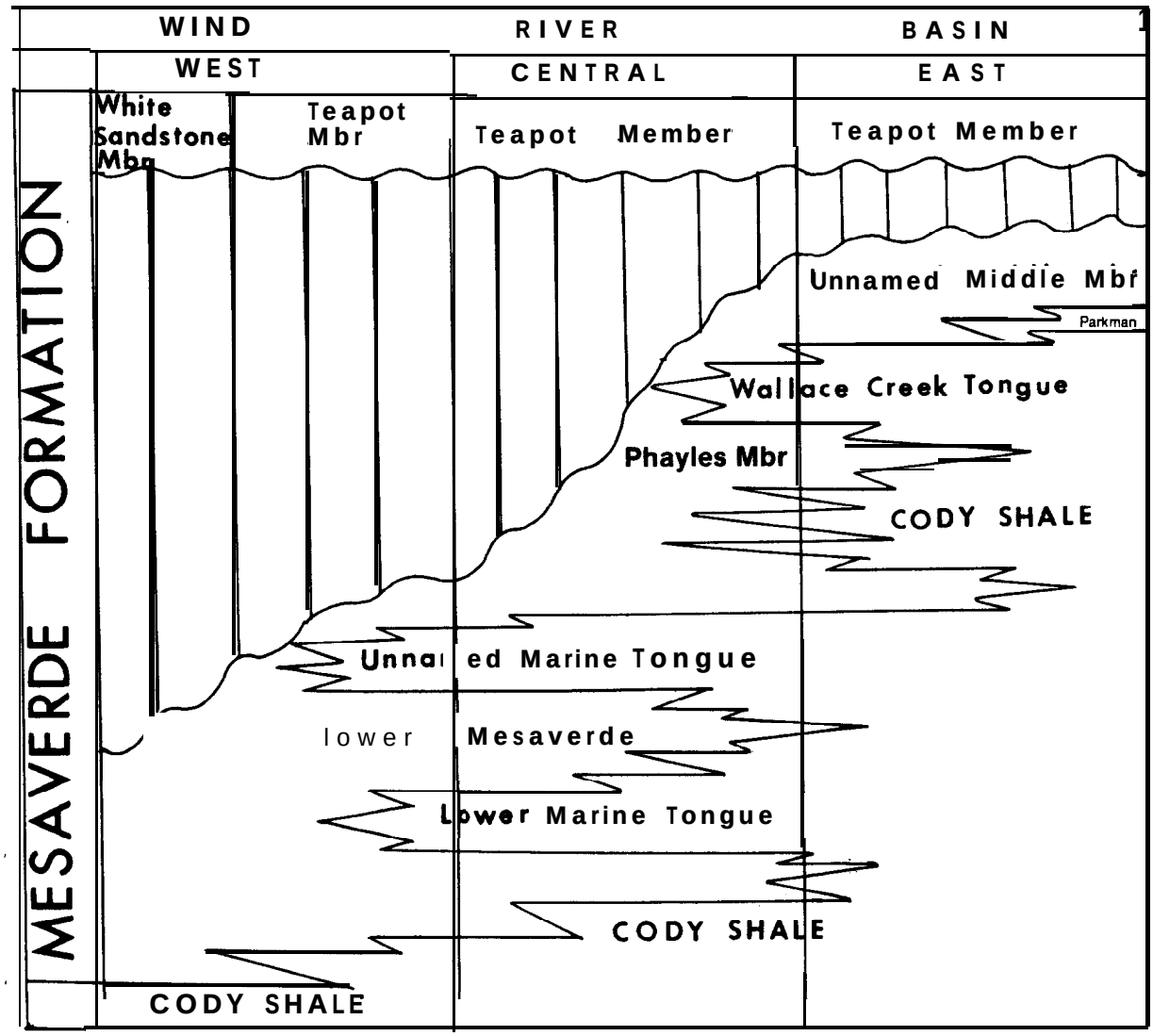


Figure 4-12 Subsurface Mesaverde/Cody Stratigraphic Nomenclature in the Wind River Basin (Shapurji, 1978) (Courtesy of the Wyoming Geological Association)

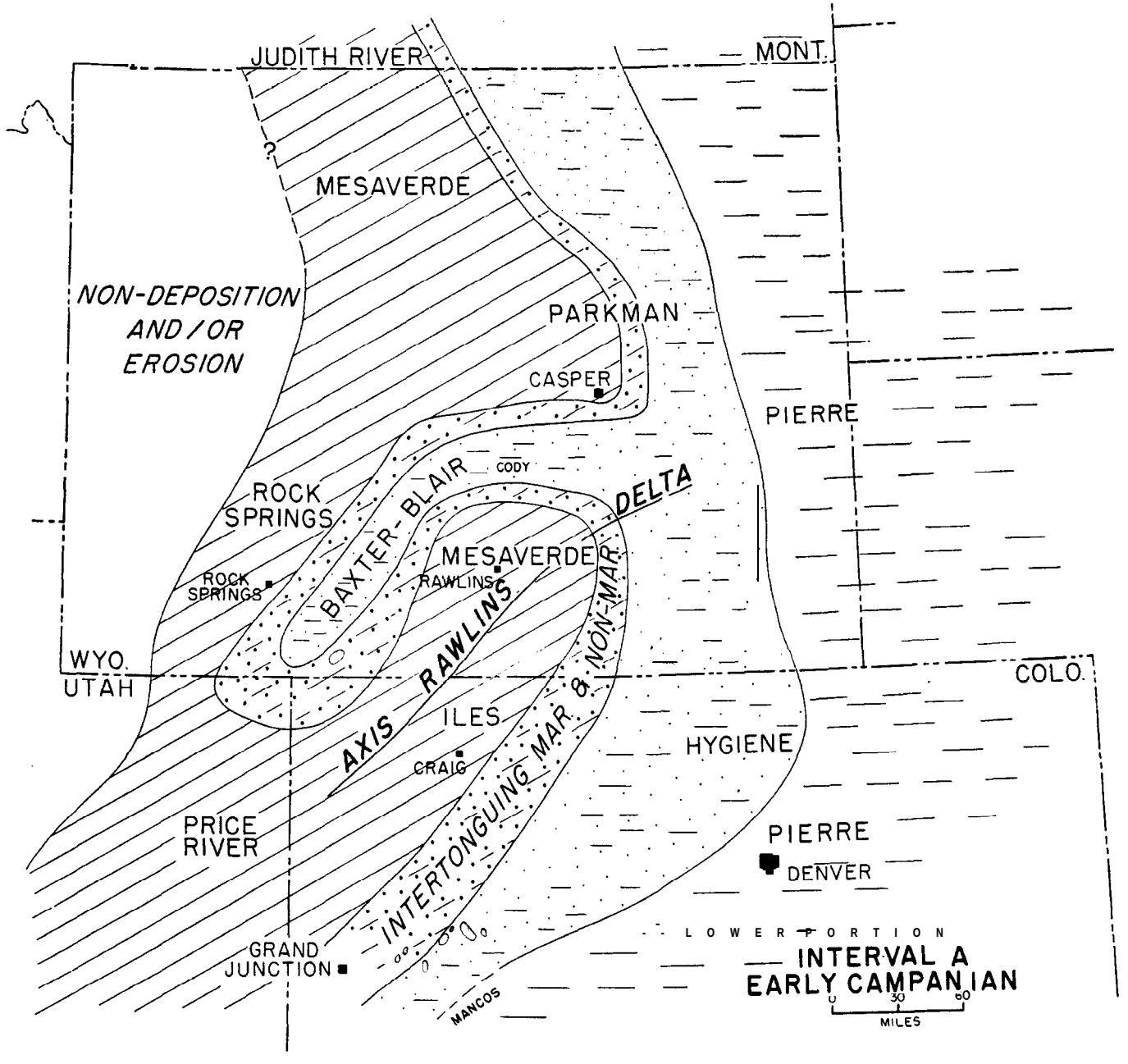


Figure 4-13. Rawlins Delta and Lithofacies Map (Weimer, 1961) (Courtesy of the Wyoming Geological Association)

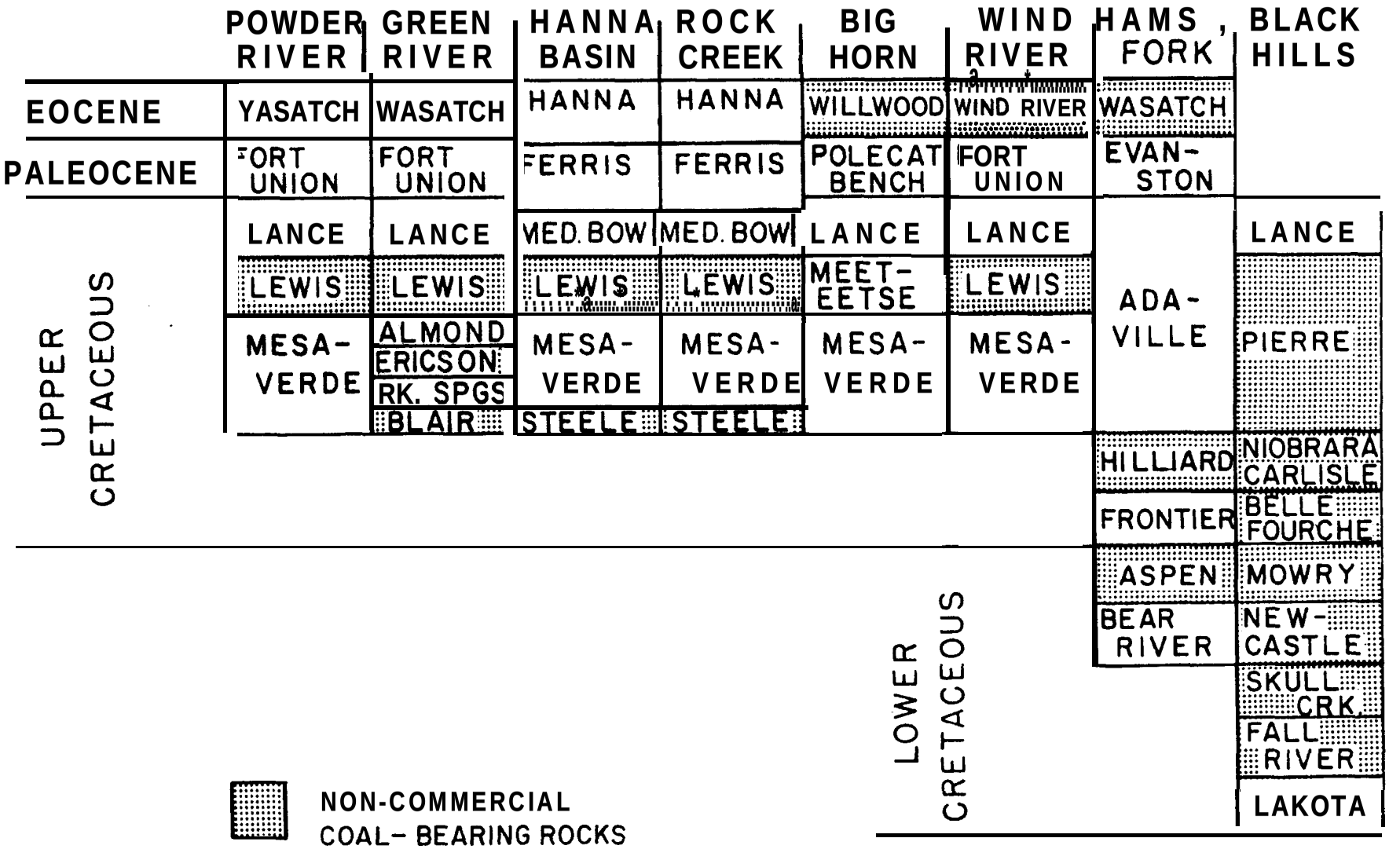


Figure 4-14. Know Major Coal-Bearing Formations of the Wind River Basin and Correlation to Other Areas in Wyoming and the Black Hills (Modified after Glass, 1978)

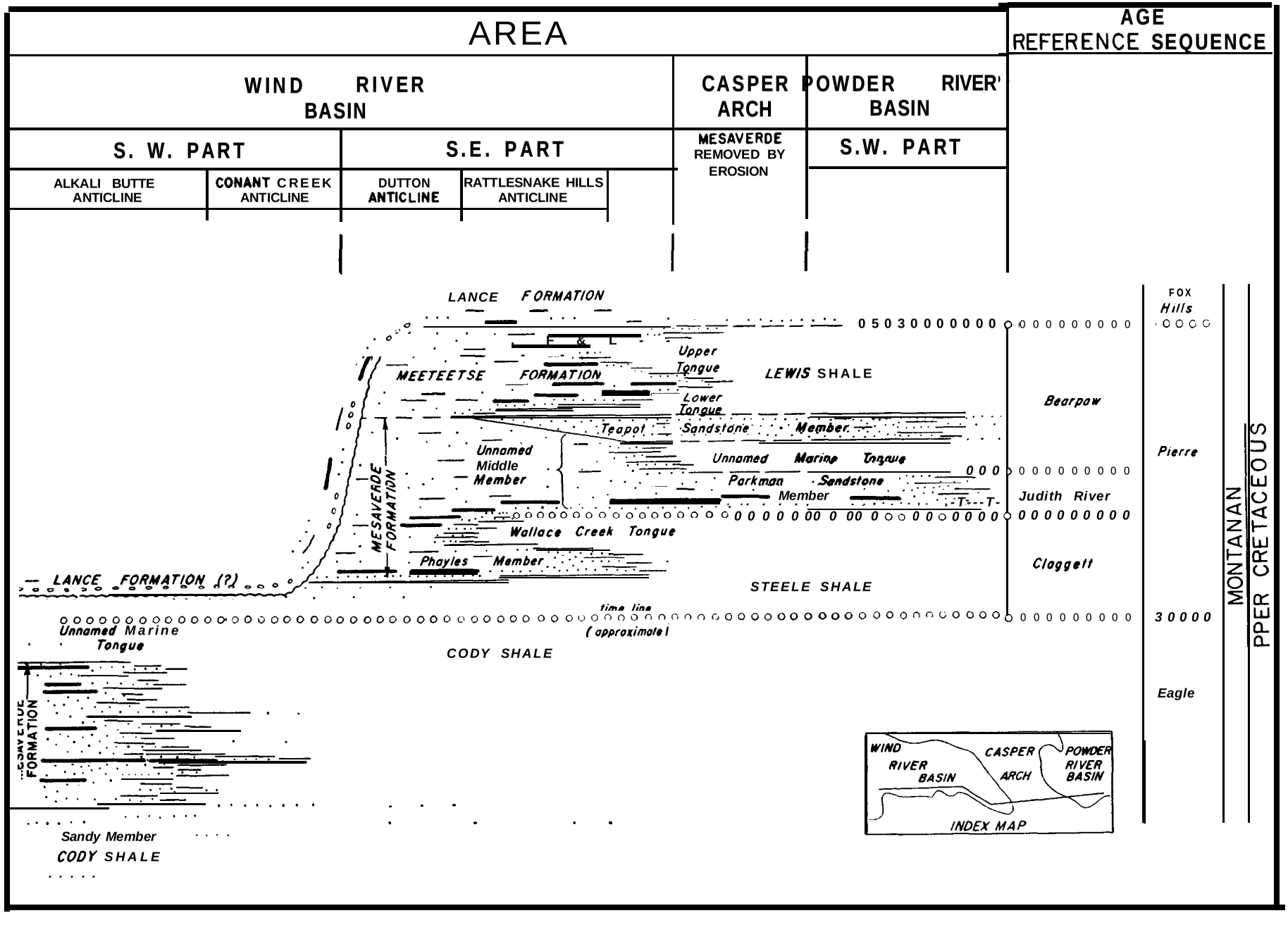
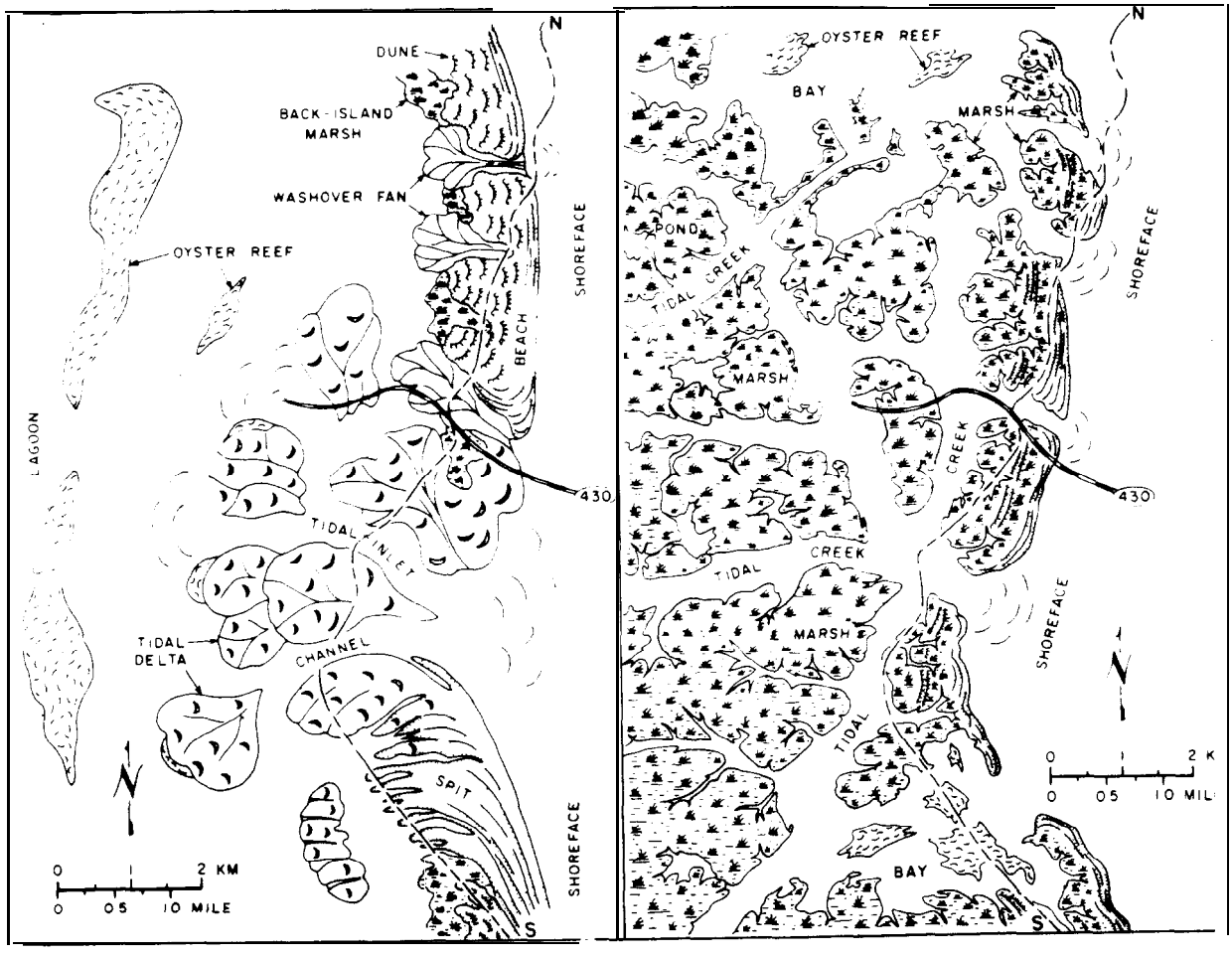


Figure 4-15. Diagrammatic Cross Section Showing the Coalbed Continuity and Stratigraphic Relationship in the Mesaverde Formation (Barwin, 1961) (Courtesy of the Wyoming Geological Association)



A B

Figure 4-16. Diagrammatic Paleographic Maps of Mesaverde Coalbed Depositional Environments, A Shows Formation of the Barrier Bar, Tidal-Inlet Channel, Tidal Delta and Washover Fan on the Seaward Side of the Lagoon. B Shows That This Paleogeography is Succeeded by Formation of Marshes in the Landward and Seaward Sides of the Nearly Filled Lagoon (Flores, 1978) (Courtesy of the Rocky Mountain Assoc. of Geologists)

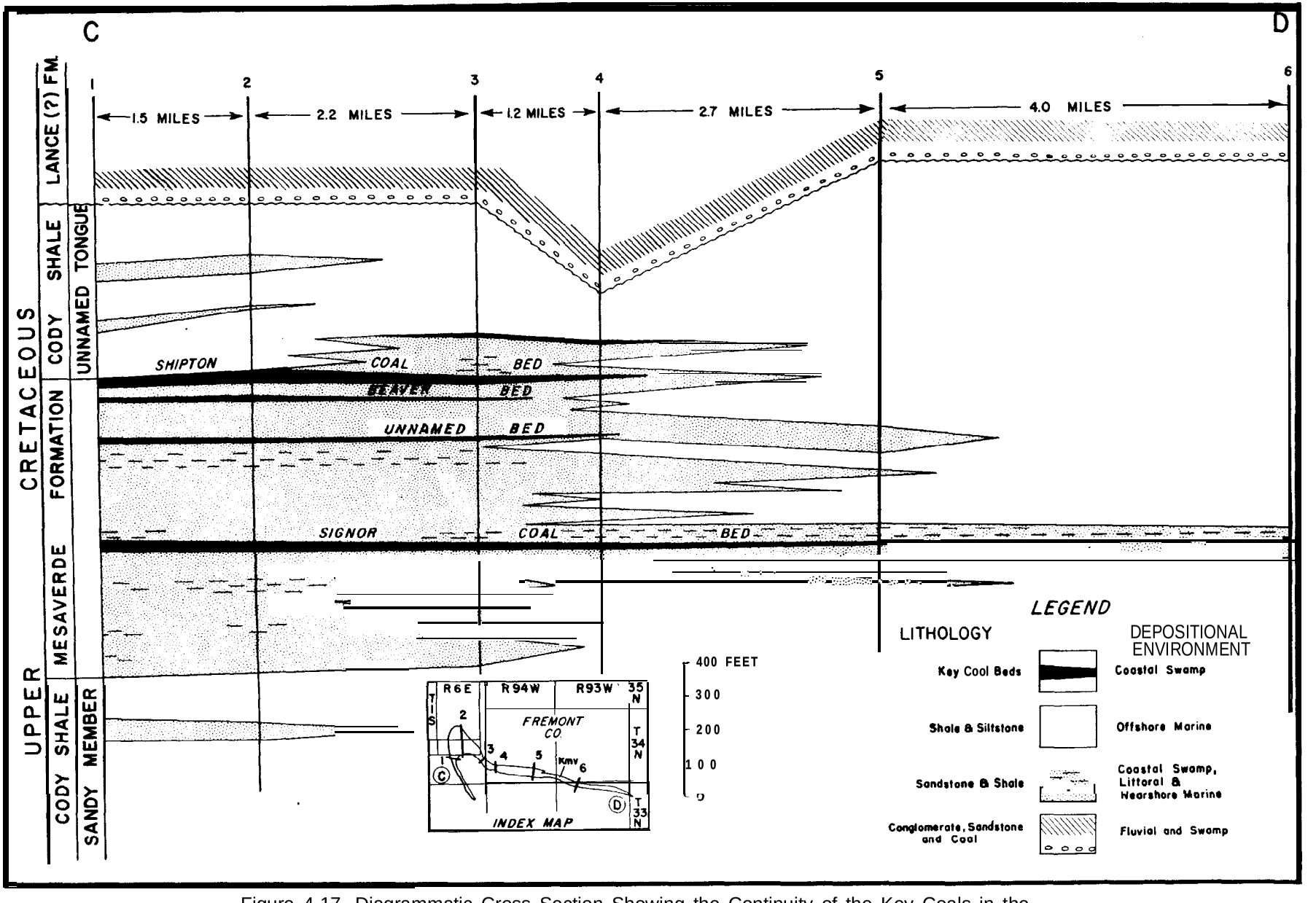


Figure 4-17. Diagrammatic Cross Section Showing the Continuity of the Key Coals in the South-Southwestern Part of the Wind River Basin (Barwin, 1961) (Courtesy of the Wyoming Geological Association)

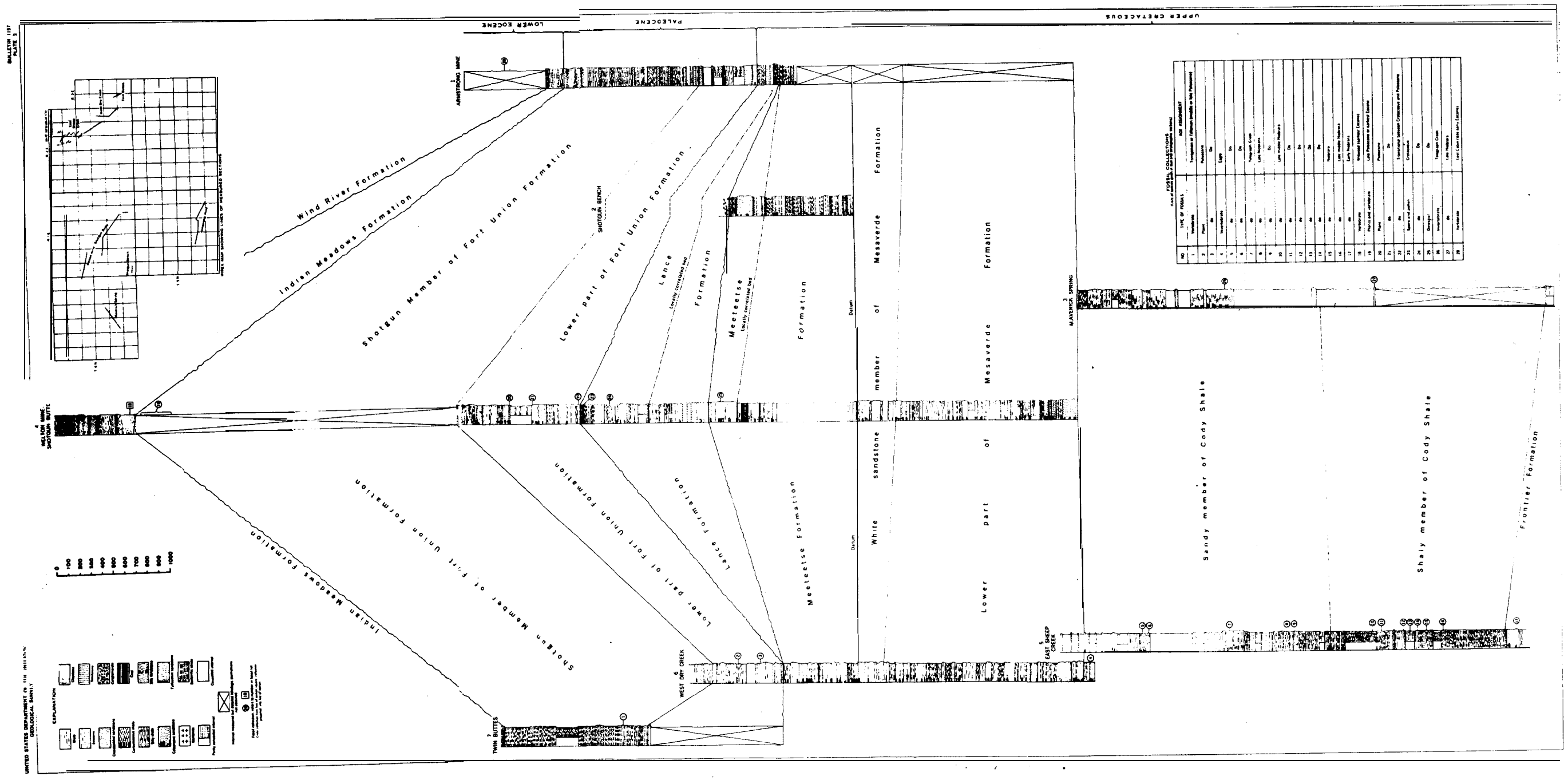


Figure 4-18. Stratigraphic Sections of Upper Cretaceous and Lower Tertiary Rocks in Shotgun Butte Area, Wyoming (Keefer and Troyer, 1964)

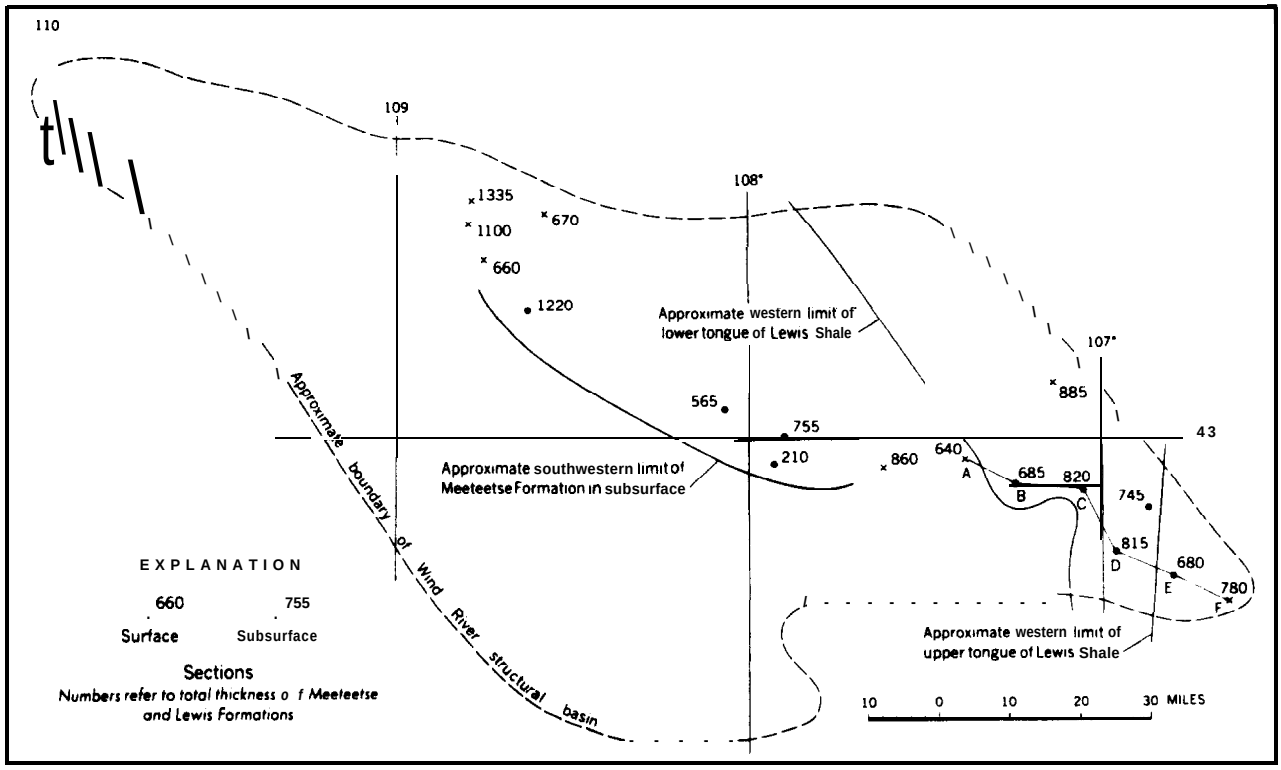


Figure 4-19. Sketch Map of the Wind River Basin Showing Thicknesses and Distribution of Meeteetse Formation and Lewis Shale (Keefer, 1965)

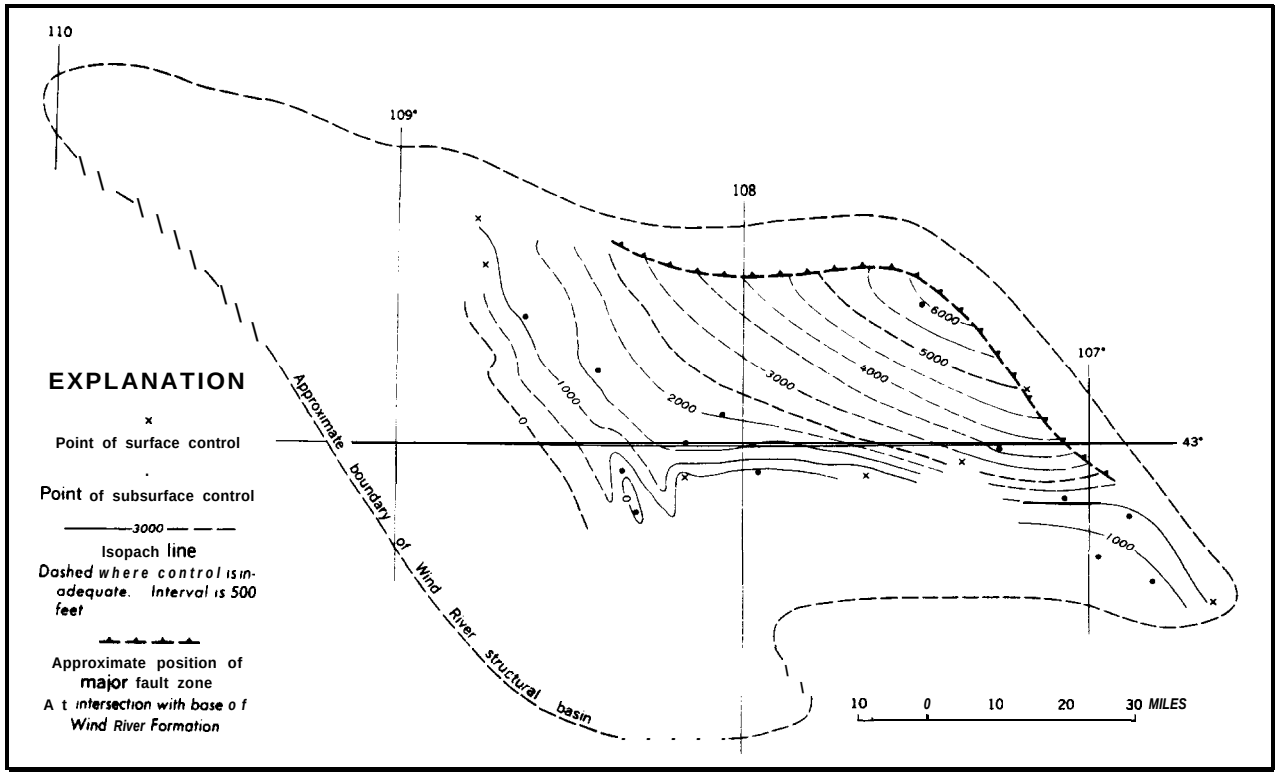


Figure 4-20. Isopach Map of the Lance Formations (Keefer, 1965)

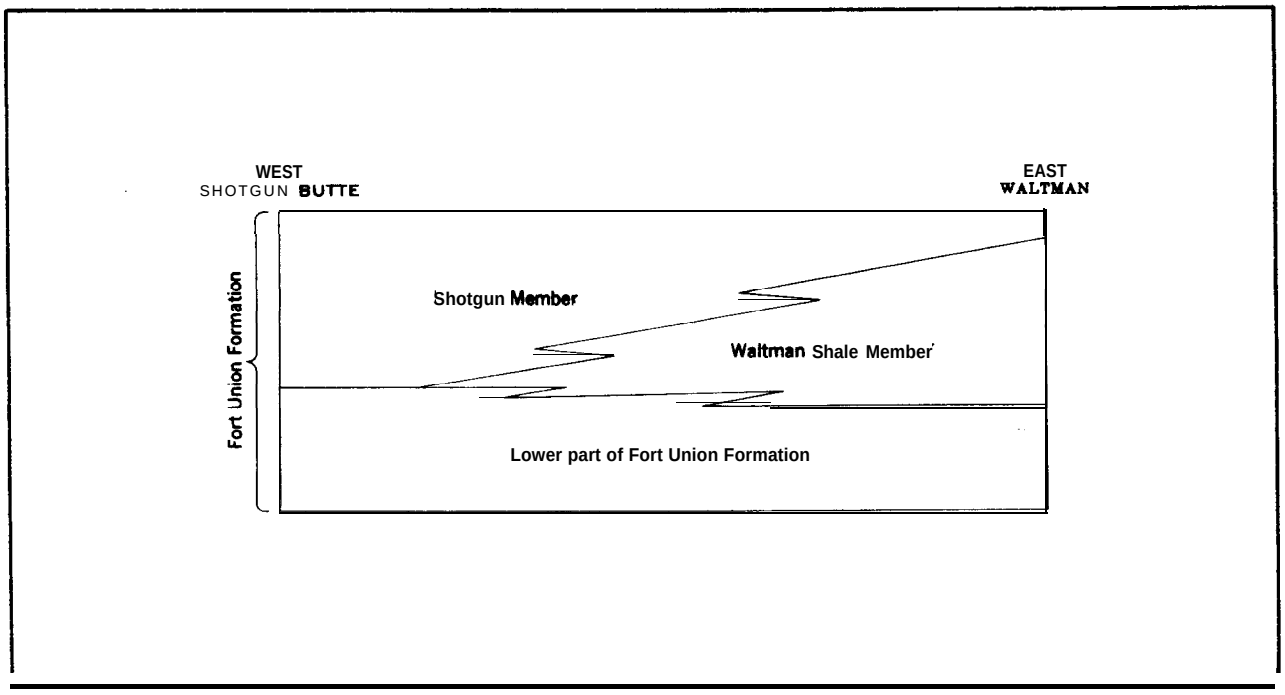


Figure 4-21. Sketch Showing General Relations of Various Members of the Fort Union Formation from West to East Along North Margin of the Wind River Basin (Keefer and Troyer, 1964)

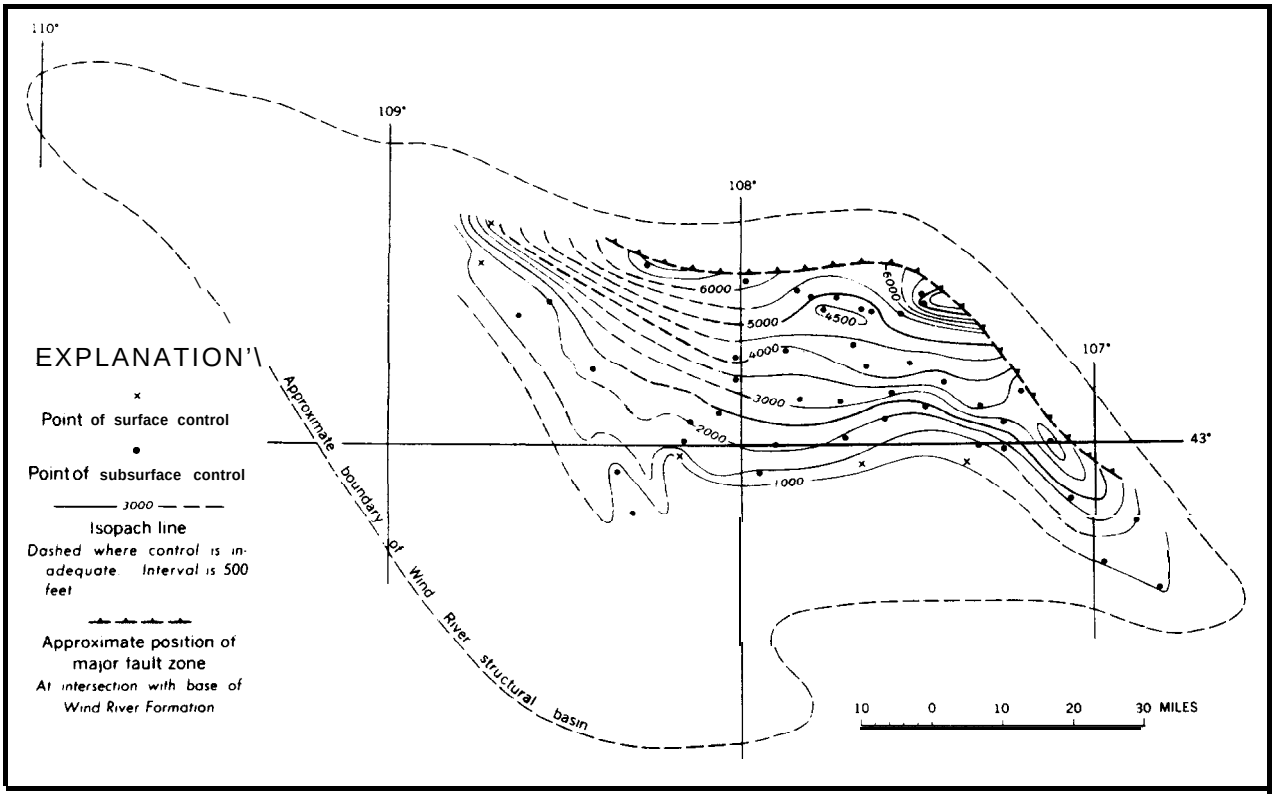
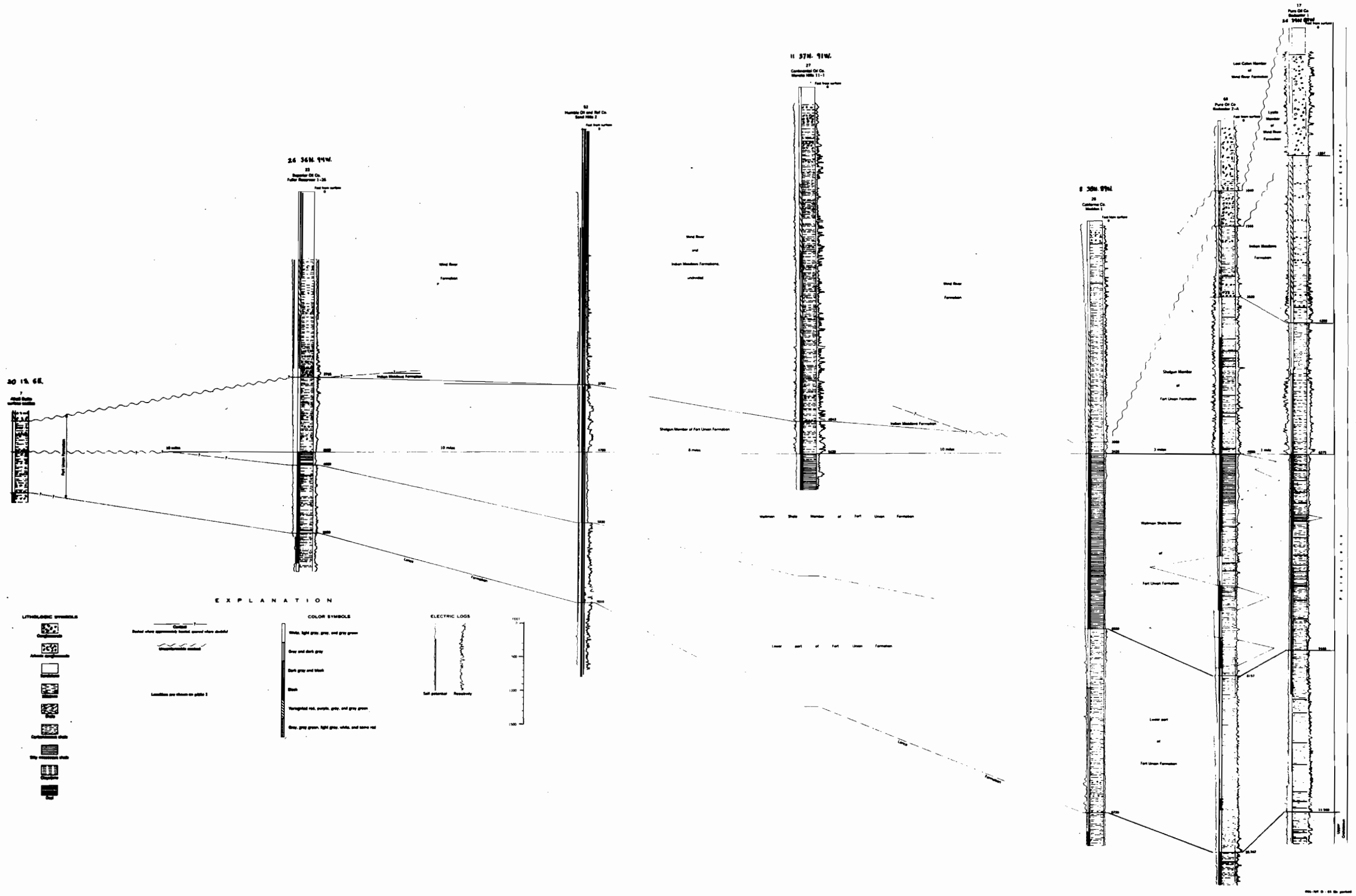


Figure 4-22. Isopach Map of the Fort Union Formation (Keefer, 1965)


26 36N. 99W.
22
Superior Oil Co.
Fuller Reservoir 1-26
Feet from surface
0
Wind River
Formation
Indian Meadows Formation
2700
4700
5000
5800
10 miles
30 1N. 6E.
7
Fort Union Formation
10 miles
52
Humble Oil and Ref Co.
Sand Hills 2
Feet from surface
0
11 37N. 91W.
27
Continental Oil Co.
Wamsutter 11-1
Feet from surface
0
Wind River
Formation
Indian Meadows Formation
Shotgun Member of Fort Union Formation
8 miles
10 miles
Wasatch Shale Member of Fort Union Formation
Lower part of Fort Union Formation
8 30N. 99W.
20
Continental Oil Co.
Madden 1
Feet from surface
0
3 miles
Shotgun Member
of
Fort Union Formation
Wasatch Shale Member
of
Fort Union Formation
Lower part
of
Fort Union Formation
17
Pure Oil Co.
Sublette 1
24 30N. 99W.
Feet from surface
0
Lost Cabin Member
of
Wind River Formation
46
Pure Oil Co.
Sublette 2-A
Feet from surface
0
Lander
Member
of
Wind River
Formation
Indian Meadows
Formation
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
9000
9500
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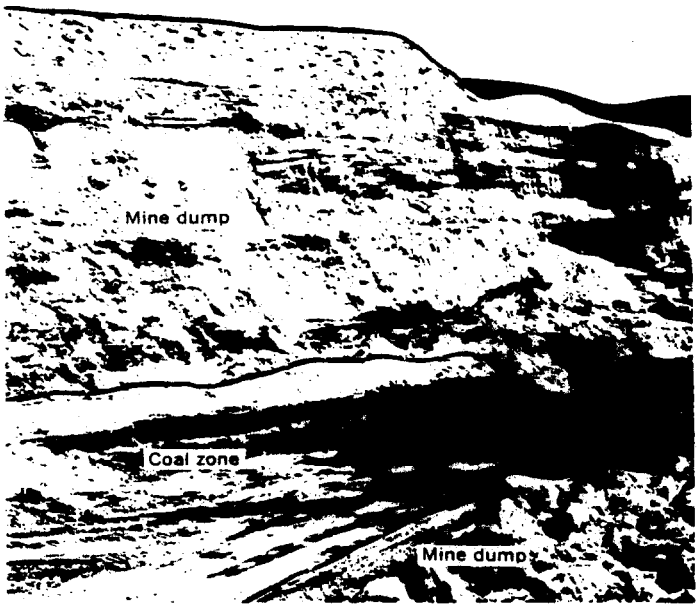
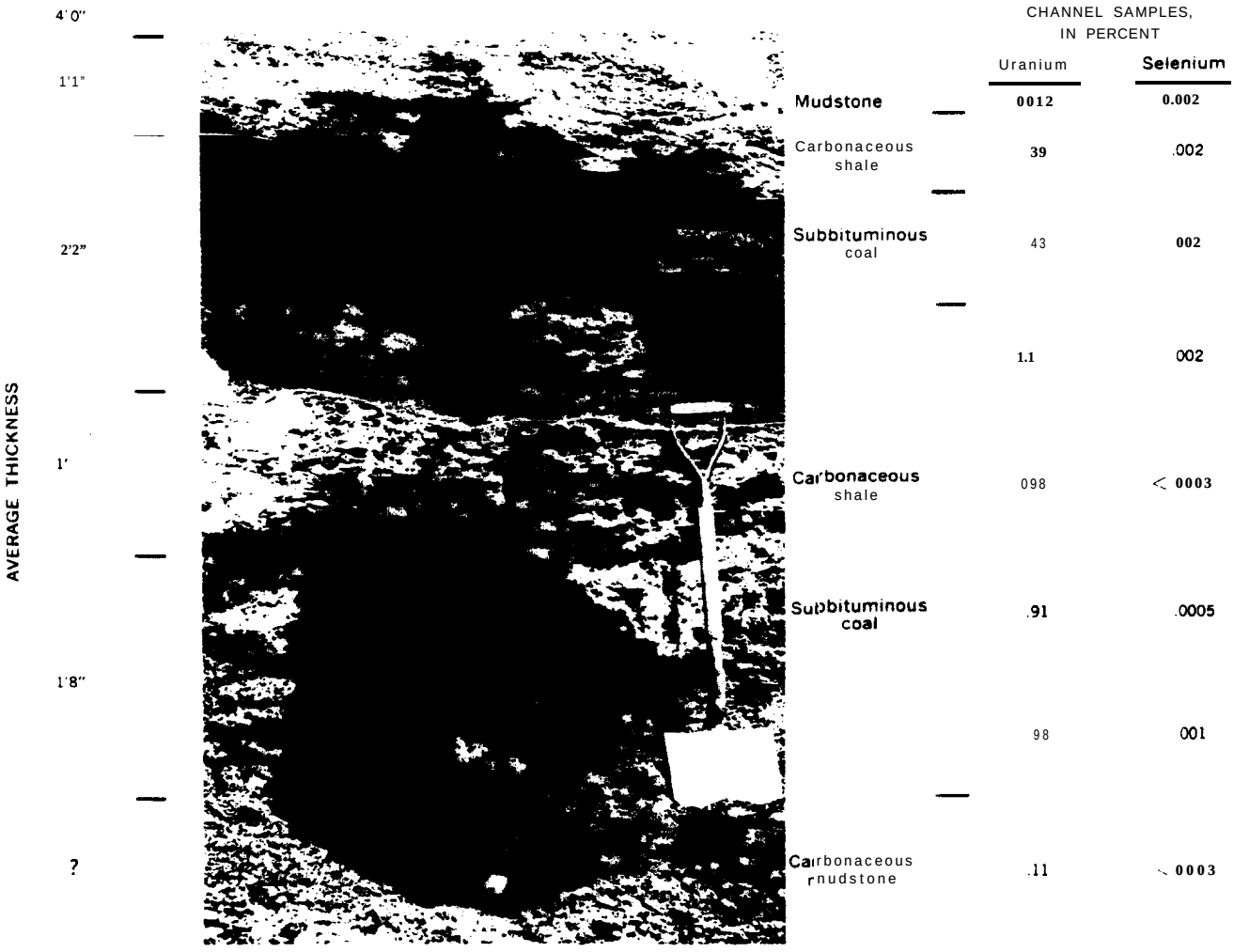


A



B

Figure 4-24. Coal and Carbonaceous Shale of the Central Carbonaceous Zone at the Lucky Mc No. 2 Open-Pit Uranium Mine. A. Distant view. B. Close view. Sec. 26, T. 32 N., R. 90 W. (Soister, 1968)

Table 4-I. Wyoming Coal Characteristics (Glass, 1978)

GEOGRAPHIC AREA	RANK	BED THICKNESSES (FEET)	MOISTURE[1] (%) (AR)	ASH[1] (%) (AR)	SULFUR[1] (%)	HEAT VALUE[1] (BTU/LB.) (AR)	HARDGROVE GRINDABILITY INDEX[1]
Northeastern Wyoming	Lignite Subbituminous' Bituminous	Max.: 220 Range': 12-100 Avg.': 70	Range 20.3-29.8 Average 26.3	Range 4.4-11.4 Average 7.9	Range 0.45-0.6 Average 0.54	Range 75508700 Average 8300	Range 30-53 Average 45
Southern Wyoming	Subbituminous' Bituminous'	Max.:50 Range': 4-35 Avg.': 20	Range 10.2-20.5 Average 12.4	Range 4.2-12.2 Average 7.1	Range 0.4-0.9 Average 0.52	Range 9270-I 1,700 Average 10,500	Range 45-80 Average 49
Western Wyoming	Subbituminous' Bituminous	Max.: 110 Range': 5-90 Avg.': 16.5	Range 20.4-20.9 Average 20.8	Range 3.0-4.8 Average 4.5	Range 0.6-0.7 Average 0.6	Range 9500-10,200 Average 9600	Range 53-57 Average 54
Northcentral Wyoming	Subbituminous' Bituminous	Max.: 50 Range': 15-20 Avg.': 13	Range 10.7-12.8 Average 12.3	Range 5.0-9.4 Average 7.4	Range 0.3-0.6 Average 0.4	Range 10,730-I 1,246 Average 10,970	Range 30-80 Average 49

'Beds currently mined. (Table compiled by Geological Survey of Wyoming, March 1978)
(AR) = As Received

Table 4-2. Facies and Depositional Environment Correlation for the Mesaverde Formation, Wind River Basin (Shapurji, 1978) (Courtesy of the Wyoming Geological Association)

ENVIRONMENTS	FACIES
MARINE Shallow Neritic — offshore marine	Dark to very dark gray shale; thin-bedded siltstone; tan sandstones.
MARINE AND TRANSITIONAL Shallow Neritic — nearshore marine Littoral	Light gray and tan massive sandstone; dark gray shale
NONMARINE Coastal swamp, lagoonal, fluvial.	Light gray and tan lenticular sandstone; dark gray shale; coal

Table 4-3. Summary of Signor and Lander Coal Analyses from the Alkali Butte and Hudson (Lander) Coal Fields, Fremont County, Wyoming (Glass, 1978)

ALKALI BUTTE

AS RECEIVED	SINGLE ANALYSIS
Moisture (%)	26.0
Volatile Matter (%)	30.7
Fixed Carbon (%)	38.1
Ash (%)	5.1
Sulfur (%)	0.6
Heat Value (Btu/lb)	8,760

HUDSON (LANDER)

		AVERAGE	
AS RECEIVED BASIS	RANGE (37 ANALYSES)[1]	PROXIMATE (37 ANALYSES)	ULTIMATE (7 ANALYSES)
Moisture (%)	16.0-24.7	21.2	
Volatile Matter (%)	29.1-38.1	32.9	
Fixed Carbon (%)	33.2-45.0	39.8	
Ash (%)	2.8-l 1.8	6.1	4.6
Sulfur (%)	0.3-l .3	0.6	0.6
Hydrogen (%)			6.2
Carbon (%)			55.2
Nitrogen (%)			1.2
Oxygen (%)			32.2
Heat Value (Btu/lb)	8,870-10,510	9,480	

'These analyses came from the Poposia. Poposia No. 2, Rogers, George, Big Dunne, Dunne Little, Schroeder, Wyoming Central, Hickey, McKinley, Indian, and Mitchell No. 2 deep mines. Samples were a mixture of channel, tipple, and delivered samples. Usually the entire bed thickness was not sampled, and many samples were cleaned or screened before analysis. Analyses were done by the U.S. Bureau of Mines and published in various reports listed in the references.

Table 4-4. Major and Minor Elements in 48 Wyoming Coal Samples in Percent on a Whole-Coal Basis (Glass, 1975; Swanson, et al., 1976)

	WYOMING RANGE	WYOMING AVERAGE	U.S. AVERAGE
Silicon	0.41-5.50	1.70	2.6
Calcium	0.13-2.10	0.75	0.54
Aluminum	0.17-2.50	0.72	1.4
Iron	0.15-2.100	0.51	1.6
Magnesium	0.026-0.340	0.17	0.12
Potassium	0.005-0.370	0.063	0.18
Sodium	0.003-0.190	0.044	0.06
Titanium	0.001-0.130	0.038	0.08
Phosphorous	0.0021-0.0440	0.0121	- -
Chlorine	0.004-0.026	0.010	- -
Manganese	0.0007-0.0492	0.004	0.01

Table 4-5. Average Trace Element Concentrations (Rank-Ordered) in 48 Wyoming Coal Samples in Parts per Million on a Whole-Coal Basis (Glass, 1975; Swanson, et al., 1976)

ELEMENT	WYOMING AVERAGE	U.S. AVERAGE
Barium	300	150
Strontium	100	100
Boron	70	50
Fluorine	70	4
Cerium	20	- -
Zinc	17.9	39
Vanadium	15	20
Zirconium	15	30
Neodymium	15	3
Copper	8	19
Chromium	7	1.5
Lanthanum	7	- -
Nickel	5	15
Yttrium	5	10
Lithium	4.6	20
Gallium	3	7
Arsenic	3	15
Lead	3	16
Thorium	2.7	4.7
Cobalt	2	7
Germanium	2	- -
Neobium	1.5	- -
Scandium	1.5	3
Molybdenum	1.0	3
Uranium	0.9	1.8
Selenium	0.8	4.1
Ytterbium	0.5	1
Antimony	0.4	1.1
Cadmium	0.15	1.3
Mercury	0.10	0.18

Table 4-6. Summary of Kinnear and Shipton Coal Analyses from Pilot Butte, Alkali Butte, and Shotgun Butte Coal Fields, Respectively, in Fremont County, Wyoming (Glass, 1978)

KINNEAR COAL

AS RECEIVED BASIS	SINGLE ANALYSIS
Moisture (%)	14.8
Volatile Matter (%)	34.0
Fixed Carbon (%)	42.6
Ash (%)	8.6
Sulfur (%)	0.9
Heat Value (Btu/lb)	10,193

SHIPTON COAL

	AS RECEIVED BASIS[1]	MOISTURE-FREE BASIS
Moisture (%)	34.1	
Volatile Matter (%)	30.4	46.2
Fixed Carbon (%)	29.3	44.4
Ash (%)	6.2	9.4
Sulfur (%)	0.6	0.9
Heat Value (Btu/lb)	6,080	9,230

WELTON COAL

AS RECEIVED BASIS	SINGLE ANALYSIS
Moisture (%)	15.7
Volatile Matter (%0	28.5
Fixed Carbon (%)	47.7
Ash (%)	8.1
Sulfur (%)	0.35
Heat value (Btu/lb)	9,920

'The sample was probably weathered as it was only 45 feet from the outcrop.

5. POTENTIAL METHANE RESOURCE

5.1 PREVIOUS STUDIES/ANALYSES

No previous studies have been concerned with the determination of coalbed methane gas in the Wind River Basin. Results presented are from cooperative arrangement between the USGS coal resource investigations group and the MRCP.

Gas emission data are nonexistent for the abandoned small mines along the rim of the coal basin (Figure 3-7). Minor amounts of methane gas have been reported from the Wyoming Central Mine in the Lander (Signor) coalbed south of Hudson, Wyoming (Figure 5-l).

5.2 WIND RIVER MRCP WELL TEST DATA

Methane Recovery from Coalbeds Project data on the methane content of Wind River Basin coals presently are limited to coring and well testing on the Wind River Indian Reservation, Fremont County, Wyoming (Figure 5-2). Seven Mesaverde coal samples have been desorbed by TRW from the three USGS wells:

- WR-11 (U); 17, 5N., 1W.: 1 core (184-190')
- WR-18 (DD); 22, 33N., 95W.: 2 cores (158-164') (188-192')
- WR-27 (A-l); 29, 1S., 6E.: 4 cores (572-578') (644-648') (830-831') (965-969')

The desorption test results are inconclusive. No gas was obtained from the cores, but proximate analyses and rank designations are scheduled for them.

5.3 ESTIMATE RESOURCE VOLUME

Absence of methane gas in the tested shallow coalbeds makes it difficult to construct a resource estimate for the Wind River Basin. USGS drill hole T, Figure 5-2, had a documented gas show in the Frontier Formation. The gas blew out the drill mud and cement in the well (Windolph, personal communication, 1981). However, it is not known whether the gas was associated with the Frontier coals.

5.3.1 Wind River Coal Resource Assessment

5.3.1.1 Early USGS Estimates

In 1917 Campbell established the first resource estimates on the amount of coal present in the Wind River Basin (Table 5-l). Unfortunately, his estimates of 17 billion short tons include the Big Horn Basin, Wyoming, and the Red Lodge coal field in Montana.

5.3.1.2 Missouri River Basin Study

Berryhill et al. (1950) estimated the coal resources in the Wind River Basin on a township and range basis, classes of reserves, and on the reliability of available data. The three coal reserve categories identifying the reliability of data are: measured, indicated, and inferred. The classes of reserves presented are subdivided according to coal rank, bed thickness, and overburden thickness.

Rank of Coal -- Coal rank is determined according to the standard ASTM specifications.

Measured Reserves -- Measured reserves include beds for which positive information as to thickness and extent is available from surveys of the outcrop and from mine workings and drill records. The points of observation and measurement are judged to be so closely spaced that the computed tonnage can be considered within 20 percent of the true tonnage. Although distances between measured sections will vary considerably in different beds and under different conditions in the same bed, the points of observation are generally about one-half mile apart. The outer limit of a block of measured reserves, therefore, usually is about one-quarter mile from the last point of definite information or approximately half the distance between points of observation. Where no data are available other than measurements along the outcrop, but where continuity of the outcrop is measured in miles and conditions suggest that the coal is present at a considerable distance from the outcrop, a smooth line drawn approximately one-half mile from the outcrop is taken as the limit of measured reserves.

Indicated Reserves -- Indicated reserves are computed partly from specific measurements and partly from the projection of visible data for considerable distances on 'geologic evidence. In general, the points of observation are approximately 1 mile apart, or as much as 1.5 miles for

beds of known continuity. For example, if drilling on half-mile centers has proved a block of coal of fairly uniform thickness and extent, the area of measured coal is considered to extend for one-quarter mile on all sides of the area actually drilled. If from geologic evidence the bed is believed to have greater continuity, this area of measured reserves is surrounded by a belt of indicated reserves that, according to the judgment of the appraiser, may be as much as 1.5 miles wide. Where only outcrop measurements are available, but where the bed is continuous over long distances and conditions suggest that the coal is present at comparable distances back of the outcrop, the area of the indicated reserves is bounded by a line drawn 2 miles behind the outcrop and the half-mile line drawn to limit measured reserves. After the total area of coal occurrence had been determined as described, it was divided on the work maps into subordinate areas of measured, indicated, and inferred reserves in accordance with the definitions outlined in preceding paragraphs. The area underlain by coal in each category, rank, and depth and thickness range was then measured with a planimeter.

Berryhill et al. (1950) established the weight of the subbituminous coal to be 1,770 tons per acre-foot. The average thickness used in calculations was a weighted average of all thickness figures within the measured areas. These figures represented the total thickness of the bed minus the total thickness of partings more than three-eighths-inch thick. All coalbeds dipping less than 18" were considered horizontal for purposes of making reserve calculations, as the correction for dip, less than 5 percent, was less than the normal variation in the thickness of the bed. Similarly, where the dip of the coalbeds was steeper than 78°, they were assumed to be vertical and to extend to a depth of 3,000 feet. A correction for dip was employed in estimating reserves in all coalbeds dipping between 18" and 78°.

Berryhill et al. (1950) reported that certain counties in Wyoming contain large areas that in all probability contain minable coal at depths of less than 3,000 feet but for which little or no information is available. Although it would have been possible for Berryhill et al. to make rough calculations on a regional basis of the coal in such areas, they decided to omit them from the accompanying estimates, which thus are

confined to areas where definite information on extent, and thickness of the coalbeds was available. Table 5-2 provides this information for Fremont and Natrona Counties, Wyoming. Tables 5-3, 5-4, and 5-5 show the results of the Berryhill study reported on a township and range basis and by coal field. The total for Fremont County is 733,760,000 tons, and for Natrona County, 167,160,000 tons. The Wind River Basin has a total of 900,920,000 tons of coal. Berryhill et al. (1950) estimated 875,660,000 tons of coal in established coal fields within the coal basin (Table 5-6).

Inferred Reserves -- Those for which estimates are based largely on broad general knowledge of the geological characteristics of the bed or region, supported by few or no actual exposures or measurements. In general, inferred reserves lie outside the limits defined above for measured and indicated reserves, but only in areas where there is good evidence for believing that coal, in the thickness and of the rank given, is actually present.

Distinction Between Original, Remaining, and Recoverable Reserves -- The estimates given by Berryhill et al. (1950) are of original coal reserves in the ground before mining. They include the narrow weathered zone at the outcrops, and coal under railways, roads, and the like, but exclude all known areas of burned coal. Calculation on the basis of original reserves, rather than of reserves remaining as of a certain date, is the only practicable procedure in Wyoming, where many coal-bearing areas have not been surveyed and where total production is relatively insignificant compared to total reserves in the Wind River Basin. Estimates of remaining and recoverable reserves as of any given time can be ascertained more readily, therefore, if records of original reserves and amount of coal mined and lost in mining are kept separately.

Methods of Estimating Reserves -- Berryhill prepared work maps, usually on the scale of 1 or 1/2 inch to the mile, on which all mapped coal outcrops, drill holes, mines, location and thickness of measured sections, and other data were plotted. In areas where several coalbeds crop out, separate maps were made for each bed.

After assembling this basic information, lines were drawn on the maps bounding the areas for which sufficient evidence was available to calculate reserves in each category, depth, and thickness range. A continuous bed

extending around a spur of the basin was considered to underlie the area enclosed by the line of outcrop. For all other beds the length of outcrop, within each thickness range, was considered to establish the presence of coal in a semicircular area extending from the outcrop and having a radius equal to half the length of the outcrop. Where the information was obtained from an isolated mine working, the coal was considered to extend beyond the working in an arc with a maximum radius of a half mile. Where the information was from an isolated drill hole too far removed from other holes or out crops to be incorporated with other established coal areas, the bed was considered to extend in a circle with a maximum radius of one-half mile beyond the hole.

Thickness of Beds -- The minimum thickness of coal included in the estimates of reserves is 14 inches for bituminous coal and 2.5 feet for subbituminous coal and lignite. Coal thicker than the minimum for each rank is divided into three thickness groups. For bituminous coal the ranges are 14 to 28, 28 to 42, and over 42 inches. For subbituminous coal and lignite the thickness ranges are 2.5 to 5, 5 to 10, and over 10 feet.

Thickness of Overburden -- The estimated reserves are subdivided into three depth ranges: less than 1,000, 1,000 to 2,000, and 2,000 to 3,000 feet. No coal under more than 3,000 feet of cover is included in the Missouri River Basin Study estimates.

5.3.1.3 Alkali Butte and Big Sand Draw Coal Reserve Study

Thompson and White (1952) estimated original coal reserves for the Alkali Butte and Big Sand Draw coal fields. Their study also included data from Berryhill et al. (1950) for the Beaver Creek coal field. Coal reserves were assigned to the Signor, Shipton, Lower Lance, and Downey coalbeds (Tables 5-7 and 5-8).

Reserve Calculations -- Because most data on coal in the Alkali Butte and the Big Sand Draw fields were obtained by surface mapping of the coal outcrops, and because of the observed lenticularity of the beds, Thompson and White (1952) found it necessary to make certain basic assumptions in calculating coal reserves. Measured coal was defined as coal lying in a block one-quarter to one-half mile downdip behind a block of measured coal. Inferred coal was defined as coal in a block one-half to one mile downdip

behind a block of measured and indicated coal, or behind a block of indicated coal. In general, no coal classed as measured is more than one-quarter mile from the outcrop; no coal classed as indicated is more than one-half mile from the outcrop; and no coal classed as inferred is more than one-mile from the outcrop.

A somewhat more conservative set of definitions was formulated for coal in the Lance bed, which is poorly exposed, bonier, and probably more lenticular than other beds in the two fields (Thompson and White, 1952). A further consideration is the fact that the Lance Formation, which contains the Lance coalbed, was deposited unconformably on underlying Cretaceous rocks, and the Lance bed may be absent locally owing to erosion during Lance time, or to topographic relief on the Cretaceous rocks. For these reasons, coal in the Lance bed was classed only as indicated or inferred, and coal classed as indicated was projected only one-quarter mile from the outcrop, and coal classed as inferred was projected only one-half mile from the outcrop.

Thompson and White (1952) reported tonnage grand totals (total measured, indicated, and inferred reserves) for the following coalbeds:

- Downey - 71,830,000
- Signor - 58,780,000
- Beaver - 3,470,000
- Shipton - 40,520,000
- Lance Coal - 5,780,000

5.3.1.4 Recent Estimates

Glass and Roberts (1978) recombined coal resource estimates from Berryhill et al. (1950), Thompson and White (1952), and Keefer and Troyer (1964) to arrive at a total original coal resource (>2.5 feet thick) of about one billion tons (Table 5-9).

This revised estimate is about 150 million tons over the original estimate made by Berryhill and others (1950). The coal lies between 0 and 3,000 feet of the surface.

Of this original resource, 100.7 million remaining tons is (1) in the measured or indicated categories of reliability, (2) less than 1,000 feet below the surface, and (3) 5 or more feet thick. These three parameters delimit today's potentially recoverable portion of the resource, called

reserve base. Allowing for future mining losses equal to production, this resource reduces to a recoverable reserve base of about 50.4 million tons.

The only known strippable coal resources in the Wind River Coal Basin are in the Signor bed of the Alkali Butte coal field and in the Wilton coalbed in the Muddy Creek coal field. Combined, they total an estimated one million tons of strippable coal in these two coalbeds. Obviously, additional strippable coal reserves exist, but documentation of these reserves awaits more detailed geologic and/or mining reports. However, because of the relatively steep dips associated with the outcropping coals in the Wind River Basin, strippable reserves probably are not large (Glass and Roberts, 1978).

5.4 WIND RIVER COALBED METHANE RESOURCE BASE

No quantitative data are available on the specific amount of methane present in coalbeds of the Wind River Basin. The in-place methane is thought to be much greater than that indicated by desorption analysis of the USGS coal samples.

Coalbeds at very shallow depths (<1,000 feet) in the Wind River Basin are low in ASTM rank and exhibit none of the maturation characteristics needed for methane gas generation. These shallow coals in the Wind River do not contain methane gas as do those of the Arkoma Basin of Oklahoma and Arkansas. This was not known until the MRCP/USGS cooperative well tests were completed in late 1980. However, it is thought that in the deeper part of the basin, below the overpressure zone, methane gas has been generated in sufficient quantities.

Miller and VerPloeg (1980) conducted an inventory of the amounts of natural gas still to be developed in Wyoming from tight gas sands. They estimated that the Wind River Basin has about 15 Tcf of gas in place. The stratigraphic intervals containing substantial amounts of natural gas in unconventional reservoirs in the Wind River Basin have been identified. The intervals cover much of the Fort Union, most of the sandstone facies in the Mesaverde Group, and individual sandstone units in the Lower Cretaceous rocks (Miller and VerPloeg, 1980). These are the same intervals which contain coalbeds, although Miller and VerPloeg (1980) did not mention the methane associated with these coalbeds.

In order to develop a rationale for establishing the coalbed resource base for the Wind River Basin, it is necessary to examine the MRCP results from the neighboring Green River Basin. The range of coalbed methane values in the Green River Basin is great: 2.9 cu ft/ton (minimum value) to 539 cu ft/ton (maximum value) (McCord, 1980). Using this data, a triangular distribution plot can be made to estimate the probable distribution of gas in that basin. Application of these values to the Wind River Basin is reasonable in providing a test case for speculative coalbed methane resource values. Figure 5-3 was developed from this data using the principles of developing triangular distributions by assigning probabilities to the amount of methane that is contained in coalbeds. The development of this approach is discussed by Megill (1977). Figure 5-3 shows the cumulative percent frequency of occurrence for gas contents in Green River coalbeds. The cumulative percent frequency values are considered to be probability values that will allow an approximation of a real distribution from only three points (minimum, most likely, and maximum) (Megill, 1977).

Another uncertainty is the maximum amount of coal present in Wind River Basin. However, using the reasonable estimates of the total coal resource base, two scenarios were generated based on the range in values in the Green River Basin data. The first (conservative) addresses the shallow coal resources that lie entirely above the overpressure zones in the basin. Using estimates of 5 to 100 cu ft./ton gives an estimated in-place gas resource of 5.2 to 103 billion cubic feet of gas. The second scenario (optimistic) deals with deep-lying coals, most of which lie directly above and below the deep overpressured zones. Estimates of the gas content for this scenario range from 5 to 539 cu ft/ton and give an in-place gas resource of 20 to 2,220 billion cubic feet of gas. The estimates of these scenarios are presented in Table 5-10 and are reasonable in light of Miller and VerPloeg's methane resource estimations for the Wind River tight sands.

5.5 ABNORMAL FLUID PRESSURE ZONES

The development of overpressuring in sedimentary rocks may involve several processes, one of which is the active generation of large amounts of wet gas, Deep drilling in the Wind River Basin has encountered high

pressured shales, high temperatures, and high pressure gradients. Overpressured zones have been identified in the Lower Fort Union, Meeteetse, Mesaverde, Cody, and Frontier (Bilyeu, 1978; Miller and VerPloeg, 1980).

Law et al. (1980) made an evaluation of the generation of gas in the Green River Basin overpressure zones. Their study indicated that high reservoir pressure in gas-bearing sandstones greatly increases the potential for large in-place gas resources. Coalbeds in such an environment would be natural candidates for generating large amounts of gaseous hydrocarbons.

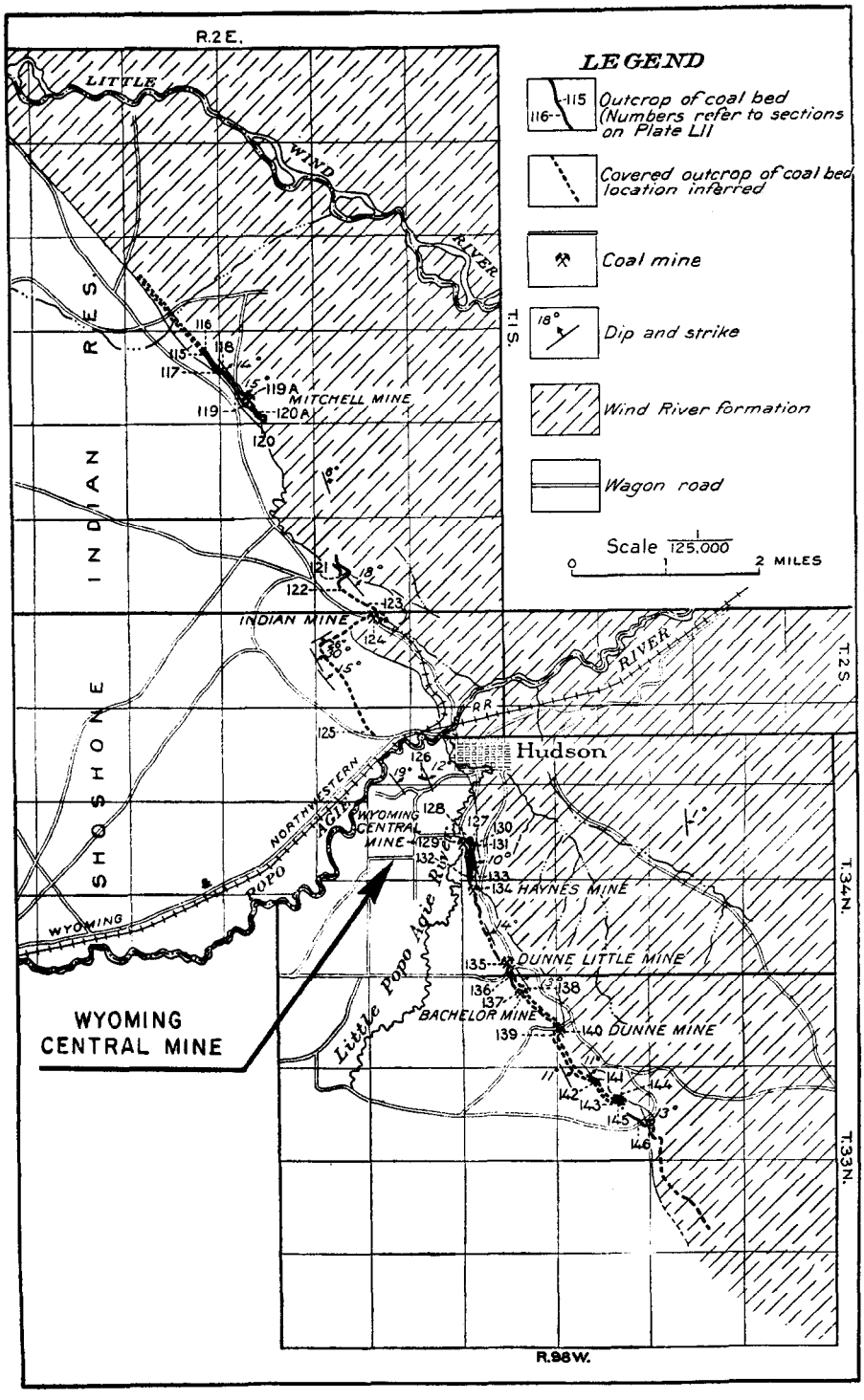


Figure 5-1. Map of the Hudson Coal Field, Fremont County, Wyoming (Woodruff and Winchester, 1912)

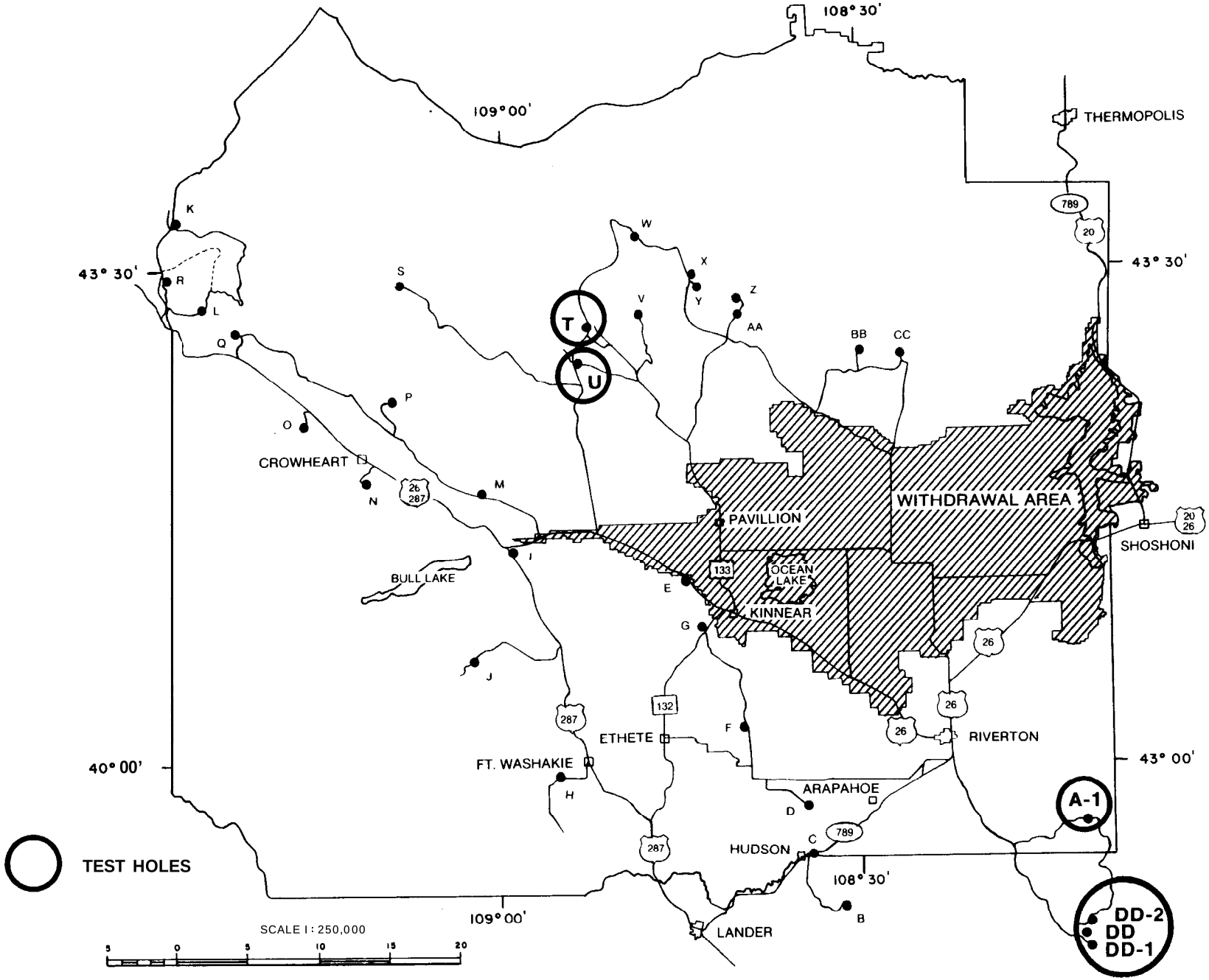


Figure 5-2. Location Map of the U.S. Geological Survey Test Holes From Which Coal Cores Were Recovered and Desorbed. Well designations A-l, DD, and U are U.S. Geological Survey field designations.

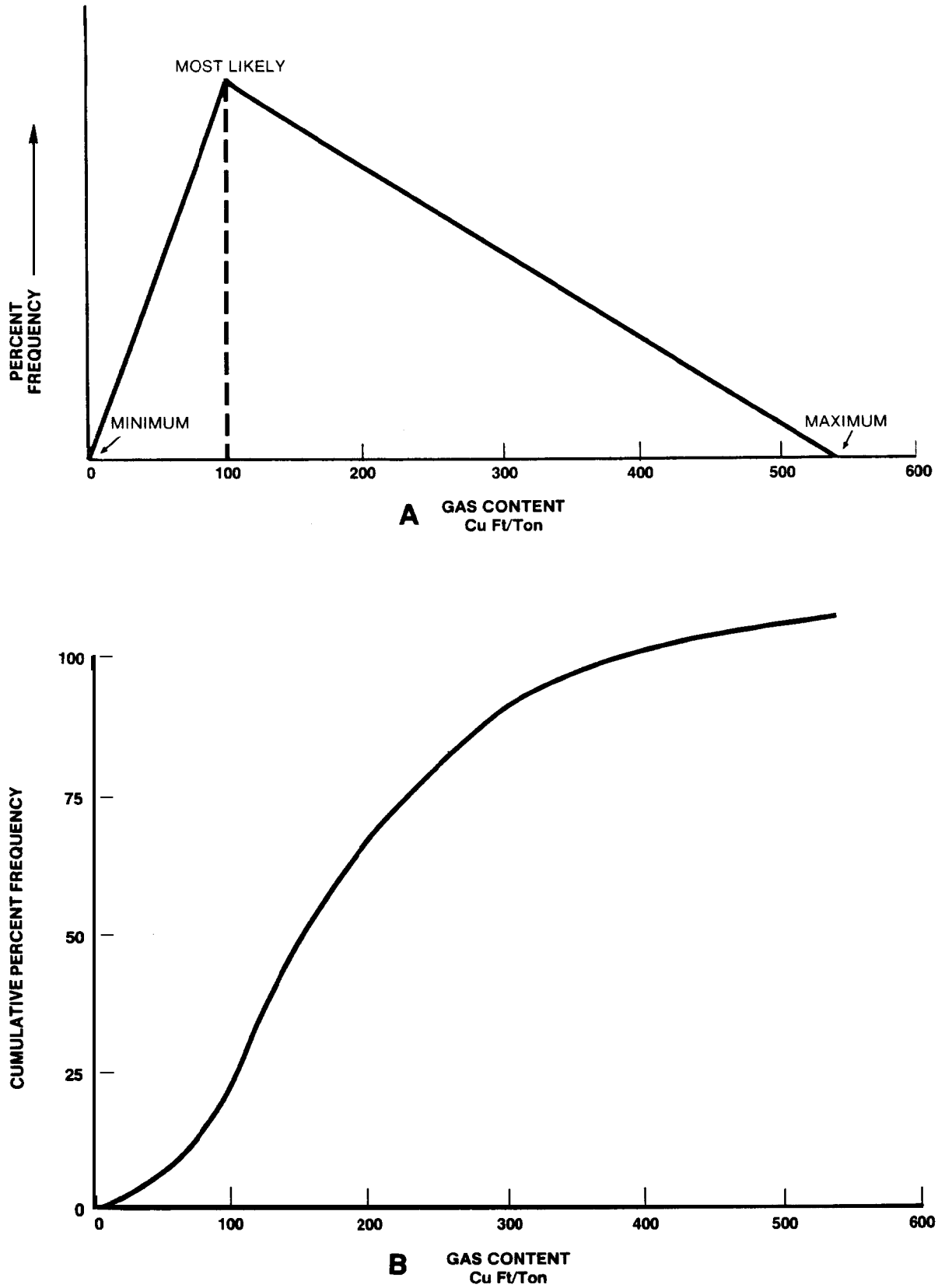


Figure 5-3. Basis for a Statistical Speculation of Methane Gas Resources in the Wind River Basin. A — triangular plot of minimum, maximum, and most likely values of the neighboring Green River Basin MRCP data. B — generated cumulative probability plot of this data.

Table 5-1. Original and Present Quantity of Coal in the Wind River Basin including the Big Horn Basin and Red Lodge Field (Campbell, 1917)

Anthracite and Semianthracite	**0**	**Coal Below Surface From 3,000 to 6,000 Feet**	12,010,000,000
Semibituminous Coal	**0**	**Production in 1913**	1,604,524
Bituminous Coal	**608.800900**	**Production in 1914**	1,612,941
Subbituminous Coal	4,706,700,000	**Total Production to End of 1914**	**15633,450**
Lignite	**0**		
Total Coal of All Ranks	5,315,500,000	**Estimated Supply Within 3,000 Feet of Surface**	5,291,000,000

Table 5-2. Areas Included in and Omitted from Reserve Estimates, by Counties (Berryhill, et al., 1950)

COUNTY	TOTAL COAL-BEARING AREA IN SQUARE MILES	COAL-BEARING AREA INCLUDED IN ESTIMATES IN SQUARE MILES	COAL-BEARING AREA OMITTED FROM ESTIMATES IN SQUARE MILES	PERCENTAGE OF COAL-BEARING AREA OMITED FROM ESTIMATES
Fremont	**2,467**	**140**	**2,327**	94.32
Natrona	**1,297**	**655**	**642**	49.50
Total	**3,764**	**795**	**2,969**	
Average		— —	— —	**72**

Table 5-3. Indicated Original Reserves of Subbituminous Coal in the Wind River Basin, in Millions of Short Tons (Berryhill, et al., 1950)

TOWNSHIP	0 TO 1,000 FEET OVERBURDEN				0 TO 1,000 FEET OVERBURDEN				2,000 TO 3,000 FEET OVERBURDEN				TOTAL IN ALL OVERBURDEN CATEGORIES			TOWNSHIP TOTAL
	THICKNESS OF BED			TOTAL	THICKNESS OF BED			TOTAL	THICKNESS OF BED			TOTAL	THICKNESS OF BED			
	2½'-5'	5-10	10' +		2½'-5	5-10	10' +		2½'-5	5-10	10' +		2½'-5'	5-10	10' +	
FREMONT COUNTY																
T.34N., R.89W.	1.25	–		1.25	–	–	–		–				1.25	–	–	
T.34N., R.90W.	2.45	.19	–	2.64	.20			.20		–		–	2.65	.19		2.84
T.35N., R.90W.	2.69	–		2.69	2.94			2 94			–		5.63	–	–	5.63
T.34N., R91.W.	9.98	5.63		15.61	12.77	1.13	–	13.90	11.10			11.10	33.85	6.76		40.61
T.34N., R.95W.	4.62	1.79	5.38	11.79	1.98	1.93	2.31	6.22	2.01	.26		2.27	8.61	3.08	7.69	20.28
T.33N., R.96W.	–	–	–		32.45	27.11	45.96	105 52	20.91	12.24	69.44	102.59	53.36	39.35	115.40	208.1 1
T.33N., R.98W.	6.01	.99		7.00	5.26	1.67	–	6.93	2.48	–		2.48	13.75	2.66		16.41
T.34N., R.98W.	3.03	.56		3.59	3.21	2.79	–	6.00	5.70	.56		6.26	11.94	3.91		15.85
T. 3N., R. 1W.	.36	–	–	.36		–					–		.36	–	–	.36
T. 5N., R. 1W.	–	.92		.92		.46	–	.46			–	–		1.38	–	1.38
T. 6N., A. 2W.	4.02	4.08		8.10	2.73	3.81	–	6.54	1 40	1 73		3.13	8.15	9.62	–	17 77
T. 6N., R. 1E.	3.20	12.25	–	15.45	–		–	–	–	–			3.20	12.25		15.45
T. 6N., R. 2E.	3.99	–	–	3.99	1.17	–	–	117	–		–		5.16			3 16
T.1S., R. 2E.	1 37		–	1.37	–	–		–		–			1.37	–		1.36
T. 2S., A. 2E.	3.63	–		3.63			–		–				3.63		–	3.63
T. 6N., R. 3E.	2.74	–		2.74	–			–	–		–		2.74		–	2.74
T. 1S., R. 6E.	–	–	–	–	.95			.95	4.83	–		4.83	5.78	–	–	5.78
T. 2S., R. 6E.	3.47	6.18	–	9.60	6.20	.37	–	6.66	2.75			2.75	12.51	6.55		1905
County total	52.81	32.59	5.38	SO.78	69.95	39.27	48.27	157.49	51.18	14.79	69.44	135.41	173.94	66.65	123.09	383.68
NATRONA COUNTY																
T.31N., N.82W.	2.32	.19	–	2.51	.34			.34		–	–	–	2.66	.19	–	2.85
T.32N., R.82W.	.27	.39		.66	.24	–		.24		–			.51	.39	–	.90
T.33N., R.82W.	.03		–	.03	–		–	–	–		–	–	.03		–	.03
T.33N., R.83W.	2.72	3.89	–	6.61	2.03	3.67	–	5.70	1.00	3.53	–	4.53	5.75	11.08	–	16.64
T.35N,, R84W.	1.83		–	1.83	1.39	–		1.39	.68	–		.68	3.90	–	–	3.90
T.35N., R85W.	14.15	2.65		16.80	11.09	.25	–	11.34	7.59			7.59	32.83	2.90	–	35.73
T.36N., R.85W.	3.78	3.91	–	7.69	2.76	2.47		5.23	1.83	1.14		2.97	8.37	7.52	–	15.89
T.33N., R.86W.	4.39	.12	–	4.51	.51	–		.51		–		–	4.90	.12	–	502
T.36N., R.86W.	9.18	2.94		12.12	8.26	2.17	–	10.43	4.98	.99		5.97	22.42	6.10	–	28.32
T.37N., R.86W.	–	8.33	–	8.33	–	7.14		7.14		3.57		3.57		19.04	–	19.04
T.33N., R.87W	5.51	2.66	–	8.17	5.84	–	–	5.84	3.16			3.16	14.51	2.66		17.17
T.34N., R.87W.	.02	–	–	.02	.74	–		.74	1.66	–		1.56	242	–	–	2.42
T.37N., R.87W.	2.74		–	2.74	2.35	–		2.35	117	–	–	1.17	6.26		–	6.26
T.34N., R.88W.	4.90	1.70		6.60	3.52	–	–	3 52	2.45	–	–	2.45	10.87	1.70	–	12.67
County Total	51.86	26.78	• –	78.62	39.07	15.70		54.777	24.52	9.23	–	33.75	115.43	51.71	–	176.14
Basin Total																550.82

Table 5-4. Inferred Original Reserves of Subbituminous Coal in the Wind River Basin, in Millions of Short Tons (Berryhill, et al., 1950)

TOWNSHIP	0 TO 1,000 FEET OVERBURDEN				1,000 TO 2,000 FEET OVERBURDEN				2,000 TO 3,000 FEET OVERBURDEN				TOTAL IN ALL OVERBURDEN CATEGORIES			TOWNSHIP TOTAL
	THICKNESS OF BED			TOTAL	THICKNESS OF BED			TOTAL	THICKNESS OF BED			TOTAL	THICKNESS OF BED			
	2½'-5'	5-10	10' +		2½'-5'	5-10	10' +		2½'-5	5-10	10' •		2½'-5	510'	10' •	
FREMONT COUNTY																
T.27N., R.90W.	–	.67	–	.67		–	–		–	–		–		.67	–	.67
T.28N., R.90W.	1.56	–	–	1.56							–		1.56		–	1.56
T 27N., R.93W.	–	–		–	3.32	2.21	–	5.53	7.52	5.75	2.88	16.15	10.84	7.96	2.88	2168
T.27N., R.94W.	1.33	–	–	1.33	–	–	–						1.33	–		1.33
T.34N., R.94W.	–	–	–	–	–	–	–		3.36	–		3.36	3.36		–	3.36
T.33N., R.96W.	–	–	–	–	–	–	–		48.36	33.46	122.63	204.47	48.36	33.48	122.63	20447
T.34N., R.96W.	–	–	–	–	–	–	–		19.58	10.54	64.77	94.89	19.58	10.54	64.77	94.89
T. 1S., R. 6E.		–	–	–	–	–	–		.41			.41	.41	–		
County Total	2.89	.67	–	3.56	3.32	2.21	–	5.53	79.23	49.77	190.28	319.28	85.44	52.65	190.28	328.37
Basin Total																328.47

Table 5-5. Original Reserves, in All Categories, of Subbituminous Coal in the Wind River Basin, in Millions of Short Tons (Berryhill, et al., 1950)

TOWNSHIP	0 TO 1,000 FEET OVERBURDEN				1,000 TO 2,000 FEET OVERBURDEN				2,000 TO 3,960 FEET OVERBURDEN				TOTAL IN ALL OVERBURDEN CATEGORIES			TOWNSHIP TOTAL
	THICKNESS OF BED			TOTAL	THICKNESS OF BED			TOTAL	THICKNESS OF BED			TOTAL	THICKNESS OF BED			
	2½'-5	5-10	10' +		2½'-5	5-10	10' +		2½'-5	5-10	10' +		2½'-5	5-10'	10' +	
FREMONT COUNTY																
T.34N., R.89W.	1.25	—	—	1.25	—	—	—	—	—	—			1 25	—	—	1.25
T.33N., R.90W.	0.67	—	—	0.67	—	—	—	—	—	—	—	—	—	0.67	—	0.67
T.28N., R.90W.	1.56	—	—	1.56								—	1.56		—	1.56
T.34N., R.90W.	2.45	0.19	—	2.64	0.20	—	—	0.20	—	—			2.65	0.19		284
T.35N., R.90W.	2.69	—		2.69	2.94	—	—	2.94		—	—	—	5.63	—		5.63
T.27N., R.94W.	1.33	—	—	1.33	3.32	2.21		5.63	7.52	5.75	2.88	16.15	10.84	7.96	288	21.68
T.34N., R.94W.	9.98	5.63		15.61	12.77	1.13							1.33	—		1.33
T.34N., R.95W.	4.62	1.79	5.38	11.79	1.98	1.93	2.31	1300	14.46			1446	37.21	6.76	—	43.97
								6.22	2.01	0.26	—	2.27	8.61	3.98	7.69	20.28
T.33N., R.96W.		—	—	—	32.45	27.11	45.96	105.52	69.27	45.72	192.07	307.06	101.72	72.83	238.03	412.58
T.34W., R.96W.		—	—	—	—	—			19.58	10.54	6477	94 89	19.58	10.54	64.77	94.89
T.33N., R.98W.	7.03	2.38	9.29	18.70	5.26	3.06	0.89	9.21	2.48	—	—	2 48	14.77	5.44	10 18	30.39
T.3N., R.1W.	0.36	1.95	1.78	0.96	3.21	5.58	0.89	9.58	5.70	0.56		6.26	12.82	8.03	2.67	23 58
												—	0.36		—	0.36
T.3N., R.1W.	—	0.92	—	0.92	—	0.46		0.45		—	—		—	1.38	—	1.38
T.6N., R.2W.	4.02	4.08	—	8.10	2.73	3.81	—	6.54	1.40	1.73	—	3.13	815	9.62		17.77
T.6N., R.1E.	3.20	12.25	—	16.45	—	—	—		—	—			3.20	12.25	—	15.45
T.5N., R.2E.	3.99	—	—	3.99	1.17	—	—	1.17	—	—	—	—	6.16	—		5.16
T.1S., R.2E.	1.37			1.37	—		—				—		1.37	—	—	1.37
T.2S., R.2E.	3.63	—	—	3.63	—		—	—			—	—	3.63			3.63
T.6W., R.3E.	2.74	—	—	2.74	—	—		—	—	—			2.74	—		2.74
T.1S., R.6E.		—	—	—	0.95	—	—	0.95	5.24	—		5.24	6.19	—		6.19
T.2S., R.6E.	3.47	6.18	—	9.65	6.29	0.37	—	6.66	2.75	—	—	2.75	1251	6.55	—	19.06
County Total	67.80	36.04	16.45	110.09	73.27	45.66	50.05	168.98	130.41	64.56	259.72	454.69	261.28	146.26	326.22	733.76
NATRONA COUNTY																
T.31N., R.82W.	2.32	0.19	—	2.51	0.34	—	—	0.34	—	—	—	—	2.66	0.19	—	2.66
T.32N., R.82W.	0.27	0.39		0.66	0.24			0.24			—		0.51	0.39	—	0.90
T.33N., R.82W.	0.03	—	—	0.03	—		—	—	—		—	—	0.03		—	0.03
T.33N., R.83W.	2.72	3.89		6.61	2.03	3.67		5.70	1.00	3.53	—	4.53	5 75	11.09	—	16.84
T.35N., R84W.	1.83	—	—	1.63	1.39	—		1.39	0.68		—	0.68	3.90	—	—	3.90
T.35N., R.86W.	14.15	2.65	—	16.90	11.09	0.25	—	11.34	7.59	—	—	7.59	32.83	2.90	—	35.73
T.36N., R.85W.	3.78	3.91		7.69	2.76	2.47		5.23	1.83	1.14		2.97	8.37	7.52		15.89
T.33N., R.86W.	4.39	0.12	—	4.51	0.51		—	0.51		—	—	—	4.90	0.12		5.02
T.36N., R.86W.	9.18	2.94	—	12.12	8.26	2.17		10.43	4.98	0.99		5.97	22.42	6.10		28.52
T.37N., R.86W.	—	8.33		8.33		7.14		7 14	—	3.57	—	3.57		19.04	—	1904
T.33N., R.87W.	5.51	2.66	—	8.17	5.84	—	—	5.84	3.16	—		3.16	14.51	2.66	—	17.17
T.34N., R.87W.	0.02	—	—	0.02	0.74	—		0 74	1.66	—	—	1.66	2.42	—	—	2.42
T.37N., R.87W.	2.74	—	—	2.74	2.35		—	2.35	1.17	—		1.17	6.26	—	—	6.26
T.34N., R.88W.	4.90	1.70	—	6.60	3.52	—		3.52	2 45.		—	2.45	10.87	1.70	—	12.57
County Total	51.84	26.78	—	78.62	39.07	15.70	—	54.77	24.52	9.23	—	33.75	115.43	51.71	—	167.16
Basin Total																900.92

Table 5-6. Estimated Original Coal Reserves in the Wind River Basin Coal Basin, by Coal Field (Berryhill, et al., 1950)

FIELD	BITUMINOUS				SUB-BITUMINOUS				TOTAL IN ALL RANKS AND CATEGORIES
	MEASURED	INDICATED	INFERRED	TOTAL	MEASURED	INDICATED	INFERRED	TOTAL	
Muddy Creek	—	—	—	—	—	42.50		42.50	42.50
Pilot Butte	—	—	—	—	—	.36	—	.36	.36
Hudson	—	—	—	—	21.71	37.26	—	58.97	58.97
Alkali Butte	—	—	—	—	—	85.73	3.77	89.50	89.50
Ts. 33-34 N.. R.96W	—	—	—	—	—	208.11	299.36	507.47	507.47
Arminto (Powder River)	—	—	—	—	—	176.86	—	176.86	176.86
Total	—	—	—	—	21.71	550.82	303.13	875.66	875.66

Table 5-7. Estimated Original Coal Reserves in the Mesaverde Formation in the Alkali Butte Field, Fremont County, Wyoming, in Millions of Short Tons (All Coal is of Subbituminous Rank.) (Thompson and White, 1952)

BED	AREA (ACRES)	WGTED. AVERAGE THICK-NESS IN FEET	OVER-BURDEN	MEASURED RESERVES				INDICATED RESERVES				INFERRED RESERVES				TOTAL MEASURED INDICATED AND INFERRED RESERVES
				THICKNESS OF BED			TOTAL	THICKNESS OF BED			TOTAL				TOTAL	
				2½'-5'	5-10	10' +		2½'-5	5.10	10' +		2% -5	510	10' +		
T. 2 S, A. 6 E. (PARTIAL TOWNSHIP)																
Signor	78	8	0-1000	—	1.10		1.10			—				—	—	1.10
Signor	656	6.5	0-1000	—	—				7.53		7.53	—	—	—	—	7.53
Signor	104	6	1000-2000		—	—			1.10		1.10			—		1.10
Signor	6	7	0-1000	—	—		—	—	—			—	0 74		0.74	74
Signor	922	7	1000-2000	—	—				—			—	11 42		11.42	11.42
Signor	325	7	2000-3000	—	—						—		4.03		4.03	4.03
Beaver	557	3	0-1000	—	—			2.96			2.96		—	—		2.96
Beaver	96	3	1000-2000	—	—		—	.51	—	—	.51	—			—	51
Shipton	219	9	0-1000	—	3.49	—	3.49		—				—			3.49
Shipton	421	9	0.1000	—	—		—		6.71		6.71		—		—	6 71
Shipton	253	9	1000-2000	—	—		—		4.03		4.03		—	—		4.03
Shipton	230	9	0-1000	—	—	—			—		—		3.66		3.66	3.66
Shipton	653	9	1000-2000	—	—			—					10.40	—	10.40	10.40
Shipton	226	9	2000-3000	—	—		—		—	—			3.60		3.60	3.60
Total					4.59		4.59	3.47	19.37		22 84		33.85		33.86	61 28
T. 1 S., R. 6 E. (PARTIAL TOWNSHIP)																
Signor	29	7	2000-3000	—	—	—	—	—	—	—	—	—	0.36	—	0.36	0.36
Shipton	208	5	1000-2000	—	—	—	—		—			1.84	—	—	1.84	1.84
Shipton	38	8	2000-3000	—	—	—	—		—			—	.54		.54	1.84
Total												1.84	0.90		2.74	2.74
T. 34 N., R. 95 W. (PARTIAL TOWNSHIP)																
Signor	58	13	0-1000	—	—	1.15	1.15	—	—	—		—	—	—	—	1.15
Signor	13	13	0-1000	—	—	—	—		—	0 29	0.29	—	—	—	—	0.29
Signor	42	13	1000-2000	—	—			—		.97	.97		—	—	—	0.97
Signor	32	13	1000-2000	—	—				—		—	—	—	0.74	0.74	0.74
Signor	a3	15	0-1000	—		2.20	2.20			—	—	—	—	—	—	2.20
Signor	107	3.5	0-1000	0.66	—	—	.66				—	—	—		—	.66
Signor	14.4	15	0-1000	—	—	—	—			.38	.38	—	—	—	—	.38
Signor	115	11	0-1000	—		—				2.24	2.24	—	—		—	2.24
Signor	80	3.5	0-1000	—	—			.50	—		.50	—	—			.50
Signor	51	9	1000-2000	—	—	—			0.81		0.81			—		.81
Signor	53	9	0-1000	—	—	—	—	—	—		—	—	0.84	—	.84	.a4
Signor	a6	9	1000-2000	—	—	—	—		—	—	—	—	1.37		1.37	1.37
Signor	160	3.5	1000-2000	—	—	—				—		0.99	—	—	.99	.99
Signor	130	9	2000-3000	—	—	—			—	—	—		2.07	—	2.07	2.07
Shipton	70	9.5	0-1000	—	1.18	—	1.18			—	—	—	—			1.18
Shipton	118	9.6	0-1000	—	—	—	—	—	1.98	—	1.98	—	—	—	—	1.98
Shipton	6	9.5	1000-2000	—	—				.10	—	.10	—		—	—	.10
Shipton	16	9.5	0-1000	—		—		—	—	—	—	—	.27	—	.27	.27
Shipton	149	9.6	1000-2000	—	—	—	—		—	—	—	—	2.50	—	2.50	2.50
Shipton	13	9.5	2000-3000	—	—	—			—		—		.22	—	.22	.22
Total				0.66	1.18	3.35	5.19	0 50	2.89	3.88	7.27	0.99	7.27	0.74	9.00	21.46
T. 34 N.. R. 94 W. (SOUTHWEST CORNER)																
Signor	98	13	1000-2000	—	2.76	—	2.76	—	—	—	—	—	—	2.04	—	2.04
Signor	173	9	0-1000	—		—	—	—	3.52	—	3.52	—		—	—	2.76
Signor	221	9	0-1000	—			—	—	.68	—	.68	—	—	—	—	3.52
Signor	43	9	1000-2000	—		—	—	—	—	—	—		3.71	—	3.71	.68
Signor	349	6	0-1000	—	—	—		—				—	3.84	—	3.84	3.71
Signor	362	6	1000-2000	—	—	—	—		—	—	—	—	.74		.74	3.84
Signor	70	6	2000-3000	—	—	—					4.20		8.29	2.04	10.33	.74
Total					2.76		2.76		4.20							17.29
Grand Total				0.66	8.53	3.35	12.64	3.97	26.46	3.88	34 31	2.83	50.31	2.78	55.92	102.77

Table 5-8. Estimated Original Coal Reserves in the Lance Formation in the Alkali Butte Field, and the Downey Bed in the Big Sand Draw Field, Fremont County, Wyoming, in Millions of Short Tons (Thompson and White, 1952)

AREA BED (ACRES)	WT'D. AVG. THICK-NESS IN FT.	OVER-BURDEN	MEASURED RESERVES THICKNESS OF BED 2½'-5'	5-10	10'+	TOTAL	INDICATED RESERVES THICKNESS OF BED 2½'-5'	5-10'	10'+	TOTAL	TOTAL MEASURED AND INDICATED RESERVES
T. 2 S., R. 6 E. (PARTIAL TOWNSHIP)											
Lance Coal 42	4	o- 1000	0.29	–	–	0.29	–	–	–	–	0.29
Lance Coal 11	4	0-1000	–	–	–	–	0.08	–	–	0.08	.08
Total			0.29			0.29	0.08			0.08	0.37
T. 1 S., R. 6 E. (PARTIAL TOWNSHIP)											
Lance Coal 205	4	0-1000	1.45	–	–	1.45	–	–	–	–	1.45
Lance Coal 566	4	0-1000	–	–	–	–	3.96	–	–	3.96	3.96
Total			1.45			1.45	3.96			3.96	5.41
Grand Total			1.74			1.74	4.04			4.04	5.78

BED	AREA (ACRES)	WT'D. AVG.[1] THICK-NESS IN FT.	OVER-BURDEN	MEASURED RESERVES THICKNESS OF BED 10' +	TOTAL	INDICATED RESERVES THICKNESS OF BED 10' +	TOTAL	INFERRED RESERVES THICKNESS OF BED 10' +	TOTAL	TOTAL MEASURED INDICATED AND INFERRED RESERVES
T. 33 N., R. 6 E.										
Downey	179	28	0-2000	8.87[2]	8.87	–	–	–	–	8.87
	379	28	0-2000	–	–	18.78	18.78	–	–	18.78
	1248	20	0-3000	–	–	–	–	44.18	44.18	44.18
Total				8.87	8.87	18.78	18.78	44.18	44.18	71.83

[1] Thickness figures supplied by George Downey, February 1951, and not checked by writers because mine was caved in.

[2] Estimate of 10,000 short tons taken from Downey Mine. Computed February 1951.

Table 5-9. Coal Resources and Reserves Base in the Wind River Coal Basin of Wyoming (Glass and Roberts, 1978)

ORIGINAL SUBBITUMINOUS COAL RESOURCES (MILLIONS OF TONS)[1]

COAL THICKNESS (FEET)	0-1,000 FEET OF OVERBURDEN[2]	1,000-2,000 FEET OF OVERBURDEN[2]	2,000-3,000 FEET OF OVERBURDEN[2]	TOTAL[2]
2.5-5	112.32	109.91	147.41	396.84
5-10	86.04	91.29	79.35	256.68
10	41.98	76.71	280.78	399.47
Total	240.34	277.91	507.54	1,025.79

Reserve base (Coal beds 5 feet or greater in thickness, under less than 1,000 feet of cover, only measured and indicated categories of reliability)	108.67
Production 1970 - present[3]	3.98
Mining losses (equal to production)	3.98
Remaining reserve base	100.71
Remaining recoverable reserve base (Assume future mining losses equal future production)	50.36

[1]Includes measured, indicated, and inferred categories of reliability.

[2]Berryhill, et. al., (1950) modified by Thompson and White (1952) and Keefer and Troyer (1964)

[3]Assumes most mining occurred on beds 5 feet or greater in thickness.

RESOURCE BASE (MILLIONS OF TONS)[1]

	COAL RESOURCE[1]	REMAINING RESERVE BASE
Alkali Butte Coal Field	166.74	34.53
Arminto Coal Field	176.86	26.97
Beaver Creek Coal Field	507.47	0
Big Sandy Draw Coal Field	71.83	13.82
Hudson Coal Field	58.97	7.46
Muddy Creek Coal Field	43.56	17.93
Pilot Butte Coal Field	.36	0
	1,025.79	100.71

[1]Includes measured, indicated, and inferred resources for coals greater than 2.5 feet thick between 0-3,000 feet of cover.

Table 5-10. Estimated Coalbed Methane Resource in the Wind River Coal Basin — Two Scenarios

CONSERVATIVE SCENARIO (ORIGINAL SHALLOW ($\leq$3000') COAL RESOURCES — SEE TABLE 5-9)

COALBEDS >2.5'	GAS RESOURCE IN CUBIC FEET				
SHORT TONS	5 CU FT/TON	10 CU FT/TON	20 CU FT/TON	50 CU FT/TON	100 CU FT/TON
1.03×10^9 2.06×10^9	5.15×10^9 10.30×10^9	10.03×10^9 20.60×10^9	20.06×10^9 40.12×10^9	51.50×10^9 103×10^9	103×10^9 206×10^9

OPTIMISTIC SCENARIO (ORIGINAL DEEP ($\geq$3000') COAL RESOURCES — SHOWN BY FIGURE 3-5)

COALBEDS > 2.5'	GAS RESOURCE IN CUBIC FEET				
SHORT TONS	5 CU FT/TON	100 CU FT/TON	121 CU FT/TON	273 CU FT/TON	539 CU FT/TON
4.12×10^9	0.02×10^{12}	0.41×10^{12}	0.50×10^{12}	1.12×10^{12}	2.22×10^{12}

Assumptions:

Shallow coalbeds maximum original coal resources is twice report for the whole basin.

Maximum desorbed gas value is the maximum value assigned to subbituminous coals in the Green River Basin.

Deep coal beds is assumed to be 2 times that of the shallow beds — based on reported very deep lying thick coals.

Maximum desorbed gas value corresponds to that for deep lying Green River coals.

Mostly value is 273 cu ft/ton derived from Green River data.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 EXPLORATION CRITERIA

Data worldwide tend to indicate that petroleum and natural gas generation and entrapment are enhanced in basins of high heat flow. Iannacchione and Puglio (1980) worked on the premise that methane gas was generated with increased thermal maturation (coalification). Kim (1978) pointed out that the gas content of a coalbed depends primarily upon rank, temperature, and pressure. However, it must be noted that coals of the same rank may exhibit a lO,OOO-fold difference in gas content (Kim, 1978). This is an indication that present gas content of a coalbed is related not only to gas formation during coalification but also to the post-deposition geologic history of the coalbed. The degree of fracturing, distance to outcrop, depositional environment, depth of burial, bed thickness, rate of burial, and permeability of adjacent strata could be important. Keeping this information in mind, the following criteria were developed for use in designating areas with the greatest potential methane resource. Reference is made to Section 4.4.

- Thick continuous coalbeds
- High cumulative coal thickness
- High ASTM coal rank
- Deep coals
- High geothermal gradient
- Abnormally high fluid pressure environments.

6.2 TARGET AREAS

An initial MRCP target area of approximately 8,100 square miles of the Wind River structural basin was selected for early testing. This area was thought to contain ample opportunities for testing those coals having the greatest potential for commercialization of the coalbed methane resource. The primary target areas now believed to best meet these criteria are shown in Figure 6-l. The reasons for its selection are:

- Existence of overpressured zones
- Reports of thick coalbeds lying in the interval between 3,000 and 14,000 feet

- Presence of gas and oil in great quantities
- Continuity of major coal-bearing zones.

Recommendations for completing delineation of the Wind River coalbed methane resource base area are discussed below.

6.2.1 Shallow Exploration

In the initial phase of framework development of the MRCP Wind River Basin data base, only those coals in the upper 3,000 feet should be sampled and tested. The magnitude and distribution of the methane resource should be fairly well understood to this depth. The economic producibility of these coalbeds should be demonstrated before deeper sampling and testing are undertaken. Therefore, the basic criterion for establishing subareas for the initial sampling and testing of coals in the Wind River Basin is to outline those areas within the region containing one or more of the coal-bearing units within 3,000 feet of the surface.

6.2.2 Deep Exploration

It can be expected that coals lying at depths greater than 3,000 feet in the Wind River Basin could probably be of higher ASTM rank (bituminous) than the shallow coals. Higher rank means higher methane values. Oil and gas wells are routinely drilled to these depths in the basin. Cooperation with the oil and gas industry will provide the MRCP with these deep tests. Coalbed methane resource calculations should reflect potentials of both the shallow and deep coals.

6.3 RECOMMENDATIONS

The investigation completed in the latter part of 1980 surveyed the available resource data and the results of MRCP testing. As a result of this study, the initially defined target area has been redefined to concentrate further on the gas-in-place in the deeper portion of the basin. Further resource characterization detailing variability of the coals' total gas contents is needed in order to properly evaluate their contribution to the total coalbed methane resource of the basin. The following approach is recommended for use in defining the primary areas with the greatest potential coalbed methane resource in the Wind River Basin.

- Coalbed methane reservoir characterization through continued cooperation with the USGS Wind River Indian Reservation coal evaluation program supervised by John Windolph, Jr. (Figure 5-2)

- Additional characterization testing, where appropriate, in conventional gas or oil wells being drilled to potential reservoirs below the coal (Figure 6-1):

  - Shallow (<3,000 ft)

    1) Overthrust
    2) Central and northern parts of the basin

  - Deep (>3,000 ft)

    1) Overthrust
    2) Northeastern portion of the basin

A program for investigating the methane recovery potential of the Wind River Basin should include the following additional activities:

- Obtain geophysical logs and gas information from oil and gas wells penetrating coal-bearing zones in the basin.

- Continue to cooperate with the USGS, other surveys, and private organizations to collect coal core, coal chip, and gas samples to perform methane desorption tests and analyses.

- Collect other pertinent information through logs, personal contacts, reports, mine data, and from personnel working within the basin area.

- Cooperate with the local oil industry on deep tests.

- Participate in a detailed study of the target area to help pinpoint test sites for methane exploration.

- Perform drilling, logging, sampling, and flow testing of test sites chosen by the detailed study.

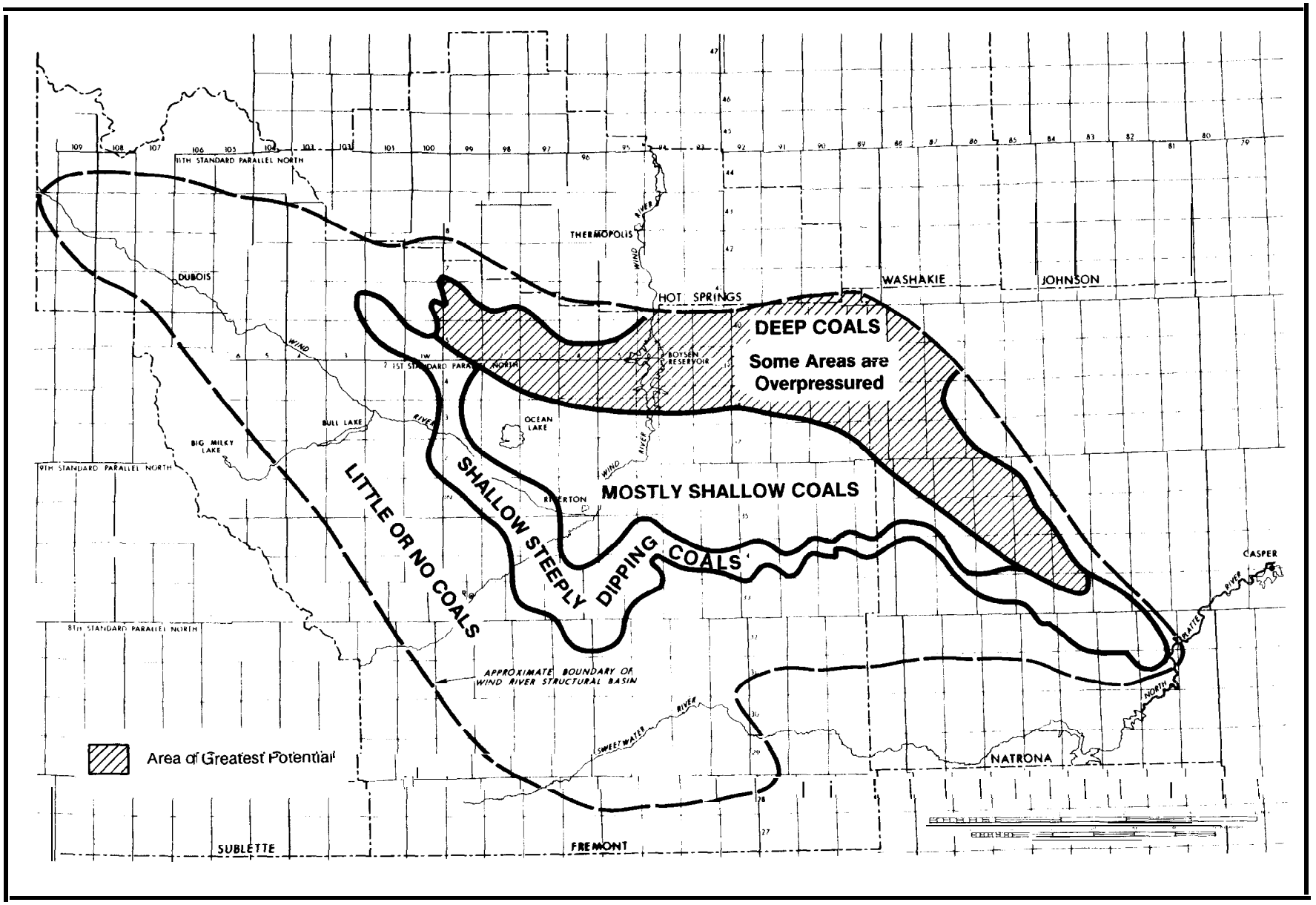


Figure 6-I. Primary Target Areas in the Wind River Basin

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APPENDIX A

TOPOGRAPHIC MAPS COVERING THE WIND RIVER BASIN

ENCLOSURES:

A-l USGS Topographic Map Index -- Scale 1:250,000

A-2 USGS Topographic Map Index to Wyoming (7-1/2')

A-3 Index to Topographic Maps of the United States at a Scale of 1:1,000,000

A-4 Cheyenne, United States -- Scale: 1:1,000,000

A-5 Great Salt Lake, United States -- Scale: 1:1,000,000

CHEYENNE, U.S. 1:1,000,000

TOPOGRAPHIC MAP

CURRENTLY OUT OF PRINT

WILL BE INCLUDED IN UPDATE

APPENDIX B

GEOLOGIC MAPS COVERING THE WIND RIVER BASIN

ENCLOSURE:

B-l Geologic Map Index of Wyoming, 1977

APPENDIX C

WATER-RESOURCES INVESTIGATIONS IN THE WIND RIVER BASIN

ENCLOSURE:

C-l Water-Resources Investigations in Wyoming, 1977