THE GEOLOGICAL SURVEY OF WYOMING

Gary B. Glass, State Geologist

Open File Report 86-11

COAL RESOURCES OF THE TONGUE RIVER MEMBER, FORT UNION FORMATION (PALEOCENE), PWODER RIVER BASIN, WYOMING AND MONTANA

by

W.B. Ayers, Jr.

Laramie, Wyoming

1986

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Preface

The results of this investigation were published by the Geological Survey of Wyoming because they emphasize the conservative nature of previous coal resource estimates for the Powder River Basin of Wyoming. The previous estimates did not account for much of the vast resources that lie at depths greater than 1,000 feet in this basin.

Care, however, should be taken in the use of the resource estimate provided in this report. First, the resource estimate tabulates in-place coal resources (the total amount of coal underlying the area) and does not attempt to define what part of the resource is mineable. Second, the resource estimate is only for coal occurring in the Tongue River Member of the Fort Union Formation. There are additional coal resources in the overlying Wasatch Formation. Third, the resource estimate was not made in conformance with techniques outlined by the U.S. Geological Survey or commonly used by others. In particular, the estimate includes some coals that are thinner (2-2.5 feet thick) than those normally included in resource estimates, and the estimate is not subdivided into the standard reliability categories of measured, indicated, inferred or hypothetical resources.

However, the coal resource estimate in this report is a significant contribution to the evaluation of the coal resources of Wyoming's Powder River Basin because it essentially doubles any previous estimate of the identified and hypothetical resources. It also indicates that the resources are even greater than the report estimates, since coal resources in the Wasatch Formation were not considered.

Gary B. Glass
State Geologist

Laramie
March 19, 1986

Abstract

The Tongue River Member contains more than 1.16 trillion short tons of low-sulfur subbituminous coal to a depth of 3,000 feet in the Powder River Basin of Wyoming and Montana. Coal occurs in thick (commonly greater than 60 feet), laterally extensive beds that have been correlated more than 50 miles along strike.

In a regional subsurface study, data from 1,790 geophysical well logs were used to map Tongue River coal beds and calculate resources for an area of 9,651 square miles. As many as 32 coal seams are present; net thickness of coal exceeds 300 feet at places in the center of the basin. Much of the Powder River Basin's coal resources are contained in two thick strike-parallel coal beds. The first (commonly called the Wyodak coal bed) crops out along the east margin of the basin where it is exploited by surface mining; the second seam (identified as Seam 14 in this study) lies basinward (west) of the first at depths of 1,000 to 2,000 feet.

Introduction

Statement of problem

The Powder River Basin, located in northeastern Wyoming and southeastern Montana **(Figure 1)**, contains a large part of the nation's low-sulphur coal (Matson and Pinchock, 1976). Within the basin, the Tongue River Member of the Fort Union Formation **(Figure 2)** is the major coal-bearing unit; it commonly contains eight to twelve thick, persistent subbituminous coal seams in northern and eastern Wyoming (Glass, 1982). Coal seams presently mined in the Wyoming part of the basin range from ten to 100 feet thick. In Wyoming, coal production from this basin has set new records every year since 1972. In 1984, 84.3 million short tons were produced from these coals in the Wyoming region alone (Glass, in press). All production in both Wyoming and Montana was from strip mines. Thunder Basin Coal Company's (ARCO's) Black Thunder mine, located along the east-central margin of the basin, was the largest producing mine in the United States in 1984 (21.2 million tons) (Glass, in press).

Despite a record of production extending back over a century, coal resources in the Powder River Basin have not been adequately assessed because deep-basin resources have not been included in many past estimates. Resource estimates for western coal are based mainly on older reports that relied almost entirely on outcrop measurements; therefore, estimates are biased toward resources less than 1,000 feet deep (Glass, 1981; Tewalt and others, 1983). Tremendous coal resources occur below this depth in the Powder River Basin (Wold and Woodward, 1968; Hicks and Woodward, 1969; Pierce and others, 1982; Tewalt and others, 1983).

A vast regional data base exists in the form of induction logs run in oil and gas tests. The objectives of this study were to use induction logs to map coal beds and evaluate coal resources for the Tongue River Member in the Powder River Basin of Wyoming and Montana.

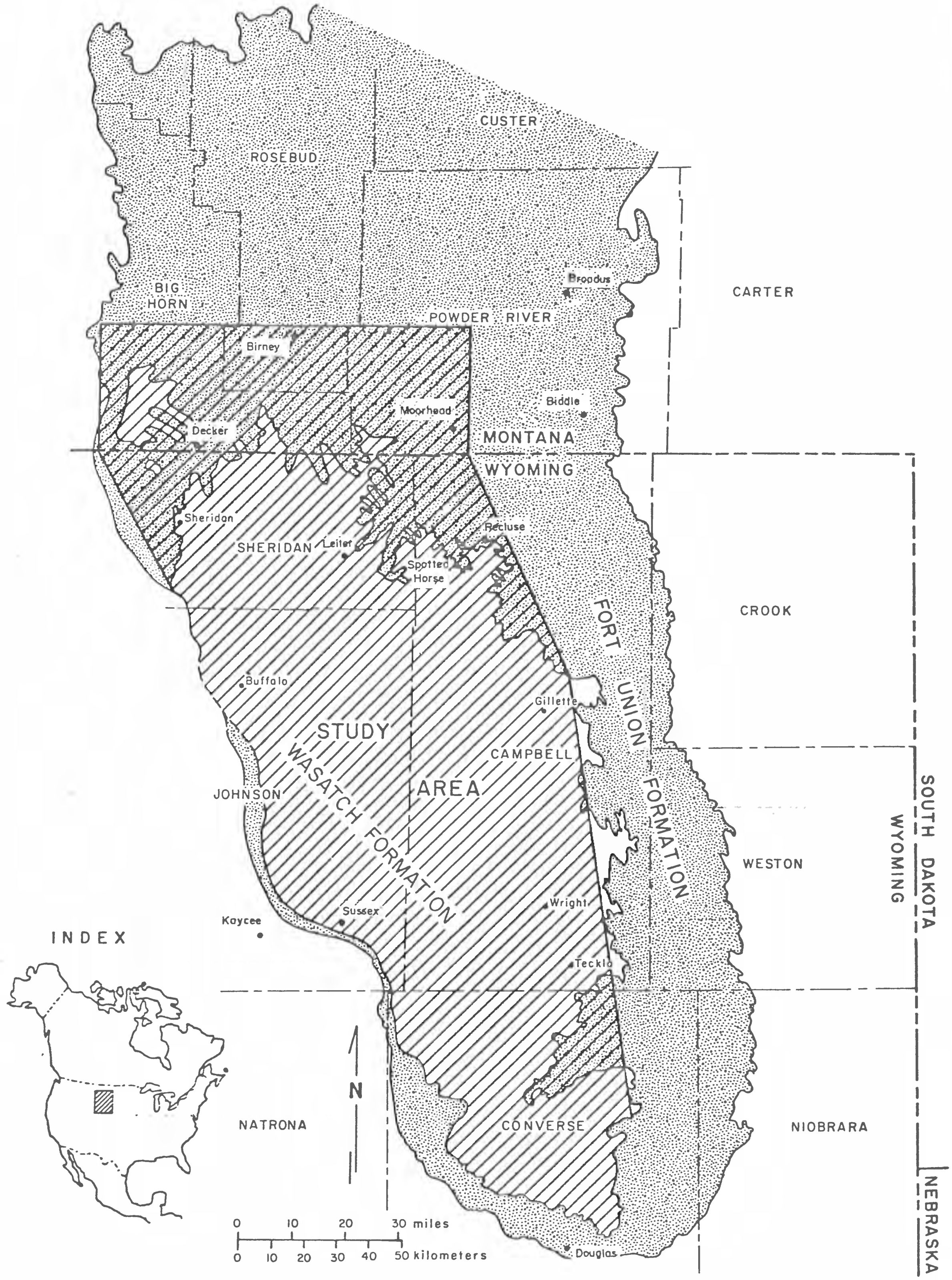

Figure 1. Location of the study area in the Powder River Basin. Geologic contacts are from Love and others (1955) and Ross and others (1955). The structural asymmetry of the basin is apparent from variations in the width of outcrops. Note that much of the Wyoming part of the study area is overlain by the Wasatch Formation.

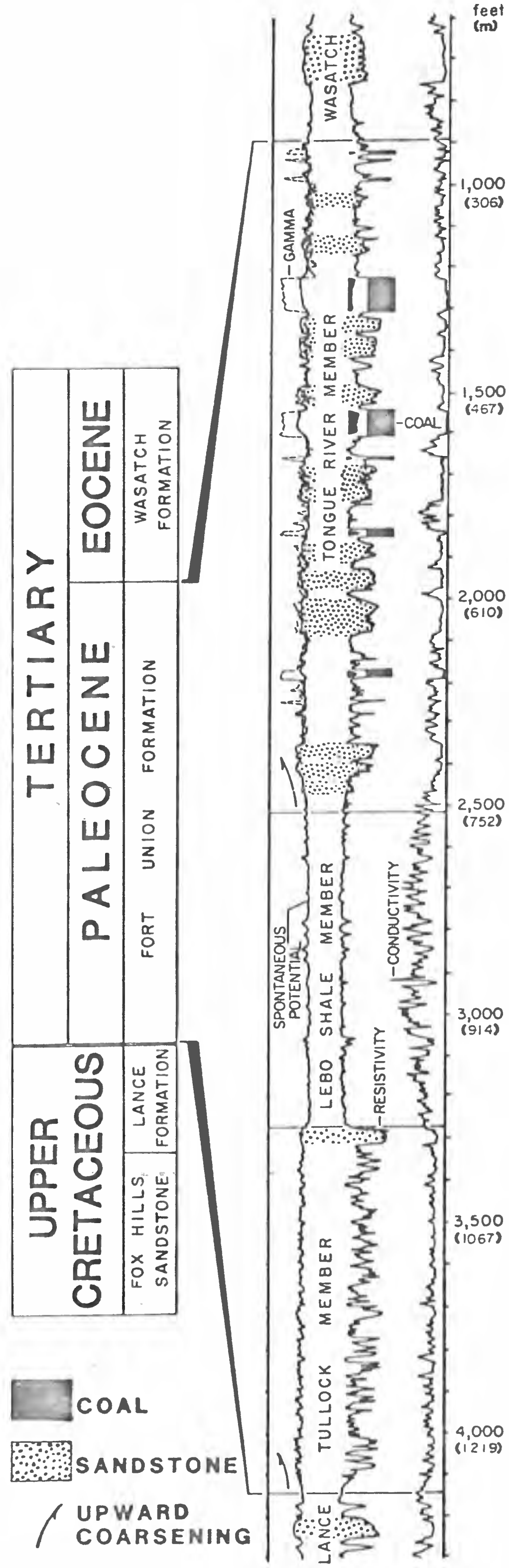

Figure 2. Composite electric log showing Fort Union stratigraphy in the Powder River Basin. Thick coal seams occur in the upper Tongue River Member.

Geologic setting

From outcrop studies at the northern end of the Powder River Basin, Flores (1979; 1980; 1981; 1983), suggested that Tongue River coals (peats) formed on the alluvial plain of a northward-flowing fluvial system. However, Ayers and Kaiser (1984) pointed out that the alluvial plain setting lacks the temporal stability required for the accumulation of thick, extensive, low-ash peats; their regional subsurface study shows that a thick Tongue River coal seam (Seam 14) in the deep basin formed in an interdeltaic setting, associated with a fresh-water lake (Lake Lebo).

The Powder River Basin formed during the Paleocene Epoch due to the Laramide orogeny. As a result of rapid basin subsidence, a lake (Lebo Shale Member; **Figures 2 and 3)** developed along the axis of the basin during the middle Paleocene and spread rapidly over an area greater than 10,000 square miles. Middle to late Paleocene fluvial-deltaic systems (Tongue River Member), with source areas in the surrounding Laramide highlands, filled Lake Lebo, primarily from the eastern margin **(Figure 3)**, and formed platforms for the development of peat swamps (Ayers and Kaiser, 1984).

Lithofacies maps and coal maps (Tewalt and others, 1983; Ayers and Kaiser, 1984) show that a thick (as much as 200 feet) Tongue River coal bed (seam 14) in the deep basin formed in an interdeltaic setting **(Figure 3)**. Peat swamps, which developed at loci of regional ground-water discharge in interdistributary and interdeltaic plain settings, persisted vertically and intertongued basinward (westward) with lacustrine muds **(Figure 4)**. Along strike, interdeltaic peats interfingered with fluvial-deltaic framework facies (Tongue River Member) **(Figure 5)**. Delta abandonment allowed interdistributary and interdeltaic plain peats to ultimately overspread foundering delta lobes, forming extensive, elongate peat deposits parallel to depositional strike (Ayers and Kaiser, 1984).

A structure map **(Figure 6)** drawn on top of the Tullock Member **(Figure 2)** reveals an asymmetrical basin with the axis near the west margin. Regional dip varies from less than one degree at the north and east margins, to more than 25 degrees along the west margin of the basin. Faults, uncommon in the east and northeast parts of the basin, are reported in the west (Glass, 1982) and northwest (Widmayer, 1977; Lewis and Roberts, 1978), but vertical displacements rarely exceed a few hundred feet.

Methodology

Conventional exploratory coal drilling is limited to depths of a few hundred feet and, therefore, resources are commonly delineated only along the margins of coal basins. The primary source of data used for this study, geophysical well logs run in oil and gas wells, penetrate the entire Tertiary coal-bearing sequence, allowing delineation of resources in the deep basin. Because the Powder River Basin is a mature petroleum basin, thousands of induction logs were available for regional evaluation of coal resources; 1,437 were used in this study **(Figure 7)**.

Curves available on the induction logs were the induction resistivity, short-normal resistivity, conductivity, spontaneous potential and, less commonly, the natural gamma ray. Recently, the attributes of these logs were recognized in a U.S. Geological Survey coal resources publication (Wood and others, 1983). However, criteria for the identification of coal on geophysical well logs run in oil and gas tests are well established (Bond and others, 1971; Schlumberger, 1972), and this source of data has been used in coal studies of the Illinois Basin (Hopkins 1958;

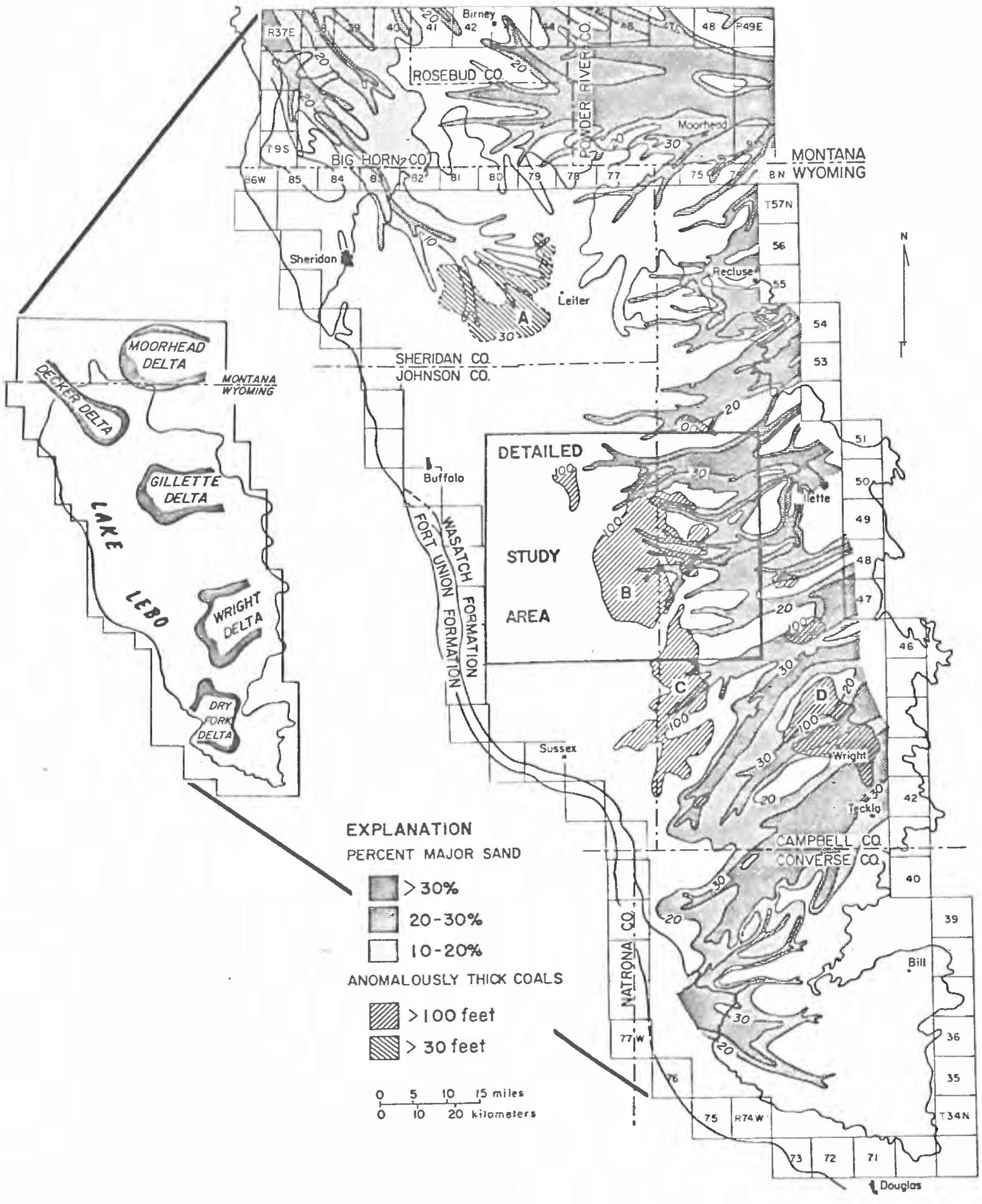

Figure 3. Map showing percentage of major sands in the basin fill. Sands are the framework facies of deltas that prograded into Lake Lebo from its margins. Anomalously thick coal (B) in the deep basin is located on the interdeltaic coastal plain between the Gillette and Wright deltas (see seam 14 on Figures 4 and 5).

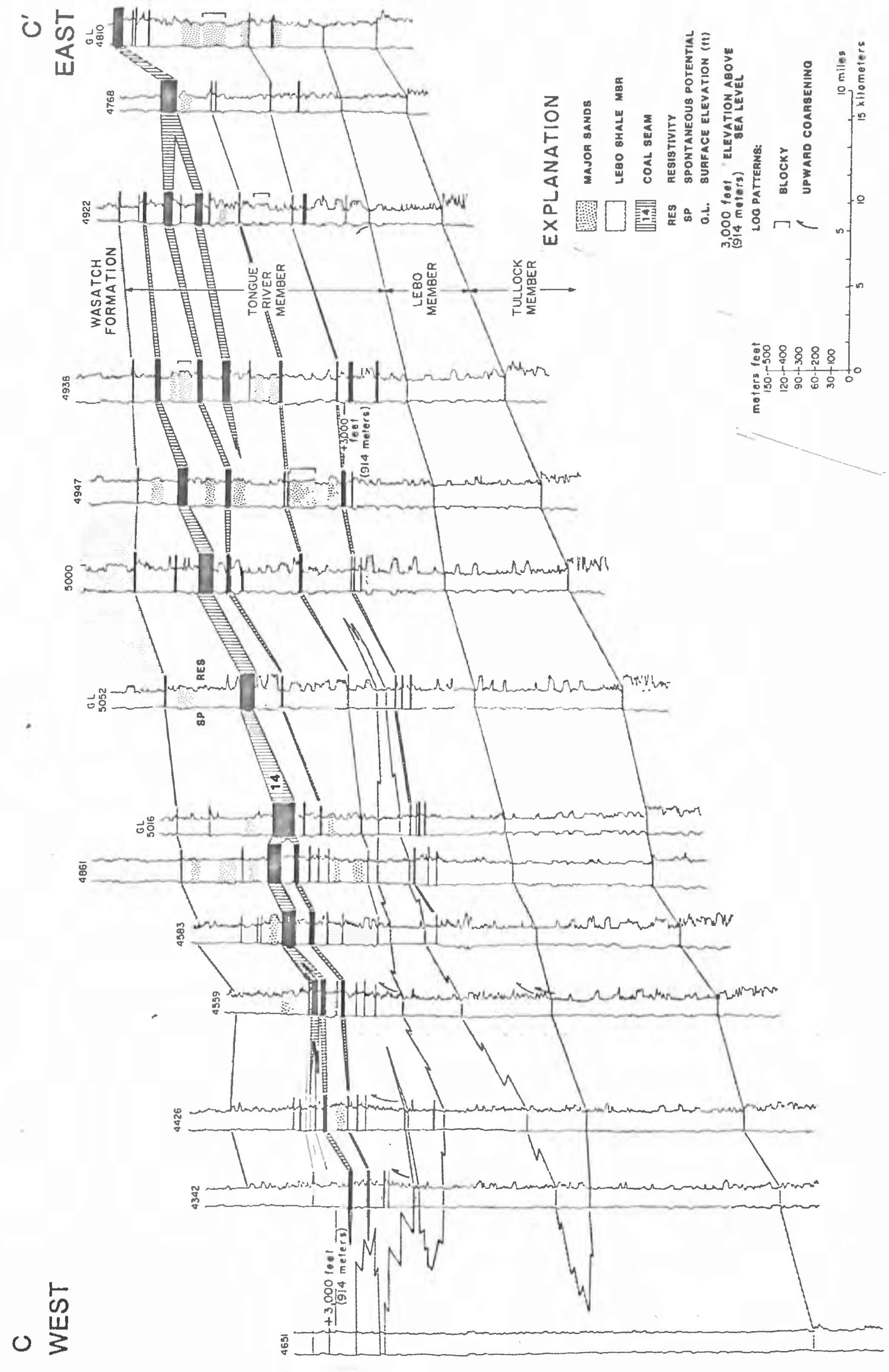

Figure 4. Cross section C-C', oriented parallel to dip, showing a thick coal seam that is mined along the east margin of the basin. A second thick seam (14), which formed in an interdeltaic plain setting, splits westward as the Tongue River fluvial-deltaic sediments intertongue with Lebo lacustrine muds. Datum is sea level. (See Figures 7 and 9 for location of the cross section.)

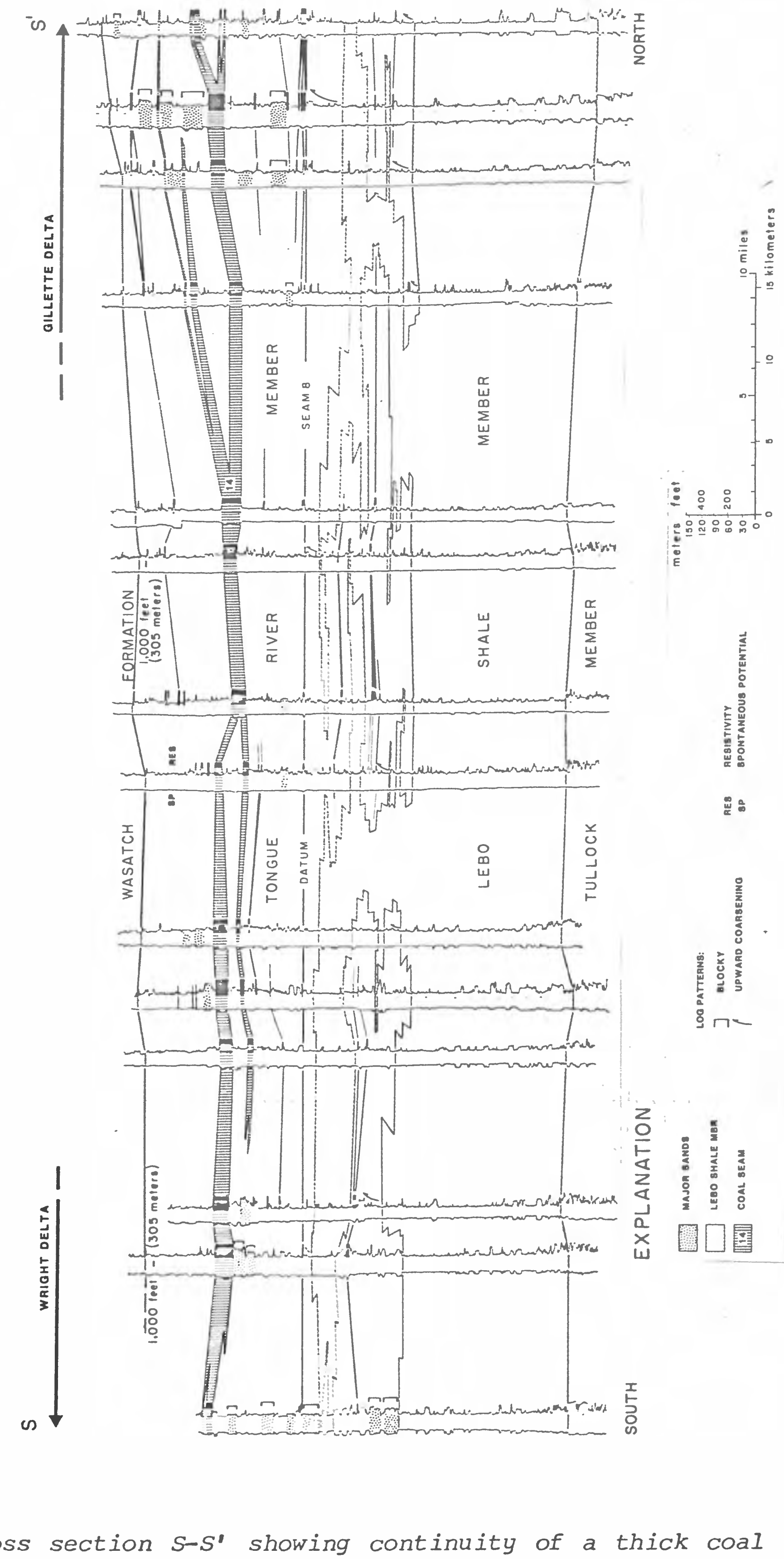

Figure 5. Cross section S-S' showing continuity of a thick coal seam (14) along strike. This interdeltaic-plain coal splits northward and southward into the Gillette and Wright deltas. (See Figures 7 and 9 for location of cross section.)

Figure 6. Structure contour map drawn on the top of the Tullock Member (sea level datum). The basin's structural axis is six to ten miles from its west margin.

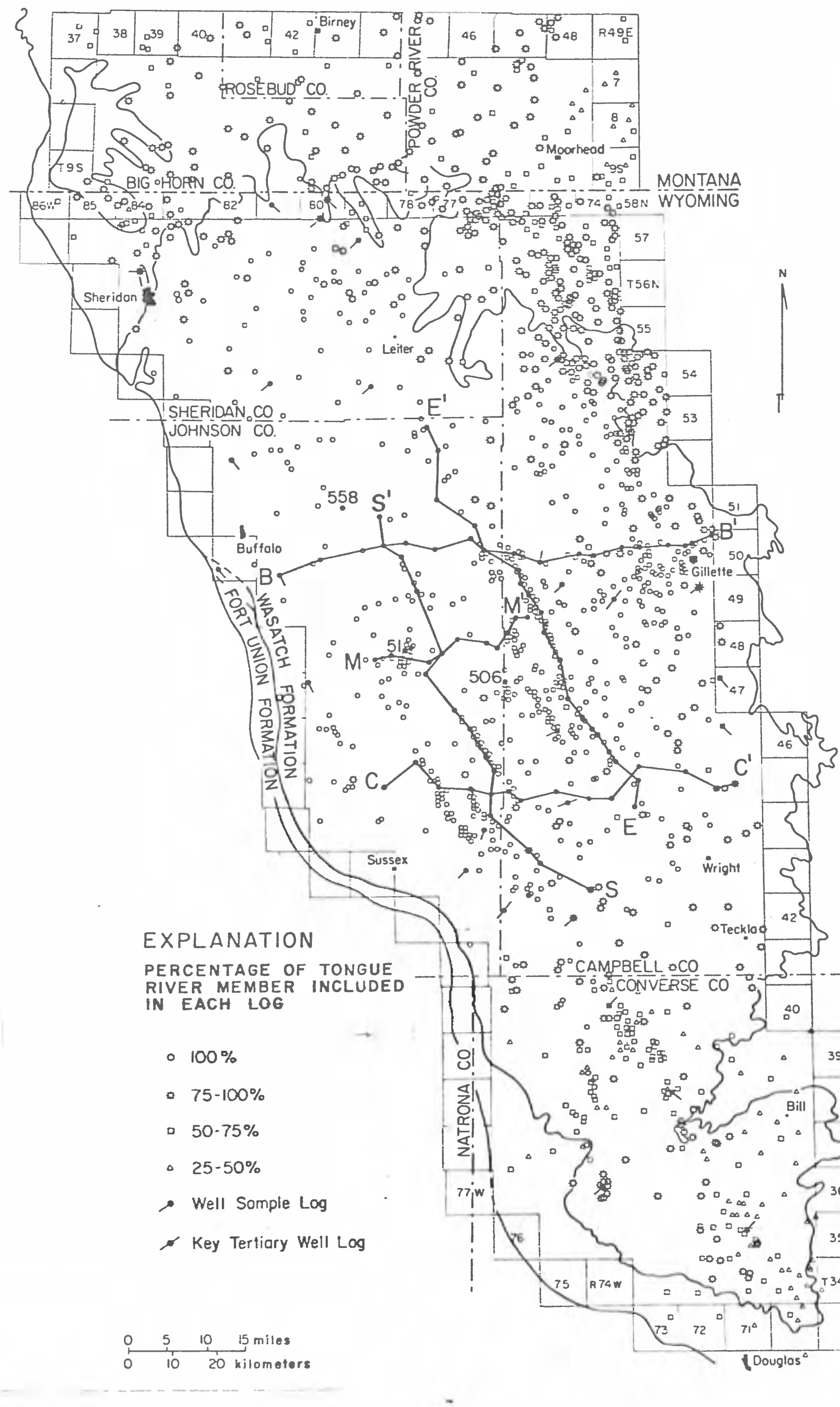

Figure 7. Location and distribution of the 1,437 geophysical well logs used in this study. Locations of an additional 353 shallow natural gamma ray and density logs used along the east margin of the basin in Wyoming are not shown.

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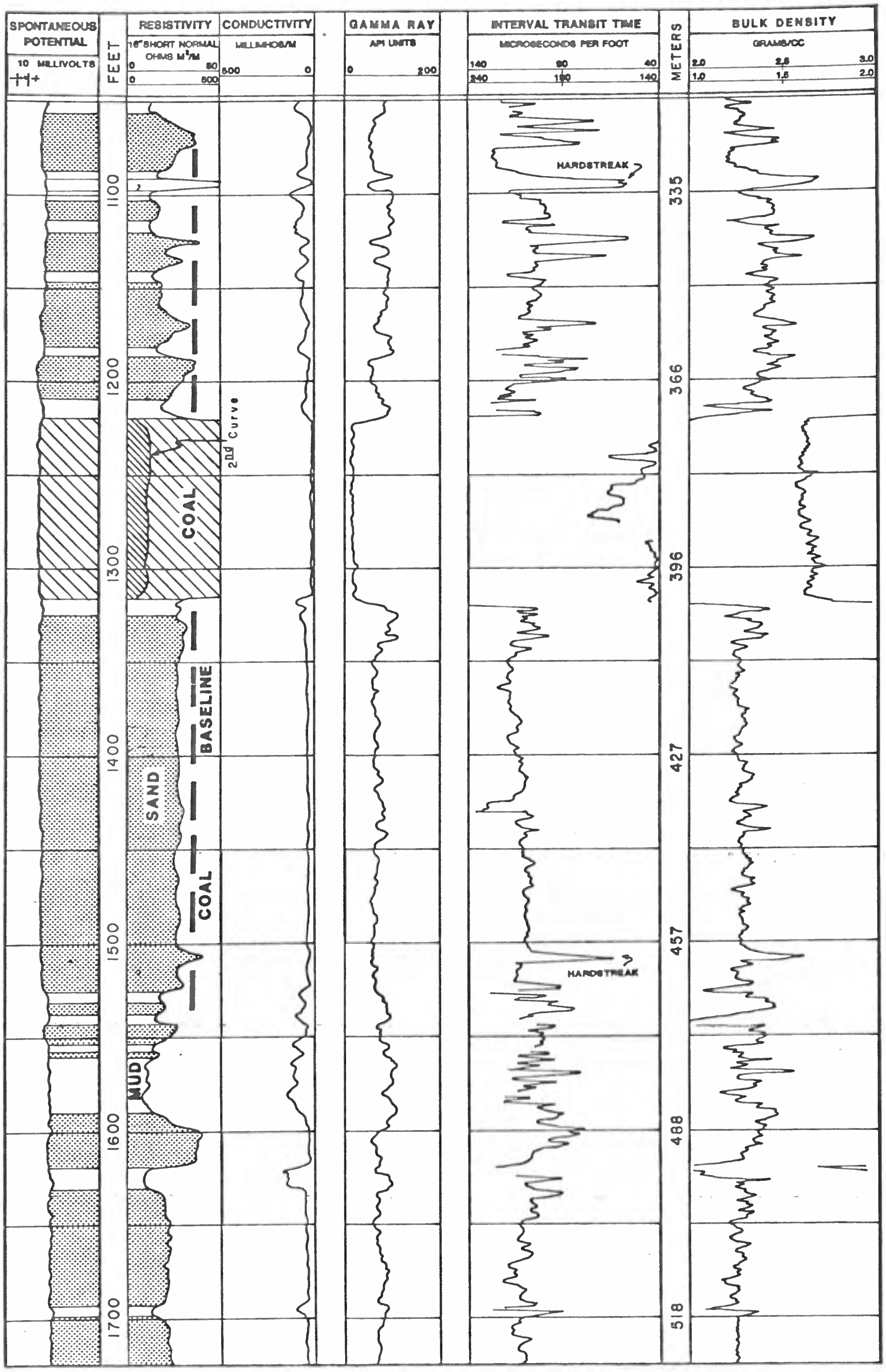

Figure 8. Thick coal seams of the upper Tongue River Member are typically interbedded with mudstones and thick sandstones. The identification of coal on resistivity curves is verified by natural gamma ray, density and acoustic curves. (See Figure 7 for location of this well, number 506.)

Allgaier and Hopkins 1975); the Appalachian Basin (Sholes and others, 1979); the Gulf Coast Basin (McGowen, 1968; Kaiser, 1974; Kaiser and others, 1978); the Williston Basin (Rehbein, 1978); and the Powder River Basin (Wold and Woodward, 1968; Nelms, 1976; Ayers and Kaiser, 1982; Tewalt and others, 1983).

Nelms (1976) showed that coals in the Tongue River Member can be identified on geophysical well logs by their high resistivities; 100 percent of the beds with resistivities greater than 120 ohm-m^2/m and 92 percent with resistivities between 35 and 120 ohm-m^2/m are coals. Rather than measure the resistivities of individual coal beds, it was more expedient in this study to draw a coal baseline to the right of the sandstone response on the resistivity curve; those beds more resistive than sandstone were interpreted as coals **(Figure 8)**. The reliability of the method derives from a thorough knowledge of regional stratigraphy. Outcrop studies and analyses of 25 well sample logs from throughout the basin **(Figure 7)** revealed no other highly resistive units with the thickness and lateral continuity of Tongue River coal beds. Carbonate beds and "hardstreaks" (carbonate-cemented sandstones), the only other highly resistive units in the Tongue River Member, are thin and laterally discontinuous. The presence of coal, identified from the resistivity curve, was confirmed by low natural gamma ray counts **(Figure 8)** (Bond and others, 1971; Schlumberger, 1972).

In this study, data from the geophysical logs were used to map the (a) total number of coal beds greater than two feet thick; (b) thickness of the thickest coal in each borehole; (c) average coal thickness; and (d) total thickness of coal for the Tongue River Member. Resources were calculated from the coal isolith map.

Coal occurrences

Before discussing coal occurrences, it is important to discuss the limitations imposed by the data base. Surface casing in most oil and gas wells precluded resistivity logging in the upper parts of the wells and resulted in loss of information in the shallow subsurface. To compensate, 185 natural gamma ray logs from oil and gas tests (which allow identification of coal through the casing) and 168 density logs from U.S. Geological Survey open-file reports of coal drilling were used to complete two maps of outcrops along the east margin of the basin where mining activity is greatest. However, more seams than delineated may be present in the shallow subsurface in the Fort Union outcrop in Montana where natural gamma and density logs were not used. Therefore, coal mapping is probably conservative in that region.

Maximum coal

In the Powder River Basin, thick coal seams are most abundant in the upper Tongue River Member where they are interbedded with mudstones and thick sandstones **(Figures 2 and 8)**. At the outcrop, mined coals average 22 to 30 percent moisture, four to eleven percent ash, 0.4 to 0.6 percent sulfur and 8,200 to 9,600 Btu/lb, on an as-received basis (Glass, 1982).

The map of the thickest Tongue River coal seam in each borehole, regardless of its stratigraphic position **(Figure 9)**, reveals two regional occurrences of thick coal oriented parallel to the basin axis. The first, the Wyodak coal sequence, is commonly more than 60 feet thick, and crops out along the east margin of the basin where its coincidence with active and proposed surface mines

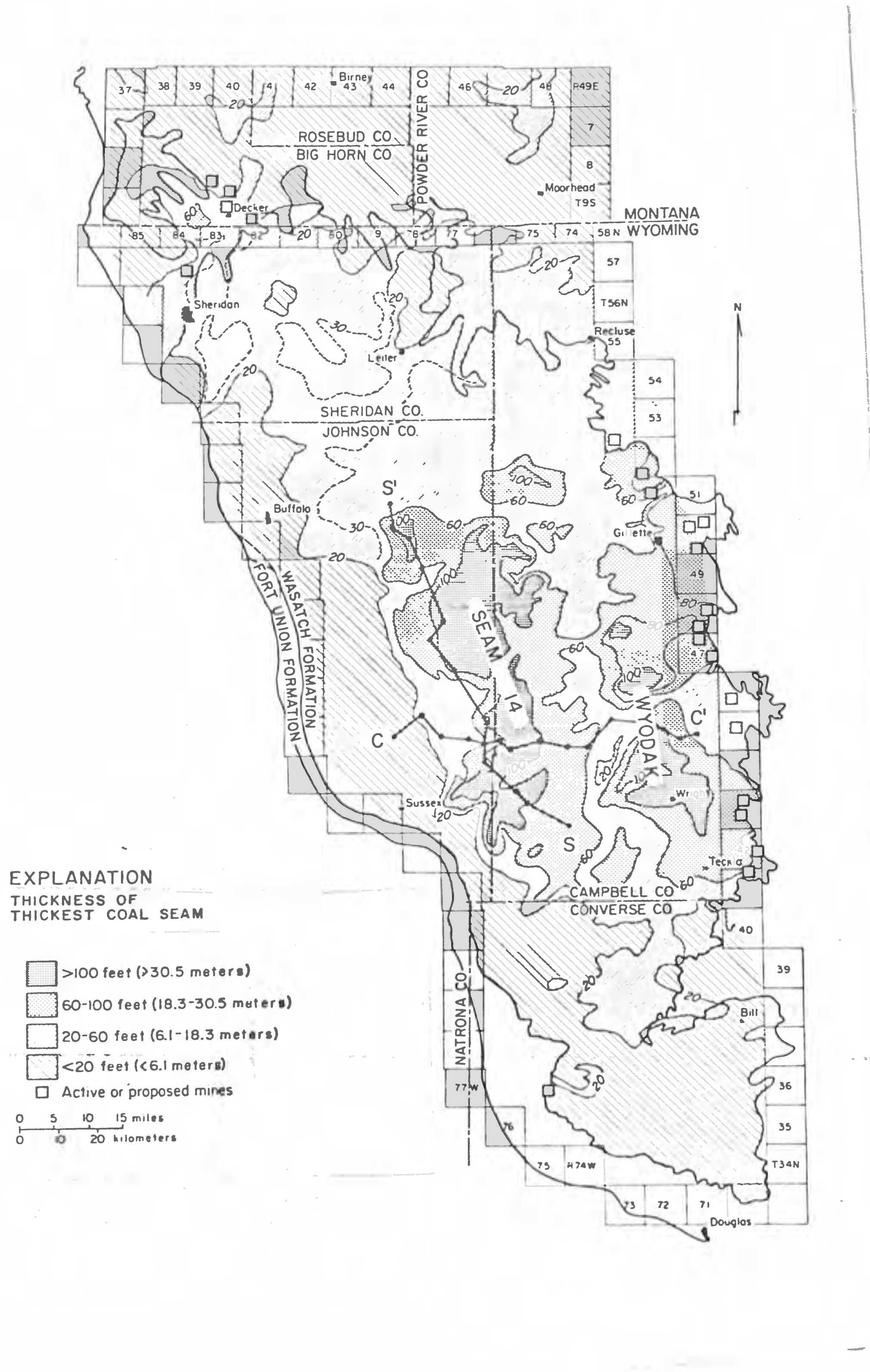

Figure 9. Maximum coal map for the Tongue River Member. The thick strike-parallel coal (Wyodak coal sequence) at the outcrop coincides with locations of surface mines. The second thick coal (seam 14), traversed by cross section S-S', formed in an interdeltaic plain setting (Figure 3). The map was constructed by contouring the thicknesses of the thickest coal seam in each borehole.

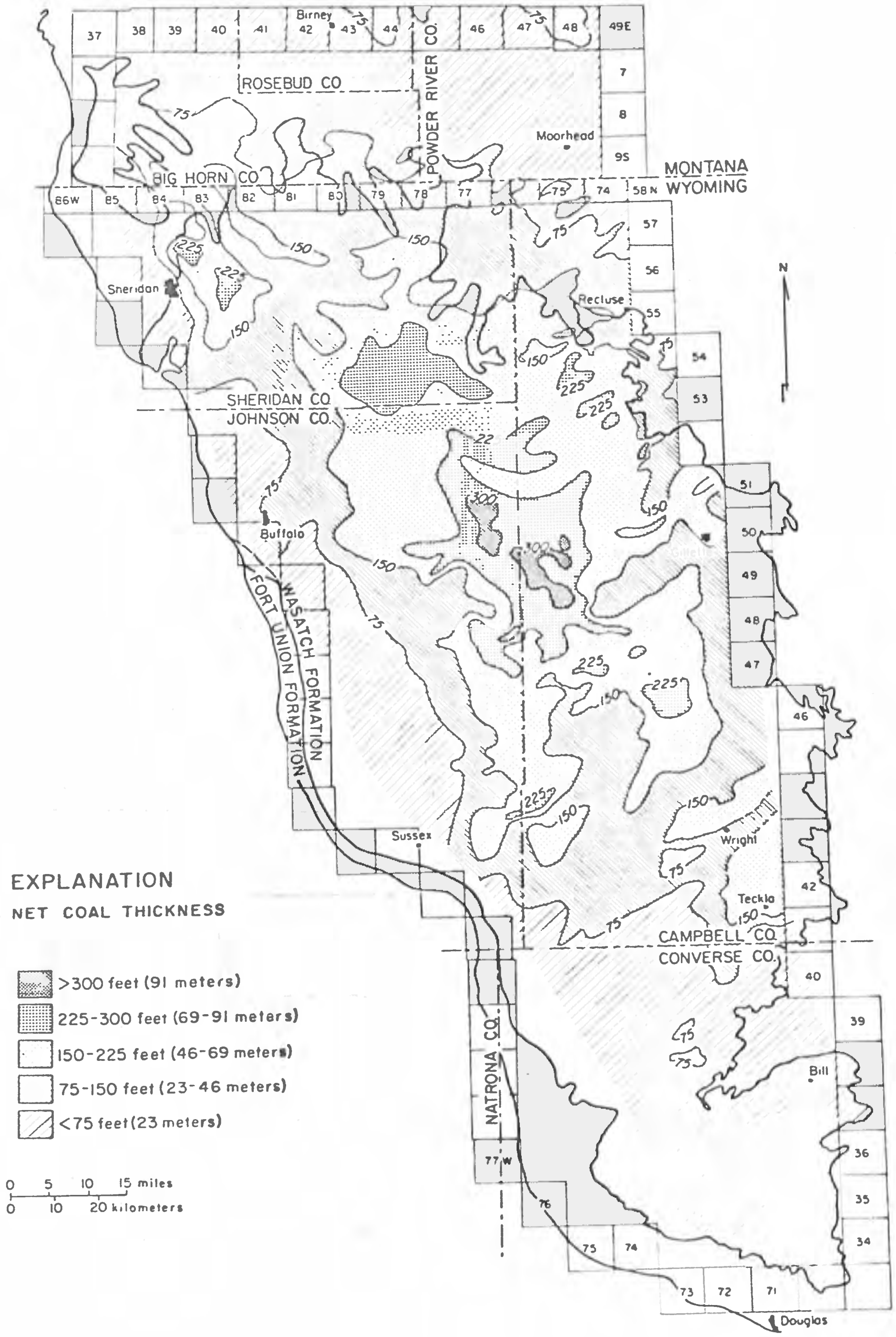

Figure 10. Coal isolith map showing that the net thickness of coal is greatest in the center of the Wyoming part of the basin and northeast of Sheridan, Wyoming. Net thickness is nearly zero between Buffalo and Sussex, and between Douglas and Bill, Wyoming, which were areas of muddy lacustrine sedimentation.

demonstrates the value of the maximum coal map as an exploration tool. The second thick coal (seam 14) is stratigraphically above the first bed and is offset toward the basin axis (**Figures 4** and **9**). It extends more than 50 miles along strike (**Figure 5**; bed 14) and 30 miles downdip (**Figure 4**). Over much of its extent, it is 60 to 100 feet thick; in places its thickness exceeds 200 feet. An interdeltaic depositional setting has been postulated for this seam, as discussed earlier (Ayers and Kaiser, 1984). Anomalously thick coals associated with the Decker delta (**Figure 3**) in the northwest and the Dry Fork delta at the southwest margin of the basin appear to have formed in delta plain settings. Coals are thin or absent along the basin axis, where sedimentary fill is predominantly lacustrine mudstone.

Coal isolith

The coal isolith map (**Figure 10**) was made by contouring the net thickness of coal for each borehole. The greatest net thickness occurs in the center of the Powder River Basin and includes the previously described thick coal bed (seam 14) in the deep basin. A large region encompassed by the 225-foot isolith on **Figure 10**, was identified in the late 1960s and 22 billion tons of coal resources were calculated between 1,000 and 2,000 feet deep (Wold and Woodward, 1968; Hicks and Woodward 1969).

Net coal thickness exceeds 75 feet along the eastern margin of the basin, from T.42N. through T.58N. Low coal isolith values in the Fort Union outcrop in Montana may reflect data limitations and(or) depositional controls. Northeast of Sheridan, net coal thickness exceeds 150 feet marginal to the Decker delta (**Figure 10**). Lacustrine facies dominate along the axis of the basin and, consequently, net coal thickness is low in that region.

Number of coal seams and average seam thickness

The greatest number of Tongue River coal seams (**Figure 11**) occurs in the north-central Powder River Basin where more than 24 coal beds, having an average thickness of six to twelve feet, (**Figure 12**) and a net thickness in excess of 225 feet (**Figure 10**), are found between and flanking the Wright, Gillette and Moorehead deltas (**Figure 3**). In contrast, maps of the number of coal beds and average bed thickness (**Figures 11** and **12**), and dip section C-C' (**Figure 4**), show that in the region of the two thick, strike-parallel coal beds (the Wyodak and seam 14) (**Figure 9**), a few thick coal seams comprise the majority of the coal resources.

Coal resources

Glass (1981) asserted that estimates of Wyoming coal resources (Averitt, 1975) were conservative, in part because they were based upon compilation of older reports (82 percent were done prior to 1950) that, as acknowledged by Averitt (1975), emphasized outcrop measurements and shallow resources less than 1,000 feet deep. **Figure 13** reflects this limited data base. Thick coal seams are depicted around the margins of the Powder River Basin in Wyoming, whereas the central part of the basin is characterized by question marks. Yet, thick coal seams were identified on geophysical well logs from the center of the basin as early as the mid-1960s (Wold and Woodward, 1968).

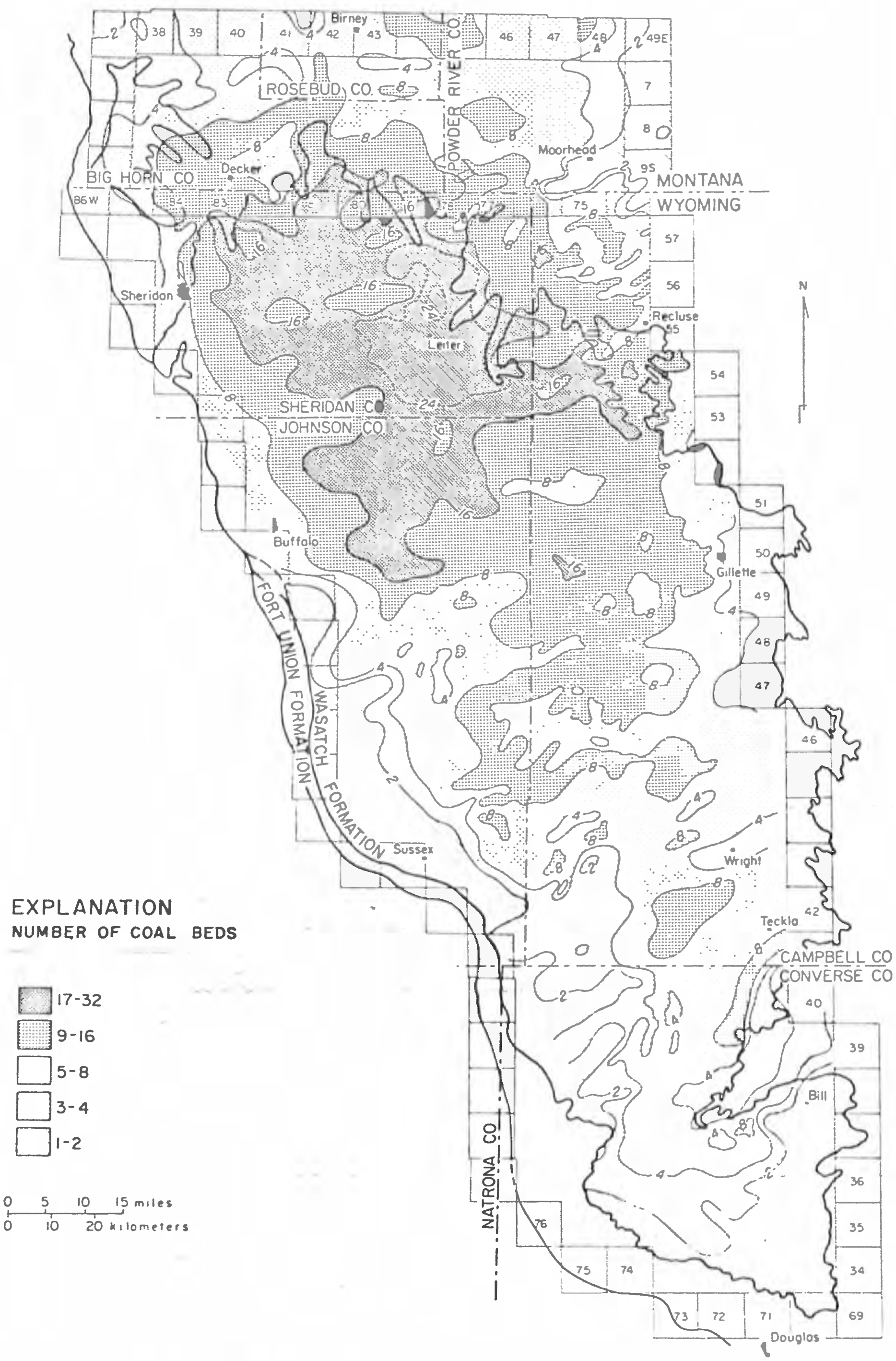

Figure 11. Coal isopleth map revealing that the greatest number of coal seams is in the north-central part of the basin. In the two areas of thick strike-parallel coals (Figure 9) there are fewer seams, but they have a greater average thickness (Figure 12). Few seams are present along the west and south margins of the basin.

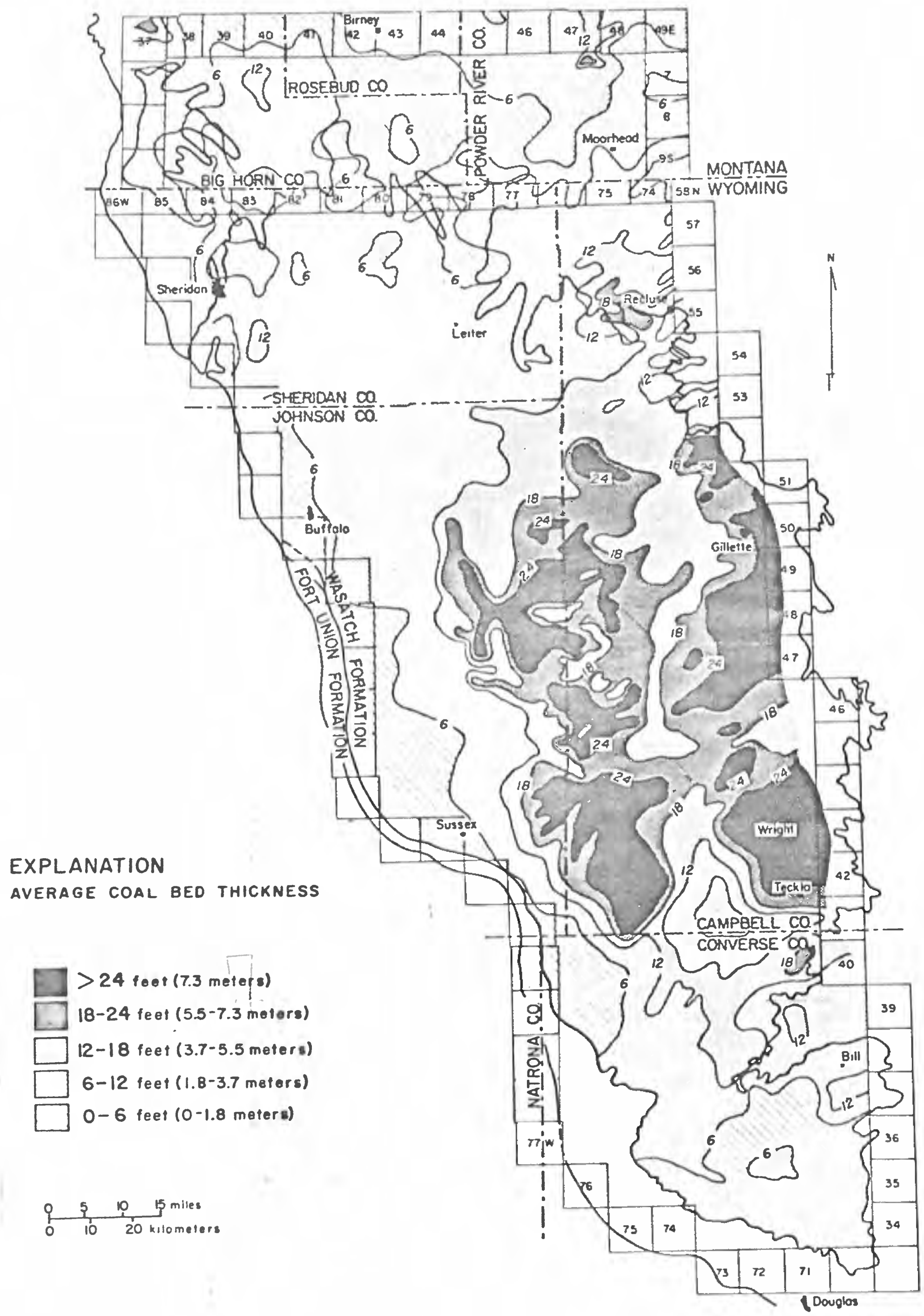

Figure 12. The average thickness of Tongue River coal seams is greatest in the areas of thick, strike-parallel coal (delineated on Figure 9) between and flanking the Gillette and Wright deltas.

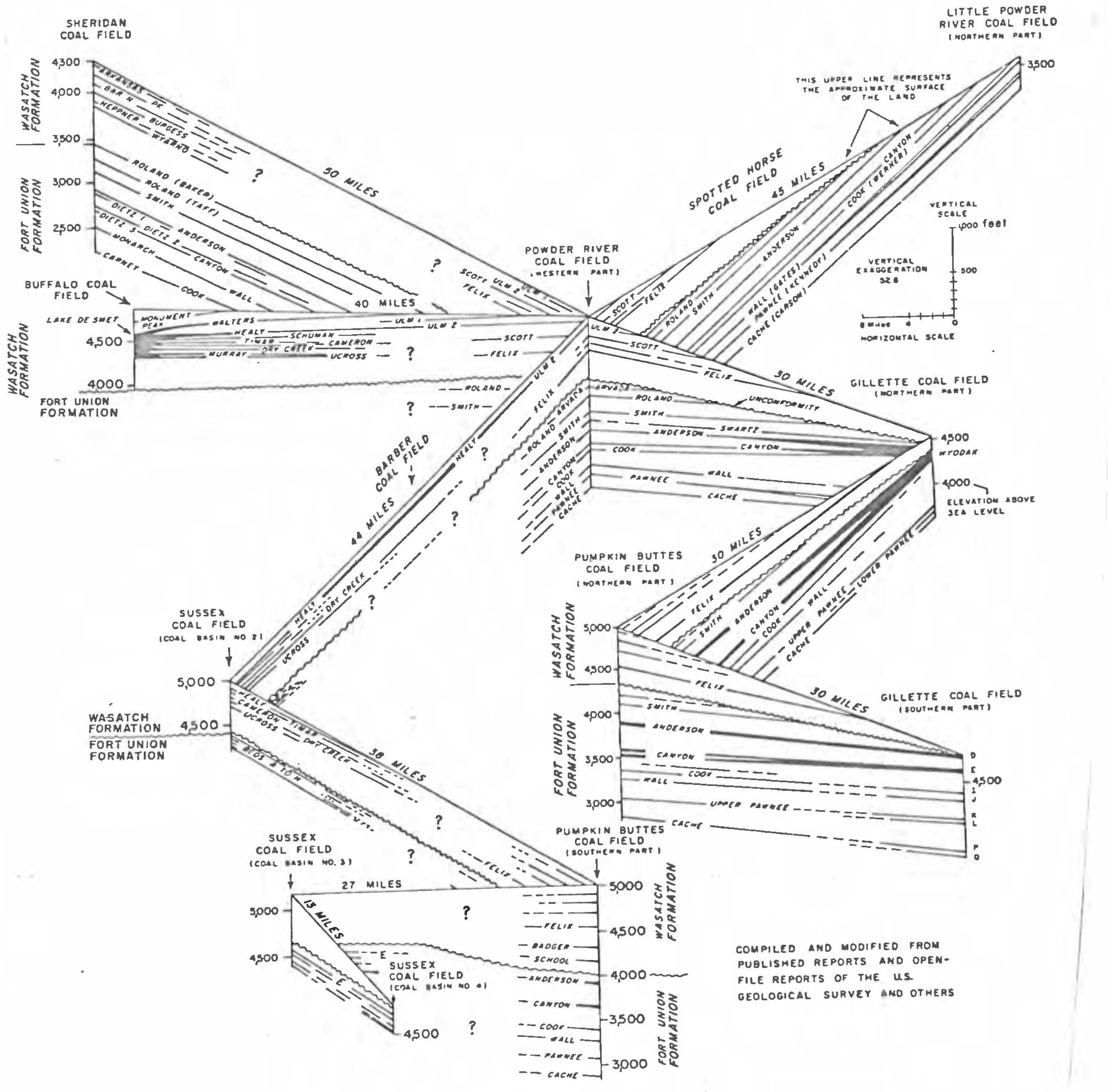

Figure 13. Fence diagram showing identification and correlation of coal seams in the Wyoming part of the Powder River Basin (from Glass, 1982). A thick undepicted coal bed (seam 14 of this report) occurs in the central part of the diagram characterized by question marks.

In this study, coal resources were calculated for coal seams in the Tongue River Member of the Fort Union Formation in both Wyoming and Montana. Data for Wyoming consisted of 1,639 geophysical well logs with the following breakdown: 1,286 induction logs from oil and gas wells, many with natural gamma ray curves; an additional 185 natural gamma ray logs run through casing in shallow wells along the east margin; and 168 density logs from U.S. Geological Survey coal drilling projects published as Open-File Reports. Locations of data from the latter two data sets are not shown on the base map **(Figure 7)**. The area of investigation was 7,932.2 square miles; borehole density was one well per 4.8 square miles for Wyoming. For Montana, 151 logs from oil and gas tests were used to calculate resources for an area of 1,766.7 square miles; borehole density was one well per 11.7 square miles.

The spacing between data points is, of course, not uniform; it varies from hundreds of feet to ten miles. If resources were calculated by the methods prescribed by the U.S. Geological Survey (Wood and others, 1983), they would appear in the measured, indicated, inferred and hypothetical categories. However, that method requires detailed correlations and the calculation of resources on a bed-by-bed basis, a herculean task considering the number of seams, variable spacing of data points and the size of the basin.

Coal seams were not correlated in this regional resource estimate. Instead, resources were calculated for the summation of coal seams (total coal). Attempts to correlate seams across an entire basin are not only futile, but are also counter to our understanding of the existing coal depositional systems. Previous studies (Ayers and Kaiser, 1982; 1984; Tewalt and others, 1983) show that the boundaries of Tongue River coal seams are established by the framework elements of the host sediments. Major coal seams are continuous over distances of tens of miles (commonly 30 to 50 miles).

Resource estimates for Tongue River coal seams greater than two feet thick occurring to a depth of 3,000 feet were calculated by planimetering the coal isolith map **(Figure 10)** [short tons = area (acres) x coal thickness (feet) x 1,770 tons per acre-feet]. Calculated Tongue River coal resources in Wyoming and Montana are 1,164,902,000,000 tons; 91 percent (1,058,660,000,000 tons) are in Wyoming, and nine percent (106,235,000,000 tons) are in Montana. Direct comparison of these resource estimates with those of Averitt (1975), Cole and others (1982) and Glass (1982) are speculative because of differences in the methods of calculation. Also, the U.S. Geological Survey does not calculate resources for subbituminous coal seams less than 2.5 feet thick. Beds between two and 2.5 feet thick, however, make up less than one percent of the resources reported in this study.

Resources calculated in this study for the Tongue River Member in Wyoming are greater than resources estimated by Glass (1982) for all coal-bearing formations (110,219,000,000 tons) in the Wyoming part of the Powder River Basin. Glass' resource estimate was updated from an earlier report by Berryhill and others (1950) that relied heavily upon outcrop measurements. It is apparent when comparing the coal isolith map **(Figure 10)** with the fence diagram **(Figure 13)** that the increase calculated in this study results from the delineation of tremendous coal resources that fill in the question marks on **Figure 13** and confirm the conclusion (Glass, 1981) that Wyoming coal resource estimates are conservative. In fact, this present estimate is probably conservative because data is scarce near outcrops.

Montana coal resources are difficult to evaluate and are probably also conservative because much of the studied area lies within the Fort Union outcrop and information is lost due to surface casings in wells. In addition, well control is less dense in Montana. Direct comparison of resource estimates of this study with published estimates (Cole and others, 1982; Matson, 1975) are invalid because those studies report only strippable coal to depths of 250 feet. Montana resources (106,235,000,000 tons) to a depth of 3,000 feet are approximately three times greater than the strippable resources reported (Cole and others, 1982) for the Powder River coal region of Montana, which is larger than the region of Montana discussed in this study.

Coal resources of the Tongue River Member to a depth of 3,000 feet (1,164,902,000,000 tons) are 32 percent of the total identified and hypothetical coal resources of the United States (3,580,568,000,000 tons) (Averitt, 1975) to the same depth. The present resource estimate does not include all of the Montana part of the basin, nor does it include other coal-bearing formations. In particular, the Wasatch Formation (Eocene) contains several thick coal seams. Without doubt, the Powder River Basin is one of the most coal-rich basins in the United States. The resources calculated in this study equal 22,366 quads of energy, or the equivalent of 3.86 x 10^{12} barrels of crude oil (assuming 9,600 Btu/pound for coal [Glass, 1982] and 5,800,000 Btu/barrel for crude oil).

Conclusions

1. Geophysical well logs from oil and gas wells provide a readily available source of data for the regional evaluation of coal resources in deep coal basins.

2. The maximum coal map is an excellent exploration tool, as is demonstrated by its success in predicting the locations of surface mines in the Powder River Basin.

3. Thick coal seams (greater than 60 feet) occur parallel to the basin axis in two regions. The first seam, located along the east margin of the basin is the target of more than a dozen surface mines. The second seam lies in the center of the basin at depths greater than 1,000 feet; exploitation of this deep-basin coal will require more innovative recovery techniques than currently available.

4. Coal resources of the Tongue River Member (1.16 trillion tons) exceed published resource estimates for all coal-bearing strata in the Powder River Basin. The large resource estimates calculated in this study result from using induction well logs to delineate deep-basin coal resources excluded in previous estimates. This non-traditional source of data should be used routinely in coal resource assessment.

Acknowledgments

This paper represents part of the author's dissertation research under the supervision of W.R. Kaiser and A.J. Scott. Their comments, and suggestions by G.B. Glass, significantly improved the manuscript. Well logs were provided by M.J. Systems, the Geological Survey of Wyoming, Cities Service Oil and Gas Corporation, American Stratigraphic Company and Carter Mining Company. Field work was supported by the University of Texas at Austin Geology Foundation, and by Grants-in-Aid from the American Association of Petroleum Geologists and Sigma Xi, The Scientific Research Society. I wish to express my appreciation to AMAX Coal Company and Big Horn Coal Company for mine access, and to the many landowners who permitted field work on their ranches. Drafting expenses were defrayed, in part, by a grant from the Owen-Coates Fund of the University of

Texas. Figures were drafted by R. Longoria and C. Wilson, and by the cartographic staff of the University of Texas Bureau of Economic Geology, under the direction of D.F. Scranton. The Department of Geological Sciences of the University of Texas at Austin provided funds for word processing.

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