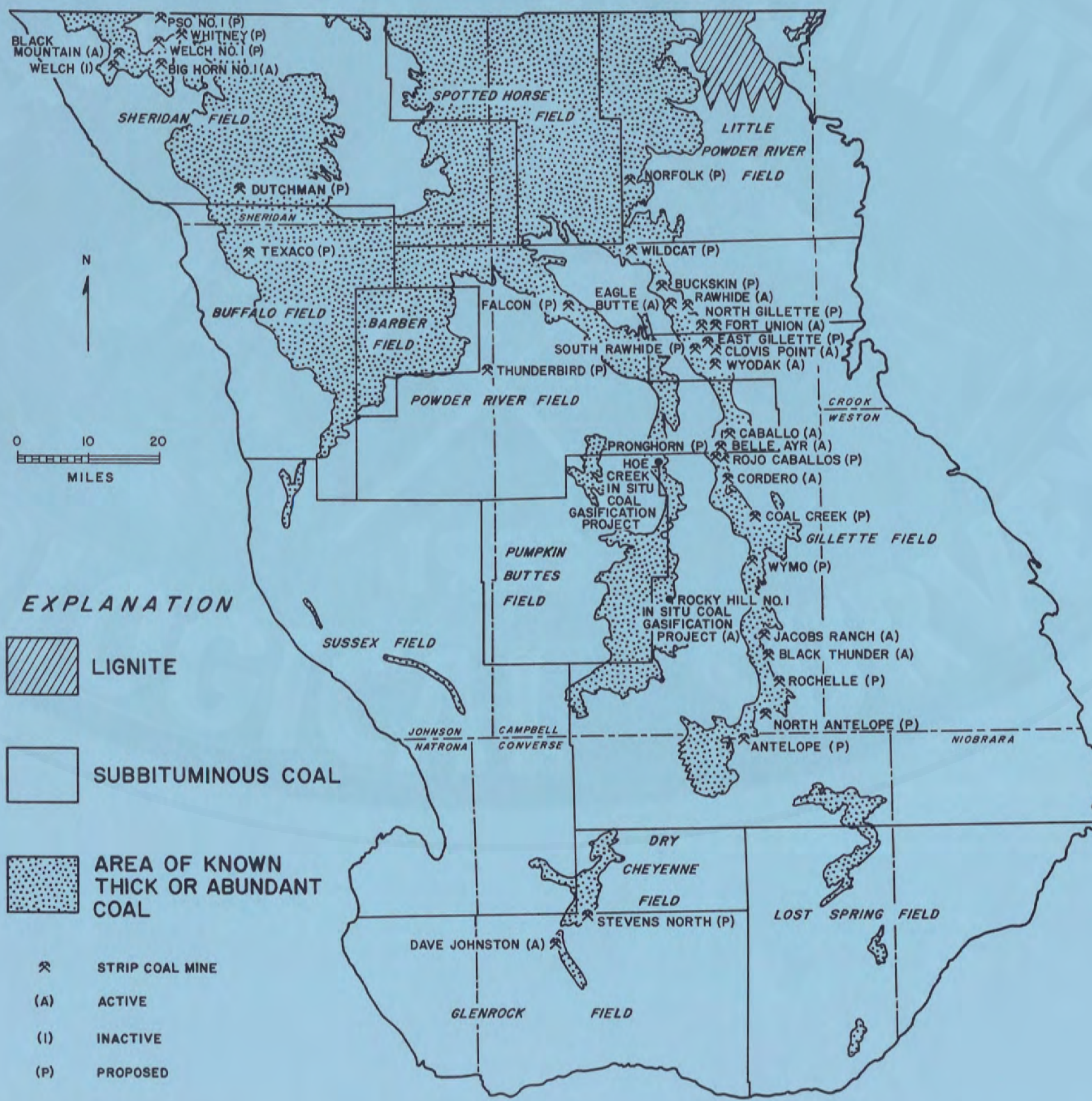
THE GEOLOGICAL SURVEY OF WYOMING

Daniel N. Miller, Jr., State Geologist

PUBLIC INFORMATION CIRCULAR No. 14

GUIDEBOOK TO THE COAL GEOLOGY OF THE POWDER RIVER COAL BASIN, WYOMING

edited by Gary B. Glass



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A reprint of much of the material from a guidebook that accompanied Field Trip No. 5 of the Energy Minerals Division, American Association of Petroleum Geologists, June 12-14, 1980.

LARAMIE, WYOMING

1980

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INTRODUCTION

Although Wyoming's Powder River Coal Basin has been the object of several field trips within the last decade, these trips were more economically-oriented than geological in scope. During an EMD Field Trip in June 1980, coal geology and more specifically environments of coal deposition were stressed. The depositional models and paleoenvironmental ideas presented during that trip and reprinted in this report should help unravel the geological history of coal deposition in the basin and at least provide viable working hypotheses to explain the accumulation of numerous thick Tertiary coals that are typical of the basin.

The editor would also like to thank the capable authors of the enclosed papers for their fine contributions as well as for the editorial license they permitted him. The final manuscript was very ably typed by Mrs. Ellen Barnes.

STATE OF WYOMING

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GEOLOGICAL SURVEY

REGIONAL DEPOSITIONAL FRAMEWORK OF THE URANIUM- AND COAL-BEARING WASATCH (EOCENE) AND FORT UNION (PALEOCENE) FORMATIONS, POWDER RIVER BASIN, WYOMING

by

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INTRODUCTION

Information pertinent to the regional depositional framework of the Wasatch and Fort Union formations (Figure 1) in the Powder River Basin is taken largely from the work of Sharp et al. (1964), Obernyer (1978), Galloway (1979), Flores (1979), Jackson and Ethridge (1979), Deutsch et al. (1979), and Jackson (1979).

Sharp et al. (1964) present an overview of the grain-size facies of the Wasatch Formation within the Powder River Basin. A south to north transect along the basin axis (Figure 2) reveals three facies: a medium- to coarse-grained sandstone facies along the southern basin axis grades northward into an area of interbedded sandstone and fine-grained sediments (silt, clay, and organics) that in turn grades northward into fine-grained deposits. A conglomeratic facies (the "Moncrief beds") along the northwest flank of the basin marks an area where basin margin alluvial fans are preserved (Figure 2; Obernyer, 1978). In other areas lateral to the basin axis, fine-grained deposits dominate the sedimentary sequence. These grain-size relations coupled with data on sediment transport directions lead Seeland (1976) to suggest a general drainage pattern for Wasatch (Eocene) streams within the Powder River and adjacent basins to the south and west (Figure 3). This drainage pattern has many similarities to the upper Fort Union drainage pattern presented by Galloway (1979) (Figure 4). In both instances the trunk stream flowed northward along the basinal axis. In the southern portion of the basin, bed-load to mixed-load channels dominate the axis of the system. The deposits of these channels grade down-channel (northward) into deposits of mixed-load and suspended-load channels.

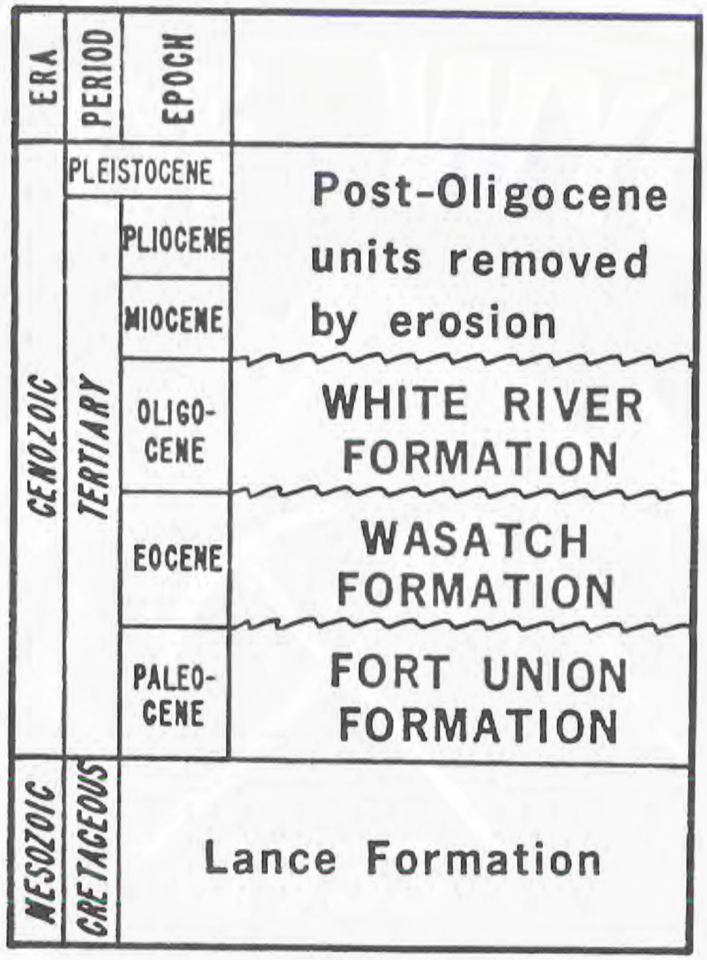

Figure 1. Tertiary stratigraphic nomenclature for the Powder River Basin, Wyoming (from Dahl and Hagmaier, 1976, p. 245, Figure 3) Note: There is no physical evidence for an unconformity between the Wasatch and Fort Union Formations in the vicinity of the SEAM study site (Location of SEAM study site given in Fig. 5).

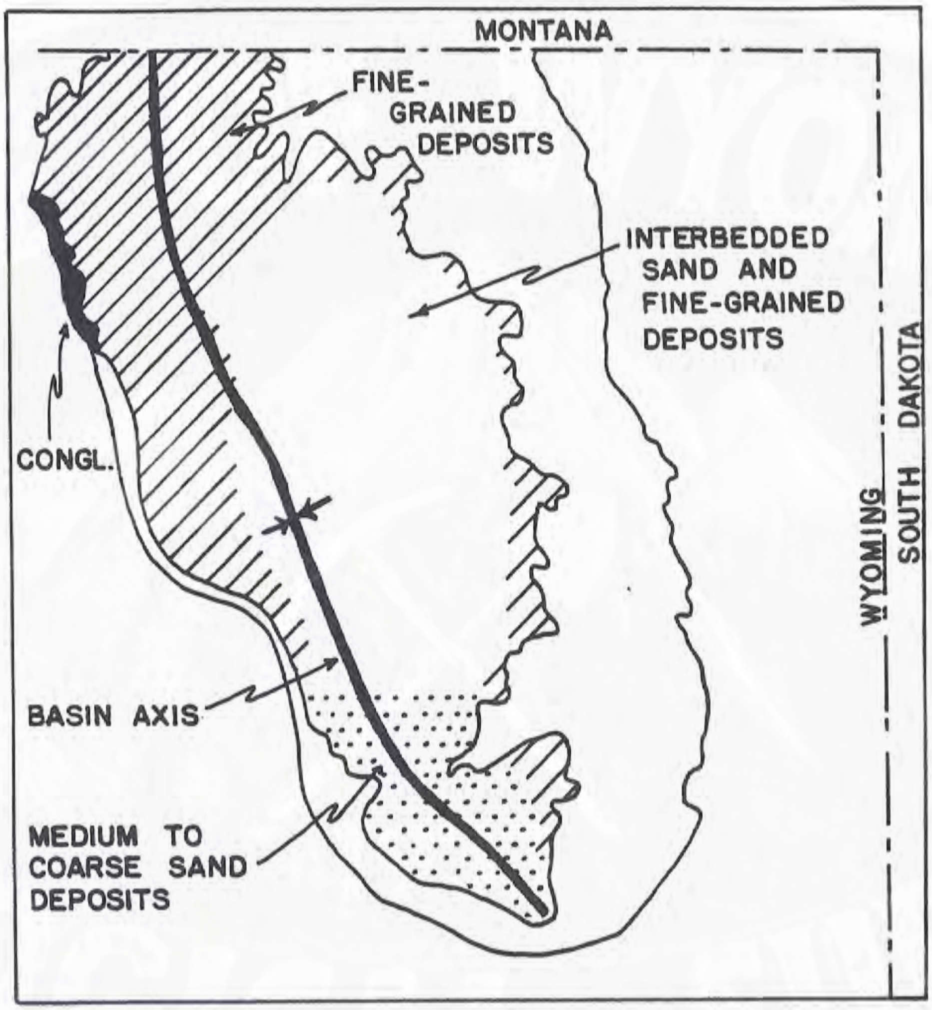

Figure 2. Lithofacies relations in exposed portions of Wasatch Formation, Powder River Basin, Wyoming (modified from Sharp et al. 1964, Plate 10).

The bed-load to mixed-load channels in the southern portion of the basin contain medium- to coarse-grained sandstone, with beds of sandy conglomerate and thin clay drapes, have sharp and irregular basal contacts, display poorly developed fining-upward sequences and are sharply overlain by overbank mudstones, siltstones, and coals (Galloway, 1979). Finer-grained basin axis deposits to the north reveal the classic fining-upward sequence of grain size and thinning-upward sequence of structures associated with point bar deposits of a meandering stream (Obernyer, 1978; Galloway, 1979; and Flores, 1979). These channel deposits are interbedded with finer-grained crevasse splay and overbank deposits. Point bar deposits of mixed-load to suspended-load meandering channels and associated overbank deposits are also described from the eastern portion of the basin (Figure 5; SEAM Study Site) by Deutsch, et al. (1979) and Jackson and Ethridge (1979). These deposits, which will be discussed in detail later, represent the basin margin alluvial facies (floodplain-tributary facies of Galloway, 1979). Based on data from Sharp et al. (1964), Glass (1976), and others, the thick (7 to 220 feet), laterally continuous coals within the basin occur in a linear belt peripheral to the basin axis fluvial system and at the lower edge of the basin margin tributary system.

In conclusion, the depositional framework of the Fort Union and Wasatch formations is characterized by a northward-flowing intermountain basinal fluvial system. This fluvial system has three major components: a major trunk stream along the basin axis, a tributary subsystem along the basin margin and a paludal subsystem lying between the trunk stream and the tributary subsystem. Along the northwest flank of the basin, local conglomerates of alluvial fan origin are present (Figure 2) (Obernyer, 1978).

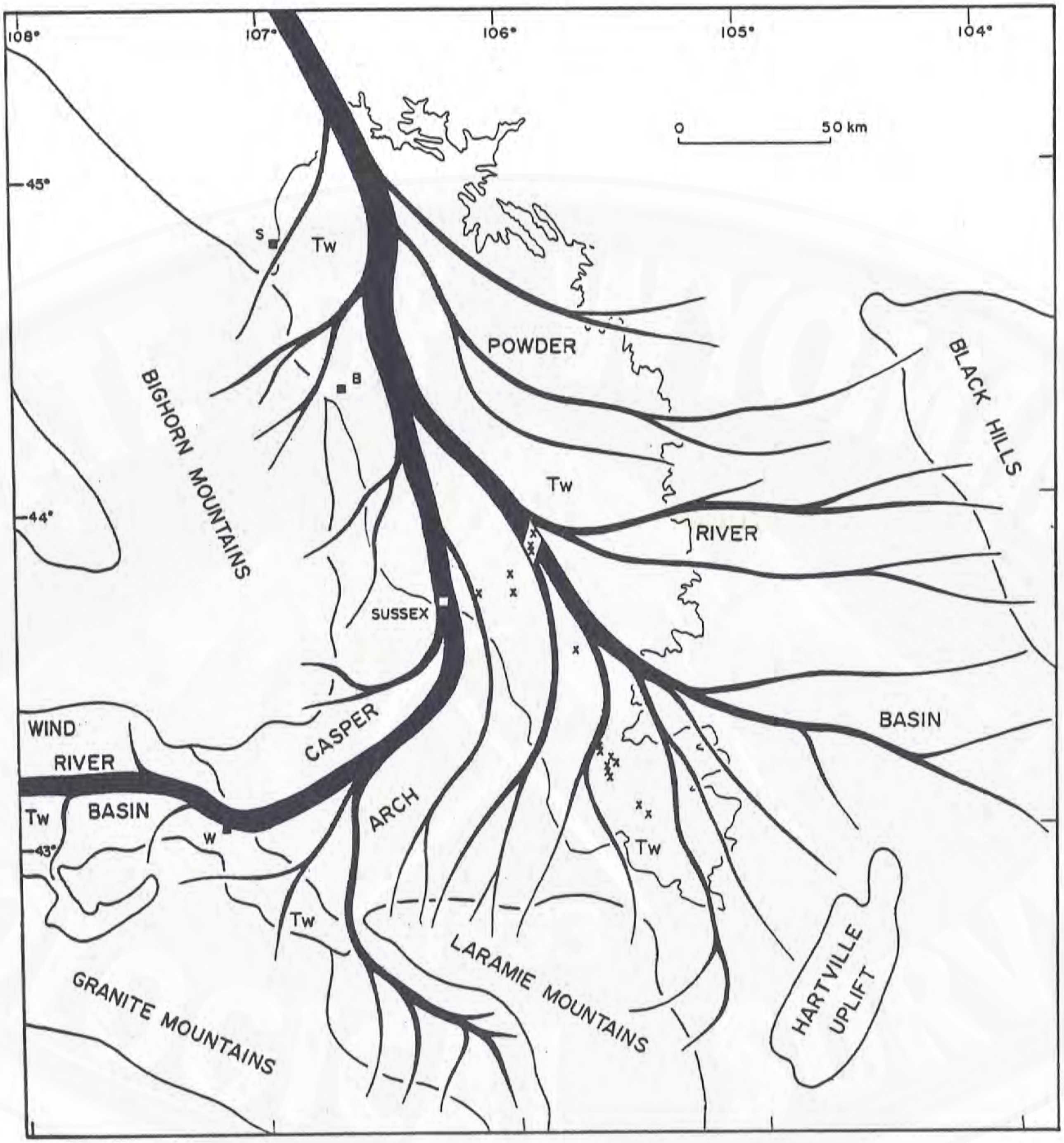

Figure 3. Interpretative map of Eocene paleogeography of northeastern Wyoming (from Seeland, 1976, p. 63, Figure 8).

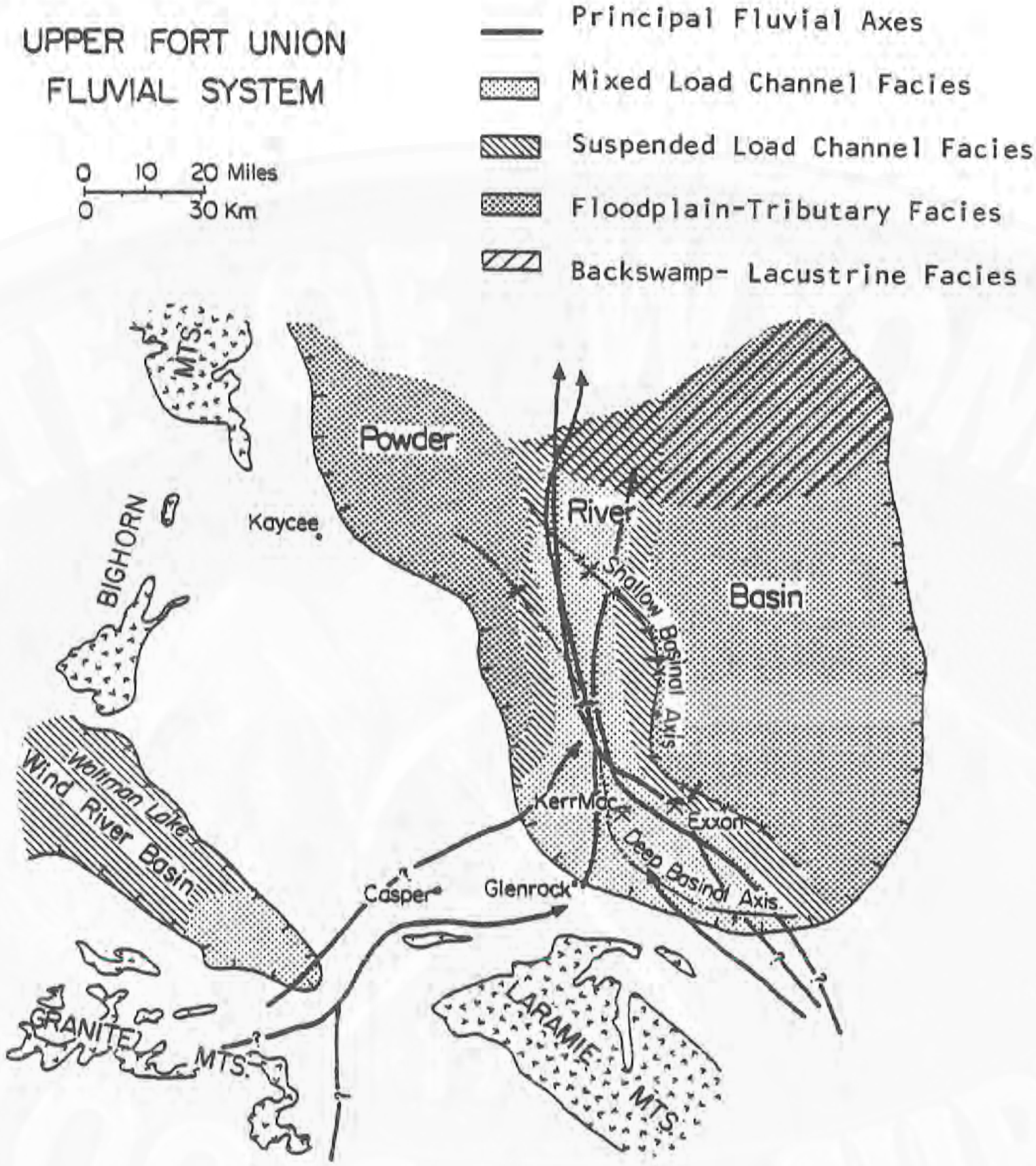

Figure 4. Inferred basin framework and facies distribution of the upper Fort Union fluvial facies. Proximal tributary channels probably collected sediment from the Granite Mountain and Laramie-Hartsville Uplift areas before coalescing at the southern end of the Powder River Basin. Bed-load and mixed-load channel-fill facies probably dominated the axis of the system in the southern basin; increasing percentages of suspended-load sediment caused a down channel evolution into mixed-load to suspended-load channels to the north along the main trunk stream. Note: Study area discussed in detail in the chapter is in floodplain - tributary facies east of principal fluvial axis (from Galloway, 1979, p. 204, Figure 1).

Thick coal deposits such as the Anderson and Wyodak coal beds probably originated in the paludal system (see discussion below). Uranium ore is generally concentrated along alteration fronts (roll-fronts) within and along the flanks of the major sandstone belts (major trunk streams) which contain mixed-load to bed-load channel deposits (Galloway, 1979). Details of one of these ore bodies (the Highland deposit, in Converse County) is described by Langen and Kidwell (1974) and by Dahl and Hagmaier (1974 and 1976). According to these authors, uranium is concentrated in individual sandstone units of the upper Fort Union Formation. These sandstone units appear to be tongue-like extensions off the eastern edge of the main Highland sandstone. This breakup of the major sandstone belt is interpreted to be the product of lateral migration of point bars. Uranium deposits at the Bear Creek mine (Stop 1 of this field trip) are concentrated in the lower Wasatch Formation (Buturla and Schwenk, 1976).

BASIN HYDROLOGY AND ORIGIN OF THE THICK COALS

Groundwater flow patterns in the Powder River Basin during Paleocene and Eocene time probably paralleled the tributary drainage towards the basin axis in a manner similar to that described by Williams (1968) (Figure 6). The adjacent uplifts and basin margin areas served as major recharge areas while the basin axis was the site of groundwater discharge. It was along this discharge zone, peripheral to the main trunk stream and down-flow from the recharge areas, that the major coal forming swamps probably developed (Jackson, 1979, and Mike Boyles, personal communication). This hypothesis for the origin and distribution of the thick Powder River coals is illustrated by a generalized model (Jackson, 1979; Figure 7) and is supported by palynology and paleobotany data from both the coals and

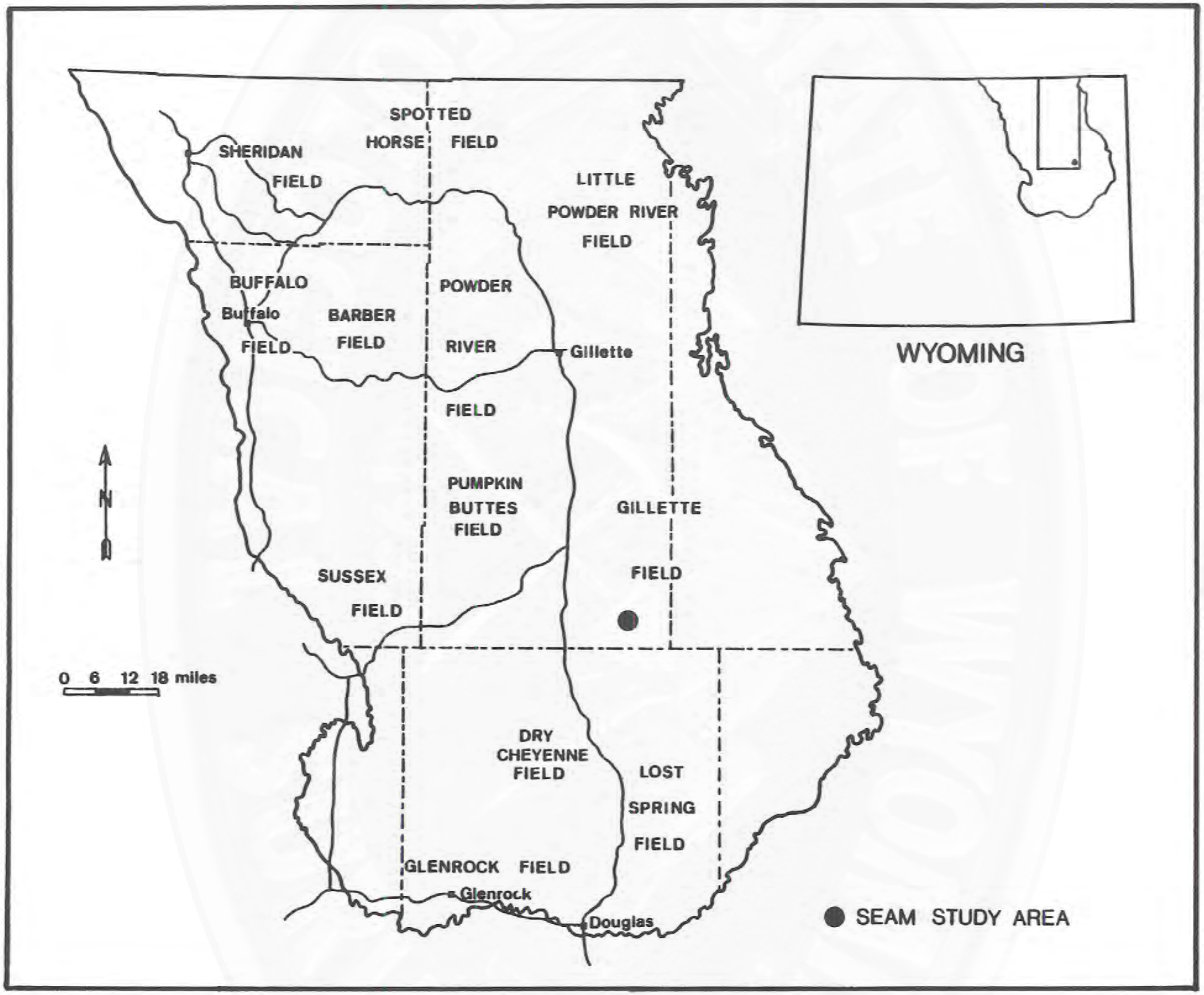

Figure 5. Location map showing study site in southeastern Campbell County, Wyoming.

the associated alluvial sediments (Tidwell, 1975; Tschudy, 1976; and Jansen, 1978). These data suggest that the climate was sub-tropical and moist and that the coal forming swamps supported a diverse flora which implies an abundance of nutrients, probably supplied by groundwaters (Stach, 1975).

The low ash content of these coals and their significant thickness and apparent lateral extent, however, present a serious problem in view of the associated thick fluvial deposits. It would appear reasonable to assume that the fluvial system would have periodically flooded, contaminated and/or destroyed the peat swamps. Modern eutrophic swamps usually occur in topographic lows subject to periodic flooding (Stach, 1975). However, some tropical peats in Malaya form topographic platforms with surfaces up to 46 feet (14 meters) above the level of local rivers (Anderson, 1964). The rivers are thus confined from shifting, and adjacent floodplains are narrow, even though the streams carry large amounts of sediment. These swamps cover large areas and occur in close proximity to mountains. However, the analogy to the Powder River Basin coals is incomplete for several reasons: these modern coal forming swamps are nutrient poor because of flushing by heavy rainfall; they are developed in a deltaic plain and the rivers have a pronounced tidal influence; and finally, the diversity of flora is low. Nevertheless, these Holocene peat deposits suggest a possible mechanism for the production of extensive Tertiary peat deposits that segregate themselves from adjacent alluvial sedimentation by building above the level of flooding (Jackson, 1979). This hypothesis contrasts with one proposed by Obernyer (1978) who suggests that the thickness and linear orientation of one of the thick coal seams (the Healy bed at Lake de Smet) was controlled by a basin-margin fault.

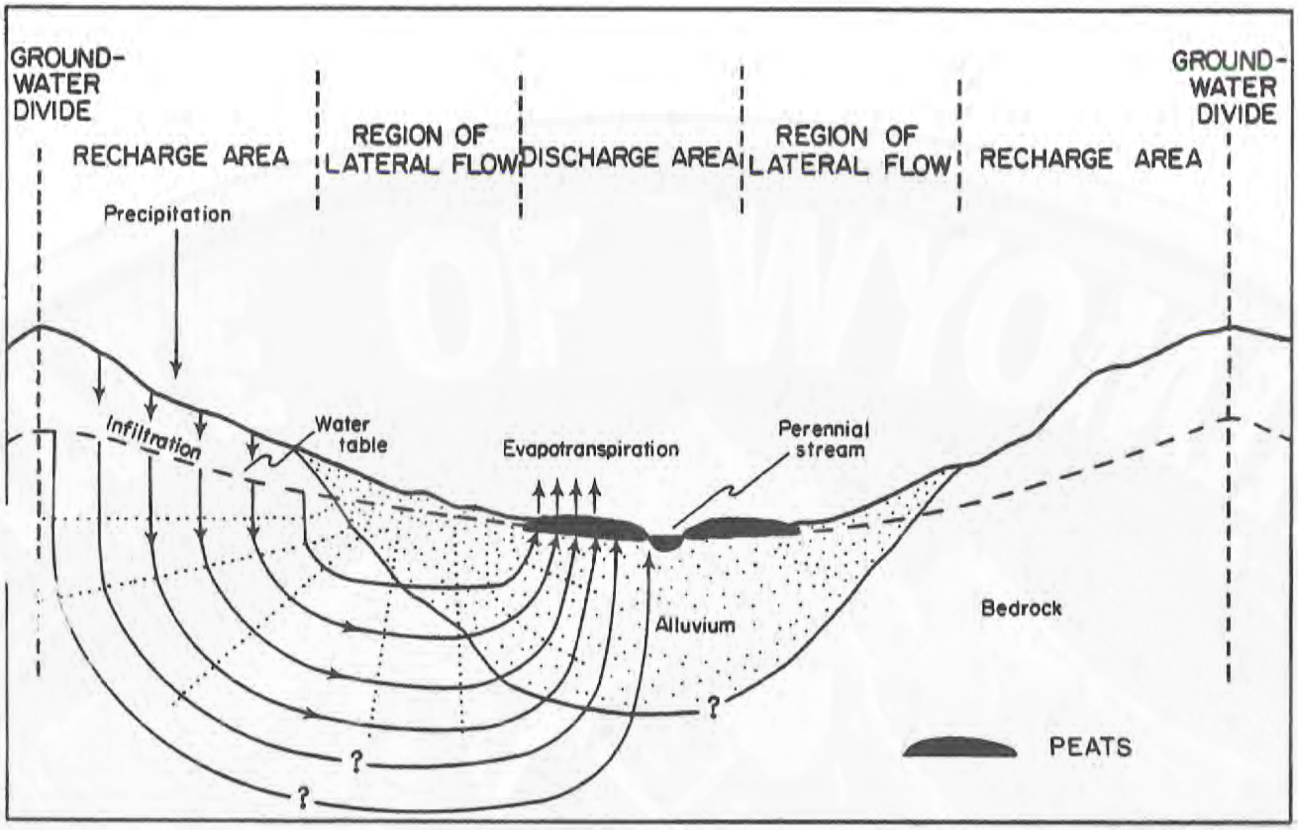

Figure 6. Generalized groundwater flow system in an alluvial valley and inferred location of thick peats (modified after Williams, 1968, p. 185, Figure 2).

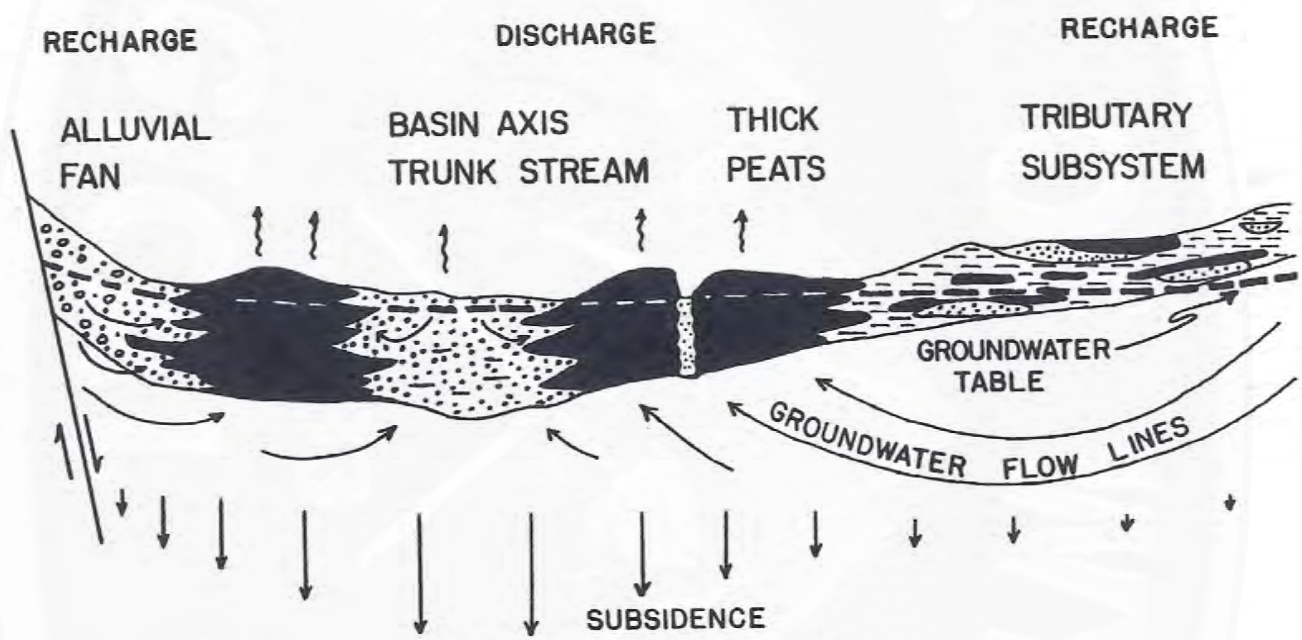

Figure 7. Generalized model for development of thick coals of the Powder River Basin. Illustrates relation of sedimentary facies to groundwater hydrology, uplift and subsidence. Note relation of thin coals in tributary subsystem to crevasse splay sandstones on right side of diagram (From Jackson, 1979, Figure 5).

DEPOSITIONAL ENVIRONMENTS OF THE TRIBUTARY SUBSYSTEM SOUTHEASTERN CAMPBELL COUNTY

GENERAL

During a recent investigation of the physical and geochemical characteristics of overburden material in southeastern Campbell County (Figure 5), eighteen continuous cores were taken in the lower Wasatch and upper Fort Union formations. Detailed descriptions and correlations of these cores provided data for describing the Wasatch tributary subsystem. The study site consisted of a four square mile area that essentially comprised the drainage basin of Porcupine Creek and which lies east of the structural axis of the basin (Figure 8). Core hole spacing varied from 700 feet to a mile. Cores generally penetrated to within 15 to 25 feet below the Anderson or "D" coal bed which varies from 58 to 82 feet in thickness over the study area. For purposes of this investigation, the base of the Wasatch Formation was placed at the top of the Anderson coal. Due to the lack of significant outcrops in the study area, it was decided, for purposes of this field trip, to examine exposures in the Bear Creek uranium mine southwest of the original study site. Exposures in the highwalls above the main ore-bearing sandstone reveal Wasatch sediments similar to those described in the study area. Because of the active nature of this mine, the exact character of the exposures to be examined cannot be determined until just prior to the field trip. The discussion that follows is, therefore, taken from our report on the study site northeast of Stop 1 (Jackson and Ethridge, 1979 and Deutsch et al., 1979).

The Wasatch Formation within the study area (northeast of Stop 1) is composed of fine-grained sandstones, siltstones, and mudstones or claystones interbedded with thin discontinuous coal or clayey coal beds. Significant

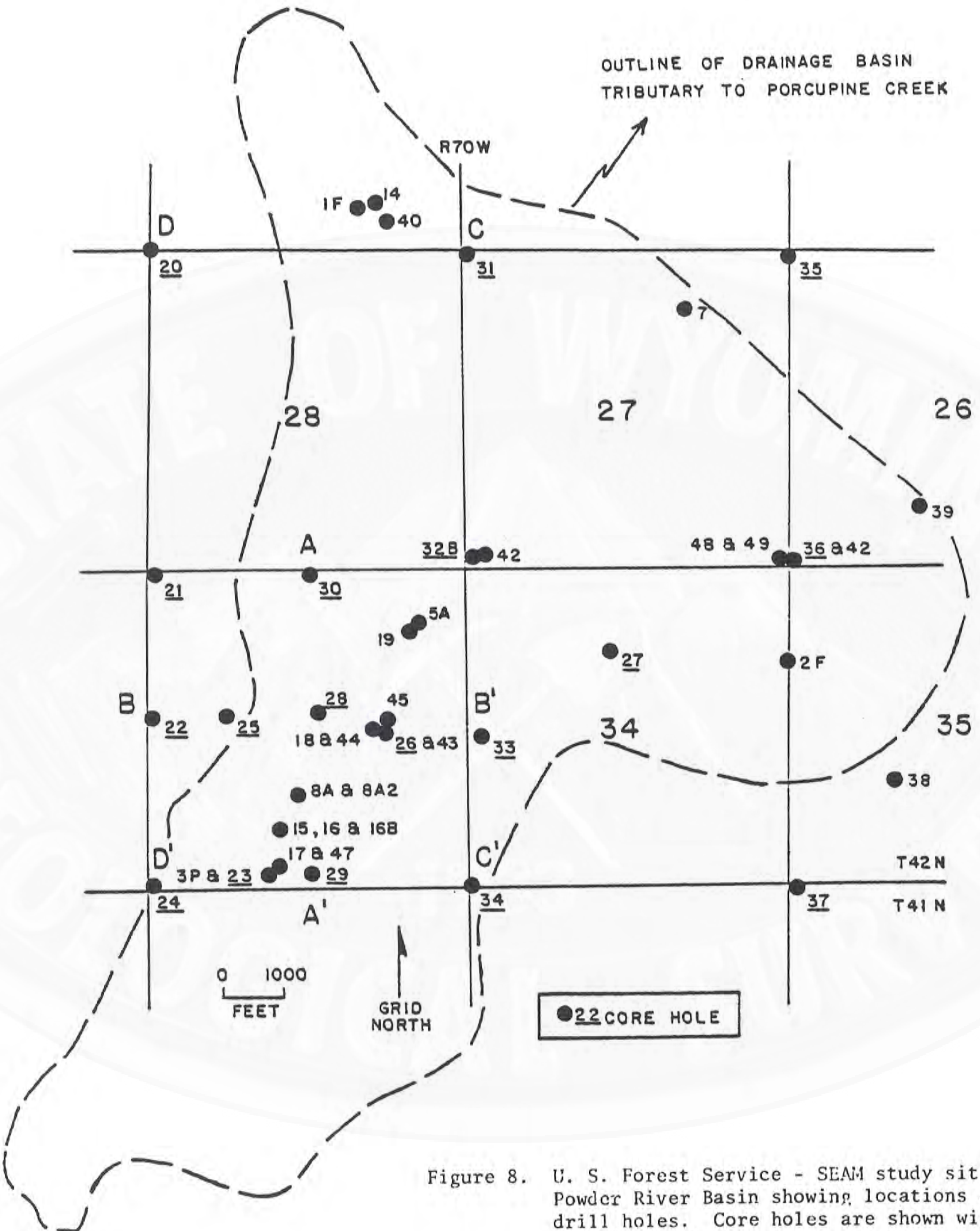

Figure 8. U. S. Forest Service - SEAM study site, Powder River Basin showing locations of drill holes. Core holes are shown with an underlined number. Large capital letters are locations of cross sections. Cross-section B-B' is shown in Figure IV-11 (from Deutsch et al., 1979).

lateral and vertical variability of lithologies is the rule rather than the exception. In most cores, mudstones or claystones and siltstones form the bulk of the stratigraphic succession. However, in a few cores sandstones are of equal or greater abundance. Mineralogically these sedimentary rocks contain relatively large amounts of feldspar and mica and moderate amounts of chert and plutonic, metamorphic, and volcanic rock fragments for their grain size. They are classed as immature, first cycle sediments (Denson and Pipiringos, 1969). Texturally, they range from immature to submature. Several different types of cementing materials, including calcite, siderite, and opal-chalcedony are present.

Only the upper 75 to 112 feet of the Fort Union Formation were investigated. The Anderson coal bed constituted the upper 58 to 82 feet of this sequence. Below this coal the characteristics of the Fort Union are similar to those of the overlying Wasatch Formation. For purposes of the following discussion of inferred depositional environments only the Wasatch Formation will be considered in detail.

DEPOSITIONAL ENVIRONMENTS

Many of the sedimentary rock sequences in the Wasatch Formation within the study area, have characteristics similar to those described by Coleman (1966), Krinitzsky and Smith (1969), and Krinitzsky (1970) for recent sediments of the Atchafalaya River Basin, Louisiana. This basin is bordered by meander belts of the present and former Mississippi River (Figure 9) and consists of a thick blanket of fine-grained sediments termed backswamp deposits. Specific environments recognized and characterized by Coleman (1966) and by Krinitzsky and Smith (1969) include lacustrine, lacustrine delta fill, well-drained swamp, and poorly-drained swamp. These environments and point bar, abandoned channel, and levee deposits are recognized in the Wasatch Formation (Figure 10). Data used for recognizing these latter three environments were obtained from geologic investigations of the lower Mississippi valley by the U. S. Army Corps of Engineers (Kolb et al., 1968, for example) and from Reading (1978).

Obviously, the intermountain tectonic setting of the lower Wasatch Formation is not similar to that of the Atchafalaya Basin, which is located in a coastal plain setting representing a lower alluvial valley and/or an upper delta plain. However, both the ancient Wasatch floodplain-tributary subsystem and the Holocene Mississippi River floodbasins represent extensive floodplains affected by similar processes and both contain a similar set of deposits.

POINT BAR DEPOSITS

In cores, point bar deposits are recognized as fining-upward sequences of poorly-consolidated, cross-bedded sandstones that grade upward through horizontally laminated and small-scale cross-bedded sandstones. Clay clasts are common in the lower part of these sequences; iron oxide nodules are present and clay lenses and lenticular beds are common in the middle and upper parts. These sequences range from 15 to 62 feet in thickness throughout the study area. Their lateral distribution is quite variable, ranging from small isolated sandstone bodies to large meander belt complexes of stacked channels that extend from the north-central to the southeastern portion of the study area. At Stop 1 point bar deposits are readily recognized by spectacular longitudinal accretion surfaces, termed epsilon cross-stratification (Allen, 1965) which are exposed along one of the highwalls.

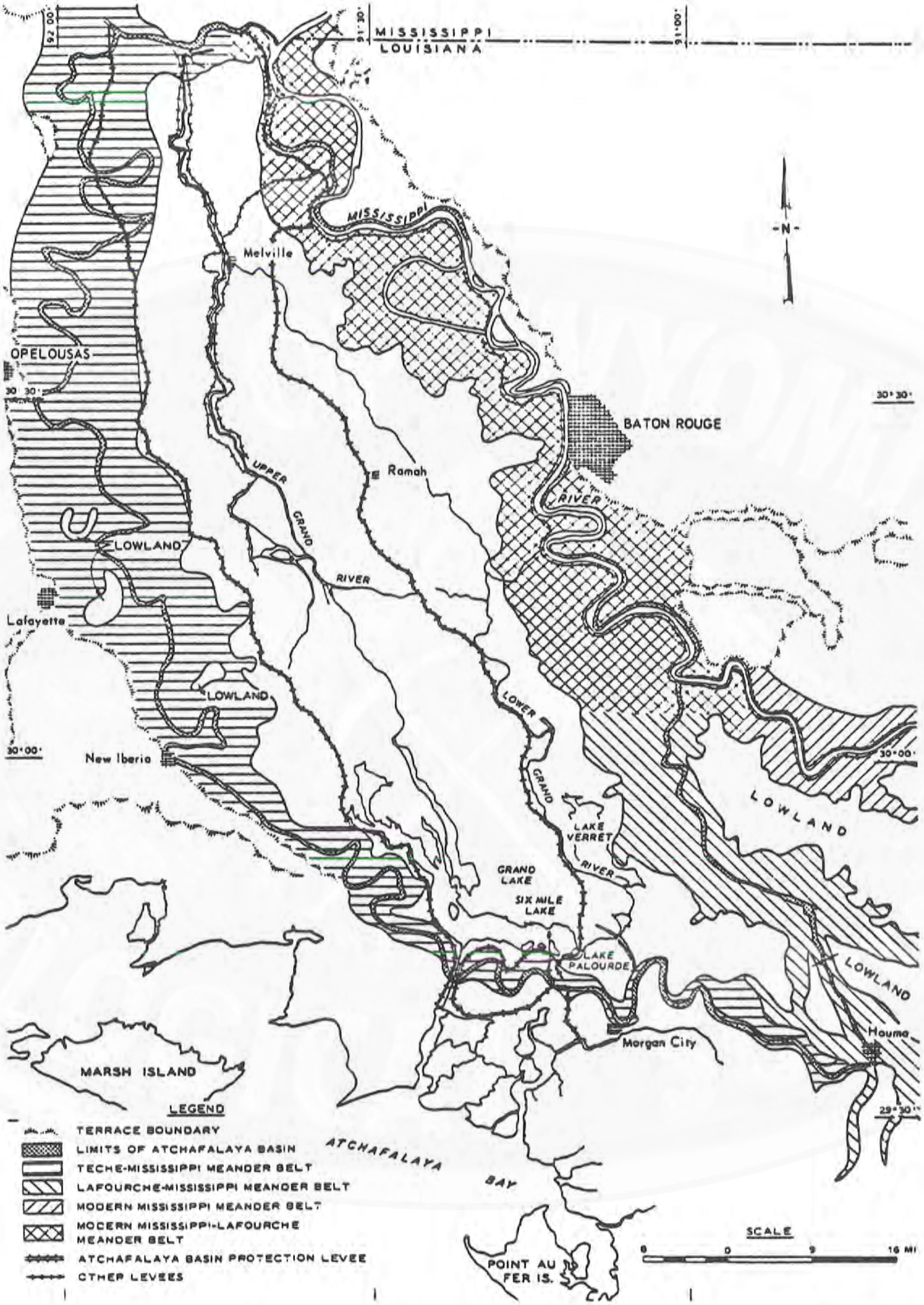

Figure 9. Physiography of the Atchafalaya Basin, Louisiana (from Krinitzsky and Smith, 1969, Figure 1).

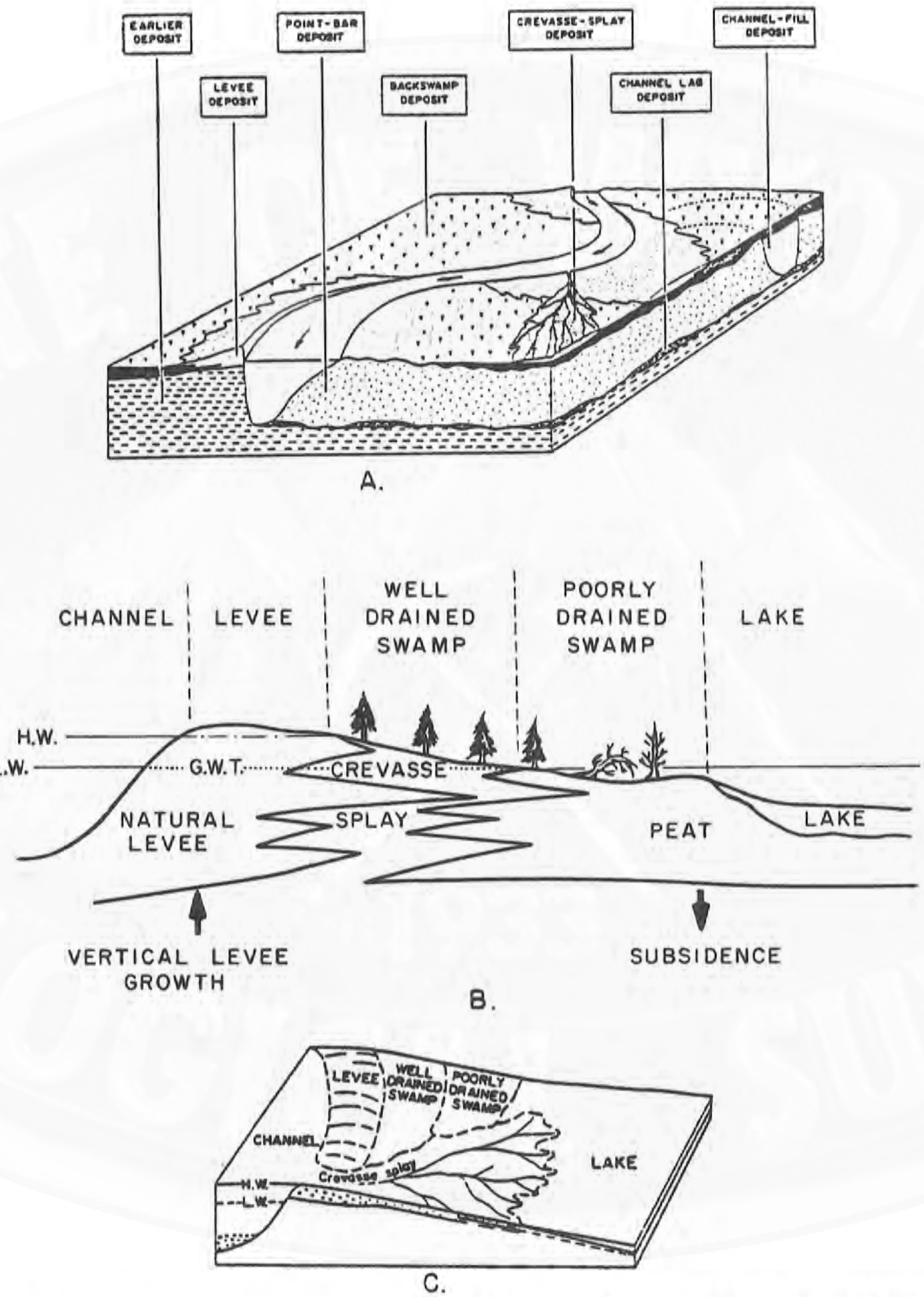

Figure 10. (A) General morphology and depositional setting of meandering river and floodplain deposits (from Allen, 1964); (B) Interpretive cross-section of channel margin environments of a meandering river-floodplain sequence (from Obernyer, 1978; modified from Weimer, 1973). (C) Block diagram showing relations of channel environments (from Weimer, 1973).

CREVASSE SPLAYS OR LACUSTRINE DELTAS

In general, crevasse splay deposits fine and thin away from channels (Figure 11) and progradation results in coarsening-upward sequences.

In cores, crevasse splay deposits generally consist of fine-grained sandstones with ripples, small-scale trough cross-stratification, parallel laminations, and scour and fill structures. The upper portions of these splays are commonly rooted, contain calcium carbonate nodules and often grade upward into well-drained swamp deposits. Thickness ranges from 1 foot (near the splay margins) to 50 feet. Laterally, composite splays have been correlated for over a mile. Where a crevasse splay debouches into a lake, a lacustrine delta is formed. Lacustrine deltas are difficult to distinguish from crevasse splays except when they display high angle foreset beds, and soft sediment deformation (Figure 12). Burrowing may be common in some sequences.

NATURAL LEVEES

Natural levees usually consist of fining-upward sequences with well stratified, burrowed, sand-to-silty lower portions grading upwards into silty clays with intense burrowing and root bioturbation (Figure 12). Nodules of iron oxide and calcium carbonate may be common and ripple-drift stratification may be present. The deposits are difficult to distinguish from upper-point bar or from proximal crevasse splay deposits and are probably more abundant in the study area than is suggested by the cores.

ABANDONED CHANNEL-FILL

Abandoned channel-fill deposits usually consist of fine-grained parallel-laminated, organic-rich clays and silts and may consist of many

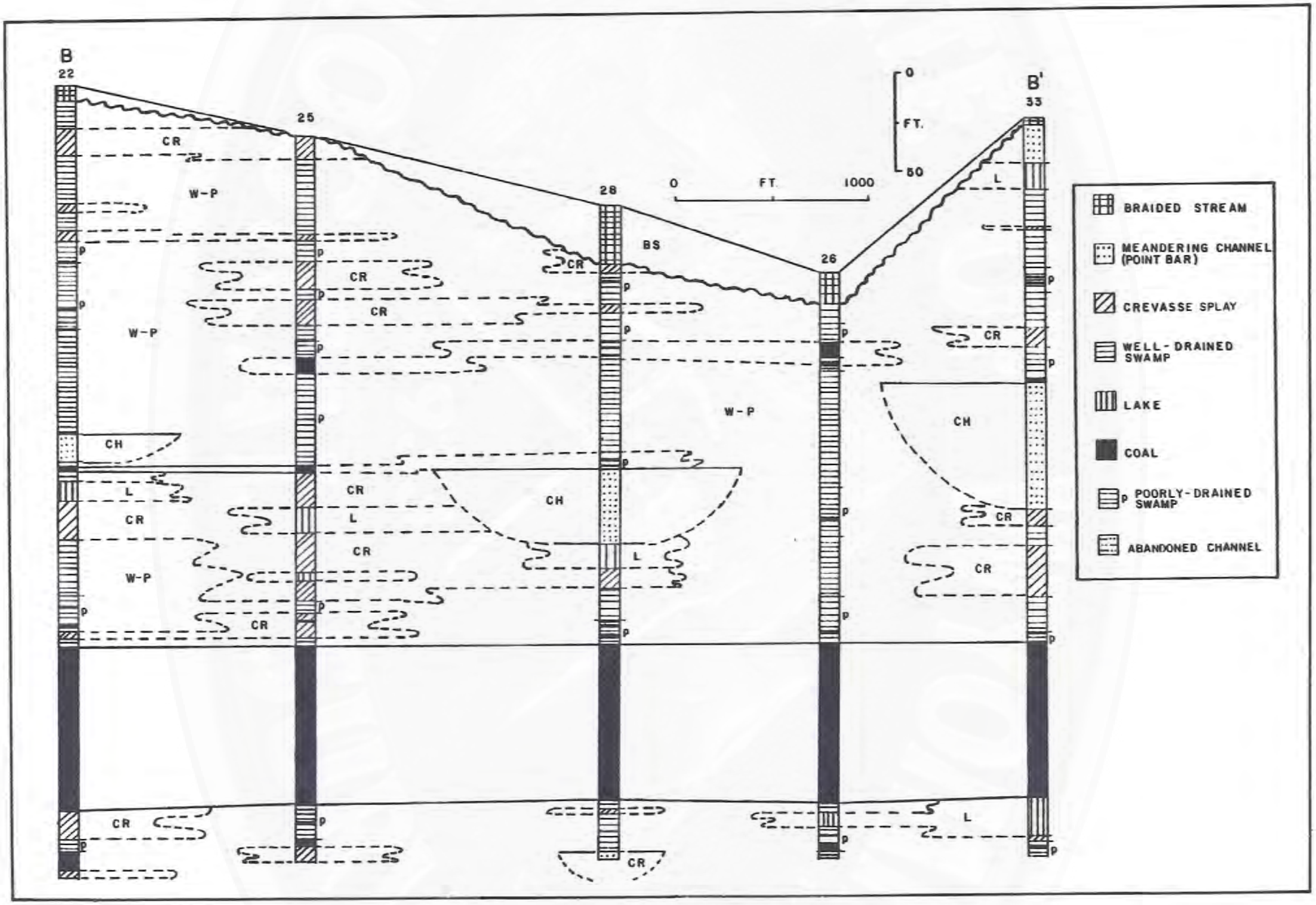

Figure 11. East-west cross-section B-B' based on inferred depositional environments, lower Wasatch and upper Fort Union Formations, Powder River Basin, SEAM study site. Core locations shown on Figure 8. Datum is top of Anderson coal bed (from Deutsch et al., 1979, p. 31, Figure 13).

different types of deposits including lacustrine, crevasse splay, and well- to poorly-drained swamp. They can only be definitely recognized by their geometry as may be seen in the highwalls of the strip mine at Stop 1.

LACUSTRINE

Lacustrine deposits are characterized by dark grey, highly organic, delicately-laminated to lenticular or burrowed clays and silts (Figure 12). Burrows commonly display well developed spriten recording the feeding activities of organisms. Some burrows closely resemble forms classified as Teichichnus, commonly reported from Cretaceous marine deposits. Lacustrine deposits may also contain pyrite or calcium carbonate nodules.

WELL- TO POORLY-DRAINED SWAMP

The most abundant deposits within the study area are those characterized by well- to poorly-drained swamps. Well-drained swamp deposits consist of light olive grey clays which contain relatively high percentages of silt and low percentages of organic debris (Figure 12). Root bioturbation structures are ubiquitous and iron oxide mottling is common. Iron deposits are often found as coatings on tubes that probably encased former roots. Calcium carbonate nodules are common and pyrite may be present in trace amounts. Crevasse splay and poorly-drained swamp deposits are usually found in close association with well-drained swamp deposits.

Poorly-drained swamp deposits consist of dark olive grey to olive black, highly organic clays with thin beds of coal, abundant coalified roots, twigs, and leaves (Figure 12). Pyrite and siderite are common as nodules and, in general, these deposits contain less coarse-grained material (silt and fine sand) than other deposits.

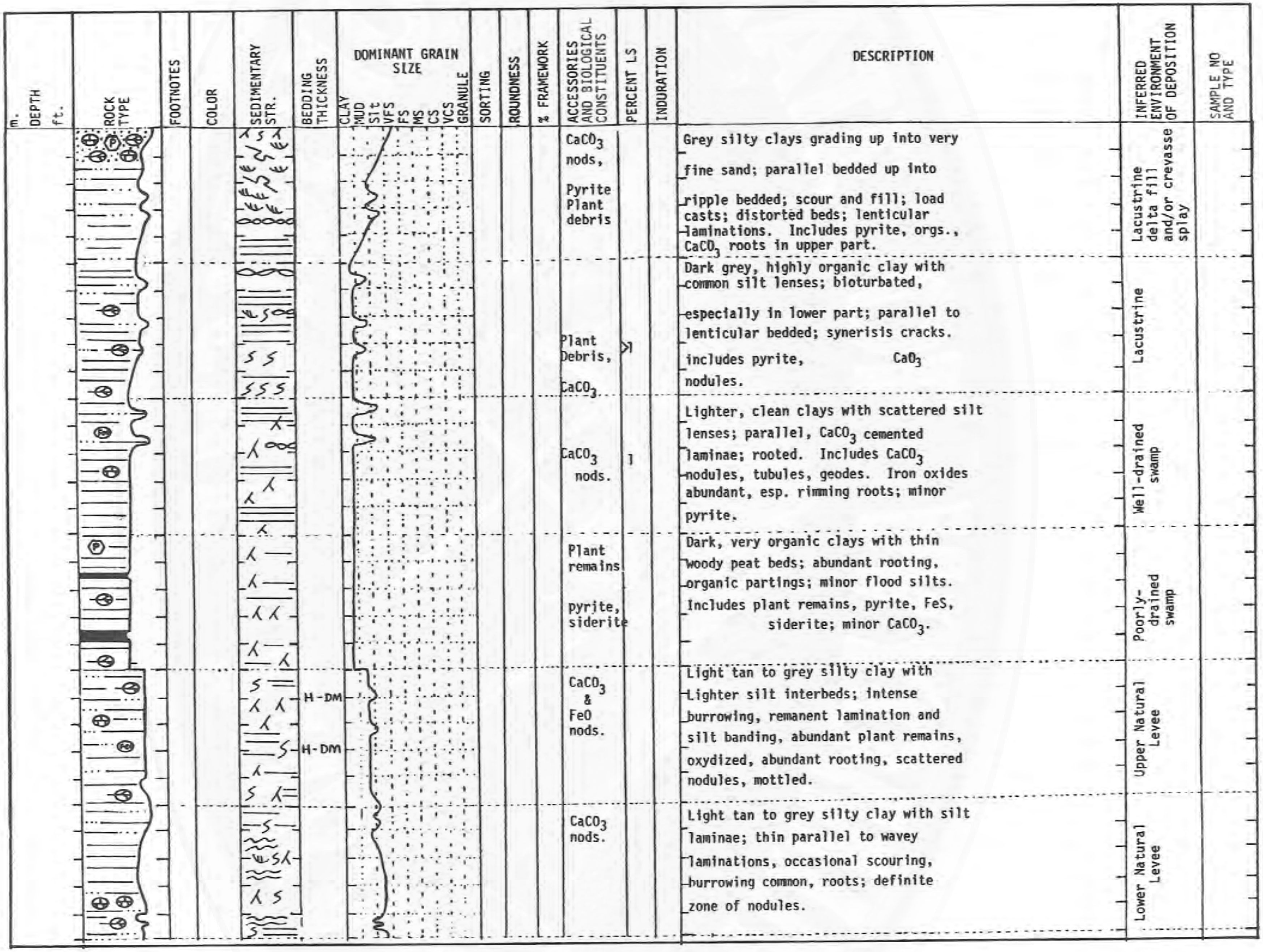

Figure 12. Idealized lithologic log of inferred paleoenvironments for the Wasatch Formation, SEAM study site, Powder River Basin, Wyoming (from Deutsch et al., 1969, p. 28 Figure 11).

Coals associated with the Wasatch tributary subsystem range in thickness from 1 to 6 feet and are generally poor in quality and limited in areal extent. While some are found associated with poorly-drained swamp deposits, many are associated with crevasse splay sands and silts (Figure 7). The implication is that small interchannel peat swamps developed on the slightly better drained splay platforms rather than the low-lying poorly drained flood-plain areas where lakes formed. The thicker Anderson coal bed, which merges to the north with the Canyon coal, represents the paludal subsystem as previously discussed and its origin is considered to be very different from that of the thin poor quality coals described above (Figure 7).

ACKNOWLEDGMENTS

We gratefully acknowledge the support and cooperation of the Rocky Mountain Energy Company and especially Mr. W. F. Baumann, mine superintendent, for permission to visit their Bear Creek Mine in Converse County. Research in the SEAM Study Site area was funded by the U. S. Forest Service - SEAM. The cooperation and active participation in this project by Mr. Grant Davis and Mr. Alv D. Youngberg of the U. S. Forest Service is gratefully acknowledged. Continuous cores at the study site were taken by Peabody Coal Company.

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THE LAKE DE SMET COAL SEAM: THE PRODUCT OF ACTIVE BASIN-MARGIN SEDIMENTATION AND TECTONICS IN THE BUFFALO-LAKE DE SMET AREA, JOHNSON COUNTY, WYOMING, DURING EOCENE WASATCH TIME

by

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Golden, Colorado

ABSTRACT

The Wasatch Formation in the study area displays a rapid and relatively sharp change from alluvial fan and braided stream deposits to a poorly drained alluvial plain sequence represented by meander channel, levee, crevasse splay, paludal, and lacustrine deposits. The change from one depositional environment to the other is marked by a very thick, linear, carbonaceous shale and coal sequence, the Lake De Smet coal bed, which ranges from approximately 65-250 feet (20-75 m.) thick. From an area north of Lake De Smet, the bed extends at least 15 miles (24 km.) southward. Its extent south of Buffalo is undetermined. The Lake De Smet coal bed is quite narrow compared to its length--in most places it is no more than ½-2 miles (1-3 km.) wide. Its western boundary is quite sharp; the coal fingers out into thin carbonaceous shale and coal stringers which pinch out abruptly to the west. Braided stream deposits characterize the strata west of the coal seam. On the east, the coal splits into five major mappable coal beds, each of which possesses significant coal reserves. The coal beds which are correlative with the Lake De Smet coal bed include the Ucross, Murray, Cameron, Healy, and Walters. Intervening deposits between these coals consist of related alluvial plain deposits. The sandstones in this interval are very fine to medium grained and well sorted; they persist as thick, regionally extensive sheets.

The unusual thickness of the Lake De Smet coal bed reflects a delicate balance between tectonics and sedimentation. The coal bed's great length, narrow width, and orientation (with its long dimension roughly parallel to

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This report is abstracted from the author's M.S. thesis, Colorado School of Mines. The field work was supported by the U.S. Geological Survey.

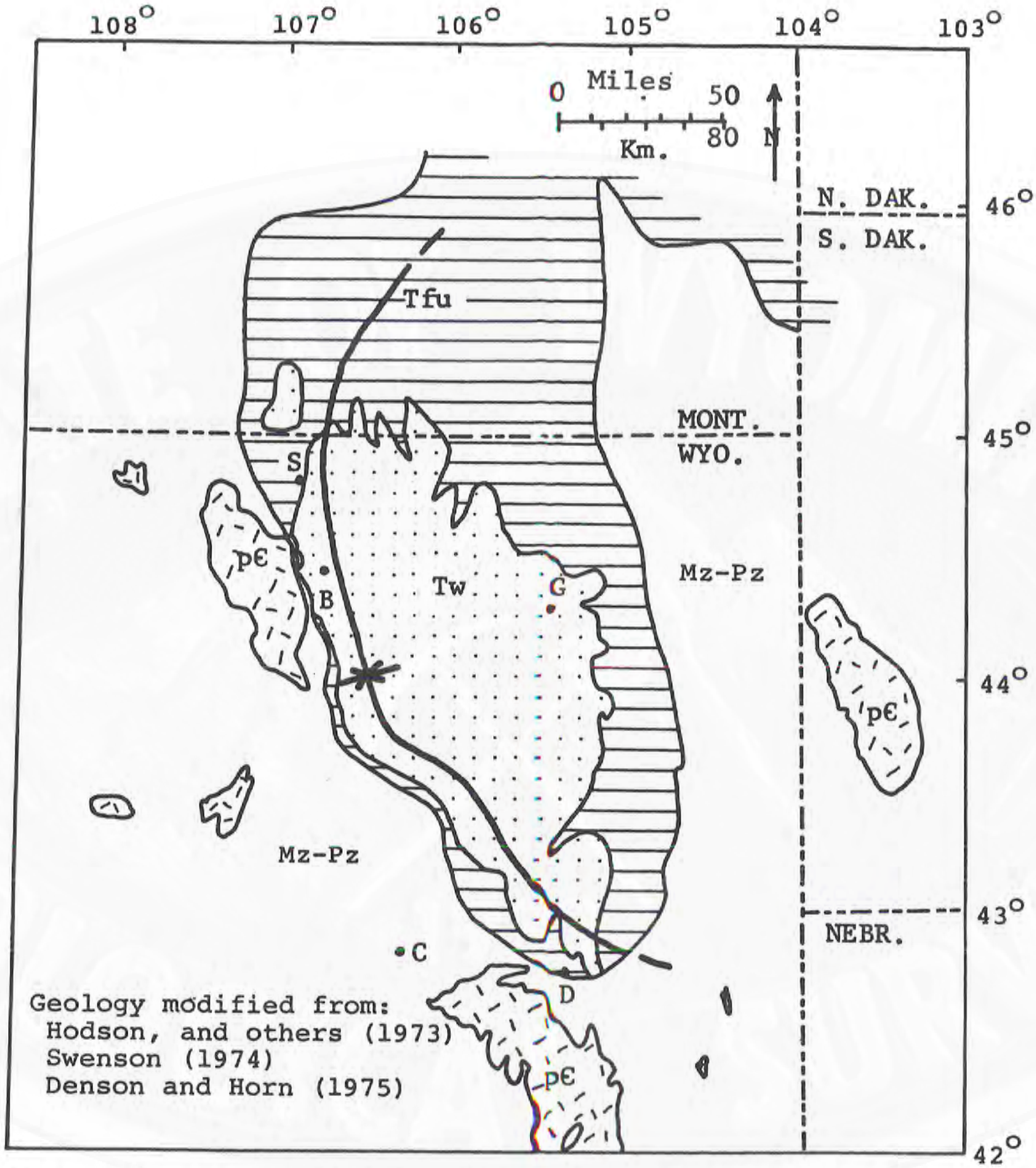


Figure 1: General geology of the Powder River Basin with the structural axis based on the top of the Madison Limestone. Tw = Wasatch Fm.; Tfu = Ft. Union Fm.; Mz-Pz = Mesozoic and Paleozoic; pЄ - Precambrian. B = Buffalo; C = Casper; D = Douglas; G = Gillette; S = Sheridan.

the uplift) suggest that a basement fault(s) may be a controlling factor in the coal's location and formation. Relatively greater uplift on the west prevented coal formation there while relatively greater subsidence on the east resulted in a splitting of the coal bed with substantial clastic intervals separating the coals.

INTRODUCTION

The Lake De Smet coal bed and accompanying deposits lie along the east flank of the Bighorn Mountains in northern Johnson County, Wyoming. Tectonic activity of the Late Cretaceous and early Tertiary was perhaps more profound in this locality than in any other around the periphery of the Powder River Basin. The doubly plunging synclinal axis of the Powder River Basin, as shown atop the Madison Limestone by Swenson (1974; fig. 1), lies almost directly under Buffalo and Lake De Smet. Structural relief from the lowest point in the basin, which lies south of Buffalo, to the top of the Bighorn uplift is in excess of 30,000 feet (9146 m.).

The Paleozoic, Mesozoic, and early Tertiary deposits display relatively broad outcrop patterns and shallow dips along the eastern side of the basin adjacent to the Black Hills uplift, whereas narrow outcrop bands and steep dips prevail along the western margin of the Powder River Basin in the vicinity of Buffalo (Figure 1). However, dips for Wasatch strata covering the study area rapidly flatten out to near-horizontal dips within 4-5 miles of their westernmost occurrence.

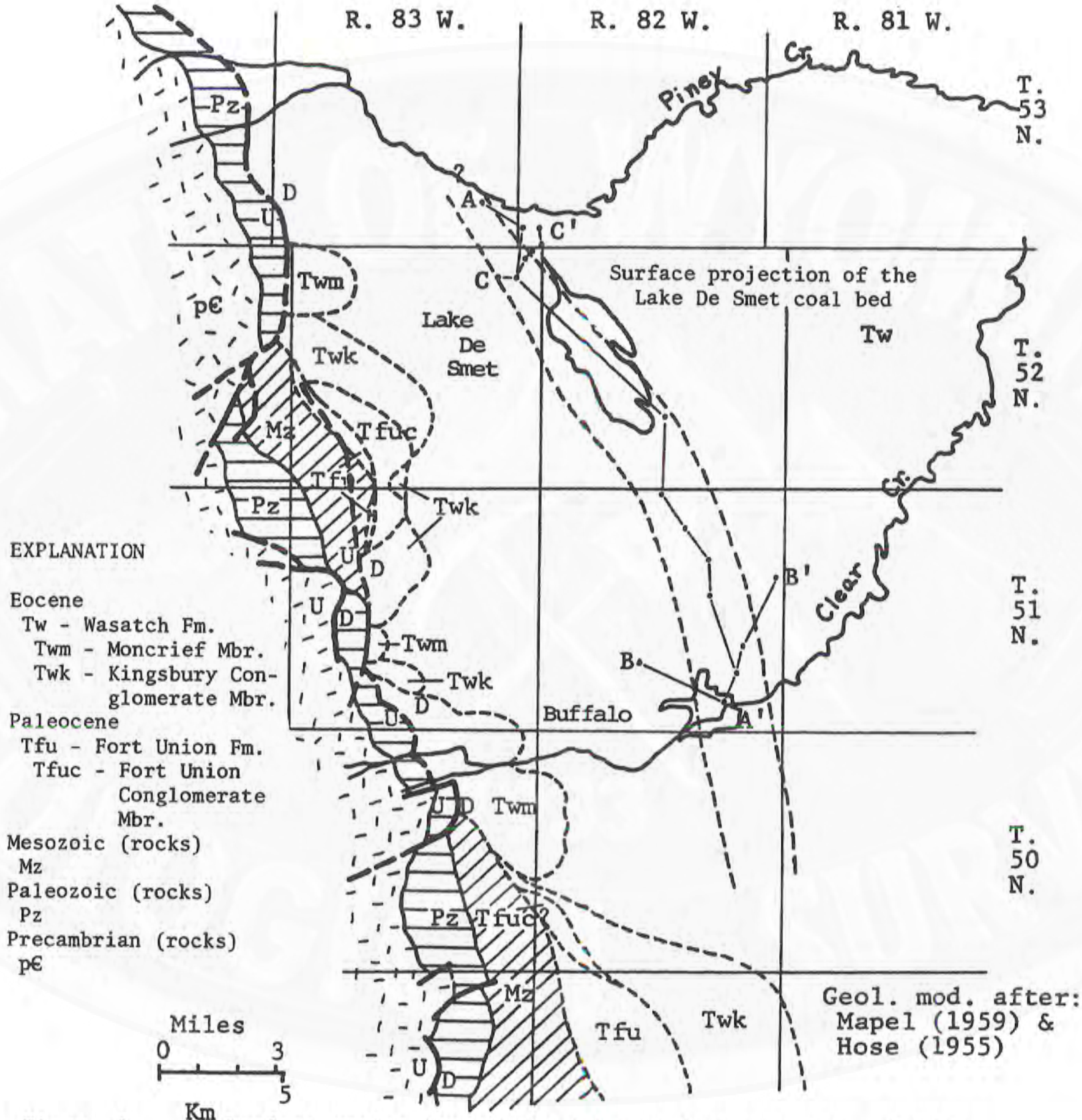


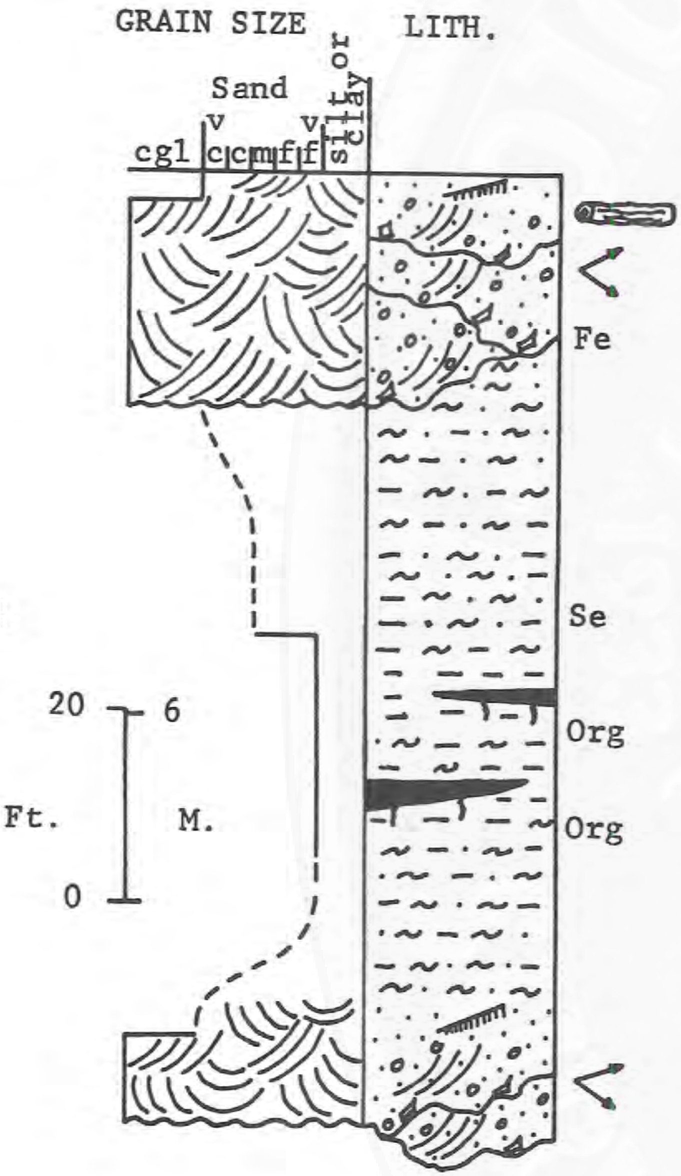
Figure 2. Surface projection of the Lake De Smet coal bed. Cross-sections A-A', B-B', and C-C' appear in Figures 4, 5, and 6, respectively.

DESCRIPTIVE STRATIGRAPHY

The lithologies of the Wasatch coal-bearing beds in the study area are characterized by two types of sandstones. They are lithologically and geometrically different, laterally correlative, and separated by the thick Lake De Smet coal bed (Figure 2 shows the approximate position of the Lake De Smet coal bed). Sandstones west of the Lake De Smet coal bed are thin, lenticular, and conglomeratic. Thick, broad sheets of well sorted, very fine- to medium-grained sandstones dominate the stratigraphy east of the coal bed. Thick, areally extensive coals are present east of the Lake De Smet coal bed, but only thin carbonaceous shales and coals exist to the west.

CONGLOMERATIC SANDSTONE SEQUENCE

Lenticular, interbedded, poorly consolidated, conglomeratic sandstones, sandstones, siltstones, mudstones, and thin organic and carbonaceous shales and coal stringers dominate the equivalent strata west of the Lake De Smet coal bed. These lithologies interfinger to the west with the conglomerate facies and, to the east, with the Lake De Smet coal bed. Figure 3 is a composite section of a sequence representative of the strata west of the Lake De Smet coal bed. It is based on limited outcrop exposures and one drill hole in sec. 28, T. 51N., R. 82W. Sequences which become finer grained upward are characteristic of these strata. This pattern is repeated many times, and the grain size may or may not coarsen again toward the top of each unit. Coal and shales rich in organic material locally are present. Field observations suggest that lateral continuity of any single lithologic unit is very limited.



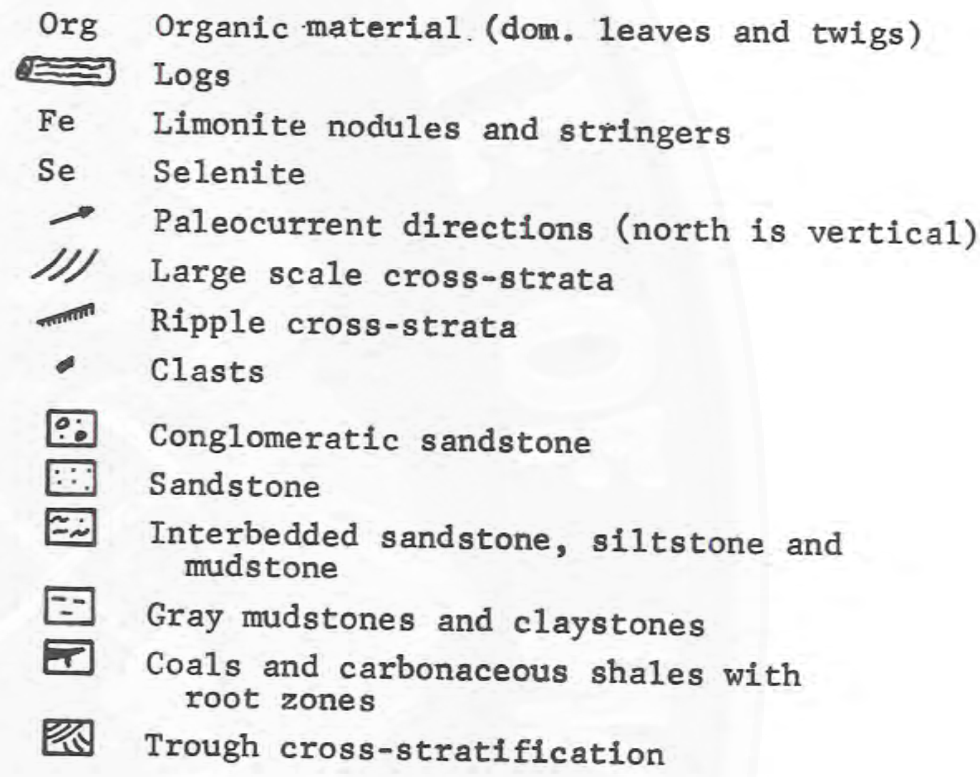


Figure 3 : A composite vertical section showing a representative fining-upward sequence within the coal-bearing strata west of the Lake De Smet coal bed.

The conglomeratic sandstones and sandstones are tan to pale yellowish orange. They contain angular to subangular, silt to pebble-sized, micaceous, arkosic detritus derived primarily from Precambrian rocks. Virtually all the sandstones contain abundant carbonaceous material. Sorting varies from fair to poor, with fine-grained sandstones being better sorted than coarse-grained sandstones. Wood fragments, in situ roots, and logs serve as loci for numerous brown, calcareously cemented concretions. Many limonite nodules less than one centimeter in size are sprinkled throughout the sandstones. The conglomeratic sandstones and sandstones occur as lenses up to 40 feet (12 m.) thick and greater than 20 feet (6 m.) wide. Scour surfaces occur at the base and within the sandstone lenses.

Most of the conglomeratic sandstone lenses become finer grained upward. They also display sets of cross-strata which decrease in thickness upward. A few lenses may become coarser grained upward. Irregular water energies during deposition are reflected in the grain size distributions, as individual cross-stratified beds contain much coarser material than adjacent layers. Trough cross-strata up to 4 feet (1.2 m.) thick near the base of the lenses are replaced vertically by smaller trough sets, parallel laminations, and ripple cross-stratification. Angular siltstone and mudstone clasts cluster near the base of many trough sets as well as above the scour surfaces of the sandstone lenses.

Laterally and vertically, these thick conglomeratic sandstone lenses grade into interbedded, poorly sorted, thin- to thick-bedded, pale-yellowish-orange conglomeratic sandstones and sandstones, and greenish-gray siltstones and mudstones. These interbedded units have a much greater lateral extent than the conglomeratic lenses described above. Sandstones in the interbedded sequences display few scour surfaces. Their contacts are frequently limonite cemented. Stratification is often either disrupted or impossible to discern although large-scale and ripple cross-strata are occasionally observed. The thick sandstone beds locally contain clasts. A proportionate decrease in sandstone volume occurs both laterally and vertically with increasing distance from the conglomeratic sandstone lenses.

The siltstones and mudstones are very carbonaceous and contain numerous imprints of twigs and leaves. At two localities (N½, sec. 35 and NW¼, sec. 15, T. 51N., R. 82W.), tree trunks 1-2 feet (.3-.6 m.) in diameter are buried upright, normal to the bedding, in a sequence of interbedded sandstones, siltstones, and mudstones. Some siltstones contain ripple stratification, but the mudstones are not stratified.

Occasional thin lenses of brown shale contain abundant plant debris, carbonaceous shale, and woody coals up to 5 feet (1.5 m.) thick. Root zones penetrate underlying clays, silts, and sands. Yellow resins and occasional pyrite crystals can be found within these units. Both laterally and vertically adjacent to these units, yellowish-orange sandstones are generally absent or are present in minor quantities.

THE LAKE DE SMET BED

Reputed to be the thickest coal seam in the United States and the second thickest in the world (Texaco press release, 1975), the Lake De Smet coal bed stretches north-south through the study area for more than 15 miles (24 km.); it has a thickness ranging from 65 feet (20 m.) to more than 250 feet (75 m.) and a width of approximately ½-2 miles (1-3 km.)(Figure 2). The existence of this thick coal deposit was first reported by Mapel, Schopf, and Gill (1953) after the U.S. Geological Survey and the U.S. Bureau of Reclamation drilled several holes at the northern and southern ends of Lake De Smet. Subsequent drilling by several industrial concerns has vastly extended the length and breadth of the initial reported discovery.

Although hundreds of holes have been drilled in the Buffalo-Lake De Smet area, few holes, aside from those drilled by the Government agencies, are available because of proprietary rights cited by the companies concerned. The drill-hole data are of highly variable quality. Some describe the lithologies only in terms of the presence or absence of coal. Others, such as the hole drilled in Buffalo by the U.S. Geological Survey in 1975, portray very detailed lithologic breakdowns (Farrow, 1976). Few lithologic logs have accompanying geophysical logs. It is questionable whether some of the holes actually penetrated the total thickness of the Lake De Smet coal bed, as some of the holes either stopped in coal or within a few feet below a coal layer. A basal fossiliferous mudstone, which might be used as a marker bed, has been reported to underlie the Lake De Smet coal bed at Buffalo and along the northern and western margins of Lake De Smet; however, apparently little effort has been made to verify its existence elsewhere. With these limitations, selected drill holes were assembled to construct north-south and east-west cross sections (Figures 2, 4, 5, and 6) to delineate the extent and thickness of the coal. The thickest coals are north of Lake De Smet and in the vicinity of Buffalo. One drill hole, in sec. 10, T. 51N., R. 82W. apparently contained no coal.

Many lenticular, thin partings of very fine-grained to medium-grained sandstone, siltstone, mudstone, claystone, and organic shale occur throughout the coal. Sandstone and siltstone partings are more abundant to the west than

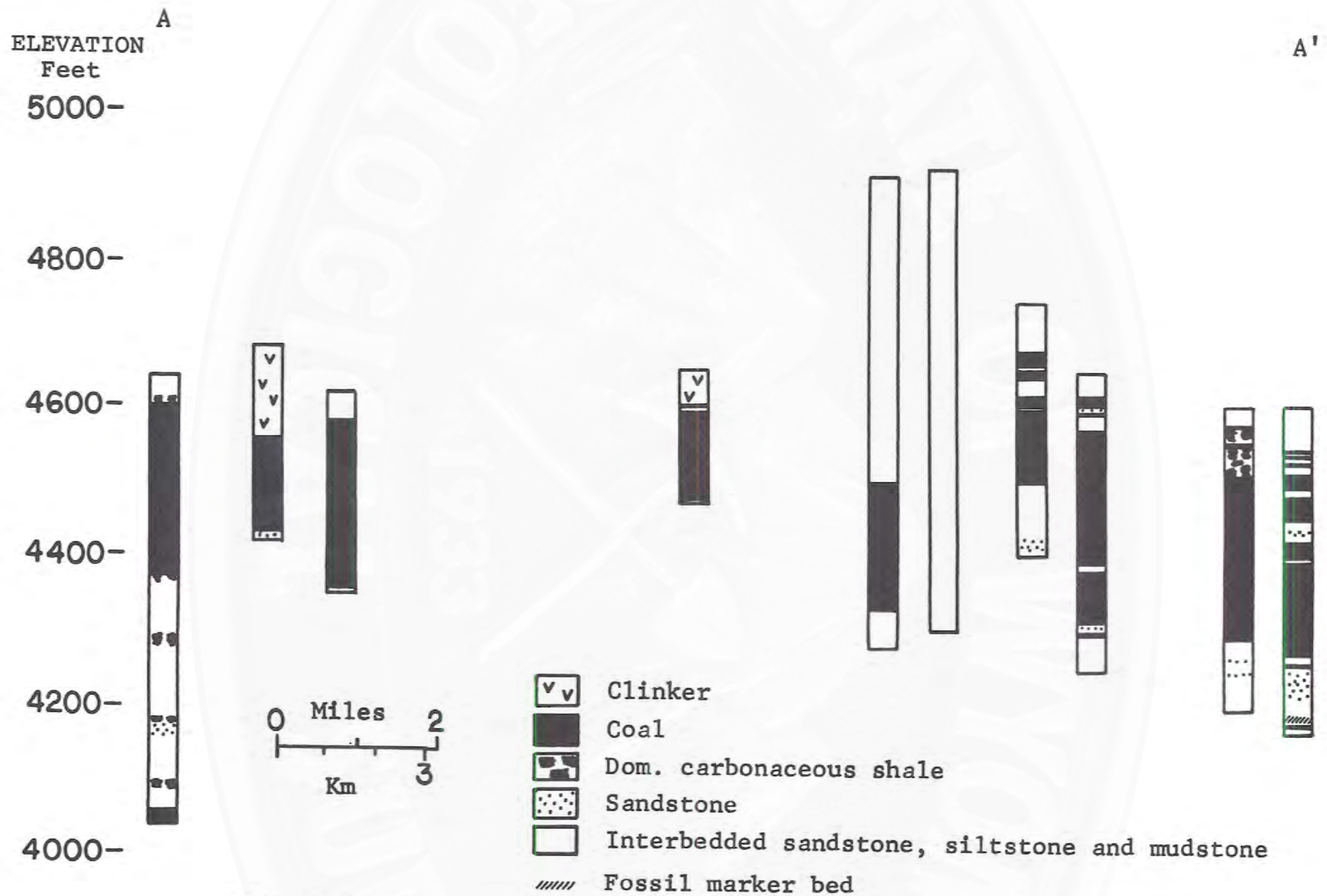


Figure 4: Cross section A-A' (from Figure 2) based on drill hole lithologic logs.

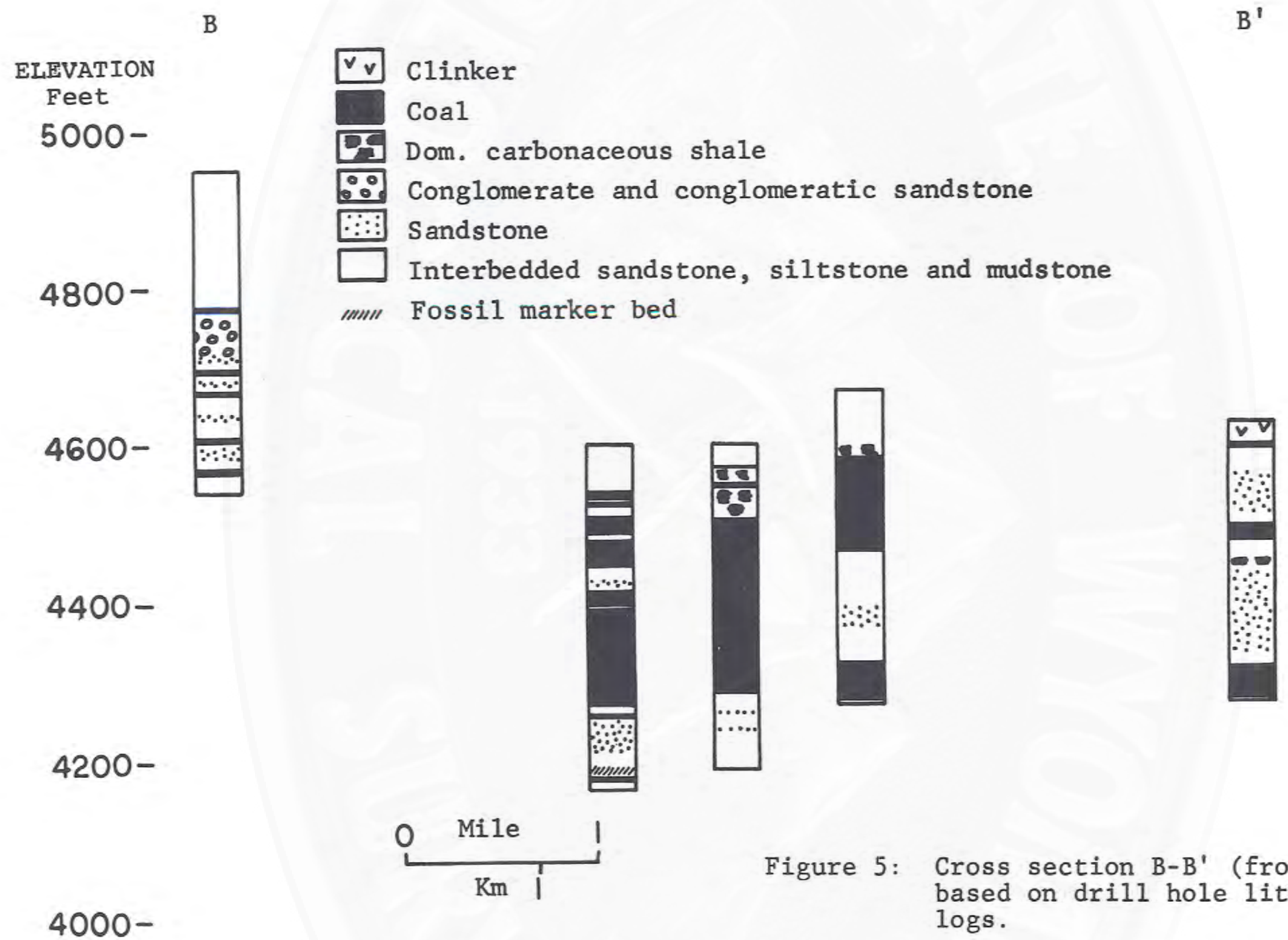


Figure 5: Cross section B-B' (from Figure 2) based on drill hole lithologic logs.

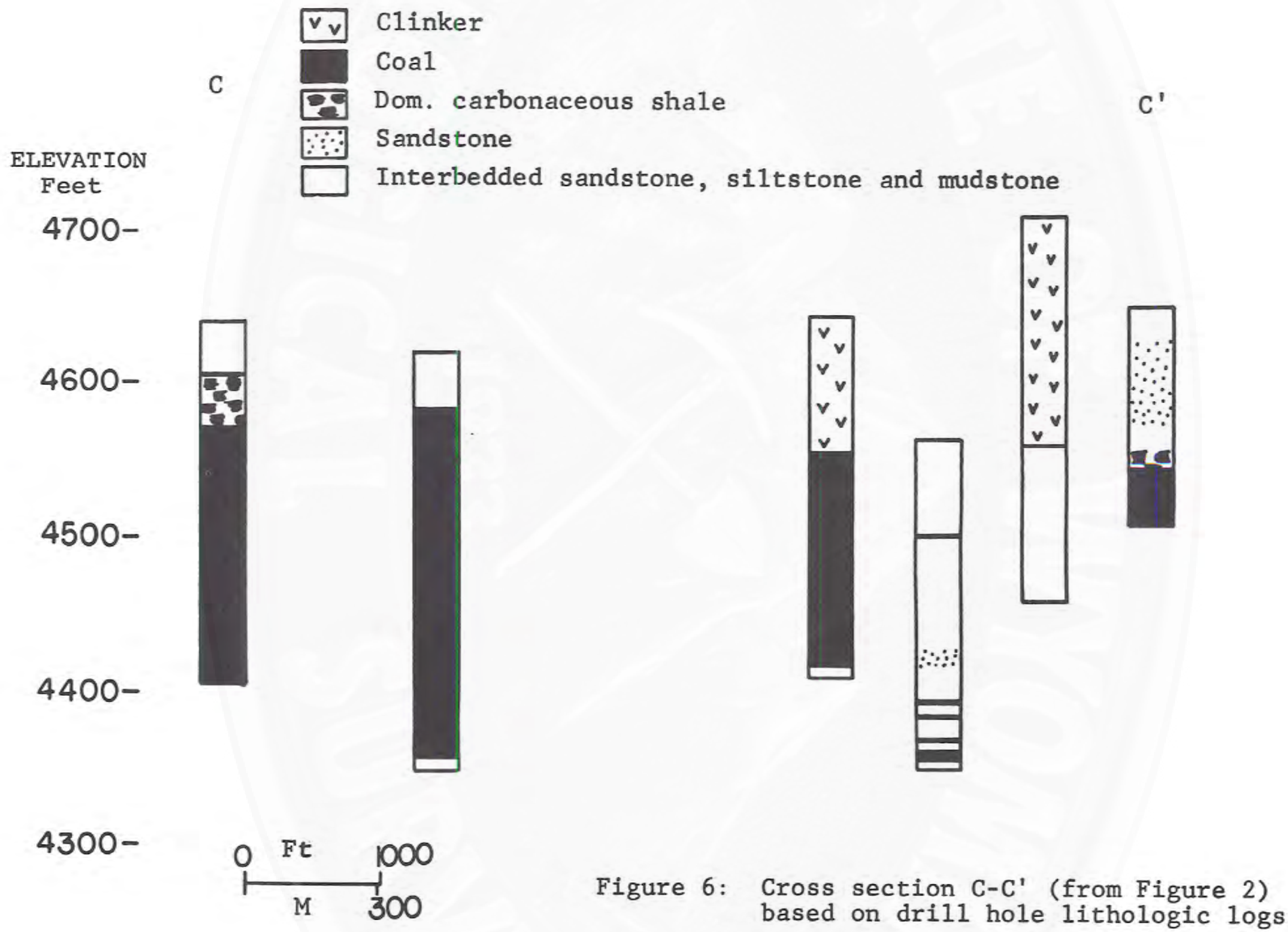


Figure 6: Cross section C-C' (from Figure 2) based on drill hole lithologic logs.

to the east. The western boundary of the coal is relatively sharp, with the coal rapidly fingering out into thin organic shale, carbonaceous shale, and coal stringers that pinch out to the west. Where these stringers are observable at outcrops, they are directly underlain by pale-yellowish-orange conglomeratic sandstone displaying root zones.

To the east of the Lake De Smet coal bed, the coal beds are generally underlain by dark gray clays which commonly are conchoidally fractured and possess grooves resembling slickensides. "Clay skins" is the term often applied to such structures. They may result from roots penetrating and expanding in the clay zones. These features may also be the result of differential compaction.

Five major coal beds, which merge westward to form the Lake De Smet coal bed, can be traced over a large area both in outcrops and in the subsurface (Figure 7). The five coal beds include the Ucross, Murray, Cameron, Healy, and Walters. Mapel, Schopf, and Gill (1953, p. 3) and Mapel (1959, p. 84-85) tentatively identified a portion of the Lake De Smet coal to be the equivalent to the Healy bed. Subsequent work by oil companies has resulted in correlating the lowermost coal fingering eastward from the Lake De Smet coal bed with the Ucross coal bed. The Walters coal bed is interpreted by this author to be the uppermost coal that can be identified as part of the Lake De Smet coal bed. Two pieces of field evidence support this conclusion. The lowest conglomeratic sandstone east of the Lake De Smet coal bed is above the Walters coal bed. Small channel deposits trending east and northeast also were exposed by construction crews in the NE¼, sec. 28, T. 52N., R. 82W. and in the W½, sec. 1, T. 51N., R. 82W. A coquina mudstone of wide areal extent also overlies the Walters coal bed, but underlies the conglomeratic

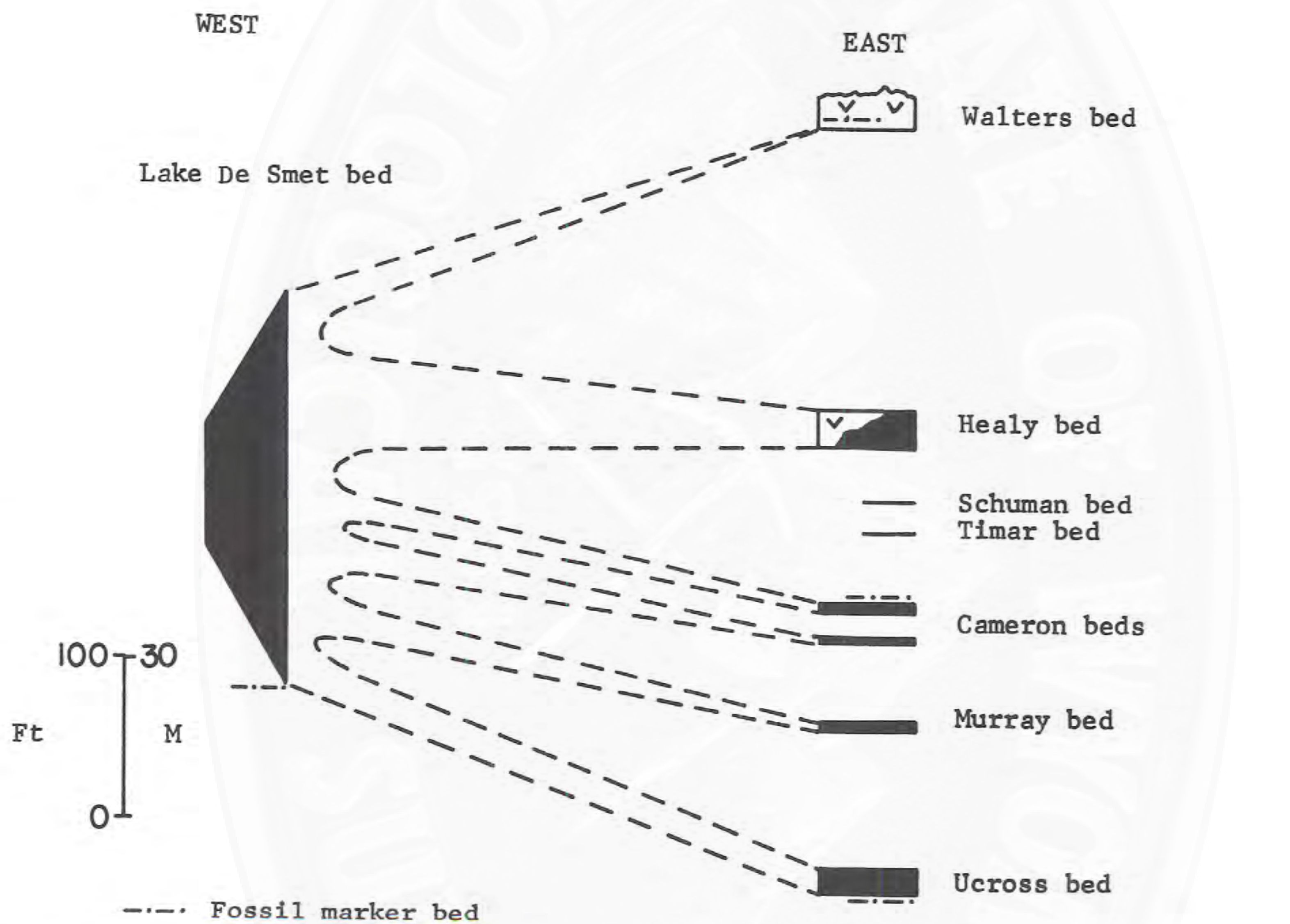


Figure 7: Schematic diagram showing the relationship of the Lake De Smet coal bed with the major coal beds to the east using Mapel's (1959) coal bed designations. This diagram is not drawn to scale horizontally.

sandstone east and south of Lake De Smet. This fossil bed exists above a thick coal sequence, interpreted to be a portion of the Lake De Smet coal bed that was unearthed by construction crews at the southeast corner of Lake De Smet.

Mapel, Schopf, and Gill (1953) reported the coal's rank to be borderline between subbituminous C and lignite (ASTM classification). The coal is dull black when wet, is brown when dry, and has a strong tendency to break down upon exposure to the air. Metamorphism of the coal has not progressed sufficiently to produce characteristic vitrain. Fusain is thought to represent less than one percent of the deposit. Core analyses reveal that woody material makes up 34-39 percent of the coal. Numerous partially coalified tree trunks litter the outcrops of the thin coaly splits along the western margin of the coal bed. Tree stumps as much as 4 feet (1.2 m.) in diameter are commonly found near or at the base of a coal layer.

VERY FINE- TO MEDIUM-GRAINED SANDSTONE SEQUENCE

The clastic intervals separating the coal beds east of the Lake De Smet coal bed consist of very fine- to medium-grained sandstones, siltstones, mudstones, claystones, and occasional thin, lenticular coals and shales rich in plant material. The intervening clastic intervals range from a few meters thick between the Lower and Upper Cameron beds to greater than 200 feet (61 m.) between the Healy and Walters coal beds. These clastic intervals are absent in the Lake De Smet coal bed, but increase to the reported thicknesses in horizontal distances of 200-500 feet (60-150 m.) to the east of that bed. Figure 8 is a schematic section of the intervening clastic interval between the Healy and Walters coal beds. Field work and drill core data suggest that this stratigraphic section represents the other clastic intervals as well.

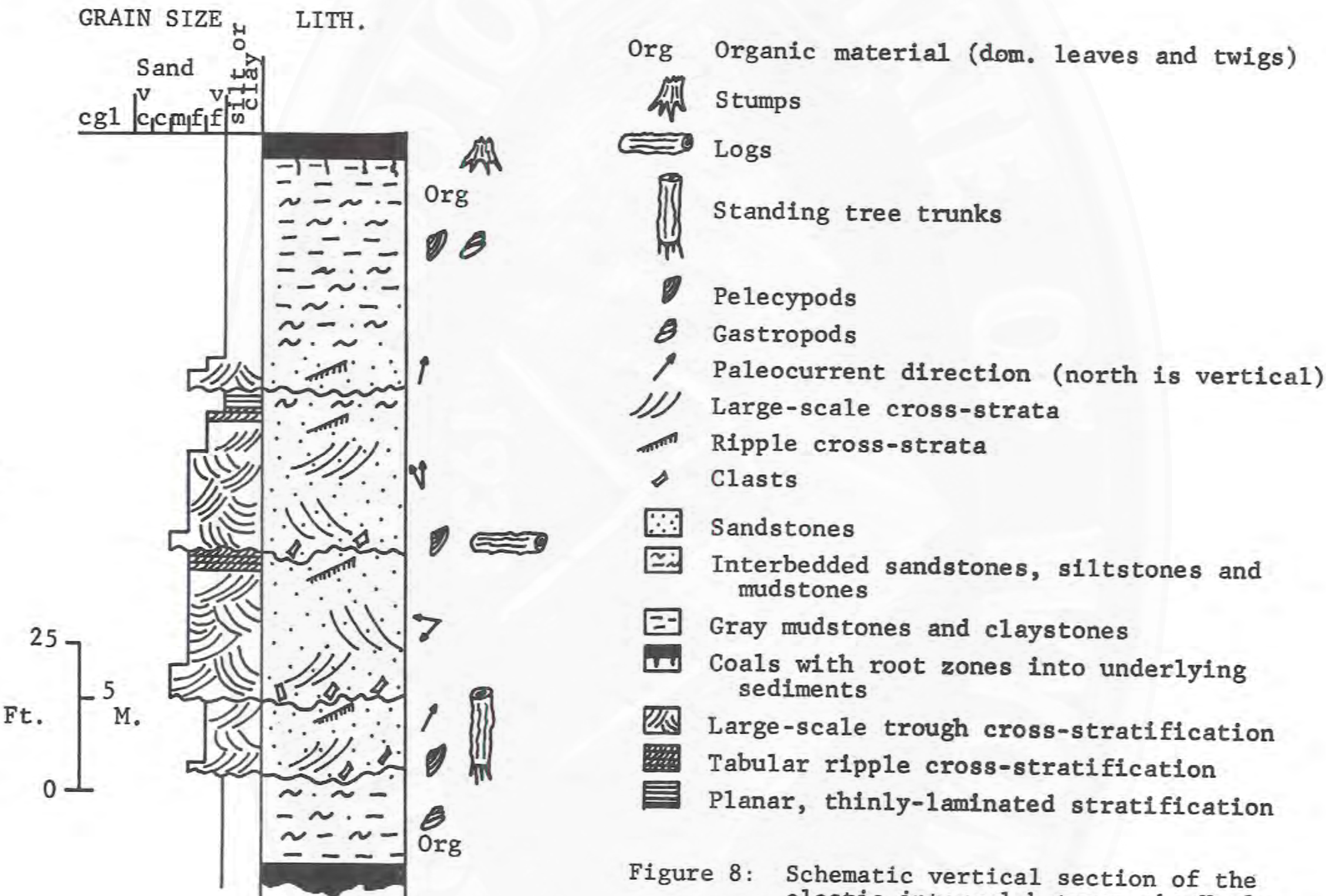


Figure 8: Schematic vertical section of the clastic interval between the Healy and Walters coal beds as developed from studies of outcrops along Boxelder Creek east of Lake De Smet.

The sandstones are gray tan to pale yellowish orange, very fine to medium grained, poorly consolidated, micacous, and arkosic, with both grain size and bed thickness decreasing upward. The sand grains are angular to subangular and well sorted. Abundant fine- to coarse-grained carbonaceous detritus commonly outlines bedding plane surfaces. Some portions of the sandstones display calcareous cementation; however, the resulting concretionary aspect of the sandstone displays no continuity with the stratification. Commonly, logs, tree trunks, and tree roots are associated with the sandstones where cemented with calcite.

Bed thicknesses within the sandstones range from approximately 5 feet (1.5 m.) at the base to less than 1 inch (2.2 cm.) at the top. Trough cross-stratification gives way upward to tabular ripple cross-stratification and parallel lamination. Asymmetrical, symmetrical, and climbing ripple forms are variously present. Thus, the stratification reveals an upward decrease in the inferred water energies during deposition.

These sandstones are composed of one to four genetic units which become finer grained upward (Figure 8). Each genetic unit has a scour base which is most easily distinguished by the sudden change in stratification and in the thickness of sets of cross-strata. Angular to subrounded claystone, siltstone, and sandstone clasts, as well as lag deposits of pelecypod and gastropod shell fragments, often occur near the bases of the sandstone units.

Paleocurrent directions vary widely throughout from southward to nearly eastward although a regional flow direction to the north is indicated. However, within each genetic unit, the paleocurrent direction is constant in one direction (Figure 8).

Petrified logs (partially replaced by silica and calcite), both parallel and normal or nearly normal to the strata, and imprints of large tree roots are common. Generally, transported logs are near the base of channel sandstone units and are parallel to the strata. Logs normal to the strata, actually in situ buried tree trunks, crop out in clusters (the best locations for observing such occurrences are in sec. 2, T. 51N., R. 82W.; SE¼, sec. 32, T. 53N., R. 81W.; and NW¼, sec. 31, T. 51N., R. 80W.). Some of these tree trunks occur in sandstone while others are present in interbedded yellowish-orange sandstones and gray siltstones and mudstones.

In a broad sense, these sandstones appear to be broad, regionally extensive sandstone sheets. Thicknesses range from a few meters to almost 100 feet (30 m.). The sandstone between the Healy and Walters coal beds is continuous and extends beyond the boundaries of the study area eastward from the Lake De Smet coal bed.

Interbedded yellowish-orange sandstones and gray siltstones, mudstones, and claystones are above and below the sandstones. The thick sandstones are in sharp contact with the rocks below, but are gradational with the overlying rocks. Above and below the coal, in a typical section, the yellowish-orange cast to the sandstones disappears, and the ratio of sandstone to siltstone, mudstone, and claystone decreases.

Limestone lenses, less than 4 feet (1.2 m.) thick and many tens of feet across, are scattered throughout these interbedded sequences. They generally fill shallow depressions atop sandstone or siltstone beds. The limestones are silty, very fine grained, crystalline, and contain small, thin-shelled gastropods. Jacob (1973, p. 1043), who observed similar limestones in the Paleocene Tongue River Formation[2] of North Dakota, suggests

[2] Jacob (1973, p. 1038) notes that the North Dakota Geological Survey considers the Tongue River a formation within the Fort Union Group while the U. S. Geological Survey assigns member status to the Tongue River and formation status to the Fort Union.

that these lenses formed in small isolated pools occupying depressions where evaporation and photosynthetic activity contributed to the crystallization of calcite.

Twig and leaf imprints and carbonaceous material are common in the mudstones and claystones, while carbonaceous detritus is abundant in the sandstones and siltstones. Thin, brown shale lenses containing organic material frequently supplant mudstone beds. Occasional mudstone lenses contain abundant pelecypod and gastropod shells. Some fossiliferous beds are coquinas.

The coals are physically and chemically similar to those of the Lake De Smet coal bed. Laterally, they display great variations in thickness, physical character, and quality. Root zones extending downward into the underlying claystones attest to the in situ origins of the coals. Many of the coals were burned as a result of spontaneous combustion after the coal was exposed to the atmosphere by erosion (Rogers, 1917, p. 1-4). This burning resulted in baking of the strata overlying the coal beds. The clinker, as the baked strata are called, forms the characteristic resistive, reddish-colored butte topography.

FOSSIL MARKER BEDS

Three fossiliferous beds are regional in extent and, hence, are excellent marker beds within a formation that is characterized by rapid lateral and vertical lithologic changes. One of the fossiliferous beds underlies the Lake De Smet coal bed. In addition to a gastropod and pelecypod assemblage, pyritized gar scales and vertebrae have been recovered from this bed (Waynard Olsen, oral communication, 1976).

The second marker bed is a fossiliferous limestone above the Upper Cameron coal bed. Mapel (1959, p. 72) reports its areal extent to be greater than 125 square miles (320 square km.). Much of this limestone is a few centimeters to approximately 2 feet (0.6 m.) thick and lies less than 5 feet (1.5 m.) above the coal bed.

Unlike the fossil bed above the Upper Cameron coal bed, the fossiliferous mudstone above the Walters coal bed lies variously from 3 feet (1 m.) to approximately 5 feet (1.5 m.) above the coal. This fossil bed, which includes gastropods and pelecypods, ranges in thickness from less than 1 foot (0.3 m.) to over 25 feet (7 m.). In a deep manmade cut at the southeast corner of Lake De Smet, the fossil bed is split into two beds several meters apart. They occur approximately 5 feet (1.5 m.) above what is interpreted to be the uppermost coal split of the Lake De Smet coal bed.

ENVIRONMENTS OF DEPOSITION

The wide range of lithologies described for the Fort Union and Wasatch formations is the result of the environments in which they were deposited. The rapid change from high-energy to low-energy depositional environments was controlled by the intense tectonic activity along the boundary between the basin and uplift blocks. Lateral facies changes reflect the tectonic framework and the instability of the region.

The entire range of lithologies can be related to an alluvial valley model (LeBlanc, 1972, p. 137). The Kingsbury Conglomerate and Moncrief members of the Wasatch are interpreted to have been deposited as alluvial fans fronting the Bighorn uplift. The distal portions and areas adjacent to the base of the alluvial fans are composed of migrating lobes of braided stream systems. They are characterized by small conglomeratic sandstone lenses and interbedded sandstones, siltstones, mudstones, and thin coals. These coarse deposits spilled onto a broad alluvial plain dominated by meander channels and related levee and crevasse splay systems, swamps and lakes (Figure 9). The alluvial plain environments are characterized by very fine- to medium-grained sandstones, siltstones, mudstones, claystones, and thick coals.

Channel systems trend perpendicular to the mountain front west of the Lake De Smet coal bed and parallel to the mountain front (and to the axis of the basin) east of the Lake De Smet coal bed (Figures 10 and 13). These conclusions coincide with Seeland's (1976, p. 63; fig. 11) interpretation of the major Eocene paleodrainage pattern for the Powder River Basin. Coals within the study area form marginally to the channels.

BRAIDED STREAM ENVIRONMENTS

The braided channel systems associated with the distal portions of alluvial fans are interpreted to extend beyond the base of the alluvial fans into the coal-bearing strata. These braided systems are represented by the coarse sandstones, siltstones, mudstones, and thin coals west of the Lake De Smet coal bed. Models and descriptions of braided stream deposits from recent sediment studies are not as easily applied as are those for alluvial fan or deltaic environments. Some of the characteristics listed below have been frequently cited, while others have been infrequently observed or reported or are in opposition to generally accepted criteria used to identify braided stream deposits:

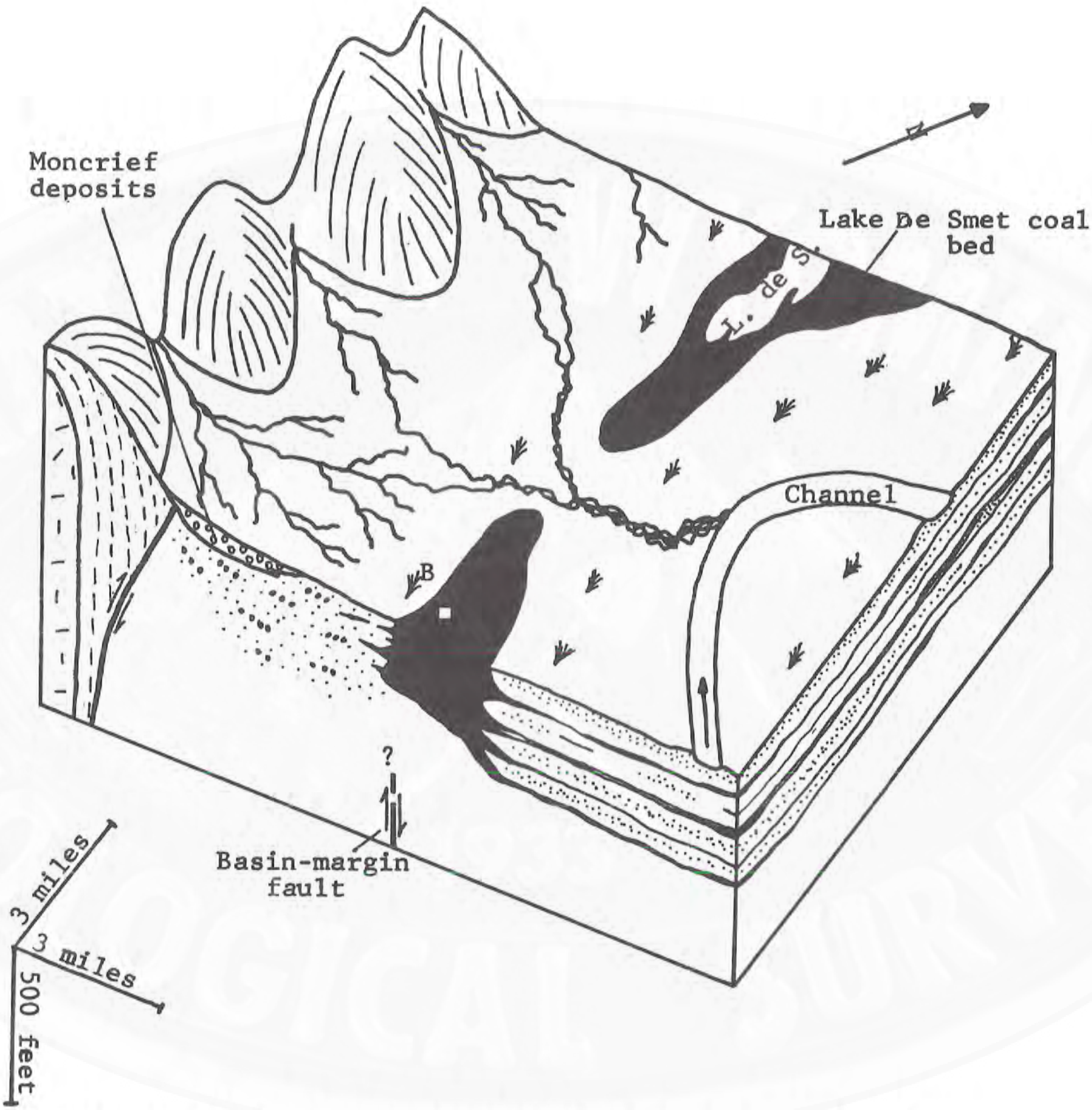


Figure 9: Block diagram showing the proposed relationships between faulting and sedimentation during Moncrief deposition. The uppermost coal bed east of the Lake De Smet coal bed is the Healy. B = Buffalo; L. De S. = Lake De Smet.

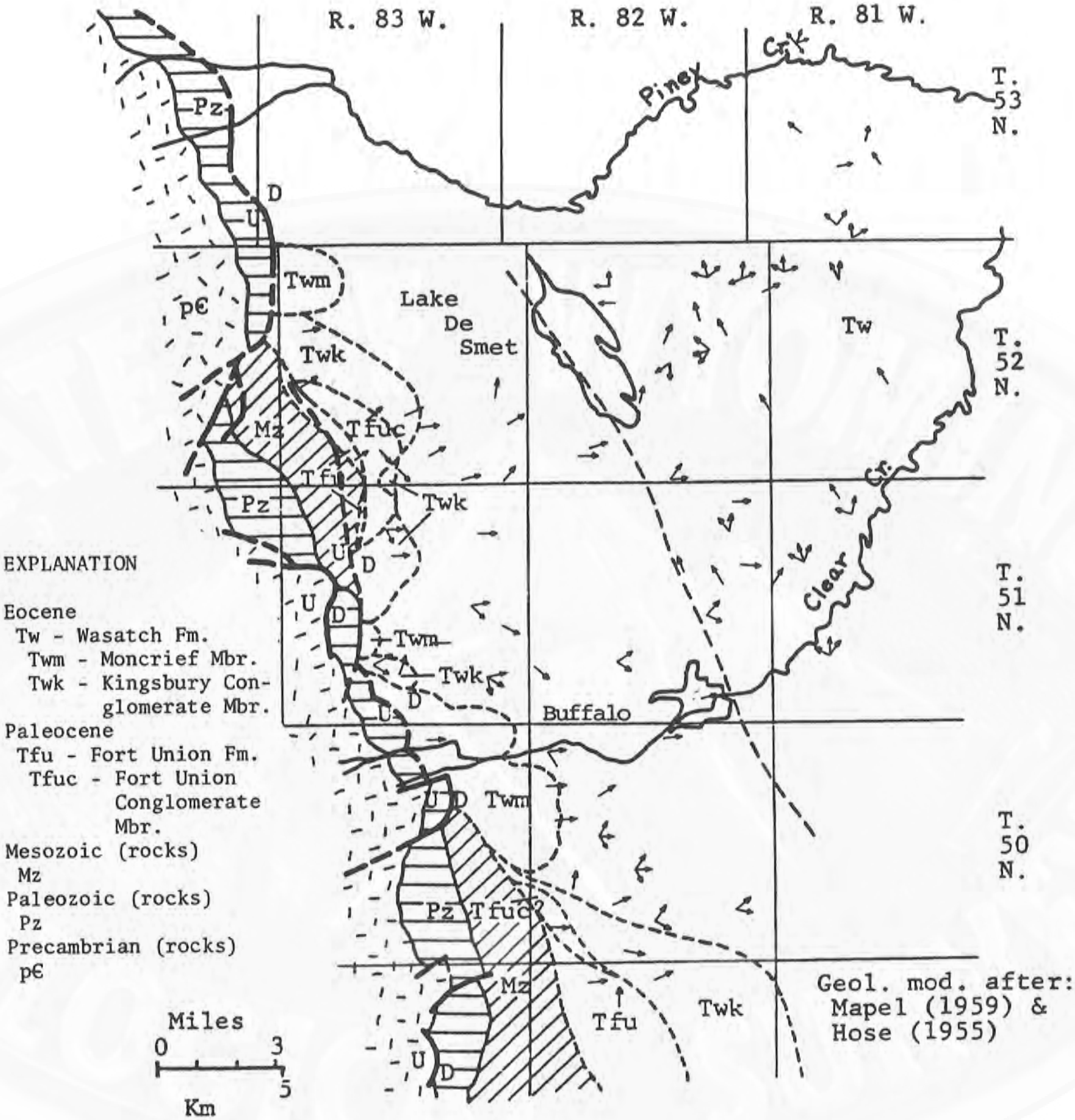


Figure 10. Map displays representative paleocurrent direction readings (arrows) obtained largely from cross-strata. Readings west of the dashed line show easterly drainage of the alluvial fan and braided stream environments. Readings east of the dashed line show a north-northwest drainage pattern for the alluvial plain environments.

1. Figure 3 illustrates repeated sequences of units becoming finer-grained upward. A gradual coarsening of some sandstones may occur near the top of the unit. Pettijohn (1975, p. 549) notes a general absence of upward decreasing grain size in most braided stream deposits.
2. Irregular scour surfaces occur within the channel deposit as well as at the base.
3. Channel sandstones generally become finer grained upward. A few channel deposits display coarsening upward grain-size trends while others maintain a constant grain size throughout the sandstone. Weimer and Erickson (1976, p. 127-137) noted that each genetic unit within the upper and lower members of the Lyons Formation (Permian), interpreted as fluvial channel deposits, becomes finer grained upward.
4. Channel sandstones are very poorly sorted. Alternating layers of coarse and fine-grained detritus in adjacent cross-bed laminations reflect fluctuating water energies.
5. Trough cross-stratification is the dominant sedimentary structure. Ripple trough cross-stratification is common near the top of the channel deposit.
6. Interbedded yellowish-orange sandstone and greenish-gray siltstone and mudstone sequences, observed above, below, and lateral to the channel deposits, are interpreted as levee and crevasse splay deposits. Coleman (1969, p. 230-232) reports numerous levee and crevasse splay deposits in the alluvial valley of the Brahmaputra River.
7. Large volumes of siltstone and mudstone and minor concentrations of brown shale rich in plant remains and coal are present. This is contrary

to virtually every reported modern or ancient analogue. Smith (1970, p. 3010) and Pettijohn (1975, p. 549-550) cite the absence of significant amounts of silt and clay as a criterion for identifying braided stream deposits.

The key to identifying this environment as one characterized by braided stream processes is with the channel deposits. The poor sorting of the sandstones and the irregular scour surfaces which cut into the channel and adjacent levee deposits suggest irregular fluvial energies and high sediment transport accompanied by frequent channel shifting. These features are common in modern braided stream environments.

Levee, crevasse splay, and swamp deposits are also present. As depicted in Figure 9, the alluvial fans are interpreted to have spilled onto an alluvial plain. The braided stream systems operating in the distal regions of the alluvial fans fingered out onto the alluvial plain where they were rapidly engulfed. Between the stream channels, swamps flourished. The alluvial fans built outward in a manner resembling that of deltas. The alluvial fans periodically shifted their depocenters to satisfy the dynamics required to transport and deposit the sediment loads. These shifts of depocenters, combined with subsidence, resulted in the formation of the interbedded sequences that are identified as levee, crevasse splay, and swamp deposits.

ALLUVIAL VALLEY ENVIRONMENTS

Wasatch sediments east of and including the Lake De Smet coal bed consist of meander channel, levee, crevasse splay, paludal, and lacustrine deposits. The pattern of increasingly finer grained sediments upward (depicted in Figure 8), as well as the range of environments, is one commonly attributed to alluvial valley or upper deltaic systems where meandering streams flow. However, the last vestiges of the short-lived Cannonball Sea exited from the northern Powder River Basin during the Paleocene (Mallory, 1972, p. 234-237). The location of the sea in geographic relationship with the Powder River Basin during the Eocene is unknown. The Paleocene and Eocene Golden Valley Formation in North Dakota is lithologically similar to the Wasatch Formation in the Powder River Basin. Hence, during the Eocene, the Powder River Basin may have been the site of either the upper reaches of a vast deltaic complex or, more likely, a partially closed interior basin, characterized by alluvial valley environments, which narrowed at the north end, channeling its waters north onto an alluvial or deltaic plain. In either case, economic coal deposits thin and disappear to the south (Keefer and Schmidt, 1973). The study area is on the flank of the upper reaches of this vast, poorly drained alluvial plain.

The thick, very fine- to medium-grained sandstones which show one to four genetic units are interpreted to be meander channel complexes. Meandering of the stream resulted in broad scour surfaces at the base of each unit. Direction of sediment transport varies with each unit from east to southwest with the basin's principal paleodrainage system trending north-northwest (Figures 10 and 11).

Levee and crevasse splay deposits form adjacent to the channels (Figure 12). The characteristic lithologies of both types of deposits are interbedded, yellowish-orange sandstones and greenish-gray siltstones and mudstones. Allen (1965a, p. 146; 1965b, p. 571), Coleman (1969, p. 231), Jacob (1973, p. 1043), and Weimer (1973, p. 71), in various studies of

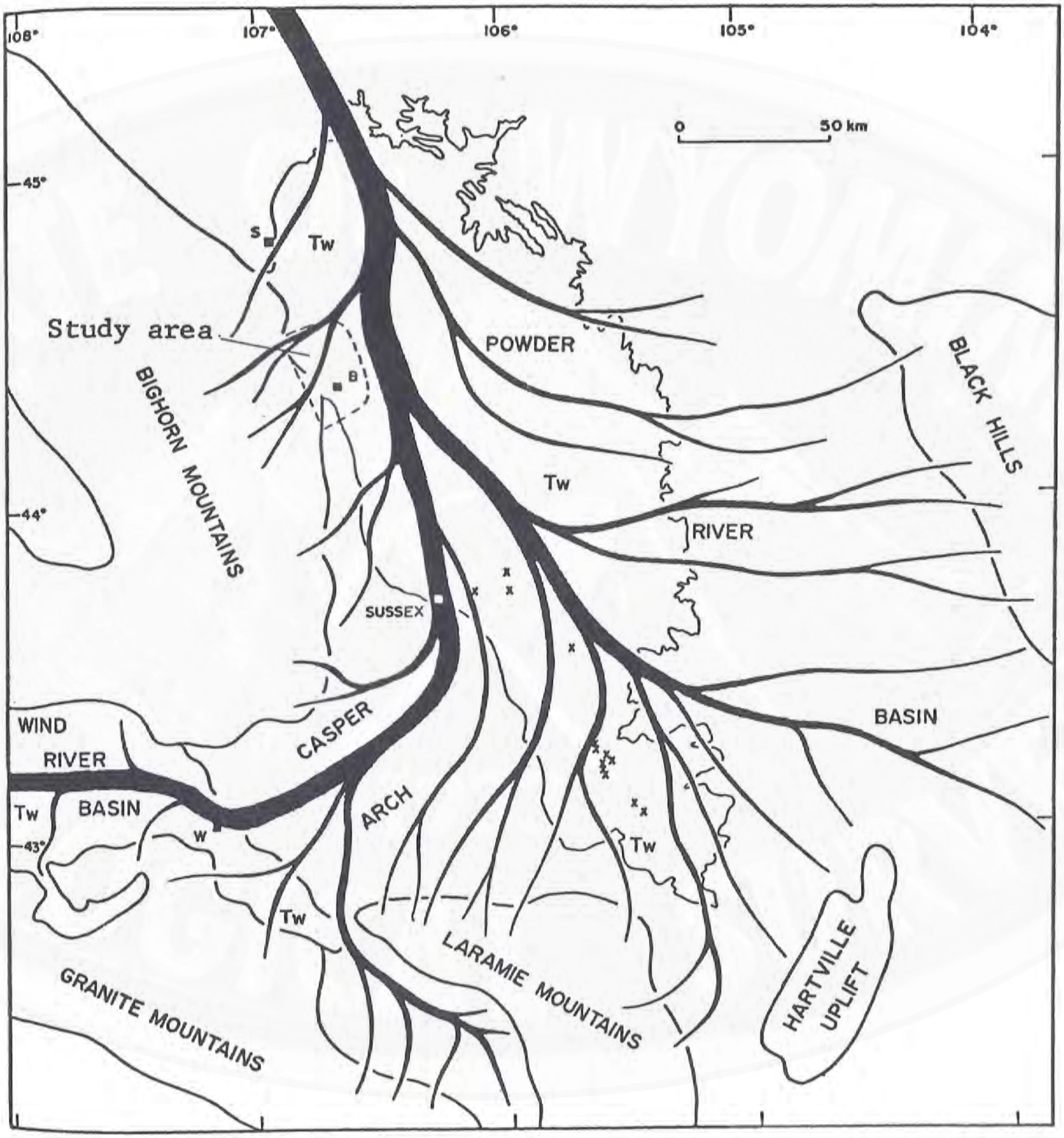


Figure 11: Interpretative diagram of the Eocene paleodrainage for the Powder River Basin. Tw = Wasatch Formation; B = Buffalo; S = Sheridan. From Seeland, 1976.

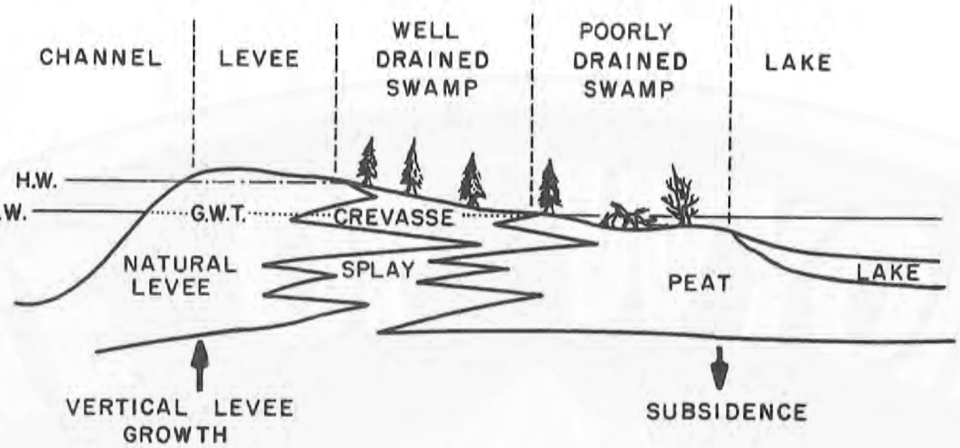
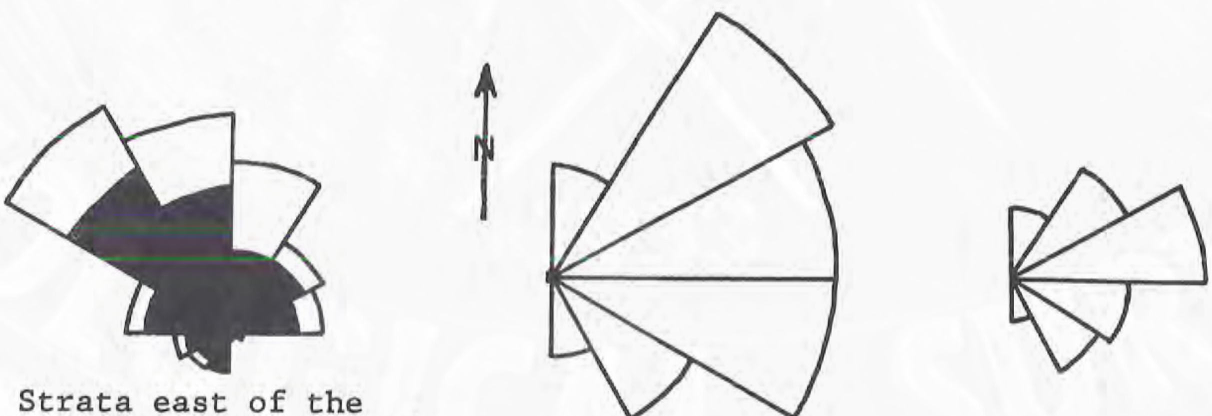


Figure 12: Environments of deposition interpreted for lithologies described for the alluvial plain facies. H.W. = flood stage water level. L.W. = normal water level. G.W.T. = ground water table. Modified after Weimer (1973, p. 71).



Strata east of the Lake De Smet coal bed.

Shaded area = Healy-Walters clastic interval.

130 measurements.

Strata west of the Lake De Smet coal bed excluding cgls.

129 measurements.

Conglomerates west of Lake De Smet coal bed.

71 measurements.

Figure 13: Rose diagrams for transport directions in the study area.

ancient and modern sediment and stratigraphic sequences, have interpreted similar deposits displaying vertical alternation between coarse and fine sediments to be levee and crevasse splay deposits. Weimer (1973, p. 71-72) reported that crevasse splay channels exhibit scour surfaces and generally coarser-grained sequences close to the main channel, while their distal portions become finer grained and merge with lacustrine or bay deposits and are virtually indistinguishable from them. Local concentrations of logs at the base of sandstone units may indicate crevasse splay channel locations. However, limited outcrops prevented verification of this interpretation in the Buffalo-Lake De Smet area.

Crevasse splays are the sites of more rapid rates of sediment accumulation than are levees. Growth of levees generally keeps pace with the rate of subsidence while crevasse splays build subdelta complexes adjacent to the channels during peak flow periods. Modern studies of the Mississippi River delta region indicate rapid lateral and vertical growth of crevasse splay deltas (Morgan, 1970, p. 113). Hence, evidence of rapid accumulation of thick sediment sequences, such as tree trunks buried in their growth positions, may well indicate sites of crevasse splay deposits. Jacob (1973, p. 1042) describes buried tree trunks in interbedded coarse and fine sediments in the Tongue River Formation of western North Dakota, but he attributes burial to rapid vertical growth of the levees. Climbing ripple-stratification, another indicator of rapid sedimentation, is common in both environments, and results from peak flow periods which affect both environments. Decrease in flow energy away from the channel produces rapid sedimentation, particularly when the suspended load is high, thus creating an excellent environment for the formation of climbing ripple-stratification.

Flanking the levees and crevasse splays are the flood basins, whose principal environments are swamps and lakes (Figure 12). Dark-gray clays, carbonaceous shales, and coals were deposited in poorly drained swamps where the depositional interface was continuously under water. Fossiliferous mudstones and limestones indicate numerous fresh-water lakes. The areal extent of many of these beds indicates that the flood basin between channels often covered hundreds of square kilometers.

The cyclic repetition of these alluvial plain deposits indicates shifting of the channel systems into and out of the study area. When the stream channel was diverted to the east, swamps and lakes formed in the region previously occupied by the channel. The thickness of the coals, in some instances more than 40 feet (12 m.), suggests that the life of any particular environment in a given area was not always a short one.

TECTONICS AND SEDIMENTATION

COALS AND TECTONICS

Coal deposits are very sensitive to sedimentary and tectonic influences. Weimer (1977, p. 10) summarized several geologic factors which control the formation and thickness of coal deposits. His factors include: (a) fresh, clear water conditions with little or no detrital influx; (b) the accumulation of land-derived organics; (c) a balance between the ground-water table and the depositional interface such that the swamp does not dry up and permit oxidation of the organics, or that the water does not become so deep that a lake forms; (d) a favorable climate where abundant vegetation is produced; and (e) a persistence of these conditions in time and space. The last factor implies that sedimentation must equal subsidence for the swamp to continue to flourish.

Given these constraints, some of the problems encountered in interpreting and recreating the depositional environment can be understood. The thickness of the Lake De Smet coal bed suggests an extremely long period of continuous peat deposition. Weimer (1977, p. 10) suggests a compaction factor of 5 feet (1.5 m.) of peat to produce 1 foot (0.3 m.) of bituminous coal. If one assumes 100-200 feet (30-60 m.) of coal for the Lake De Smet coal bed, then 500-1000 feet (150-300 m.) of peat were deposited. Weimer (1977, p. 10) cited a 1970 study of the Klang-Langat delta of Malaysia by Coleman, Gagliano, and Smith, in which the rate of peat accumulation was determined to be .33 feet (0.10 m.) of peat per century. Frazier and Osanik (1969, p. 78) reported .57 feet (0.15 m.) of peat accumulation per century in the Mississippi delta. Assuming .57 feet (0.15 m.) of peat accumulation per century and assuming comparable accumulation rates, the life of the Lake De Smet coal swamp was 100,000-200,000 years.

The disposal of the coarse clastics shed from the uplift poses a problem since no channel has been identified which would divert the clastics around or through the swamp forming the Lake De Smet coal bed. Drill data do indicate one area, sec. 10, T. 51N., R. 82W., where no coal was deposited (Figures 2 and 4). Unfortunately, no lithologic or geophysical logs are available, and the drill data in this area are of poor quality. A channel to the north or south of the study area may be an alternate explanation.

Structural relationships suggest that the Lake De Smet coal bed is correlative with the finer grained sediments immediately below the Moncrief

Member (Figure 5). If a constant dip of 1-5 degrees is assumed for the Moncrief and equivalent strata from the mouth of Clear Creek to Buffalo, the base of the Moncrief can be projected to the upper portion of the Lake De Smet coal bed. If this correlation is valid, a combination of increased tectonic activity and increased coarse sediment influx can be inferred to have terminated the Lake De Smet coal swamp.

A unique feature of the Lake De Smet coal bed is its relatively straight, linear orientation parallel to the axis of the basin and its proximity to the Bighorn uplift, which was shedding coarse clastics. One possible explanation establishing its position and length may be a postulated subsurface fault which does not cut the Tertiary sediments. Foster, Goodwin, and Fisher (1969), utilizing seismic data, proposed such a subsurface fault along the length of the Powder River Basin from Casper to north of Buffalo. The hypothetical fault plane is 4-20 miles (6-30 km.) eastward from the mountain front, and near Buffalo, the fault may have separation of nearly 4000 feet (1220 m.). However, its position relative to the Lake De Smet coal bed is not known. Such a feature, active during the Laramide Orogeny, would affect local depositional patterns.

SUMMARY

1. The Lake De Smet bed lies along the western margin of a poorly drained alluvial plain. To the west are small lenses of conglomeratic sandstone reflecting braided-stream channels emanating from alluvial fans. To the east, thick broad sheets of very fine-grained to medium-grained sandstone representing meander channel deposits exist.

2. The alluvial-plain environment is characterized by channel, levee, crevasse-splay, paludal, and lacustrine deposits.
3. The braided-stream deposits are characterized by levee deposits, considerable silt and clay, and minor carbonaceous shale and coal units. Braided stream deposits are not normally characterized by these fine-sediment sequences. However, an unstable tectonic environment coupled with shifting alluvial-fan depocenters serves to preserve significant silt, clay, and organic sequences.
4. The coals were formed in a back-levee or flood-basin swamp marginal to leveed channels.
5. The Lake De Smet bed divides into five major, mappable, economic coal beds to the east. From oldest to youngest, these coals include the Ucross, Murray, Cameron, Healy, and Walters.
6. The thickness of the Lake De Smet bed and its linear orientation axial to the basin may mark the location of a basin-margin fault. A fault at depth is postulated to have been active during Eocene time and to have played a prominent role in the formation of the Lake De Smet bed.

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FLUVIAL COAL SETTINGS OF THE TONGUE RIVER MEMBER OF THE FORT UNION FORMATION IN THE POWDER RIVER-CLEAR CREEK AREA, WYOMING

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INTRODUCTION

The valley walls of the Powder River and of Clear Creek in northeastern Wyoming (Fig. 1) provide excellent exposures for analysis of the stratigraphic relationship and specific depositional settings of coal deposits of the upper part of the Paleocene Tongue River Member of the Fort Union Formation. A rare combination of almost continuous exposures along moderately high cliffs of the river valleys and along dissected areas of their tributaries affords an opportunity to study the three-dimensional characteristics of the stratigraphic-environmental relationships of the Tongue River Member.

The objective of this segment of the field trip in the Powder River Basin is to provide a field guide to the vertical and lateral relationships of the clastic and carbonate rocks of the Tongue River Member in the Powder River-Clear Creek area, which were deposited in fluvial environments. In addition, the influence of specific fluvial-subenvironmental settings on coal accumulations will be explored. In order to accomplish these objectives in a very short period of time in the field, two major stops will be visited to observe the vertical variations and sedimentary properties of lithogenetic units that represent the entire stratigraphic interval exposed in the study area. The lateral variations of the lithogenetic units will be demonstrated by cross-section panels constructed from 65 stratigraphic sections measured at an average of about 0.4 miles apart. Sixty additional stratigraphic sections measured in outlying areas were utilized to illustrate the areal distributions of the thick coal deposits.

At the outset it should be made clear that the results presented in this paper represent a small part of a larger, continuing study in the Powder River area and outlying areas of Wyoming and Montana. The con-

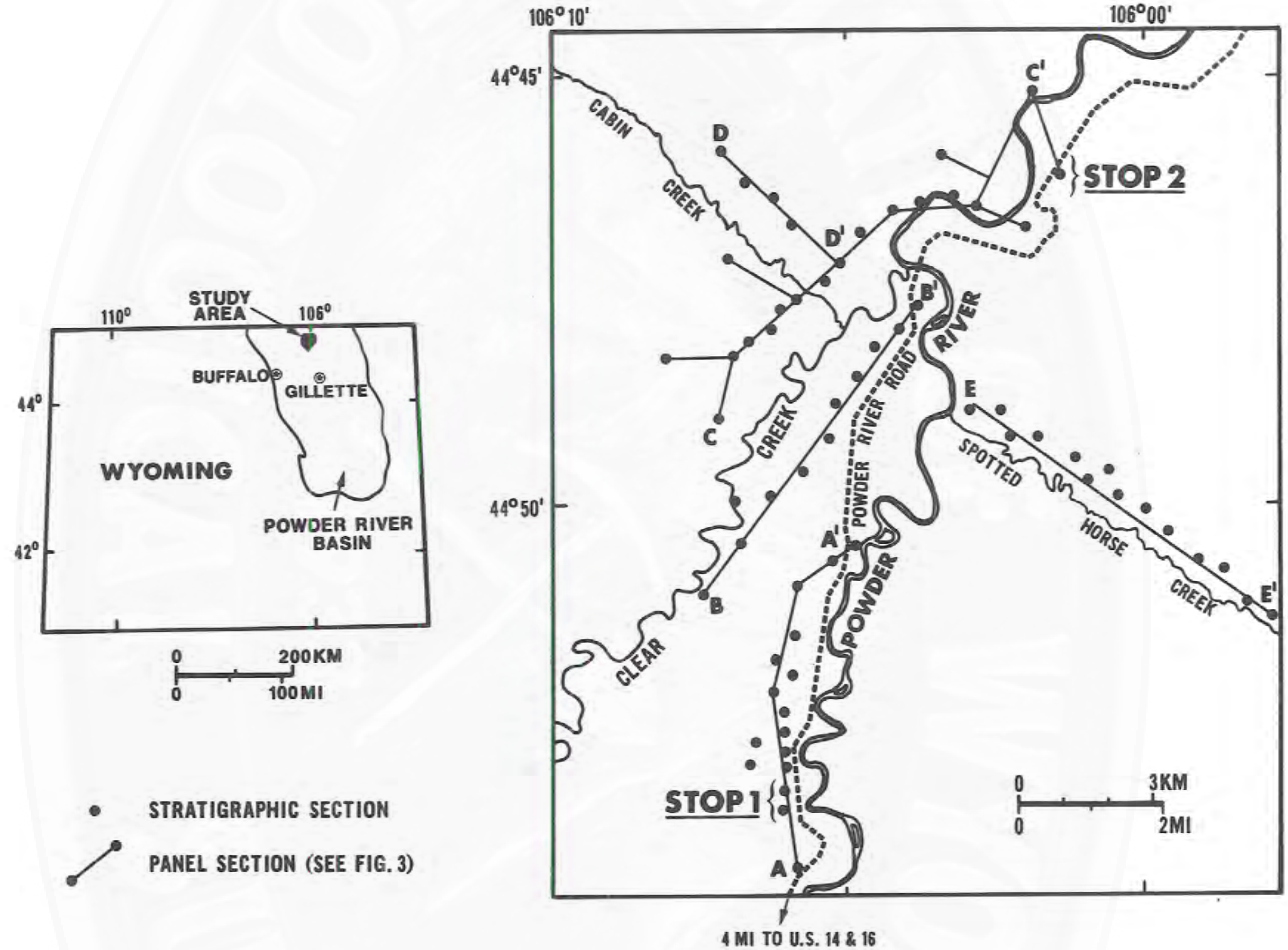

Figure 1. Map of Powder River-Clear Creek area, Wyoming, showing location of the stratigraphic sections and lines of cross sections.

tinuing study on depositional environments of coal deposits in the Powder River area benefited from the theses of D. Canavello and L. Lynn of North Carolina State University who worked with the author during the summers of 1978 and 1979. The results of these studies are published in Flores and Canavello, 1979, Flores, 1979a, Canavello, Flores, and Cavaroc, 1979, and Lynn, Flores, and Cavaroc, 1980.

STRATIGRAPHIC ANALYSIS

The Tongue River Member of the Fort Union Formation exposed near and along the Powder River in Wyoming and Montana is 1500 ft. thick and its composite section is shown in Figure 2. On the basis of the abundance of fluvial channel sandstone in the lower 1100 ft. and the common occurrence of fresh-water mollusk-bearing limestone in the upper 400 ft., the Tongue River Member was subdivided into a fluvial channel-dominated facies and a fluvial lake-dominated facies, respectively (Flores, 1979b; Flores, in press). In the Powder River-Clear Creek area the study interval includes the upper 600 ft. of the Tongue River Member and contains the entire 400 ft.-thick deposits of the fluvial lake-dominated facies and the upper 200 ft.-thick deposits of the fluvial channel-dominated facies (see Figure 2).

Stop 1 will visit an almost complete vertical sequence of the fluvial lake-dominated facies. This sequence, illustrated in Figure 3, is subdivided into three subfacies: lake-lake fill, crevasse splay-crevasse channel, and fluvial channel-interchannel subfacies (Flores, 1979c). Stop 1A (see Fig. 3) includes the lake-lake fill subfacies and the crevasse splay-crevasse channel subfacies. The lake-lake fill subfacies comprises a fresh-water mollusk-bearing micritic to silty limestone that represents the lake deposit proper and an overlying lake fill detritus represented

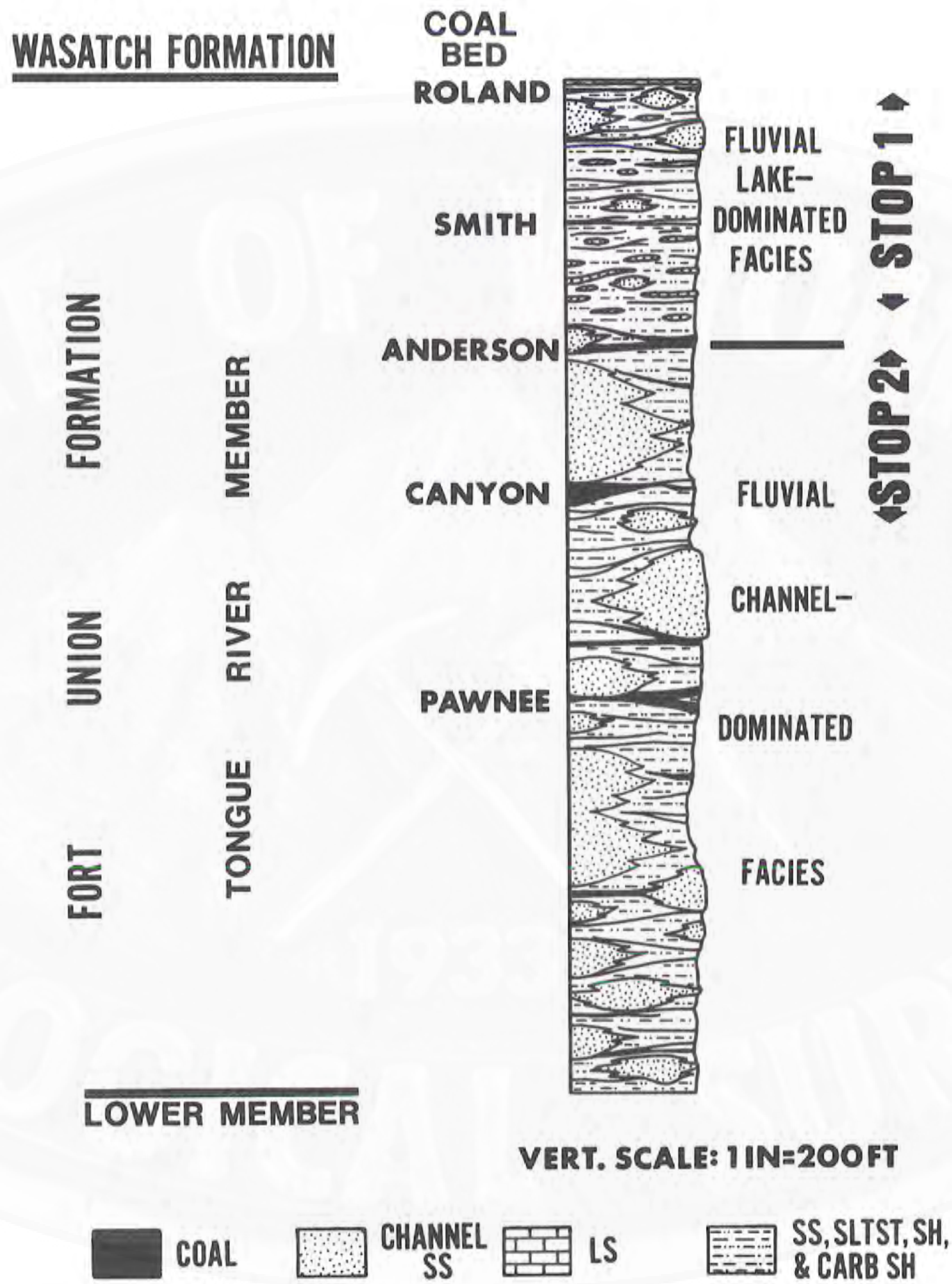

Figure 2. Composite stratigraphic section of the Tongue River Member of the Fort Union Formation in the Powder River area, Wyoming.

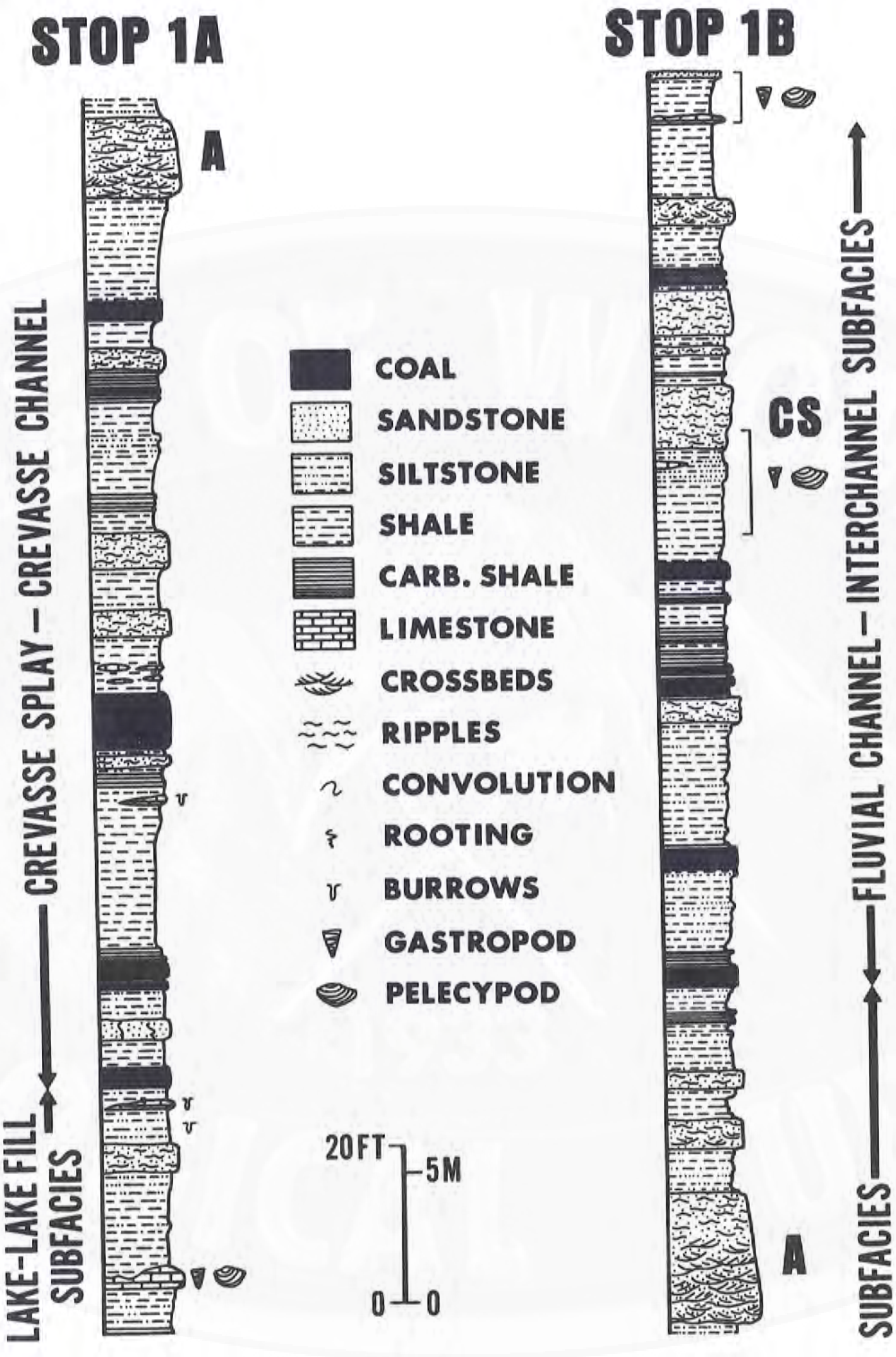

Figure 3. Stratigraphic sections showing subdivisions of subfacies of the fluvial lake-dominated facies at Stop 1.

by a thin coarsening-upward sequence of shale, siltstone, and rippled sandstone. The lake-lake fill subfacies grades vertically upward into the crevasse splay-crevasse channel subfacies. The lower part of the crevasse splay deposits here consist of shales and siltstones, and some limestone lenses and rippled sandstone beds. The upper part of the subfacies, which is continued in the lowermost part of Stop - 1B section, consists of numerous well-developed coarsening-upward sequences of shale, siltstone, and rippled sandstone and a crevasse channel sandstone (A). The coarsening-upward sequences are separated by thin to thick coal and carbonaceous shale beds.

The lowermost part of the section at Stop 1B (see Fig. 3) consists of the uppermost deposits of the crevasse splay-crevasse channel subfacies. The uppermost sandstone unit (A) in Stop 1A is equivalent to the lowermost sandstone unit (A) at Stop 1B. The interchannel deposits of the overlying fluvial channel-interchannel subfacies show characteristics similar to those of the crevasse splay-crevasse channel subfacies: coarsening-upward sequences of shale, siltstone, and rippled sandstone that is locally truncated by channel sandstone separated by thin coal and carbonaceous shale beds. However, the interchannel deposits can be traced laterally to where they merge with thick fluvial channel sandstones. A crevasse-splay sequence (CS) in the interchannel deposits is well displayed in the upper part of Stop - 1B section. The crevasse splay-sequence contains in the lower part shale and siltstone that grade upward into a silty sandstone with a limestone lens, and rippled (asymetrical and climbing) sandstone in the upper part. Fresh-water pelecypod and gastropod fossils are distributed throughout the sequence, suggesting deposition of the crevasse splay-sequence into a lake or other standing body of water.

Figure 4. Photograph showing Canyon coal overlain by the thick fluvial channel sandstone at Stop 2.

Stop 2, shown in Figure 4, will visit the uppermost part of the fluvial channel-dominated facies that includes the Canyon-Anderson coal interval. However, at this locality only the Canyon coal and an overlying fluvial channel sandstone are exposed. The Canyon coal is 28 ft. thick and the channel sandstone is 150 ft. thick. The channel sandstone shows an erosional base, festoon and planar crossbeds, and steeply dipping point bar units. The channel sandstone represents the major lithogenetic unit that separated the Canyon coal from the overlying Anderson coal.

The vertical and lateral variations of the fluvial channel-dominated facies and the subfacies of the fluvial lake-dominated facies are illustrated in a fence diagram shown in Figure 5. The lines of the cross-section panels of the fence diagram are shown in Figure 1. The stratigraphic variation of the Canyon-Anderson coal interval of the fluvial channel-dominated facies is well displayed in cross-section panel C-C'. The interval, which is dominated by thick fluvial channel sandstone at Stop 2 and vicinity, to the southwest consists of vertically and laterally interfingering overbank-crevasse splay sandstones, siltstones, shales, limestones, very thin coal beds, and channel sandstones. The Canyon coal attained a maximum thickness of 30 ft. at the locality northwest of Stop 2; however, mapping of these coal beds and contemporaneous rock units to the northeast outside the paneled area shows thinning toward that direction. An isopach map of the Canyon coal bed in that area shown in Figure 6, shows lateral merging of the coal bed to the northeast with a meander bend of a fluvial channel sandstone that is a different rock unit than that which overlies the Canyon coal at Stop 2. The isopach map also shows the uniform thickness of the Canyon coal along a northwest-southeast direction subparallel

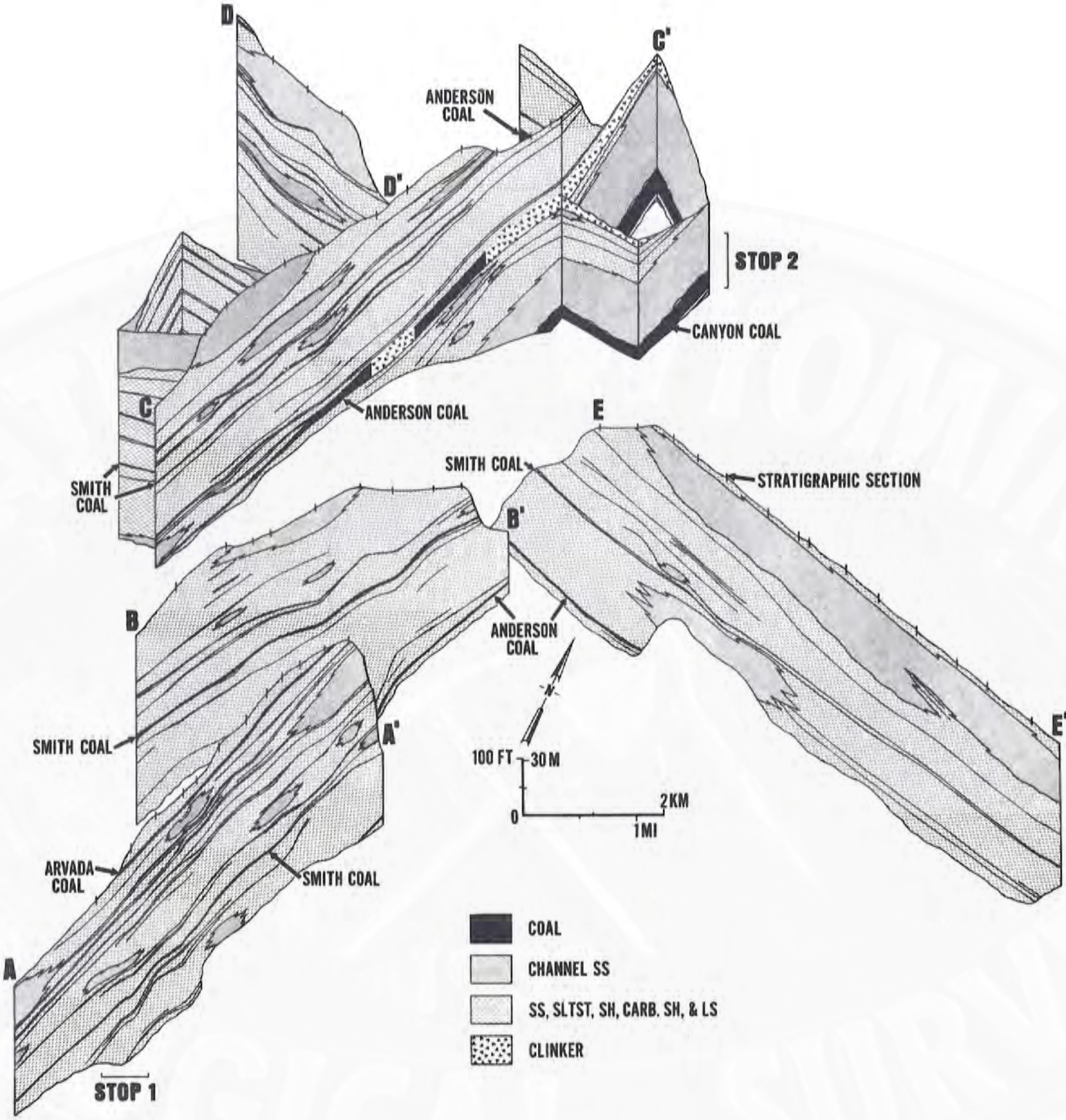

Figure 5. Fence diagram of the upper 600 feet of the Tongue River Member in the Powder River - Clear Creek area, Wyoming.

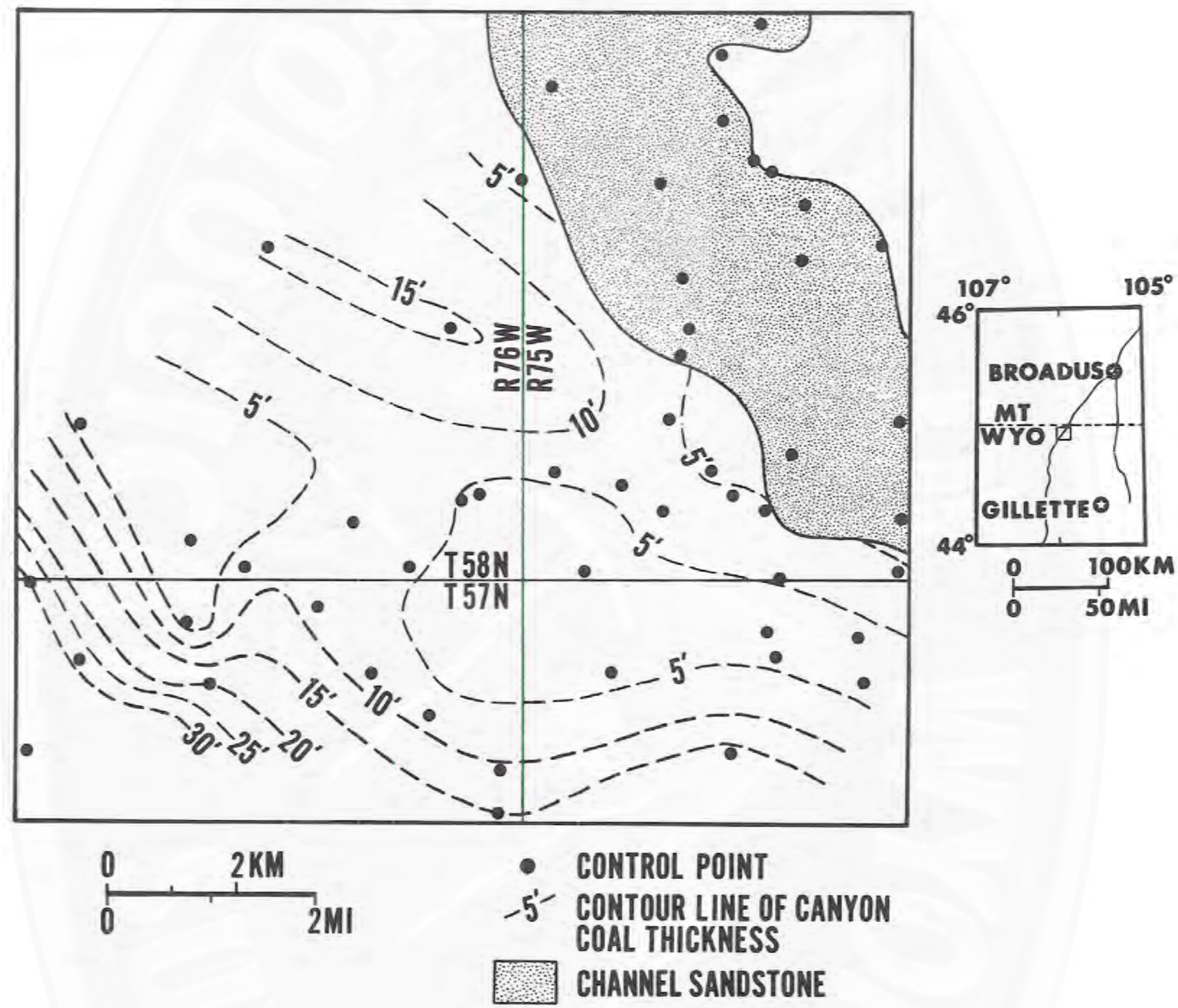

Figure 6. Isopach map of the Canyon coal northeast of the Powder River - Clear Creek area, Wyoming (see inset map). Isopach interval is 5 feet.

to the contemporaneous fluvial channel sandstone. Two local areas of thickening of the Canyon coal bed are developed 2 and 5 miles southwest of the contemporaneous channel sandstone. These areas of coal thickening are separated by an area of thin coal probably representing a topographic low that shows pronounced depressions to the northwest and southeast.

The lateral variation of the Anderson coal is best shown in cross-section panel C-C' (see Fig. 5). The coal is very thick to the northeast and thins to the southwest. The coal bed is split into a lower and an upper bed by a contemporaneous fluvial channel sandstone at the southwest end of the cross-section panel. An isopach map of the Anderson coal and lower split is shown in Figure 7. The coal shows uniform thickness along a north-south direction with the maximum thickness occurring 3 miles northeast of the contemporaneous fluvial channel sandstone.

The stratigraphic variations of the fluvial lake-dominated facies that overlies the Canyon-Anderson coal interval of the fluvial channel-dominated facies are well displayed in all the cross-section panels (see Fig. 5). The lake-lake fill subfacies between the Anderson coal and coal zone below the Smith coal (Olive, 1957) is characterized by the presence of very few, thin coals and channel sandstones. The only areas where channel sandstones are formed in this subfacies are in cross-section panels A-A' and E-E'. The crevasse splay-crevasse channel subfacies overlying the lake-lake fill subfacies is characterized by abundant thin to thick coal beds that include the Smith coal (Olive, 1957). The lateral continuity of these coals of the crevasse splay-crevasse channel subfacies, particularly the thick (as much as 8.5 ft.) Smith coal, is highly variable; thus, their correlations are tenuous where stratigraphic data are not measured at closely spaced intervals. The coals occur along the lines of cross sections as

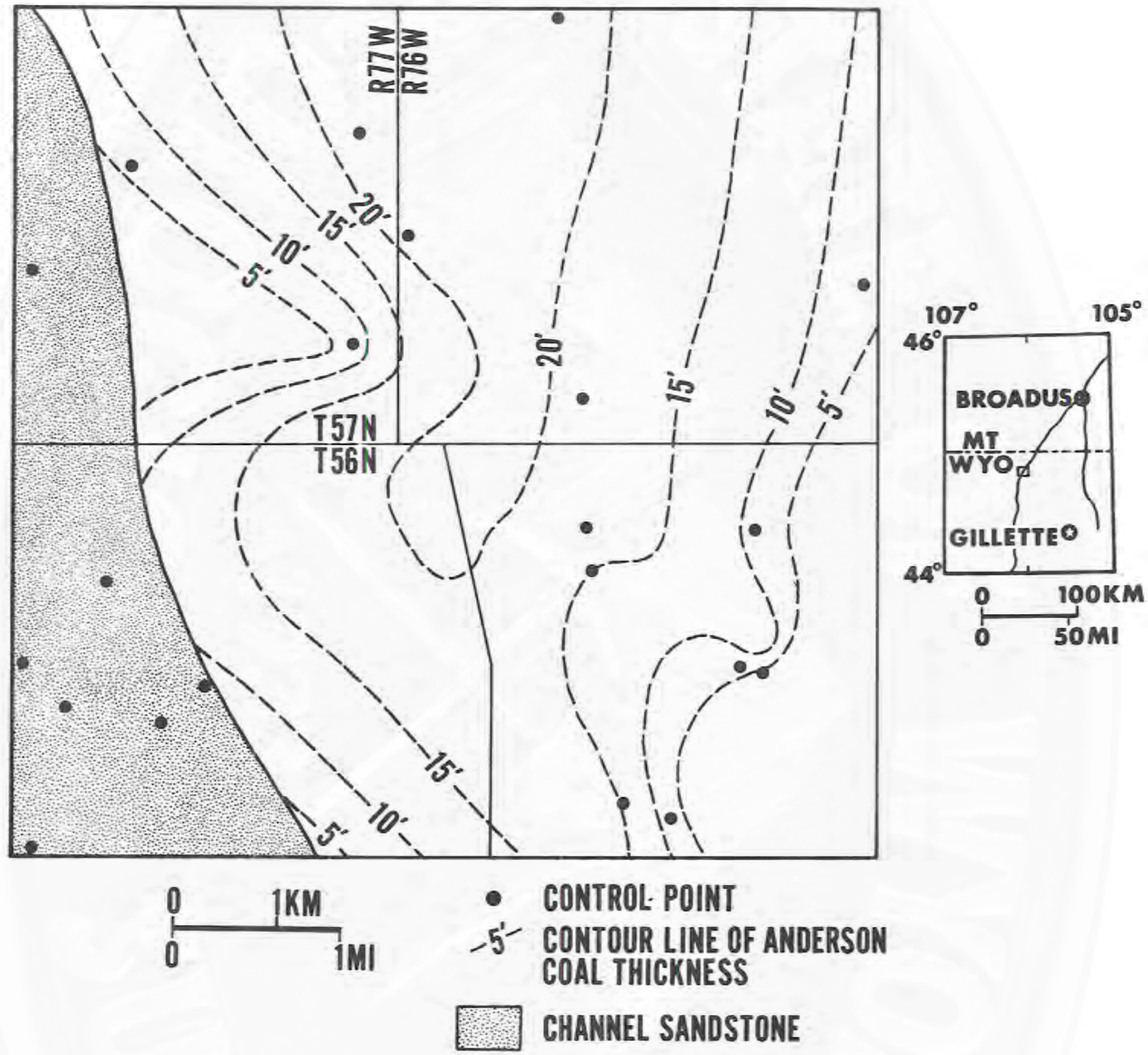

Figure 7. Isopach map of the Anderson coal in the Powder River-Clear Creek area, Wyoming (see inset map). Isopach interval is 5 feet.

continuous beds for 0.5 - 4.5 miles prior to splitting or merging. The crevasse channel sandstones of the crevasse splay deposits are concentrated in the areas of cross-section panels A-A', C-C', and D-D'.

The fluvial channel-interchannel subfacies that overlies the crevasse splay-crevasse channel subfacies is characterized by common occurrence of fluvial channel sandstones that laterally merge with interchannel overbank-crevasse splay shales, siltstones, and sandstones, and crevasse channel sandstones. The fluvial channel sandstones range in thickness from 30 to 110 ft., contain festoon and planar crossbeds, and show deep erosional bases. The orientation of the fluvial channel sandstones along a northwest-southeast direction is partly shown by the channel sandstone in the uppermost part of cross-section panels D-D' and E-E'. The southwest margin of this channel sandstone is shown in the uppermost part of cross-section panels A-A', B-B', and C-C'. Another, partly contemporaneous fluvial channel sandstone body is at the southwest end of the uppermost part of the cross-section panel A-A'. A small channel sandstone is between these two major channel sandstone bodies in cross-section panel A-A'. The three-dimensional distribution of these fluvial channel sandstone bodies suggests a linear or slightly sinuous orientation. The vertical distribution of these fluvial channel sandstones shows a slightly offset arrangement as indicated by the distribution of associated coal beds. That is, the coal beds that directly underlie the major fluvial channel sandstone at the southwest laterally merge with the other major fluvial channel sandstone at the northeast shown in cross-section panel A-A'. In addition, younger interchannel coal beds that laterally merge with the major fluvial channel sandstone at the southwest in cross-section panel A-A' can be traced to override the major fluvial channel sandstone at the northeast.

ANALYSIS OF COAL DEPOSITIONAL SETTINGS

The recognition of specific coal depositional settings of the Tongue River Member in the Powder River-Clear Creek area is based on the vertical and lateral relationships of the lithogenetic units, sedimentary structures, textural sequences, and mollusk fossil content. The delineation of depositional subenvironments of the subfacies of the fluvial lake-dominated facies and fluvial channel-dominated facies can be readily reconstructed from the three-dimensional characteristics of the lithofacies associations established in Figure 5.

The depositional settings of coal in the fluvial channel-dominated facies is illustrated by lithogenetic model A in Figure 8. Model A represents the depositional setting of the Canyon-Anderson coal interval and shows the peat swamp environment in which the Anderson coal accumulated. The thickest accumulation of peat developed subparallel to the length of the contemporaneous channel. The Anderson coal is underlain by overbank-crevasse splay deposits that vertically and laterally interfinger with a thick fluvial channel sandstone, which in turn, overlies the Canyon coal. Mapping of the Canyon coal and contemporaneous rock units (see Fig. 6) indicates that the Powder River-Clear Creek area was probably a floodbasin during Canyon time. This floodbasin, which supported a stable peat swamp that was relatively undisturbed by overbank detrital incursions, was probably isolated as the meander bend located 5 miles to the northeast of Stop 2 was abandoned following channel avulsion. The swamp in the central part of the floodbasin probably formed a peat bog that generated and regenerated a dome-shaped peat deposit; the peat was probably as much as 150 ft. thick (compaction factor of X5) in the vicinity of Stop 2 and 15 ft. thick to the northeast of Stop 2. It is proposed that the peat bog

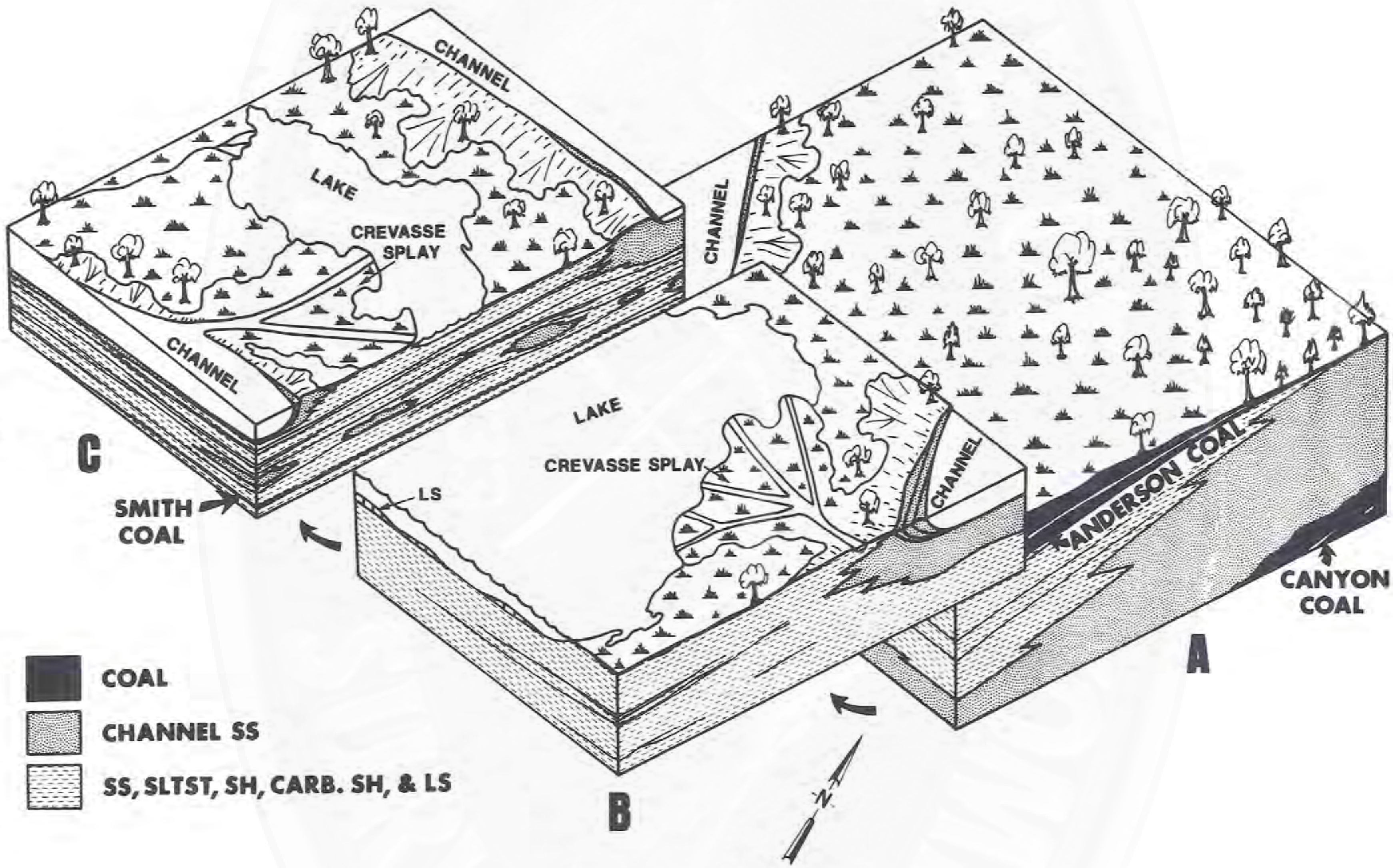

Figure 8. Lithogenetic models showing sequences of deposition of fluvial subenvironments of the fluvial channel-dominated facies and the fluvial lake-dominated facies in the Powder River-Clear Creek area, Wyoming.

was propagated by alternating upward growth of hummocks vegetated by woody plants and hollows vegetated by herbaceous plants (Flores, in press). A palynological study by R. Tschudy (U.S. Geological Survey, per. comm.) of a limited number of nonchanneled samples indicates that the Canyon and Anderson coals contain as much as 25 percent herbaceous plants. The combination of groundwater table rise by capillarity and/or increased surface runoff and gradual sinking of the peat due to compaction probably caused regeneration of thick peat bogs. Modern bog plains attain a thickness of peat as much as 100 ft.; in a rare example in an intermontane depression with internal drainage in Greece, peat and gyttja deposits are as much as 600 ft. thick (Stach and others, 1975). That the peat bogs of the Tongue River Member maintained internal drainage systems are indicated by minor depressions between domed surfaces of the Canyon coal (see Fig. 6). Excess water probably collected on these surface depressions and served as small channel reentrants into the bog plain. An extrapolation of the study of plant fossils of the Fort Union Formation in the Bighorn and Williston Basins by L. Hickey (National Museum, Smithsonian Institution, pers. comm.) indicates that these peat bogs in the Powder River Basin formed in a moderate temperate climate. Figure 9, modified from Lynn, Flores, and Cavaroc (1980), shows the evolutionary sequence of depositional events following the accumulation of the domed peat in the central part of the floodbasin. The domed peat (A) compacted under its own weight, and assuming a compaction factor of 5 ft. of peat to produce 1 ft. of coal (Weimer, 1977), peat deposits as much as 150 ft. thick that eventually produced the Canyon and Anderson coals, sank and drowned (B) through time. Prolonged sinking of compactible underlying sediments and compaction of the peat in the central backswamp created a

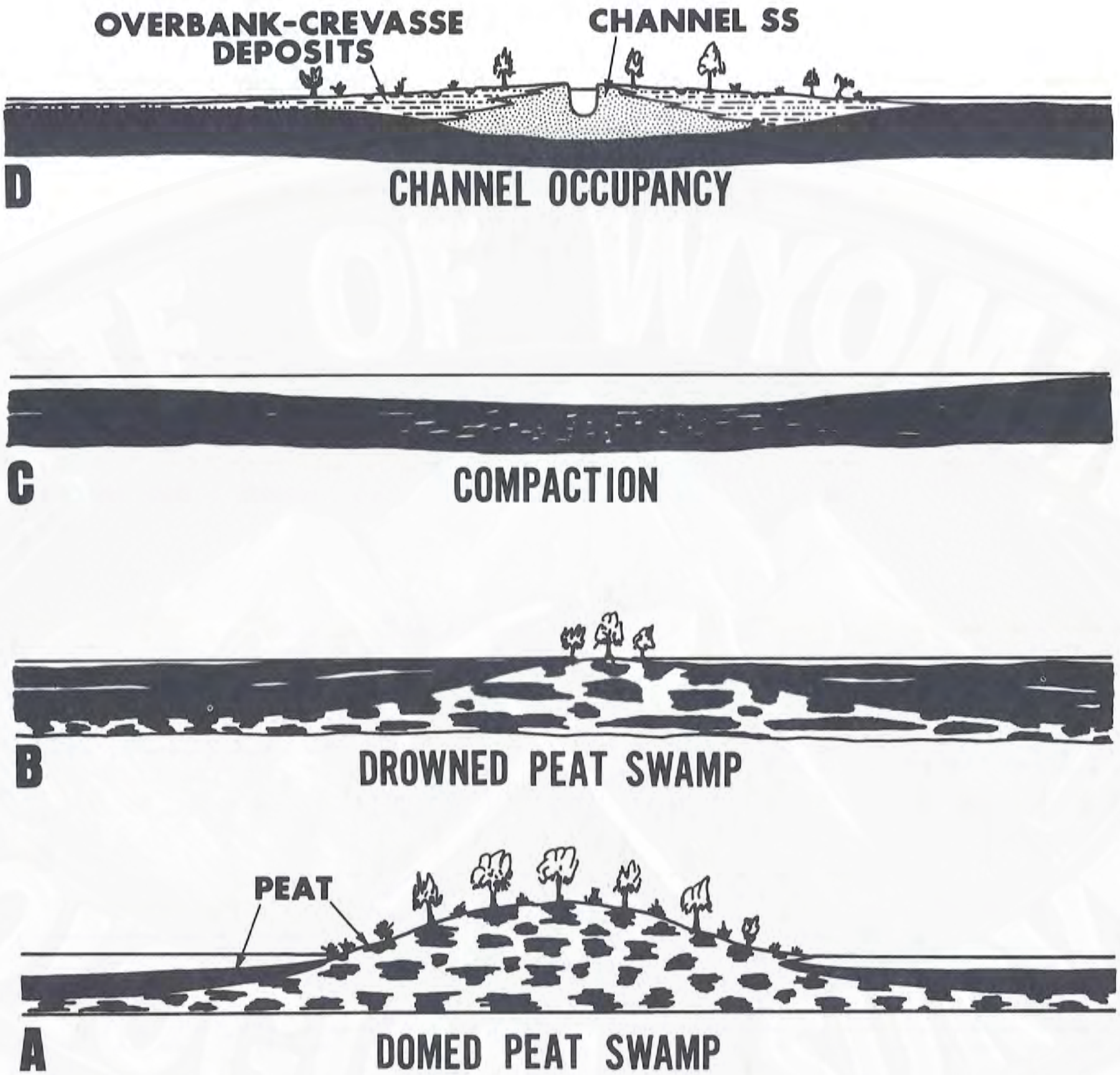

Figure 9. Evolutionary sequence of accumulation, compaction, and submergence of peat deposit and subsequent channel occupancy over the peat deposit.

topographic low (C) over the central part of the floodbasin. This condition, in turn, influenced autocyclic shift and occupancy (D) of a fluvial channel in the topographic low. These processes may represent the sequence of events of deposition of the fluvial channel sandstone that directly overlies the Canyon coal observed at Stop 2. The subsequent abandonment of the fluvial channel sandstone permitted encroachment by the peat swamp over the submergent sandstone ridge, a condition that may have influenced the deposition of the lower and upper splits of the Anderson coal. Thus, the accumulations of the Canyon and Anderson coals in a fluvial setting were directly influenced by the following factors: 1) isolation of peat swamps as a result of abandonment of meander bends by channel avulsion; 2) compaction of domed peat creating topographic lows that were occupied by fluvial channels; and 3) reoccupation by peat swamps of submergent abandoned channel sandstone ridges.

The paleogeography of the Canyon-Anderson coal interval is succeeded by the fluvial lake-dominated settings illustrated by lithogenetic models B and C (see Fig. 8). The lithogenetic model B shows a lacustrine environment at the west and a fluvial channel at the northeast of the study area. The fluvial channel at the northeast probably contributed crevasse splay detritus into the lake to the west. The thin coarsening-upward detrital sequences identified as lake-fill deposits in Stop 1A probably represent distal deposits of crevasse splay systems. The limestones associated with the lake-fill detritus probably precipitated in lake localities far removed from active detrital influxes and marked quiet sedimentation during periods of nonflood conditions. That these quiet lake-bottoms supported macrofauna is indicated by the mollusk fossils. The swamp that formed marginal to the lake was a poor area for peat accumulation probably due to constant shoreline erosion and flocculation of clays from suspended sediments. As the lake filled, areas sedimented by crevasse splays served as raised platforms on which some peat accumulated. The detrital filling of the lake by crevasse splays is comparable to the mode of sedimentation by lacustrine deltas and crevasse splays of lakes in the modern Atchafalaya-Mississippi River basins, (Coleman, 1966; Gagliano and van Beek, 1970).

The crevasse splay-crevasse channel setting, which succeeded the lake-lake fill sedimentation in the study area, probably represents continued filling of the lacustrine environment. The presence of only a few mollusk fossils in this subfacies (Flores, 1979c) suggests that the lakes supported a limited amount of bottom fauna. Rapid influx of the detrital sediments of crevasse splays into the lakes probably rendered the environment moderately inimical to mollusk habitation. In contrast to the lake-lake fill settings, the crevasse splay-crevasse channel deposits served as better swamp platforms on which peat accumulated. The frequent sedimentation of these swamp platforms by overbank-crevasse splay detritus caused common merging or splitting of the coal beds. However, some of these swamp platforms were relatively stable, unaffected by overbank-crevasse splay sedimentation, permitting accumulation of thick peat such as that which formed the Smith coal.

The lithogenetic model C (see Fig. 8) is a paleogeographic reconstruction of the fluvial channel-interchannel subfacies of the lake-dominated facies. The model shows an interchannel environment consisting of lake, crevasse splay-crevasse channel, and overbank subenvironments bounded at the north and south by fluvial channels. The fluvial channels are almost contemporaneous, with the fluvial channel at the north slightly older than the fluvial channel at the south. The intervening areas between the northwest-southeast oriented fluvial channels and lake are built by crevasse splay-crevasse channel deposits which supported peat swamps. Unlike the peat swamps of the crevasse splay-crevasse channel (subfacies) settings, the swamp in this interchannel area formed thin peat that displays more common splitting or merging toward the southwest and northeast directions than toward the northwest and southeast directions (see Fig. 5); this was probably caused by active influx of overbank-crevasse splay detritus from the adjacent fluvial channels. The crevasse splay detritus observed at Stop 1B (CS) filled the interchannel lake permitting encroachment of the peat swamp over sedimented areas.

SUMMARY

The paleogeographic reconstructions of the fluvial settings of the Tongue River Member deposits in the Powder River-Clear Creek area suggest two important subenvironments of coal accumulation. In the lower 200 ft. of the study interval, accumulations of peat which formed the very thick Canyon and Anderson coals developed in floodbasin swamps that were isolated by meander bends abandoned by channel avulsions. These swamps, relatively free from overbank and crevasse splay sedimentation, probably formed domed peat bogs as much as 150 ft. thick that compacted and sank under their own weight. Prolonged regeneration of peat during compaction and sinking of the bogs was sustained by elevation of the water table by capillarity and/or by increased surface runoff. Continued compaction of the drowned peat bogs created a topographic low that influenced autocyclic shift of fluvial channels into the central parts of the floodbasins. Subsequent filling and abandonment of the fluvial channels permitted reoccupation of abandoned sandstone ridges by peat swamps. Thus, exploration of the very thick Canyon and Anderson coals should be guided by identification of contemporaneous abandoned meander bends of fluvial channels, where coal deposits are predictably very thick on their convex sides.

In the upper 400 ft. of the Tongue River Member study interval, coal accumulation developed in highly active sedimentation areas on crevasse splay-crevasse channel platforms marginal to lakes and in inter-channel areas. The swamp platforms subjected to lake shoreline erosion, inundation by suspended sediments of flood waters, and rapid influx of detritus, formed thin to thick and rapidly merging or splitting coal beds that are associated with abundant carbonaceous shale beds.

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COAL RESOURCES OF THE POWDER RIVER COAL BASIN

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INTRODUCTION

The Powder River Coal Basin of northeastern Wyoming includes Campbell County and portions of Sheridan, Crook, Weston, Nibrara, Converse, Natrona, and Johnson counties. The 12,000 square mile coal-bearing area, which is the second largest in the state, coincides with the topographic and structural basin of the same name. As defined, however, the coal basin is limited to that portion of the Powder River Basin underlain by Mesaverde or younger rocks. This definition was chosen because the Mesaverde Formation is the oldest coal-bearing formation in the basin.

Based on early mining activity, the U.S. Geological Survey named twelve coal fields within the basin (see guidebook cover). The field boundaries have recently been revised so that the entire basinal area is included within one or another field (Glass and Roberts, in preparation).

Structurally, the basin is a broad asymmetric syncline bounded by the Bighorn Mountains to the west, the Black Hills to the east, and the Casper Arch, Laramie Mountains, and Hartville Uplift to the south. The basin continues into Montana where it is separated from the Williston Basin by the Cedar Ridge Anticline. Because the axis of the Powder River Basin is west of the basin's center, the rocks in the eastern and central portions of the basin have almost imperceptable dips compared to the steeper dips on the west flank. In all cases, the Cretaceous rocks around the flanks of the basin dip more steeply than the Tertiary rocks, which are nearly flat-lying (2-3 degrees dip) except on the west flank where at least the Paleocene rocks steepen to 10-25 degrees.

Although faulting occurs in many areas of the basin, faults are relatively rare except on the west flank, particularly in southern Johnson County. Most of the faults trend northeast-southwest with apparent maximum vertical displacements of 300-400 feet in the Sussex area.

The surface topography changes from open hills with 500-1000 feet of topographic relief in the northern part of the basin to plains and table lands with moderate relief (300-500 feet) in the south (Keefer, 1974). Surface elevations range from above 5000 feet in the south to below 4000 feet in the north.

Precipitation is small, at times less than 12 inches per year and accounts for the semi-arid conditions that prevail throughout most of the basin. Drainage is principally northward into Montana or southeastward into South Dakota.

COAL-BEARING FORMATIONS AND COAL BEDS

GENERAL

Although coals are reported in the Upper Cretaceous Mesaverde and Lance Formations, the thickest and most important coals are found in the Paleocene Fort Union Formation and the Eocene Wasatch Formation. The outcrops of these coal-bearing rocks are shown in Figure 1.

MESAVERDE FORMATION

The 500-foot thick Mesaverde Formation, which crops out on the western and southern flanks of the Powder River Basin, pinches out northward and eastward. Coals are reported in oil and gas well tests and in

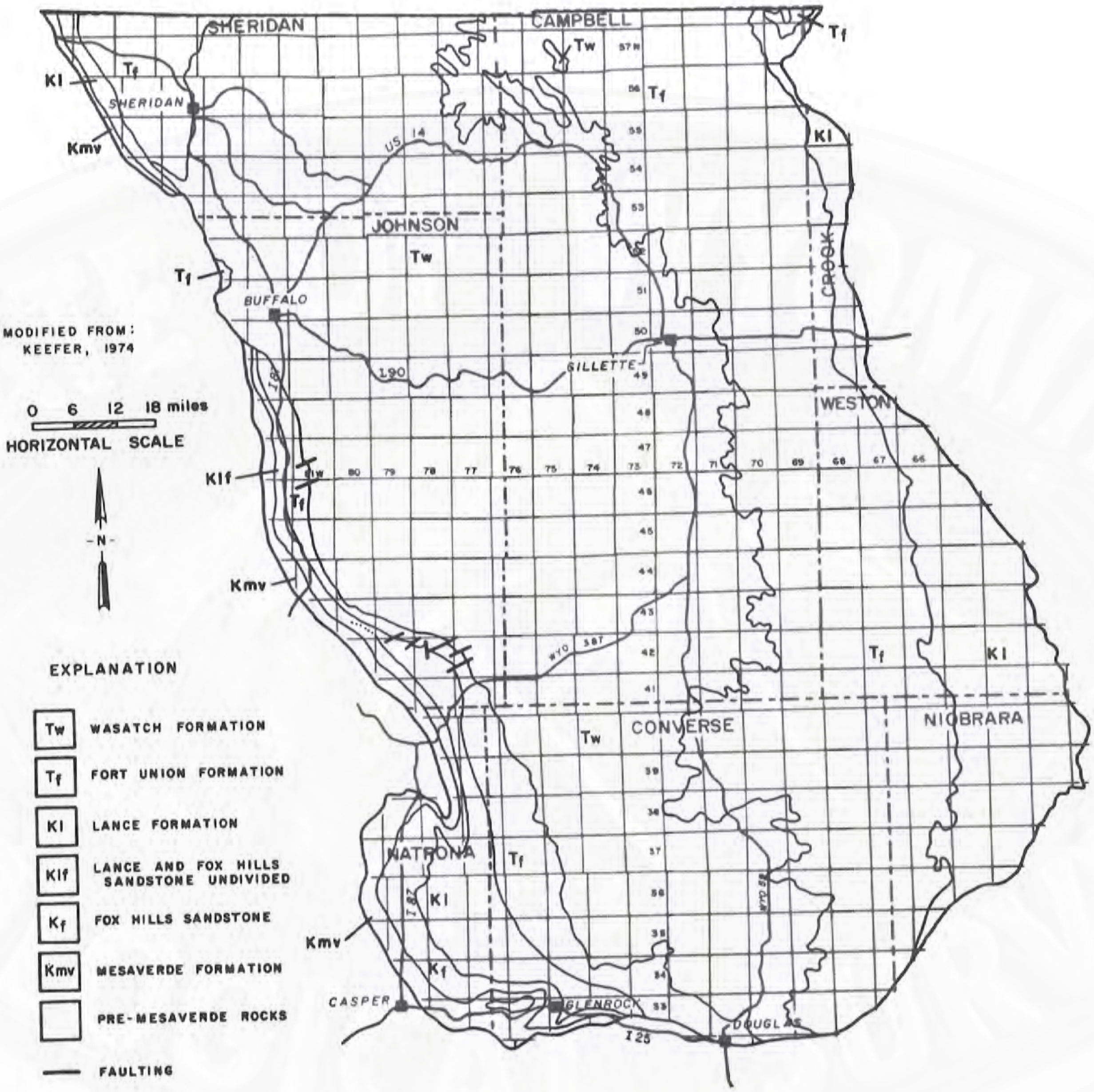

Figure 1. Geologic map of the Powder River Coal Basin.

outcrops only in the southwestern part of the basin. Coals in the Mesaverde are variously described as clean, dirty, or shaly beds generally less than one foot thick. Correlation of individual Mesaverde coals has not been attempted.

Unnamed Mesaverde coal beds: Although several subbituminous Mesaverde coals have been prospected between Casper and Glenrock, they have never been mined except on a very local basis. These prospected coals were only 1.8-3 feet thick. Although two published analyses from these prospects contained over 37 per cent ash, another two analyses revealed fairly good coal as shown below (Shaw, 1909; Fieldner, et al., 1918).

As received basis	Range (2 analyses)	Average
Moisture (%)	19.8-24.1	21.9
Volatile Matter (%)	41.4-33.6	37.5
Fixed Carbon (%)	26.2-36.8	31.5
Ash (%)	5.5-12.6	9.0
Sulfur (%)	0.72-0.70	0.71
Btu/pound	8,246-8,712	8,479

LANCE FORMATION

The 2500-foot thick Lance Formation crops out around the east and west flanks of the basin, but is covered by younger Tertiary rocks in the south. The Lance thins northward and contains no commercially valuable coals except in the southwestern part of the basin. Several coals near the base of the formation exceed three feet in thickness in the Glenrock-Big Muddy area and in Coal Basin No. 1 of the Sussex Coal Field. None of the coals in these two areas can be correlated for more than short distances.

Glenrock-Big Muddy Zone coals: This coal zone is in the basal 200-300 feet of the Lance Formation and extends from just east of Glenrock to just northeast of Casper some 15 miles to the west (Shaw, 1909). Coals are reportedly up to 6.8 feet thick and dip northeast at 3-7 degrees. The coals mined in the Glenrock area averaged about six feet thick. Coals mined near Big Muddy and Casper were all less than five feet thick. Although none of these coal beds are currently mined, they were mined for many years in the Glenrock area. Analyses of the subbituminous coals in this zone are summarized below (Fieldner, et. al., 1931).

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

Unnamed coals in the Coal Basin No. 1, Sussex Coal Field: Although as many as six coals over 1.5 feet thick occur in a 150-foot interval in this small southernmost extension of the Sussex Coal Field, only a couple exceed 2.5 feet. The maximum reported thickness for an individual one of these subbituminous beds is 7.5 feet (Wegemann, 1912). Dips on these beds are generally 4-6 degrees to the southeast although the eastern limb of a small syncline in the northern part of Basin No. 1 dips westward up to 10 degrees. Apparently, there has never been any mining in this area, and there are no analyses of the coals.

FORT UNION FORMATION

The Paleocene Fort Union Formation, which is between 2000-3000 feet thick, is perhaps the most prolific coal-bearing formation in Wyoming. Although the lower members of the formation contain coals, the most persistent and thickest coals occur in the 1500-1800 feet thick upper member, the Tongue River Member.

Tongue River Member coals are best developed in the northern and eastern portions of the Powder River Basin and consist of 8-12 subbituminous coals (Figure 2). One, the Wyodak-Anderson coal, frequently ranges between 50-100 feet thick. The outcrop of this coal, though burned in many places, is mapped for more than 100 miles along the eastern side of the basin. Although the Wyodak-Anderson coal regionally splits into two or more separate beds, coals equivalent to these beds are tentatively correlated into the Sheridan area, 60 miles across the basin. Other coal beds, as well, have been correlated over slightly smaller distances.

The correlation of many of the uppermost Fort Union and lowermost Wasatch coals, however, remains clouded. Anyone familiar with the stratigraphy in the Powder River Basin knows that the contact between the Fort Union and Wasatch Formations is still a controversy after more than

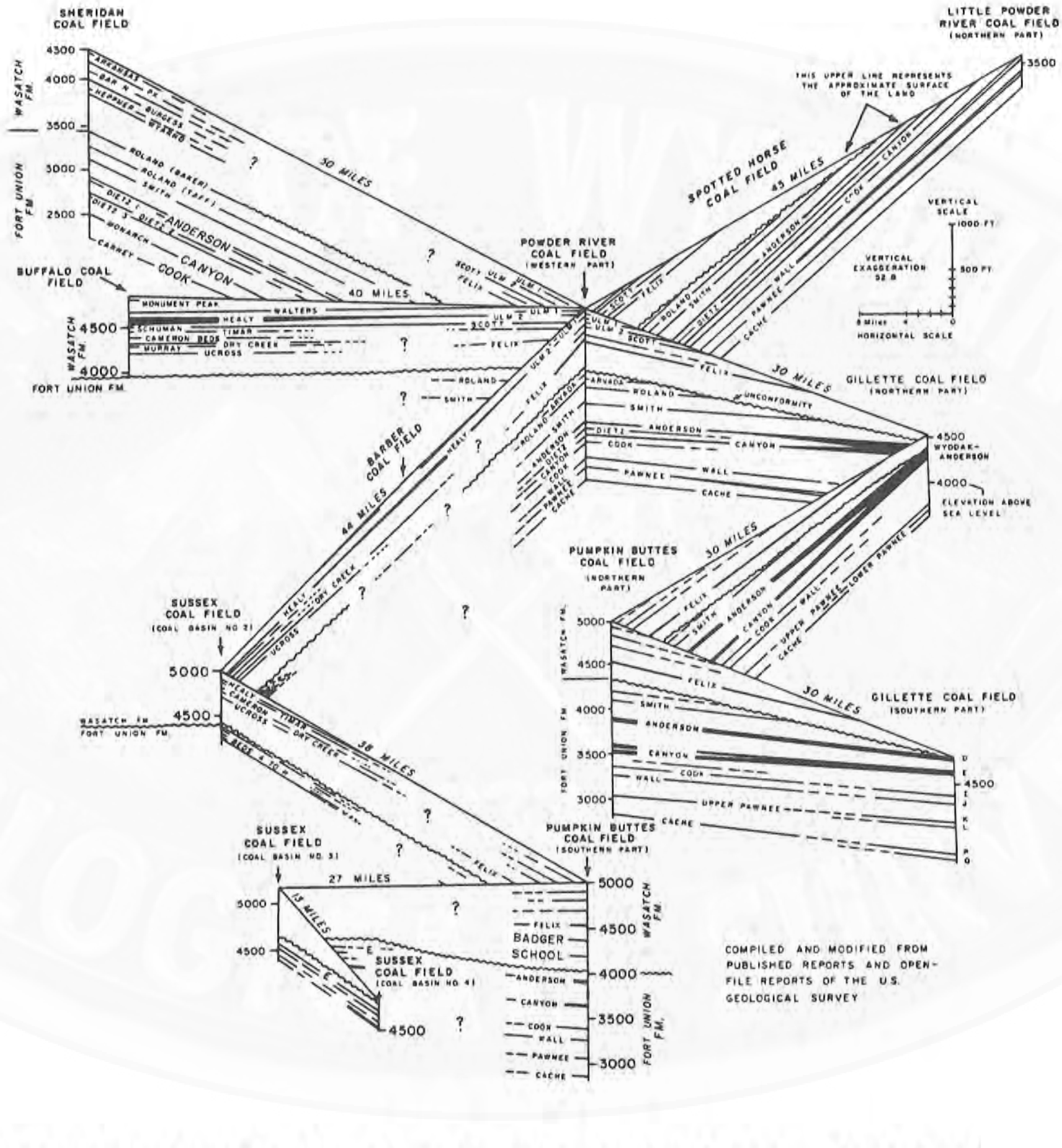

Figure 2. Correlation of coal beds in the Powder River Coal Basin.

50 years of study. This controversial contact which varies with almost each geologist that maps in the area is the cause of many correlation difficulties. In some areas of the basin, the contact is a recognizable unconformity. In other areas, the contact can only be differentiated by detailed sedimentological or palynological studies. Recent mapping by the U.S. Geological Survey is helping to clarify this controversy and may one day put this problem to rest.

Some of the more important Fort Union coal beds are discussed below.

Anderson coal bed: This Paleocene coal is well developed in all but the western part of the Powder River Basin. The Anderson coal coalesces with the Canyon and other coals in the Gillette area to form the 70-125 feet thick Wyodak-Anderson coal, which crops out on the eastern side of the basin (Denson and Keefer, 1974; Kent and Munson, 1978). Northward, eastward, and southward, the Anderson splits off the Wyodak-Anderson bed and thins to 10-50 feet thick (Figure 2).

The D coal bed of the southern part of the Gillette Field is correlative with the Anderson bed, but the Roland coal, which is stratigraphically higher, does not correlate with it as previously reported.

There are at least 250 million tons of strippable, subbituminous Anderson or D coal in the southern part of the Gillette Field (Smith, et. al., 1972). The Anderson coal, however, is only currently mined where it is combined with the Canyon coal to form the Wyodak-Anderson bed.

Nine core analyses of the Anderson coal are summarized below (U.S. Geological Survey, 1973; 1974).

As received basis	Range (9 analyses)	Average
Moisture (%)	24.9-34.1	29.5
Volatile Matter (%)	26.5-34.5	30.1
Fixed Carbon (%)	29.0-38.0	33.9
Ash (%)	3.5-12.2	6.5
Sulfur (%)	0.17-1.13	0.52
Btu/pound	7,128-8,737	7,979

Canyon coal bed: The subbituminous Canyon coal is a persistent bed over all but the southern and western flanks of the basin. In the Gillette area of Campbell County, the Canyon coalesces with the Anderson bed to form the thick Wyodak-Anderson coal (70-125 feet), which crops out on the eastern side of the basin (Figure 2). The Canyon also locally merges with the Swartz and Cook coals as well as the Anderson (Kent and Munson, 1978).

Where it is not joined with the Anderson coal, the Canyon is between 11 and 65 feet thick. The Canyon bed of the Fort Union Formation is correlated with the E coal bed of the southern part of the Gillette Field and with the Monarch bed of the Sheridan Field. The Canyon is not correlative with the stratigraphically higher Smith bed as previously reported (Culbertson, et. al., 1979).

Except for an estimated 250 million tons of strippable reserve base in the southern Gillette Field (E bed) and another 184.9 million tons along Clear Creek in the Spotted Horse Field (Smith, et. al., 1972), the strippable reserve base of the Canyon bed is reported with the Wyodak-Anderson bed or with the Monarch and Dietz beds in the Sheridan area.

The nine Canyon core analyses summarized below are from Campbell County. Monarch analyses from Sheridan County are not averaged with these because the quality of the Canyon in the two counties is quite different (see also Monarch coal bed).

As received basis	Range (9 core analyses; U.S. Geological Survey, 1973; 1974)	Average
Moisture (%)	26.5-31.5	29.6
Volatile Matter (%)	28.7-33.3	30.7
Fixed Carbon (%)	31.8-38.4	34.6
Ash (%)	3.1- 7.4	5.1
Sulfur (%)	0.14-0.92	0.34
Btu/pound	7,537-8,609	8,286

D coal bed: See Anderson coal bed.

Dietz No. 2 coal bed: This coal is locally important in the Sheridan Field where Big Horn Coal Company currently mines it as a rider coal above the Monarch and Dietz No. 3 coals. This subbituminous Fort Union Formation coal averages 12 feet in thickness, and was previously identified as the Armstrong coal in Big Horn's strip mine.

Analytical data on the Dietz No. 2 coal is summarized below.

As received basis	Range or typical analysis (5 analyses)
Moisture (%)	21.7-23.8
Volatile Matter (%)	33.6
Fixed Carbon (%)	38.5
Ash (%)	5.6- 6.6
Sulfur (%)	0.74-1.02
Btu/pound	9,220-9,387

Dietz No. 3 coal bed: This subbituminous coal is an important strippable bed in the Sheridan Field where it was once extensively deep mined. It averages 10-25 feet in thickness. Locally the Dietz No. 3 coalesces with the underlying Monarch (Canyon) coal bed to form a 40-57 feet thick coal in the Sheridan area. The Dietz No. 3 also locally coalesces with the Dietz Nos. 1 and 2 coals, reaching a cumulative thickness of 75 feet (Law, et. al., 1979).

The estimated strippable reserve base of this Fort Union Formation coal is included with the estimate for the Monarch coal, which underlies it by a few inches to 60 feet. Collectively, the strippable reserve base of the two coals originally exceeded 39 million tons (Glass, 1978).

The Dietz No. 3 is mined along with the Monarch coal in Big Horn Coal Company's Big Horn No. 1 strip mine near Acme. A typical analysis of the Dietz No. 3 in this mine is:

As received basis	Typical analysis (Glass, 1975)
Moisture (%)	19.1
Volatile Matter (%)	34.8
Fixed Carbon (%)	41.7
Ash (%)	4.4
Sulfur (%)	0.5
Btu/pound	9,710

E coal bed: See Canyon coal bed.

Monarch coal bed: The subbituminous Monarch coal is one of the most important Fort Union Formation coals in the Sheridan Field. Although it reportedly is up to 57 feet thick, the thicker occurrences apparently equate to areas where the Monarch and Dietz No. 3 coals merge into a single bed. The Monarch's normal thickness is probably between 5 and 25 feet. Recent studies suggest that the Monarch coal correlates with the Canyon coal to the east of Sheridan (Culbertson, et. al., 1979).

The U.S. Bureau of Mines estimated that there were originally 32 million tons of strippable reserve base of this coal, but these reserves include some Dietz No. 3 tonnage as well (Smith, et. al., 1972).

Currently, Big Horn Coal Company operates the only active mine on the Monarch coal. The Monarch coal is merged with the Dietz No. 3 over a large portion of Big Horn's strip mine which is located near Acme. Collectively, the two coals are over 44 feet thick in this mine.

A large number of Monarch analyses from various publications of the U.S. Bureau of Mines and U.S. Geological Survey are summarized below. Some of these published analyses, like the reserve estimates, probably include Dietz No. 3 coal.

As received basis	Range (203 analyses)	Average
Moisture (%)	14.5-26.0	21.5
Volatile Matter (%)	30.3-38.4	34.5
Fixed Carbon (%)	34.9-44.0	39.6
Ash (%)	3.1- 8.2	4.4
Sulfur (%)	0.3- 0.7	0.4
Btu/pound	9,000-10,410	9,600

Smith coal bed: This bed is particularly well developed in the

Spotted Horse Field and the western side of the Little Powder River Field. The bed is between 5 and 13 feet thick and is subbituminous. It is found near the top of the Fort Union Formation when it hasn't been cut out by the Wasatch-Fort Union unconformity (Figure 2).

In the southern part of the Spotted Horse Field, a local unnamed coal, which is 4.5-13 feet thick, underlies the Smith coal by 30 feet. There are an estimated 178 million strippable tons of the Smith coal bed and another 58.3 million strippable tons of the local coal in that area (Smith, et. al., 1972). Neither coal is mined at this time.

This Smith coal bed is not to be confused with the Canyon coal bed of the Gillette area which was miscorrelated with the Smith coal for many years. The Smith coal bed is stratigraphically higher in the Fort Union Formation than the Canyon bed (Figure 2).

A single core analysis of the Smith coal bed is given below.

As received basis	Core Analysis (U.S. Geological Survey, 1974)
Moisture (%)	31.8
Volatile Matter (%)	28.7
Fixed Carbon (%)	34.8
Ash (%)	4.7
Sulfur (%)	0.63
Btu/pound	7,991

Sussex Coal Field, "Lower coal bed": This "lower coal bed" in Basin No. 4 of the Sussex Field averages 11.8 feet thick, but reaches a maximum of 50 feet in places. A preliminary estimate of the strippable reserve base of this Fort Union Formation coal is 13.6 million tons (Smith, et. al., 1972). This coal is not mined at this time.

An analysis of the "lower bed" shows:

As received basis	One analysis (Smith, et. al., 1972)
Moisture (%)	23.5
Volatile Matter (%)	35.6
Fixed Carbon (%)	35.7
Ash (%)	5.2
Sulfur (%)	0.49
Btu/pound	9,160

Wyodak-Anderson coal bed: Outcrops show this thick coal is persistent, though extensively burned, on the eastern flank of the Powder River Basin, especially in the Gillette area. Recent geologic mapping by the U.S. Geological Survey now shows that this coal bed does not correlate with the stratigraphically higher Roland and Smith coals, as previously reported. The Wyodak-Anderson is actually the Anderson and Canyon coals coalesced into one (Denson and Keefer, 1974). In some areas the overlying Swartz and underlying Cook coals also coalesce with the Wyodak-Anderson coal (Kent and Munson, 1978).

This subbituminous coal is between 25 and 125 feet thick, and probably averages 70 feet in thickness. It commonly has an 8-inch parting 38 feet above its base, which marks the contact between the Anderson and Canyon coals.

The Wyodak-Anderson coal separates into the Anderson and Canyon coal beds to the west with the two beds each 10 to 65 feet in thickness. To the north, the Wyodak-Anderson splits into five or more beds varying from 5 to 31 feet in thickness and separated by 4 to 33 feet of claystone and shale. The coal bed also splits into the D bed (Anderson coal) and the E bed (Canyon coal) southward from Gillette (Figure 2).

The strippable reserve base of this Fort Union Formation coal is the largest for any single coal bed in Wyoming and perhaps even for any coal bed in the United States. These reserves are estimated at 19 billion tons (Smith, et. al., 1972). Since this estimate was made, strip mining has removed 107 million tons of these original strippable reserves. By the end of 1985, an estimated 600 million tons of the Wyodak-Anderson coal will have been strip mined from 9-11 large strip mines in Campbell County (Glass, 1980).

Amax Coal Company's Belle Ayr and Eagle Butte mines, Wyodak Resources' South Pit, Sunedco's Cordero mine, Carter's Caballo and Rawhide mines, Kerr-McGee's Clovis Point and Jacobs Ranch mines, Delzer's Fort Union mine, and Arco's Black Thunder mine are the only active strip mines on the Wyodak-Anderson coal bed. Kerr-McGee, Carter, Mobil, Gulf, Peabody, Cities Service, Nerco, Consol, Arco, and others have additional strip mines planned on that bed. Most of these mines will be 5-20 million tons per year mines, and will be located in Campbell County.

Fifty-nine analyses of the Wyodak-Anderson coal in the Gillette area are summarized below:

As received basis	Range (59 analyses)	Average
Moisture (%)	21.1-36.9	29.8
Volatile Matter (%)	26.5-35.5	30.7
Fixed Carbon (%)	29.6-41.4	33.5
Ash (%)	3.9-12.2	6.0
Sulfur (%)	0.2- 1.2	0.5
Btu/pound	7,420-9,600	8,224

WASATCH FORMATION

The Eocene Wasatch Formation, which is 1,000-2,000 feet thick, is another prolific coal-bearing formation rivaled in importance only by the Fort Union Formation. The Wasatch Formation crops out over much of the central portion of the Powder River Basin, and usually exhibits very shallow dips (less than 4 degrees).

The Wasatch Formation contains as many as eight thick, persistent coals (Figure 2). The thickest Wasatch coal bed occurs at Lake De Smet on the west side of the basin. There, the Healy coal locally exceeds 200 feet in thickness (Mapel, 1959). Although many Wasatch coals have been mapped and correlated for tens of miles along outcrop, these coals are thicker and more persistent in the western and central parts of the basin. Important Wasatch coals are discussed below:

Badger coal bed: This is a subbituminous coal best developed in the Glenrock Field. The coal occurs near the base of the Wasatch Formation, between the School and Felix coal beds (Denson, et. al., 1978).

The Badger coal is 17 to 20 feet in thickness and is normally 110-180 feet above the School bed. In 1972, the U.S. Bureau of Mines conservatively estimated that there were at least 9.5 million tons of strippable reserve base of this bed in Converse County (Smith, et. al., 1972). To date very little of this reserve has been mined.

The Badger coal is strip mined in Pacific Power and Light Company's Dave Johnston mine north of Glenrock, and then burned in the Dave Johnston Power plant at Glenrock. Five analyses from that mine show the following composition:

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

F coal bed: Although this Wasatch coal is persistent in portions of the Dry Cheyenne, Sussex, and Gillette fields in Converse County, it is not presently mined. Bed F has a maximum thickness of 11.6 feet, but averages only 7.5 feet (Wegemann, et. al., 1928).

The strippable reserve base of this bed is estimated at 179.5 million tons (Smith, et. al., 1972). There are no published analyses of this coal.

Felix coal bed: This is an important coal bed in the northern and eastern portions of the Powder River Basin. This Wasatch Formation coal is from 5-21 feet thick in the Spotted Horse Field in the north to as thick as 50 feet in the southern part of the Gillette Field. Partings are common and fairly persistent in places.

Smith, et. al. (1972), estimates the strippable reserve base of the Felix coal is 480.7 million tons in the Spotted Horse Field. The coal is subbituminous in rank, and is not currently mined. The Lawrence Livermore Laboratories, however, have conducted in situ gasification experiments in this coal south of Gillette.

Analyses of 42 core samples are summarized below:

As received basis	Range (42 Cores: U.S. Geological Survey, 1973; 1974)	Average
Moisture (%)	17.8-33.5	28.0
Volatile Matter (%)	29.1-36.4	31.7
Fixed Carbon (%)	28.4-39.4	32.5
Ash (%)	4.5-14.9	7.8
Sulfur (%)	0.32-3.26	0.89
Btu/pound	7,180-9,535	8,053

Healy coal bed: The Healy coal is locally the thickest coal bed in Wyoming or the United States for that matter. In the Buffalo Field of Johnson County, the Healy is 5-25 feet thick at outcrop, but is reportedly as much as 250 feet thick in some drill hole descriptions (Obernyer, 1978; Mapel, 1959). Upper portions of this Wasatch coal bed, however, are frequently burned over much of the Buffalo Field.

Tentatively, the Healy bed of the Buffalo Field is correlated with the Ulm No. 2 coal in other fields to the north and east of that area (Culbertson and Mapel, 1976). Obernyer (1978), however, suggests that the thick Healy coal at Lake De Smet represents the coalescing of five major coal beds in response to basin-margin faulting active in Eocene time (growth faulting). From oldest to youngest, these coals are the Ucross, Murray, Cameron, Healy, and Walters. If Obernyer's interpretation is correct, the thick Healy at Lake De Smet might better be called the Lake De Smet coal bed as he proposed.

The strippable reserve base of the Healy coal approximates one billion tons according to Smith, et. al. (1972). Most of these reserves are in the Lake De Smet area or southeast of there. The coal is not currently mined. Fifteen analyses of this subbituminous coal show the following range in quality (none of these analyses represent more than a portion of the total bed):

As received basis	Range (5 to 15 analyses)[1]	Average (5 analyses)
Moisture (%)	22.6-30.7	28.5
Volatile Matter (%)	28.6-31.9	30.0
Fixed Carbon (%)	32.8-34.8	33.9
Ash (%)	5.1-22.1	7.6
Sulfur (%)	0.26-3.00	0.6
Btu/pound	6,480-8,270	7,884

[1] Ten of these analyses did not include volatile matter and fixed carbon.

Lake De Smet coal bed: See Healy coal bed.

PK, Ulm 2, and Ulm 1 coal beds: These three Wasatch Formation coals are at least persistent in the central part of Sheridan County where they are 4-52 feet thick.

The PK coal bed, which locally splits into at least three benches, averages 4-18 feet thick and correlates with the Ucross bed in Johnson County (Culbertson and Mapel, 1976). The Ulm 2, which occurs about 300 feet above the PK coal zone, varies from 7-30 feet in thickness. Culbertson and Mapel (1976) equate this coal bed with the thick Healy coal of the Lake De Smet deposit in Johnson County (Figure 2). The Ulm 1 lies 50-200 feet above the Ulm 2 and is believed to be correlative with the Walters coal bed of Johnson County (Culbertson and Mapel, 1976). The Ulm 1, in Johnson and Sheridan counties, is 14-52 feet thick where it still remains. Its thickest expression, however, includes several thick shale partings.

A strippable reserve base of 1.8 billion tons has been estimated for these three coals in the Wyarno-Verona strippable deposit of central Sheridan County (Culbertson and Mapel, 1976). This potentially strippable deposit contains an estimated 200 million tons of the PK coal, 990 million tons of the Ulm 2 coal, 543 million tons of the Ulm 1 coal, and 67 million tons of other thinner and less persistent Wasatch coals. All the coals used in this estimate, however, were greater than 10 feet thick and under less than 200 feet of cover.

Although none of these coals is currently mined, at least one company has applied for a mining permit within the strippable deposit.

Analyses of these coals are few, and many were performed on badly weathered samples. Excluding all analyses where the heat value was below 6,500 Btu/pound, analyses of the Ulm 1, Ulm 2, and PK beds are averaged below:

As received basis	Range (5 analyses)	Average
Moisture (%)	30.7-27.4	30.2
Volatile Matter (%)	28.9-33.2	31.2
Fixed Carbon (%)	31.0-38.4	34.3
Ash (%)	2.3- 8.8	4.3
Sulfur (%)	0.3- 3.2	1.5
Btu/pound	7,640-8,320	8,000

School coal bed: The School coal or School House coal as it is sometimes called, is 110 to 180 feet below the Badger coal in the Glenrock Field. It is subbituminous in rank and occurs near the base of the Wasatch Formation between the Anderson and Badger beds (Denson, et. al., 1978) (Figure 2).

The coal is between 22 feet and 38 feet in thickness, but averages 35 feet. The quality of the bed deteriorates to the south due to shaly partings. Northward its quality remains good, but the bed thins.

In 1972, the U.S. Bureau of Mines estimated that there were at least 126.2 million tons of strippable reserve base of this coal in Converse County (Smith, et. al., 1972).

Pacific Power and Light Company has been mining this coal since

1958 at their Dave Johnston strip mine north of Glenrock. Three analyses from their mine show the following:

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

Ulm No. 1 coal bed: See discussion under PK coal bed.

Ulm No. 2 coal bed: See discussions under the PK coal bed and the Healy coal bed.

Walters coal bed: See discussions under the PK coal bed and the Healy coal bed.

PRODUCTION HISTORY AND FORECAST

Recorded coal mining in the Powder River Coal Basin dates back to the 1880's in Converse, Johnson, and Sheridan counties, to 1909 in Campbell County, and to 1933 in Natrona County (Table 1). There has never been any recorded production from the Powder River Basin portions of Crook, Niobrara, and Weston counties.

Traditionally, the largest coal producing county in the basin was Sheridan County, which produced in excess of 70 million tons since 1889.

Most of this tonnage came from underground mines, but over 25 million tons since 1944 came from strip mines in the Acme area. In recent years, however, Campbell County has surpassed Sheridan County with cumulative production in excess of 118.5 million tons (Table 1). Nearly all Campbell County's production has come from strip mining which dates back to 1925 (Breckenridge, et. al., 1975). Similarly, production from Converse County has almost all come from strip mines, dating back to 1958 (Lane, et. al., 1972). Less than two million tons of the cumulative coal production from Campbell and Converse counties came from underground coal mines (Glass, 1976).

Coal production from the Powder River Basin was over 48 million tons in 1979 (Figure 3). Production forecasts for the Powder River Basin show nothing but large strip mines with estimated annual production at 59.4 million tons in 1980, 119.6 million tons by 1985, and perhaps as much as 133.2 million tons by 1990. Nearly all this forecast tonnage will be burned in coal-fired power plants in various Rocky Mountain, midcontinent, and southcentral States (Figure 4). A small percentage of the future production through 1985 will be used by manufacturing industries and possibly at least one coal gasification plant (Glass, 1980). More than 90 per cent of this projected tonnage, incidentally, will come from Campbell County. The guidebook's cover depicts the active and proposed coal activities in the Powder River Basin (Hausel, et. al., 1979). Only Sheridan, Campbell, and Converse counties have active coal mines at this time.

Table 1. Reported coal production from the Powder River Coal Basin to January 1, 1980 (Millions of tons)[1].

County	Production	Estimated Mining Losses	Total Production and Mining Losses
Campbell	118.50	13.93	132.43
Converse	41.55	8.04	49.59
Crook	0.00[2]	0.00	0.00
Johnson	0.46	0.46	0.92
Natrona	0.03	0.03	0.06
Niobrara	0.00[2]	0.00	0.00
Sheridan	70.18	48.58	118.76
Weston	0.00[2]	0.00	0.00
Total for Powder River Basin	230.72	71.04	301.76[3]
Grand total for Wyoming	726.31	448.19	1,174.50[3]

[1]Sources: U.S. Geological Survey; U.S. Bureau of Mines; State Mine Inspectors

[2]No production reported from the Powder River Basin

[3]Includes production and mining losses from both strip mines and underground mines.

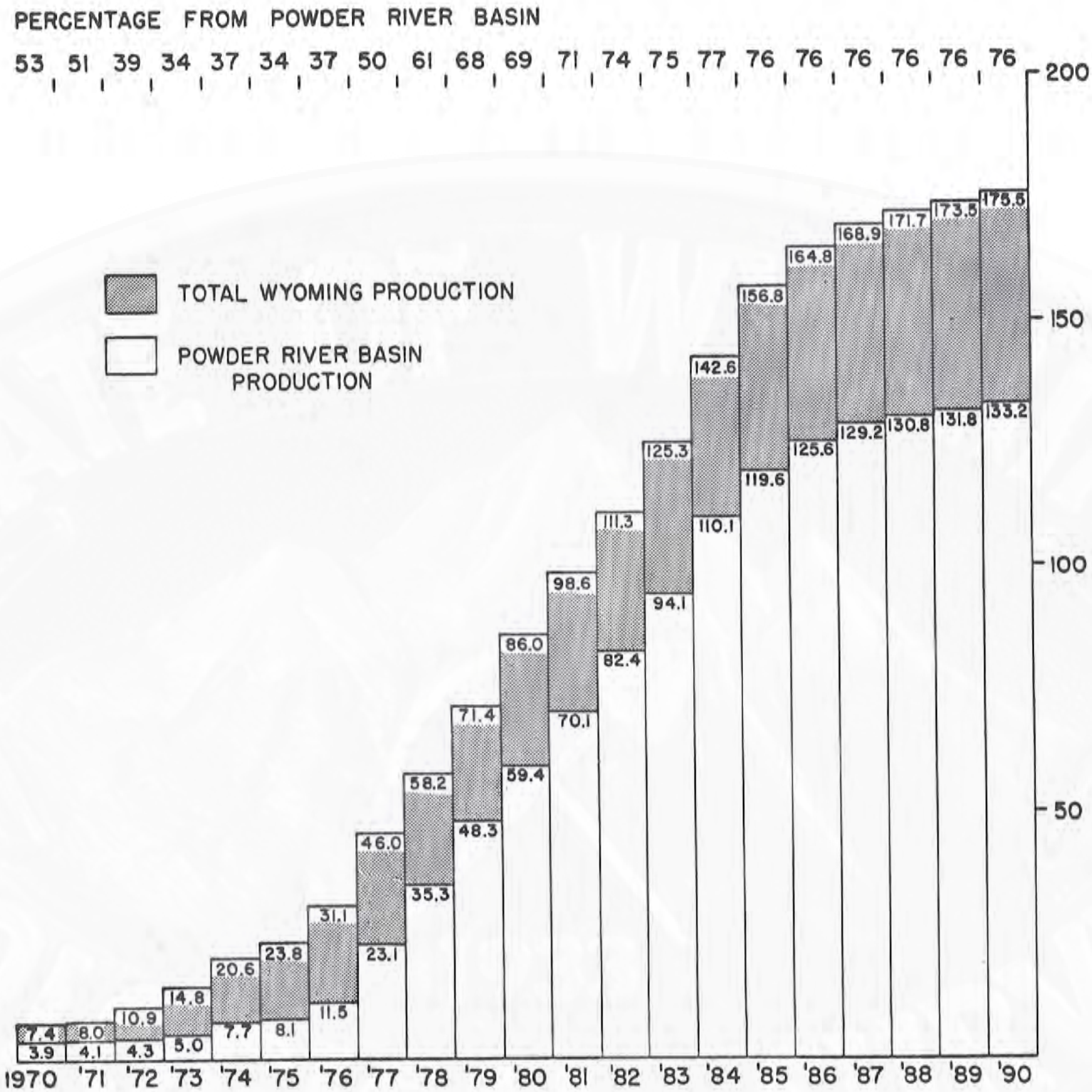

Figure 3. Coal production by year (in millions of tons).

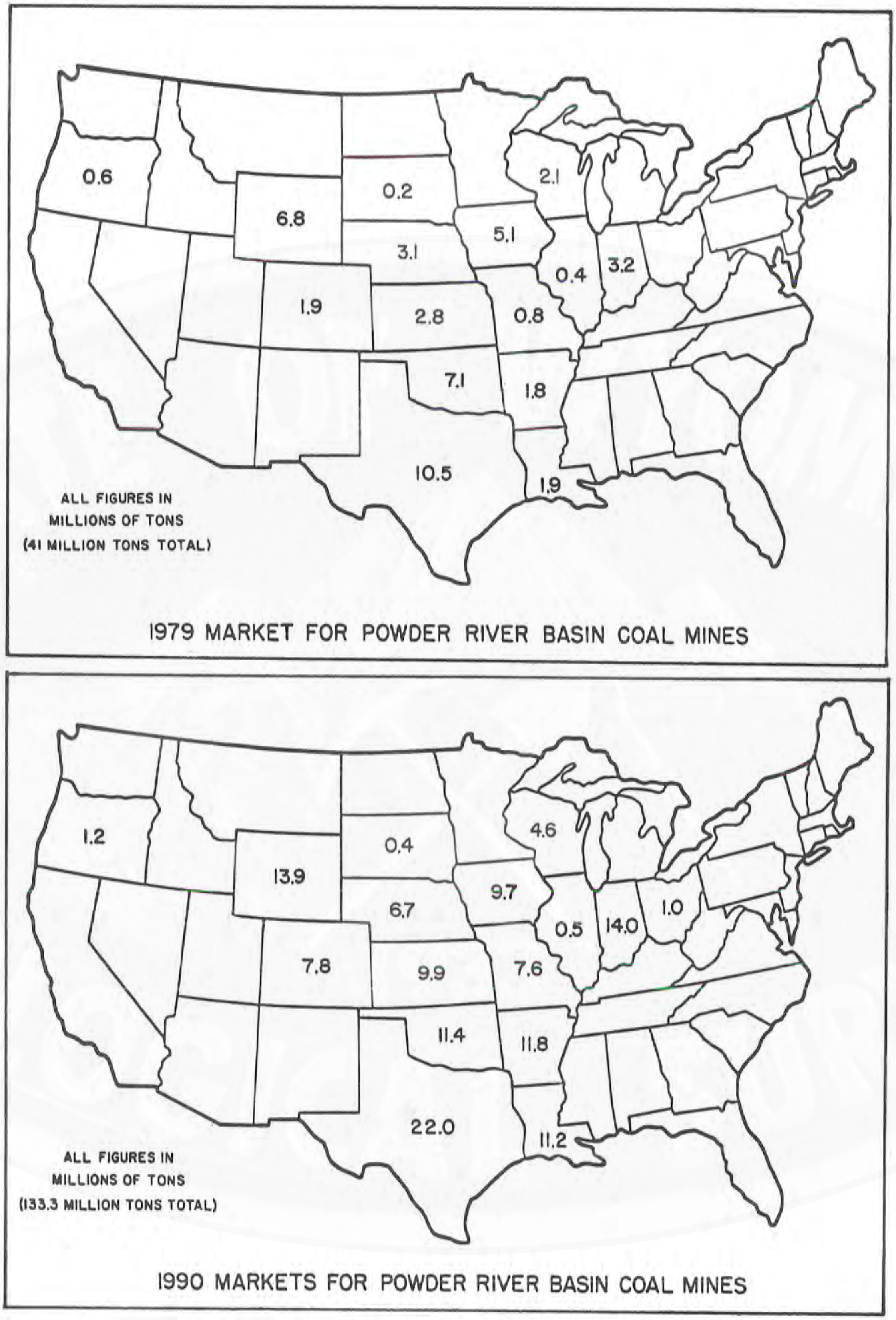

Figure 4. 1979 and projected 1990 markets for Powder River Basin coal (in millions of tons).

COAL RESOURCES AND RESERVES

Since Berryhill, et. al.'s (1950) original resource estimates, the U.S. Geological Survey has estimated another 500 billion tons of undiscovered resources underlie the Powder River Basin (Figure 5). These hypothetical and speculative resources, however, will soon move into the identified category as numerous maps and reports of the U.S. Geological Survey are published.

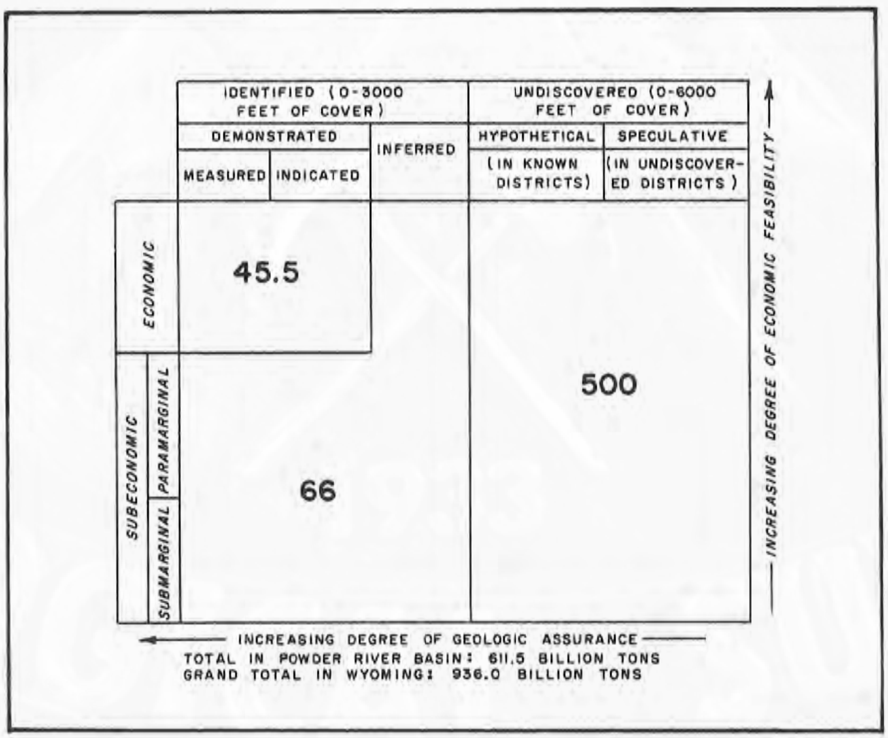

Figure 5. Remaining original coal resources in the Powder River Coal Basin in millions of tons to January 1, 1980 (modified from Hamilton, et. al., 1975, and Averitt, 1975).

All these estimated resources are for subbituminous coal since there are no resource estimates of the lignite in the northeastern corner of the basin.

The Powder River Basin's remaining identified resources are estimated at 110 billion tons (modified from Berryhill, et. al., 1950). This figure is more than 80 per cent of the total remaining identified coal resources in Wyoming. Additionally, more than 63 per cent of the Powder River Basin's remaining resources are located in Campbell County (Table 2). All these identified resources include coals 2.5 feet and thicker, in measured, indicated, and inferred categories between 0-3000 feet of cover.

Table 2. Estimate of remaining identified coal resources in the Powder River Coal Basin under less than 3000 feet of cover (modified after Berryhill, et. al., 1950).

County	Subbituminous Resources in Millions of Tons
Campbell	68,901.4
Converse	4,104.4
Crook	8.6
Johnson	12,234.7
Natrona	25.6
Niobrara	14.3
Sheridan	24,342.7
Weston	285.4
Total for Powder River Basin	109,917.1
Grand total for Wyoming	136,000.0

An estimated 45.5 billion tons of reserve base remain in the Powder River Coal Basin as of January 1, 1980. Of this reserve base, 22.6 billion tons are recoverable by underground mining methods. The other 22.9 billion tons are strippable. Collectively, these reserves are equivalent to 81 percent of the known remaining coal reserve base in Wyoming, which is estimated at 55.9 billion tons. It should also be mentioned that these reserve figures are very conservative and may be off by nearly an order of magnitude.

Table 3 shows the remaining strippable reserve base as of January 1, 1980. None of the underground reserve base has been mined since the Bureau of Mines made their estimate (Hamilton, et. al., 1975).

Table 3. Remaining strippable subbituminous coal reserves in the Powder River Coal Basin to January 1, 1980 (modified from Smith, et. al., 1972).

Coal-Bearing Area	Strippable Deposit	Coal Bed(s) (Average thickness in feet)	Acreage Estimate	Original Estimated Reserves to Jan. 1, 1979	Production and Mining Losses Since Jan. 1, 1969	Remaining Strippable Reserves to Jan. 1, 1980
Powder River Coal Basin	Acme-Kleenburn	Monarch and Dietz No. 3 (23')	2,029.0	39,300,000	19,250,000	20,050,000
	Clear Creek	Canyon (11.2')	9,337.6	184,900,000	--	184,900,000
	Dave Johnston	School (38')	2,418.0	126,200,000	35,080,000	91,120,000
		Badger (16')	390.0	9,500,000		
	Dry Cheyenne	F (7.6')	13,260.8	179,500,000	--	179,500,000
	Lake De Smet	Healy (163')	3,520.0	1,000,000,000	--	1,000,000,000
	Spotted Horse	Felix (12.5')		480,700,000	--	480,700,000
		Smith (10.0')		178,000,000	--	178,000,000
		Local (10.0')	36,736.0	58,300,000	--	58,300,000
	Sussex	Fort Union Fm., lowermost coal (11.8')	651.0	13,600,000	--	13,600,000
	Wyarno-Verona*	PK (11')		200,000,000	--	200,000,000
		Ulm 2 (20')		990,000,000	--	990,000,000
		Ulm 1 (30')		543,000,000	--	543,000,000
		Other Wasatch coals (10'+)	3,000.0	67,000,000	--	67,000,000
	Wyodak	Wyodak-Anderson (71'): Anderson (D) and Canyon (E)	155,282.0	19,000,000,000	125,200,000	18,874,800,000
		Total for Powder River Coal Basin:	226,624.4	23,070,000,000	179,530,000[1]	22,890,470,000
		Grand total for Wyoming:	304,372.4	26,725,260,000	340,880,000[1]	26,384,380,000

[1]Only includes strip mine production and mining losses.
*New reserve base from Culbertson and Mapel (1976).

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BRIEF SURVEY OF CHEMICAL AND PETROGRAPHIC CHARACTERISTICS OF POWDER RIVER BASIN COALS

by

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INTRODUCTION

It is a great misfortune that almost none of the coal from the Powder River Basin has been carefully analyzed petrographically. The great accessibility of the eastern Wyoming coals, and the tremendous volume of coal which has been located there have encouraged boom-town-style development of the coal deposits. It is also the case, however, that we really are not sure just what it is we are mining. The major oil companies may have made detailed analyses of coal composition, especially where the companies are contemplating using the coal for gasification or liquefaction. Those data are not readily available, however, and as a consequence it is nearly impossible to provide a comprehensive description of any Powder River Basin coal. By comprehensive I mean a description which includes proximate, ultimate, and petrographic analyses.

The science of coal petrology is a rather new discipline on this continent. The newness of this approach to coal characterization means that most people are unfamiliar with its application, and coal mining companies and coal users are not aware of petrology's great utility in optimizing coal use. Petrographic, or microcomponent analyses of coal, when used in conjunction with proximate and ultimate analyses and mechanical tests, provide a complete set of information which is necessary for proper coal utilization.

AN INTRODUCTION TO COAL PETROLOGY

A sharp distinction lies between the classical methods of characterizing coal (i.e. proximate and mechanical analyses) and the petrographic characterization. Ash values, moisture content, alkaline oxide concentrations, grindability, and other properties are determined routinely by nearly all coal producers. These parameters control the marketability of coal, and, 100 years ago, when coal was used primarily for boiler fuel, or to produce water gas or beehive coke, the proximate and mechanical property analysis provided sufficient information.

Technological advancements in steel making, and improvement of detection techniques allowed for refinement of coal analyses in the mid-twentieth century. Still, proximate, ultimate, and mechanical property determinations remained the only significant analyses until about 25 years ago. At that time people began investigating the microscopic composition of the organic fraction of coal in order to determine the relationship between composition and coking behavior. The relationship between proportions of microscopic organic coal components and coke quality was recognized, and the science of coal petrology was established.

Petrographic coal analyses have recently been applied to fields outside the steel-making industry. Major oil companies have been especially interested in using coal petrography to identify potential gasifier and liquefier feed stocks, and have used petrographic techniques (vitrinite reflectance) to assess potential oil producing formations. It seems now that coal petrology is destined to grow at an increasing rate as it is used more intensively by the energy companies.

All coals are composed of the accumulated debris of plants, and, rarely, may include animal remains. While all coals are derived from plants and are superficially similar (coal is either brown or black and is combustible), that is where compositional similarities end. Coal seams are really as variable as were the plant communities which produced them. Plant communities are living, changing collections of constantly fluctuating organisms that produce organic remains which are quite dissimilar from place to place. If one looks carefully at lumps of coal from a mine, these dissimilarities are visible megascopically, but also exist down to a remarkably small scale. The low rank coals from the Powder River Basin are especially interesting in this regard because original plant structures are nicely preserved. Thus, one lump of coal consists entirely of the carbonized portion of a tree trunk, while another lump is composed of finely divided, perhaps laminated pieces of many plants. It is common, for example, to find individual, compressed branches or roots mixed with an apparently amorphous ground mass of very small particles. Powder River Basin coals frequently contain minute amber colored pieces of resin in such a ground mass. Each of these coal constituents, whether it be a one kilogram chunk of wood, or a grain of pollen from an ancient cypress tree, has its peculiar appearance, origin, and chemical composition. Coal petrology identifies and quantifies these various particles. One may describe a piece of coal according to its appearance in hand specimen, i.e. megascopically. Schopf (1960) detailed the proper methodology for doing so. Megascopic descriptions are severely limited, however, insofar as they are highly subjective and depend upon one's ability to distinguish bright (vitrainic or clarainic) from dull (durainic or fusainic) coal. It is also true that terms which apply to the megascopic description of, for example, an Upper Carboniferous coal from the Dunkard Basin in Ohio, have little relevance to Tertiary coals from the Powder River Basin of Wyoming. Bright, i.e. vitrainic coals, don't exist in the Powder River Basin, even though the term vitrainic implies derivation from woody tissues. The microscopic description of Powder River Basin coals is the only logical method of qualifying them petrologically.

Microscopic organic coal constituents are referred to as macerals. Four major suites of macerals are distinguished according to appearance. A maceral's appearance may be a consequence of its original function on or within a plant, but may have been determined as well by diagenetic processes which have resulted in the particles being coalified. Pieces of wood and pollen grains preserve much of their original form, which belies their function, whereas corpohuminite, for example, is a product of diagenetic alteration of tissues.

HUMINITE MACERALS

Huminites (known as vitrinites in higher rank coals) have diverse origins. They include the woody material and corpohuminite mentioned above and are among the most visible of Powder River Basin coal components. Huminite is derived principally from woody tissues. Oftentimes the structure of the woody tissues remains visible through a microscope. If a piece of huminite retains the cellular structure, it is referred to as textinite in these low rank coals. Huminite which displays no cellular structure is termed ulminite. (See Figure 1 for a schematic representation of these macerals). Almost any combination of textinite and ulminite may be expected in Powder River Basin coals. The relative proportions of structured and unstructured materials depends upon a great variety of factors, but is most certainly dependent upon the nature of the coal-forming vegetation. Large plants which produced massive woody stems would

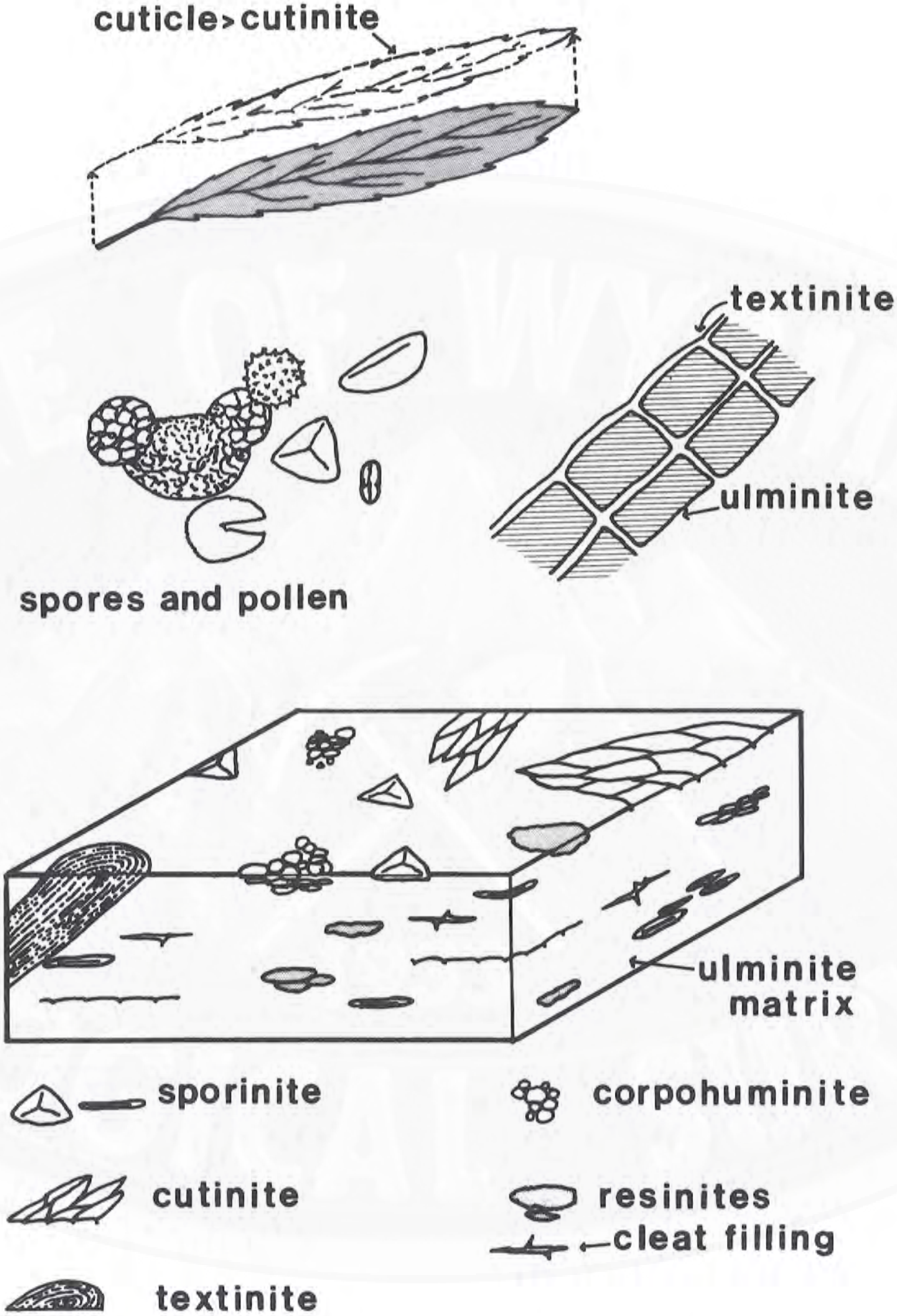

Figure 1. Coal macerals in low rank coals of the Powder River Basin, Wyoming.

obviously have produced textinite-rich coals. Plant communities which produced modest amounts of woody debris, and plants whose woody tissues were readily broken down by bacterial decay would have produced ulminite-rich coals. Generally speaking, textinite is an "immobile" coal component, i.e., it exists as distinct, structured clasts which may be compressed upon coalification, but which otherwise remain in-place during diagenesis. Ulminite, on the other hand, exists initially as mobile organic gels which may migrate fairly easily in the deposit during coalification. Ulminite, thus, is found occupying cell lumens in textinite and, more often, exists as an interstitial filling among other macerals. Ulminite is evidently the product of a series of chemical reactions which may reduce almost any plant tissue to the gel state.

THE LIPTINITE SUITE

The name liptinite suggests the composition of many of these macerals. They tend to be lipid-like, derived from an assortment of naturally occurring waxes, resins, latex, etc. Pollen, spores, and certain types of algae are very important members of this suite. Liptinites contrast markedly with huminite because individual liptinite particles are typically microscopic, as with pollen grains, fragments of resin, or minute algal colonies. Whereas textinite may compose large portions of an individual seam (the lower part of the Canyon seam, for example), liptinites are seldom the dominant coal-former. Rare occurrences of concentrated liptinites make up boghead and cannel coals. Liptinites in almost all coals are found as minute clasts occupying positions among larger coal macerals, or are found cemented in dispersed masses within an ulminite matrix.

The most interesting liptinites, from a paleoecological point of view, are pollen, spores, and algae; these are referred to as exinite in the first two cases, and alginite in the latter case. These reveal the composition of the coal-forming vegetation and provide information which is critical to understanding the environment of peat accumulation.

The most visible of the liptinites in Powder River Basin coals are the resins, or resinite. Golden accumulations of amber appear as small blebs within the coal, or are found occupying fractures (cleat) within the seams.

The fact that resinite may be found as cleat fillings points up this maceral's mobility. The resins in some seams have accumulated along migration pathways. Other liptinites also seem to be mobile, though they are invisible without a microscope. These mobile macerals are exudatinite, bituminite, and fluorinite (Stach, 1975; Spackman et. al., 1976).

THE INERTINITE SUITE

One might guess that the inertinites are inert. This term is not entirely appropriate because it refers to coal macerals which are non-reactive in a coke oven. Inertinite is not really inert under all environmental conditions. All inertinites are combustible in a boiler furnace, for example.

The most common, most easily visible inertinite is charcoal, otherwise called fusinite. Naturally-produced charcoal is common in coal. It typically occurs as dispersed fragments in virtually every sample, but also appears as thick lenses or even beds. Fusinite is brittle, friable, and sooty, and is one of the main causes for coal being so "dirty". Insofar as fires are common to modern swamps and marshes, it is likely that most fusinite formed as a result of fires. Alternate ideas exist, however, which suggest a diagenetic origin for some charcoal. Other inertinites (micrinite, macrinite, sclerotinite) are volumetrically much less important than fusinite, at least in most North American coals.

As mentioned earlier, the various macerals are distinguished by their appearances under a microscope. Transmitted light (using thin sections) is seldom used, though macerals' appearance in transmitted light was the basis for the first descriptions of coal components. Thin sections of coal are extremely difficult to make, and, in the case of the low rank western coals, thin sections are practically impossible to make. Thin sections do reveal important color differences in macerals, however. The huminite macerals are usually red or orange, the liptinites are typically yellow, and inertinites are opaque. Aside from producing rather pleasing color schemes, however, thin sections of coal are not particularly informative unless one is interested in the anatomy of plants. Certain North Dakota lignites, for example, were silicified shortly after coalification had begun, and thin sections from the coals are of great paleobotanical interest. Rather than using thin sections, coal petrography is routinely conducted using pellets of coal which has been crushed to -20 mesh. Incident light is used for pellet analyses. One must learn to distinguish among shades of grey to distinguish coal macerals in incident light. Huminites are grey, liptinites are dark grey or nearly black, and inertinites are light grey to silvery white. One must rely upon morphology as well as color, however, so the task is not as difficult as it might sound. Textinite is rather easily distinguished from ulminite because of the presence of cell walls in the former. There are certain forms of ulminite (such as humodetrinite or desmocollenite) which may be confusing, but they need not concern us here. Spores and pollen are always discrete bodies which are typically immersed in huminite, so the differences in reflectivity (i.e. color) are clear. It is also true that spores and pollen appear as ovals flattened in the plane of bedding, and this shape is distinctive. Plant cuticles typically display a reticulate or serrate pattern, depending upon whether they are viewed in bedding plane section, or perpendicular to bedding, respectively. Finally, resins are merely blobs or crack fillings and are best distinguished if one can expose them to blue light, whereupon they fluoresce yellow or orange (rarely green).

The other mobile liptinites (bituminite, exudatinite, fluorinite) are scarcely visible in incident white light, and can be confidently identified only with blue light.

It seems unlikely that anyone would have difficulty identifying fusinite in incident light, but it does happen. Aside from the bright reflectance which fusinite displays, it usually shows distinct cellular structures. Fusinite is mechanically resistant to pressures which crush and deform other macerals, thus allowing the preservation of the original cell configuration in fusinite. Much more detailed descriptions of macerals are available in Stach (1975), but I think the above discussion should suffice for now.

PETROGRAPHIC CHARACTERISTICS OF SOME POWDER RIVER BASIN COALS

Only 29 reasonably complete analyses of Powder River Basin coals seem to be available to date. The analyses were performed on samples within Penn State University's Coal Data Base collection, and include the following sample numbers and coals:

PSOC 100	Wyodak Seam
PSOC 101	Wyodak Seam
PSOC 64A, B, &C	Monarch Seam
PSOC 241	Monarch Seam
PSOC 099	School Seam
PSOC 065	Dietz Seam
PSOC 242	Dietz Seam
PSOC 525	Dietz #3 Seam
PSOC 527	Dietz #3 Seam
PSOC 528	Dietz #3 Seam
PSOC 529	Dietz #3 Seam
PSOC 530	Dietz #3 Seam
PSOC 558	Cook Seam
PSOC 559	Cook Seam
PSOC 560	Cook Seam
PSOC 571	Wall Seam
PSOC 572	Wall Seam
PSOC 573	Wall Seam
PSOC 570	Wall rider coal
PSOC 561-569	Unspecified seam, samples from a core taken near Recluse, Campbell County, Wyoming, probably Wyodak

All these samples have been analyzed petrographically, but the data for only 24 are compared here. This is due to some differences in the ways that data are presented in Penn State's Data Base.

Figure 2 illustrates four properties of each of the 24 samples. These are: hydrogen/carbon ratios, and liptinite, huminite, and inertinite compositions on a dry, weight-percent basis. The significance of the H/C ratio will be discussed shortly. In Figure 2, these coals

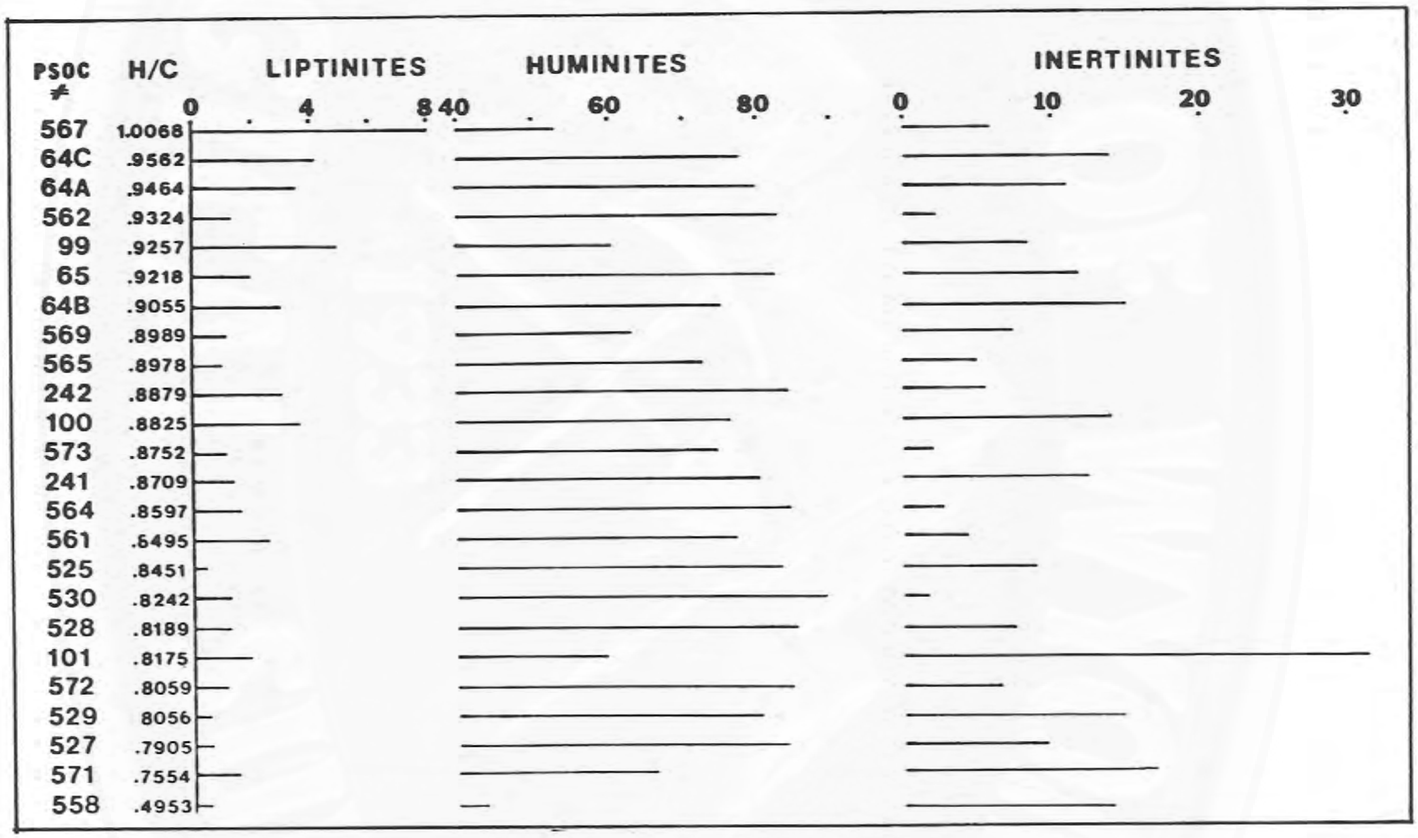

Figure 2. Comparison of hydrogen/carbon ratios and liptinite, huminite, and inertinite compositions (dry, weight percent basis) of Powder River Basin coal samples.

are ranked from top to bottom as the H/C ratio decreases.

The maceral composition of the Powder River Basin coals is reasonably consistent. Given the ranking I have presented, the huminite and inertinite contents show no particular trends. Huminites comprise anywhere from 49.0-85.6% of the coals, and inertinites range from 1.7-31.4%. The 31.4% figure comes from a Wyodak seam sample, and represents one of the Wyodak's fusinite-enriched zones. This sample would actually be suitable as a fusinite lithotype, and gives a misleading appearance to the range one might expect for inertinites in Powder River Basin coals. A more realistic range would be 1.7-14.9% inerts. Liptinites vary from 0.4-8.0% in the 24 Powder River Basin samples.

Comparison of compositions of coals from different coal provinces are often made. While these may be interesting, one must bear in mind that great variability may be found among coals from a single province. Those differences are amplified when coals of various ages from different provinces are compared. This is especially true of "western coals" whose ranks and compositions are so variable. Everything from Eocene lignites to high-volatile A bituminous Cretaceous coals are found in the western United States. Thus, an average composition of western coals is as meaningless as an average sulfur value for North American coals. In spite of that, some data are presented here for comparison.

Wadell, et. al., (1978) present data for coals from two Western provinces - the Northern Great Plains, and the Rocky Mountains. Eleven Northern Great Plains coals have the following maceral compositions:

vitrinites (huminites)	67.2 - 90.6%
inertinites	5.6 - 22.9%
liptinites	1.8 - 11.7%

Some of these Northern Great Plains coals are included in the 24 Powder River Basin samples from Figure 2 so it is not surprising that the ranges of maceral compositions for the two sample suites are coincident. Wadell, et. al., (1978) also examined 19 Rocky Mountain Province coals. Maceral compositions are as follows:

vitrinites	70.2 - 88.8%
inertinites	6.5 - 26.7%
liptinites	1.3 - 11.9%

The vitrinite suite tends overall to be better represented in the Rocky Mountain coals than in the Northern Great Plains and Powder River Basin deposits. Many of the Rocky Mountain coals are of Cretaceous age, and the vegetation from which the coals were derived was certainly different in many respects from the Early Tertiary vegetation of the Northern Great Plains and Powder River Basin swamps. That fact, and differences in sedimentary environments and geochemical conditions could easily explain the differences in vitrinite contents. At this point mention should also be made that many of the Cretaceous coals are of high enough rank that they do contain vitrinite, as opposed to the Northern Great Plains-Powder River Basin coals which are composed of the lower-rank equivalent huminites.

Inertinites in Powder River Basin coals are as abundant as they are in any coal. As fusinite is the most common inert in North American coals, this indicates the important role which fires have always had in swamp/marsh ecosystems. Fusinite is variably abundant in all coal seams (as in the Wyodak seam, PSOC samples 100 and 101). Fires have probably always been seasonally controlled in wetlands, and one should expect fusinite to occur in greater and lesser amounts throughout any coal seam.

Liptinites in Powder River Basin, Northern Great Plains, and Rocky Mountain coals show similar ranges of abundance. This is most likely due to the fact that throughout the Cretaceous and Early Tertiary, swamps were dominated by conifers. Cypress and Sequoia and their allies, especially, produced pollen and resins in fairly consistent measure throughout those plants' dominance of swamp floras. The evolutionarily conservative nature of conifer foliage should have led to characteristic amounts of waxy leaf cuticles incorporated in the deposits as well. The one liptinite which would be expected to fluctuate most greatly in its abundance is alginite. This maceral is derived solely from algae. Alginite's presence is, or was controlled by short-term habitat changes, such as variable water depth, sunlight, temperature, etc. Short-term influences would explain why some layers of coal seams are so enriched in alginite even though those layers are areally small. As far as I know, alginite is not an important maceral in any of the Northern Great Plains-Powder River Basin coals. There is one Cretaceous coal, the King Cannel of Utah, which contains an amazing quantity of alginite or alginite-related macerals.

Comparison of Powder River Basin coals with Carboniferous seams from the Eastern Province reveals greater differences in compositions. Wadell, et. al., (1978) list 54 Eastern bituminous coals of Carboniferous age. Maceral compositions are as follows:

vitrinites	46.2 - 92.5%
inertinites	7.4 - 36.1%
liptinites	0.0 - 33.6%

The most conspicuous difference between Western coals in general and Eastern Province deposits is in the quantity of liptinites. Western coals average 3.9% liptinites while the Carboniferous deposits average 7.2%. The difference probably lies in the fact that Carboniferous plants produced copious amounts of spores, thus placing many liptinite analyses at 11-15%.

UTILIZATION OF POWDER RIVER BASIN COALS

The more than 55 million tons of Powder River Basin coals that are currently mined every year are all destined for boilers. Underground gasification pilot projects at Hoe Creek and Rocky Hill, south of Gillette, consume a minute quantity of coal, but the rest of the coal is used for electrical generation.

The current world petroleum situation has brought the application of "novel" coal uses closer to necessity. One commonly hears about the great potential for coal liquefaction and gasification in the Powder River Basin. A large percentage of the tremendous reserves which the major oil companies own in the Powder River Basin are probably intended for coal conversion, but a few obstacles remain in the way of developing the coals for that use. The availability of water in the Powder River Basin will constrain all industrial uses. Another problem is that gasification and liquefaction technologies are 25 years behind in their development. It should not be long, though, before a few of the currently experimental processes will be shown to be economically feasible.

Once those processes are available on a commercial scale, and after the "refineries" are built, the business of coal petrochemical production can begin in earnest. All of that will take place quite some time in the future. For the present, our task is to identify those Powder River Basin coals which will perform the best in the liquefaction/gasification chambers. Those determinations can be made chemically or petrographically. The interface of the two techniques is briefly explained below.

"From a chemical viewpoint, the principal differences between coal and petroleum are ultimately all due to the much lower H/C ratio of coal (~ 0.7 as against >1.2 for petroleum); and it is therefore possible to transform coal into liquid hydrocarbons by direct hydrogen addition as well as by indirect hydrogenation (i.e. gasification)." (Berkowitz, 1979). The various gasification and liquefaction processes all have in common the fact that a hydrogen-rich product is desirable. Whether one is considering the HYGAS process or the SRC-II process, it is important to maintain the proper level of hydrogen in the system so that optimum coal conversion will take place and provide a product with the best fuel or petrochemical characteristics.

Hydrogen for hydrogenation reactions can come from various sources. Hydrogen gas is used in the HYGAS process, while hydrogen "donor" liquids are used in liquefaction processes. Hydrogen and hydrogen-donor solvents are expensive and can be dangerous to use. The third source of hydrogen is the coal itself. Coal is abundant, inexpensive, and safe to use, so it displays certain advantages over the other hydrogen sources. The hydrogen in coal is not there simply for the asking, but is bound in certain hydrogen-rich compounds. Once it is liberated from those compounds, hydrogen is available as a reactant for further hydrogenation, or it may be removed from the system in the form of fuel or as a petrochemical component.

Economizing coal conversion processes will include using coals which themselves will provide the greatest possible amount of hydrogen to the conversion reactions. Hydrogen gas and hydrogen-donor liquids will still have to be used to initiate and sustain most of the processes, but the most economical quantity of those reactants can be determined ahead of time if one knows how much hydrogen the coal itself contains. The volatile, hydrogen-bearing macerals are vitrinites (huminites) and liptinites. Figure 3 illustrates the relative abundances of hydrogen and carbon in bituminous coal macerals on a dry, ash-free basis (daf). It is readily apparent that liptinites contain the greatest quantity of hydrogen for a given carbon content. The high hydrogen-to-carbon ratio in liptinites is further expressed in Figure 4 which illustrates the cumulative weight loss, or devolatilization of the three maceral suites as they are heated. Liptinites register the greatest weight loss because they contain the most potentially-volatile, hydrogen-rich compounds.

The amount of hydrogen available in a coal is frequently expressed as its hydrogen/carbon ratio, or H/C. The higher the H/C ratio, the more hydrogen is available. Low rank coals generally have higher H/C ratios than high rank coals because hydrogen-bearing macerals devolatilize upon metamorphism. Hydrogen is removed from the originally complex liptinitic compounds and accumulates within seams as methane (CH_4) and other hydrocarbons.

Rank is not the only factor which determines hydrogen contents of

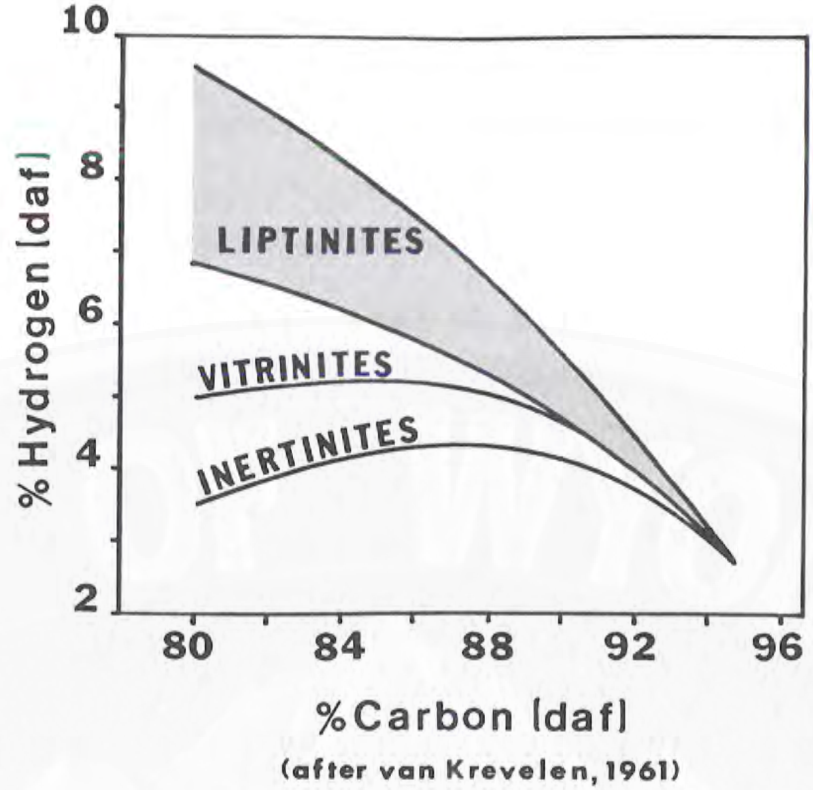

Figure 3. Relative abundances of hydrogen and carbon in bituminous coal macerals (dry, ash-free basis).

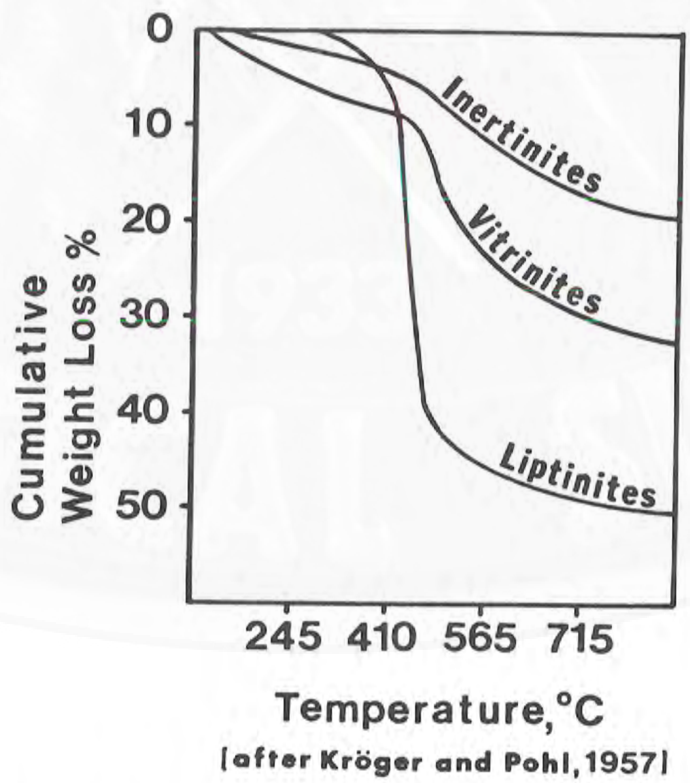

Figure 4. Cumulative weight loss or devolatilization of the three maceral groups with increasing temperature.

coal seams. This is suggested by the great variety of H/C values in Figure 2. Those 24 coals are all subbituminous C in rank, yet the H/C ratios vary by as much as a factor of 2. This is a very small sampling of Powder River Basin coals, and we will likely find an even greater spread in H/C values as more analyses are performed.

The relationship between decreasing H/C ratios and decreasing liptinite content is striking. Even though huminites contribute the largest proportion of macerals to Powder River Basin coals, it is apparent that the quantity of huminite does not affect changes in H/C ratios as much as the quantity of liptinites does. If further work shows that this relationship holds generally, the task before us is to conduct comprehensive surveys of Powder River Basin coals to determine which ones have the highest H/C ratios. Though H/C data can be determined by chemical fractionation of the coals, a faster and equally reliable method is the petrographic analysis.

The suitability for conversion of Wyoming subbituminous coals is demonstrated by data taken from Berkowitz (1979) and presented in Tables 1, 2, and 3. Though Wyoming subbituminous coal is specifically mentioned only in Table 1, the results presented for unspecified subbituminous coals in Tables 2 and 3 would very likely apply to the Wyoming deposits. It seems that gas synthesis from eastern Wyoming coals is the most productive conversion process.

Once thorough petrographic surveys of Powder River Basin coals are available, the best coals can be reserved for the time when liquefaction and gasification become commercially feasible. Coals such as PSOC 101

TABLE 1
(from Berkowitz, 1979)

Product yields from COGAS pilot plant[a]

	hvb coal, Illinois	hvb coal, Utah	Subbituminous coal, Wyoming
Char	60.7	59.0	50.0
Oils	18.7	21.9	11.2
Aqueous liquor	5.8		11.6
Gas[b]	14.6	21.5	27.2

[a]After Paige (1975), Eddinger and Sacks (1975), all yields in weight percent of dry coal.

[b]Excluding gas from downstream char gasification.

TABLE 2
(from Berkowitz, 1979)

Liquid hydrocarbon yields from hydropyrolysis[a]

Reference	Coal	Product	Best Yield
Weller et. al.(1950,1951)	hvC bituminous	Oils	16
Hiteshue et. al.(1962a,b)	hvC bituminous	Oils	40
Hiteshue et. al.(1962a,b)	Lignite;	Oils	33
	hvC bituminous;	Oils	26
	hvA bituminous	Oils	19
Hiteshue et. al.(1962a,b)	Subbituminous	Oils,[b]	40
		C_6 aromatics	6
Albright and Davis (1970)	Subbituminous	Oils	28
Squires (1975)	Bituminous	Oils[b]	31
Wood and Wiser (1976)	Subbituminous	Oils	50
Schroeder (1976)	Subbituminous	Oil and tar	70
Steinberg et. al. (1976)	Lignite	BTX,[c]	10
		benzene	9
Rosen et. al. (1976)	Subbituminous	Benzene	35

[a]All yields in weight percent of daf coal.

[b]Designated as condensate oils.

[c]This designation is used for a light oil fraction predominantly composed of benzene, toluene, and xylenes.

TABLE 3
(from Berkowitz, 1979)

500°C Fischer assays of different coals[a]

Rank	Number of samples	Tar (gal/ton)		Light Oil[b] (gal/ton)		Water (gal/ton)		Gas (scf/ton)[c]	
		Range	Average	Range	Average	Range	Average	Range	Average
lvb	17	6.3- 12.7	8.6	0.7-1.6	1.0	1.1- 6.6	3.2	1600-1960	1760
mvb	30	9.7- 25.6	18.9	1.0-2.3	1.7	2.8- 7.0	4.1	1390-2240	1940
hvAb	134	22.9- 40.7	30.9	1.5-3.3	2.3	3.0- 9.2	6.0	1690-2360	1970
hvBb	11	24.3- 43.1	30.3	1.6-3.4	2.2	10.2-13.1	11.1	1660-2420	2010
hvCb	7	18.5- 38.8	27.0	1.3-2.7	1.9	12.0-19.1	15.9	1560-2070	1800
Subbituminous A	5	18.4- 24.4	20.5	1.4-1.9	1.7				
Subbituminous B	7	13.2- 16.7	15.4	1.1-1.6	1.3	23.3-30.4	27.8	1830-2760	2260
Cannel	7	53.7-108.3	73.5	3.7-7.4	5.1	2.0- 4.8	3.7	1500-2120	1810

a After Selvig and Ode (1957)

b Light oils are usually reported separately but are, in industrial practice, the first distillate cuts of condensible by-products.

c 1000 scf (= 1 Mcf) $\simeq 31.2 m^3$.

and 527 (Figure 2) could be sent to electrical generators where the coals' high inertinite content will not impair their performance. Prime conversion coals such as PSOC 567 would be stockpiled (i.e. left in the ground) for later use as conversion coals. It is naive to think that every small volume of liptinite-rich coals could be conserved in this manner; mining economics and techniques would not allow that. It is also the case, however, that we cannot afford to burn up our best conversion coals.

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THE RAWHIDE COAL MINE, CAMPBELL COUNTY, WYOMING

by

Gary B. Glass
Geological Survey of Wyoming
Laramie, Wyoming

STATE OF WYOMING

1933

GEOLOGICAL SURVEY

BACKGROUND AND HISTORY

Specht and Bryant (1979) provide this brief history of the Rawhide mine:

> *In August, 1967, the Carter Oil Company obtained a Federal Coal Lease on approximately 5,500 acres of land lying about 12 miles north of Gillette, Wyoming. Subsequent exploration, mine design, and permitting resulted in the start of construction for a 12 million ton per year mine in September of 1974. However, on September 30, 1975, construction was halted pending resolution of the Sierra Club vs. Morton Lawsuit. In May, 1976, work on the mine facilities was resumed and in November, 1976, removal of overburden in the box cut area began, resulting in the shipment of the initial trainload of coal on August 18, 1977.*

Carter holds surface rights to 5,217 acres of land within the federal lease area and 120 acres of land adjacent to the lease (U. S. Department of Agriculture, et. al., 1974). Forty acres of the land in Section 11, T. 51N., R. 72W., are national resource lands. The remainder of the surface in the lease is held privately. All coal within the boundaries of the federal lease is owned by the U. S. Government except for a 40-acre tract in Section 6, T. 51N., R. 72W., which is leased from private mineral owners. Figures 1 and 2 show the location of the Rawhide coal lease and the position of the Rawhide mine within that lease, respectively.

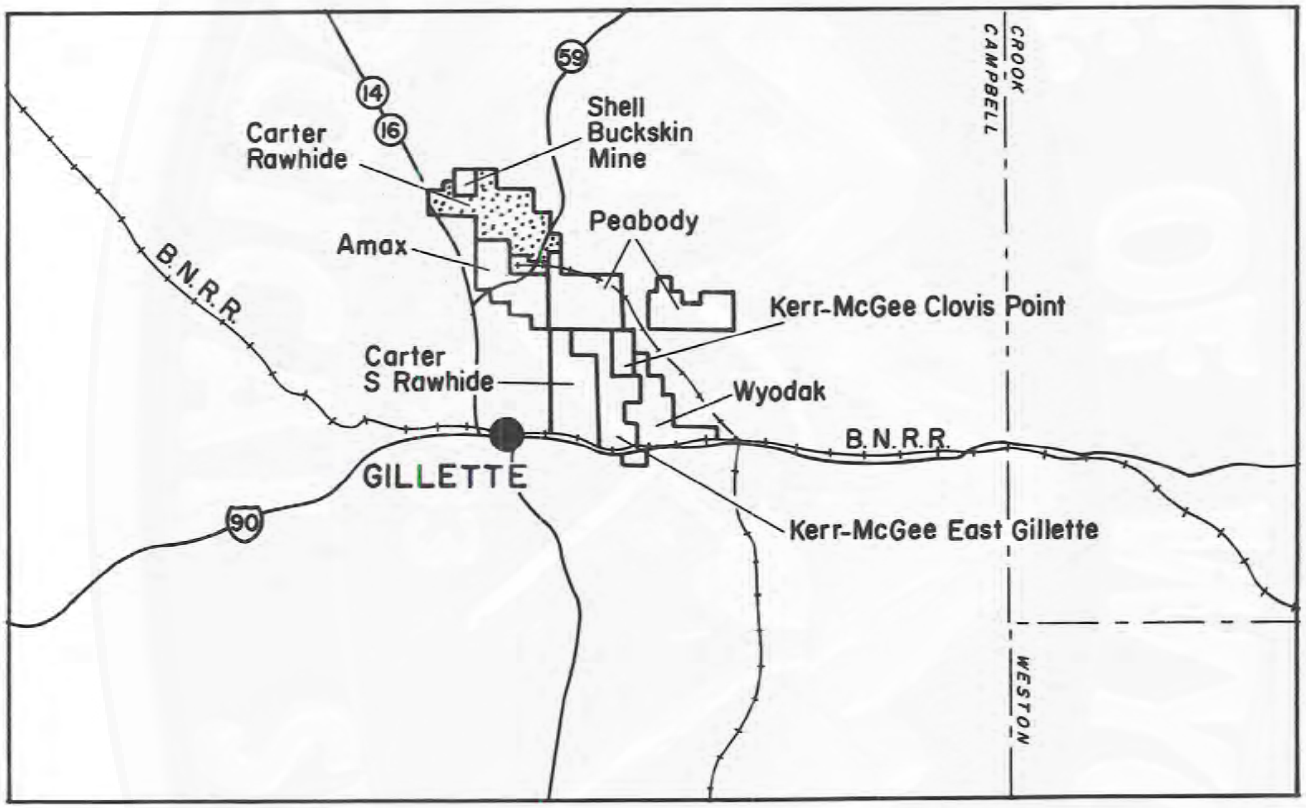

Figure 1. Location of the Rawhide Coal Lease (adapted from Carter Mining Company, 1980).

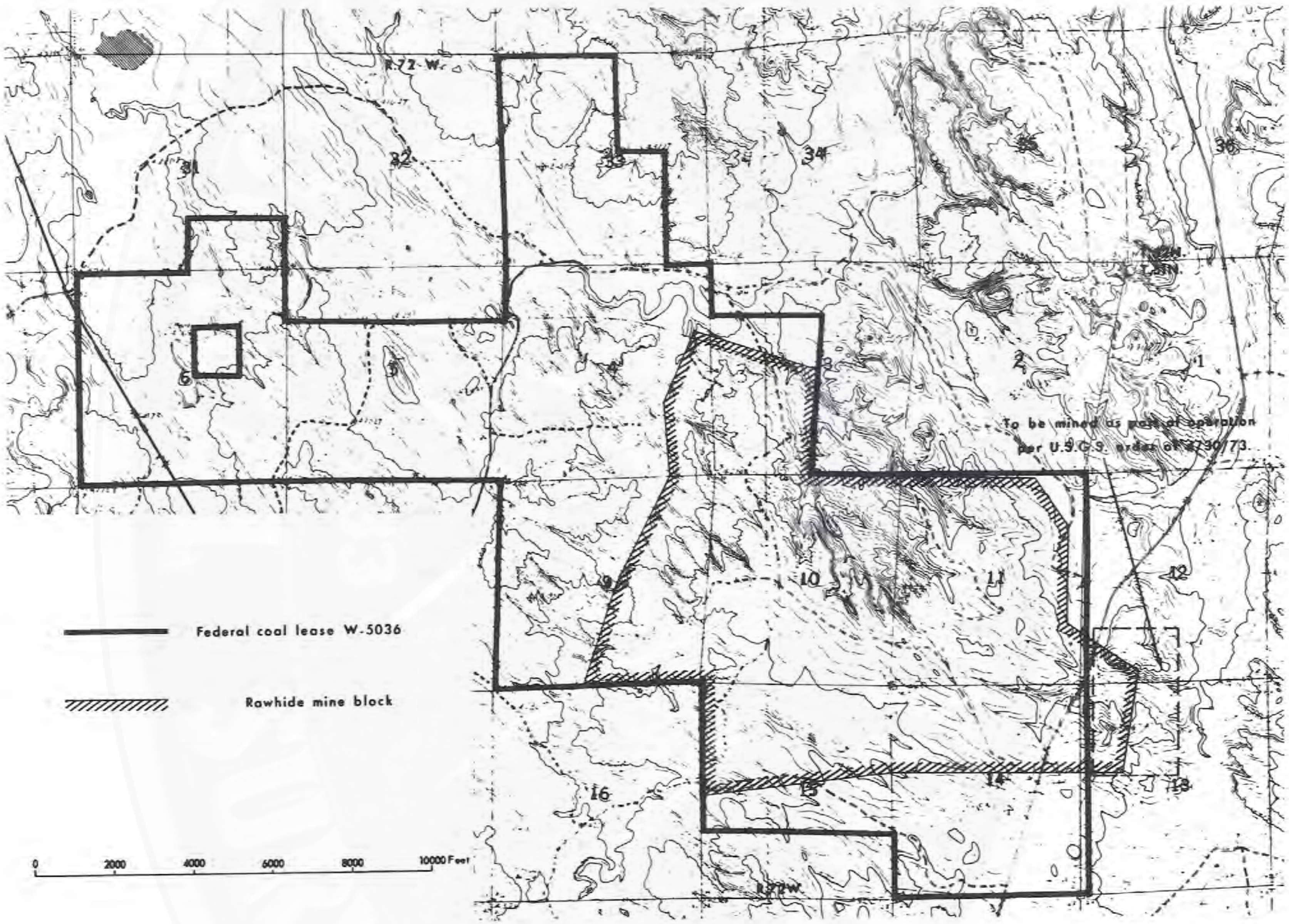

Figure 2. Location of the Rawhide mine block on Federal Coal Lease W-5036 (adapted from U.S. Department of Agriculture, et. al., 1974).

GEOLOGY OF THE MINE SITE

The Rawhide mine is located within the Powder River Coal Field on the gently dipping east flank of the Powder River Basin. Poorly exposed bedrock in the mine area consists of the Paleocene Fort Union Formation and the Eocene Wasatch Formation. The top of the Anderson (Carter's Roland) coal bed is generally used as the contact between the Fort Union and Wasatch formations in the mine area. Denson and Keefer (1974) show this contact at the eastern edge of the Rawhide mine. The contact is generally masked everywhere by alluvium or by red baked and fused rocks (clinker), which are thermally altered shales and sandstones above burned-out coal beds.

The Fort Union Formation is in turn underlain by the Upper Cretaceous Lance (Hell Creek) Formation and Fox Hills Sandstone. The base of the Fox Hills is nearly 4,000 feet below the mine (U. S. Department of Agriculture, et. al., 1974). Older Mesozoic and Paleozoic rocks occur between the base of the Fox Hills and the Precambrian basement some 15,000 feet below the surface.

At the northeastern edge of the Rawhide lease, the uppermost part of the Fort Union Formation is partially exposed. The Wyodak-Anderson coal bed, which includes a rock parting about two-thirds above the base of the coal, comprises the upper 70 to 150 feet of the formation. Carter Mining Company; however, uses the terminology of Stone and Lupton (1910) and uses the parting to separate the coal into the Roland (upper) and Smith (lower) beds. Recent mapping by the U. S. Geological Survey shows that the Wyodak-Anderson coal bed is actually the Anderson and Canyon coals combined into a single bed. The Roland and Smith coal beds are in reality younger coals which were incorrectly correlated into this part of the Gillette area (Denson and Keefer, 1974).

Below the Wyodak-Anderson coal bed, the Fort Union Formation is predominantly interbedded shales, claystones, siltstones, and sandstones. The sandstone units are usually very fine grained and moderately well cemented. Within the Fort Union Formation, the Upper and Lower Pawnee coal beds underlie the Wyodak-Anderson bed in this area by about 500 feet and 600 feet, respectively (Denson and Keefer, 1974). These coals are each reportedly 10-12 feet thick. A third coal, the Cache coal bed, is about 700 feet below the Wyodak-Anderson. Beneath the Rawhide mine, this coal is 25-28 feet thick (Mapel, 1973).

The surface over most of the Rawhide lease is underlain by lacustrine and fluviatile rocks of the Wasatch Formation. According to Law (1976), Wasatch rocks in this area are up to 500 feet thick and divisible into three units. From oldest to youngest these units are:

(1) 100 to 350 feet of tan to light-brown sandstone, interbedded with coal (at least in the western part of the Rawhide mine area), claystone, and carbonaceous shale.

(2) 200 to 350 feet of light-gray to orangish-yellow sandstone interbedded with minor siltstone, claystone, carbonaceous shale, and lenticular coal.

(3) Variable thickness (top eroded) and of lithology similar to unit (1).

At the Rawhide lease, these Wasatch rocks overlie the minable Wyodak-Anderson coal bed and are stripped as overburden. As evidenced in Figure 3,

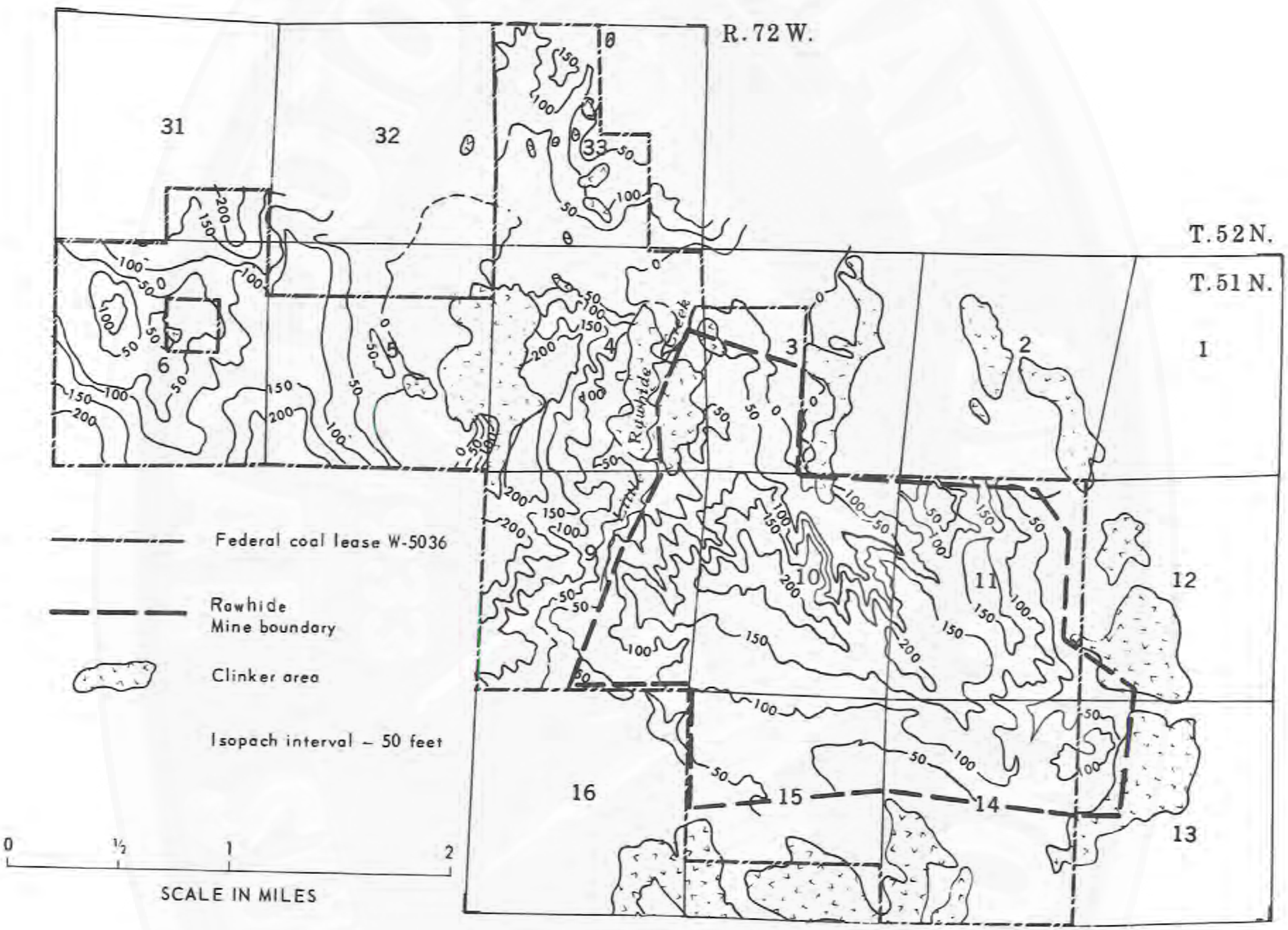

Figure 3. Map showing thickness of overburden on the Rawhide lease area (adapted from U. S. Department of Agriculture, et. al., 1974).

the overburden at the Rawhide lease is 0-240 feet thick.

Alluvium in the Rawhide mine area occurs along narrow flood plains and terraces formed by the streams which drain the region. This alluvial material is comprised of sands, silts, and clays with discontinuous sand lenses, which include platy clinker fragments (Carter Mining Company, 1980). The alluvium is up to 20 feet thick.

Bedrock in the Rawhide lease generally exhibits an imperceptible dip of 1-2 degrees to the west. Law (1976), however, noted that the structure of the younger Wasatch and upper Fort Union rocks in the Rawhide lease area is sometimes much more complex. At least locally, Fort Union rocks are standing nearly vertical. Within short distances, these same rocks are nearly flat-lying. Law (1976) attributes these drastic, rapid, lateral changes in dip to differential compaction of sediments. Lateral variation in coal bed thickness and facies changes from coal to inorganic sediments contribute to the phenomena.

As mentioned earlier, the Wyodak-Anderson coal bed at the Rawhide mine occurs as two beds separated by a shale parting that is usually 2-10 feet thick, averaging 6 feet. At the southern boundary of the lease area, however, this shale parting increases to as much as 100 feet thick (Figure 4). The upper coal bed, the Anderson (Carter's Roland), is 20-35 feet thick except where it has been eroded or burned along the eastern and southern crop lines (U. S. Department of Agriculture, et. al., 1974). The Anderson coal bed generally thickens northward across the Rawhide mine (Figure 4).

The lower coal bed, the Canyon (Carter's Smith), is 50-120 feet thick, averaging over 80 feet. The Canyon coal thickens to the south until it abruptly thins and lenses out within several hundred feet of the southern

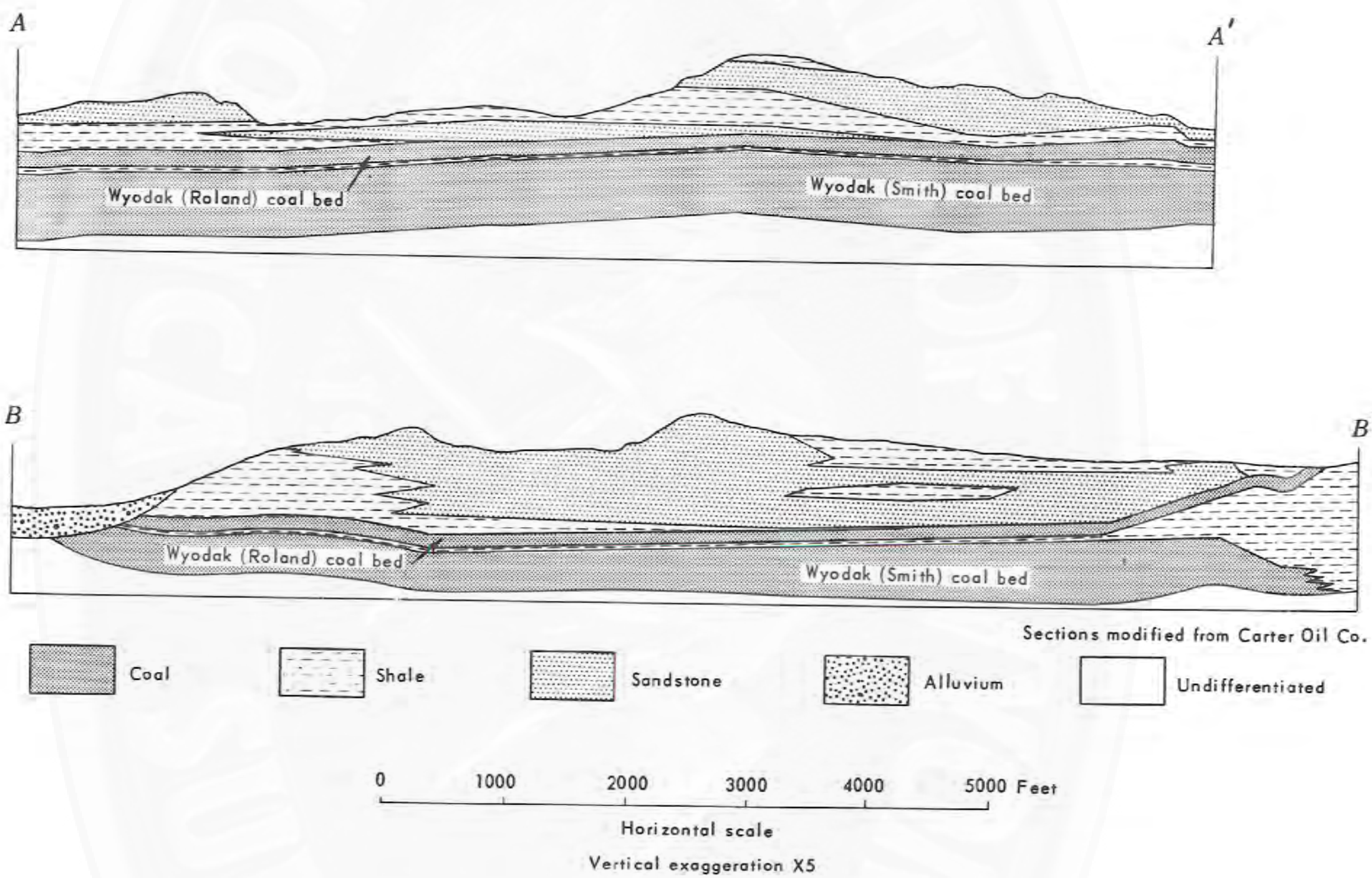

Figure 4. Cross sections A-A' and B-B' at the Rawhide mine (Lines of sections shown on Figure 5) (adapted from U. S. Department of Agriculture, et. al., 1974).

boundary of Carter's lease block (Figures 4 and 5). The coal's proximity to an ancient fluvial channel probably accounts for the abrupt termination of the Canyon coal in this area (Denson, et. al., 1973; Denson and Keefer, 1974).

The coal thickness isopached in Figure 5 is the combined thickness of the Anderson and Canyon coals, excluding the shale parting. As evidenced by Figure 5, the thickest coal occurs immediately adjacent to the abrupt thinning and facies change along the southern edge of the Rawhide lease.

COAL QUALITY

The Wyodak-Anderson coal is subbituminous C in rank. Table 1 provides some average analyses of the coal from the Rawhide mine area (U. S. Department of Agriculture, et. al., 1974). Figures 6, 7, and 8 are also taken from the Final Environmental Impact Statement for the Eastern Powder River Basin (U. S. Department of Agriculture, et. al., 1974) and depict the distribution of sulfur, ash, and heat value (Btu/lb.) at the Rawhide mine. Table 2 provides some trace element analyses for the Wyodak-Anderson coal.

COAL RESERVES AND PRODUCTION

Approximately 700 million tons of Wyodak-Anderson coal underlies Carter's Rawhide lease (Table 3). The Rawhide mine area contains about 400 million tons of that reserve base of which approximately 350 million tons is recoverable, assuming 90 percent recovery (U. S. Department of Agriculture, et. al., 1974). The Canyon coal bed accounts for about three-quarters of the recoverable coal within the mine area. Glass (1980) reports

Table 1. Average analysis of 35 coal samples from the Rawhide mine (all values except Btu and fusion temperature are in percent) (adapted from U. S. Department of Agriculture, et. al., 1974).

Proximate Analysis	As Received	Moisture Free	Ultimate Analysis	As Received	Moisture Free
Moisture	31.00	--	Moisture	31.00	--
Ash	5.96	8.64	Carbon	46.81	67.84
Volatile Matter	30.05	43.55	Hydrogen	3.25	4.71
Fixed carbon	32.78	47.51	Nitrogen	0.66	0.96
Btu	8063	11686	Chlorine	--	--
Sulfur	0.38	0.55	Sulfur	0.38	0.55
Alkalies as Na_2O	0.13	0.19	Ash	5.96	8.64
			Oxygen	11.94	17.30

Fusion Temp. of Ash °F	Reducing	Oxidizing
Initial Deformation	2147	2212
Softening (H=W)	2178	2234
Softening (H=½W)	2192	2249
Fluid Temp.	2215	2279

Oxide Analysis of Ash	
Phos pentoxide P_2O_5	0.52
Silica SiO_2	34.93
Ferric oxide Fe_2O_3	6.02
Alumina Al_2O_3	16.64
Titanium TiO_2	1.02
Lime CaO	20.68
Magnesia MgO	4.62
Sulfur trioxide SO_3	14.65
Potassium oxide K_2O	0.51
Sodium oxide Na_2O	1.11

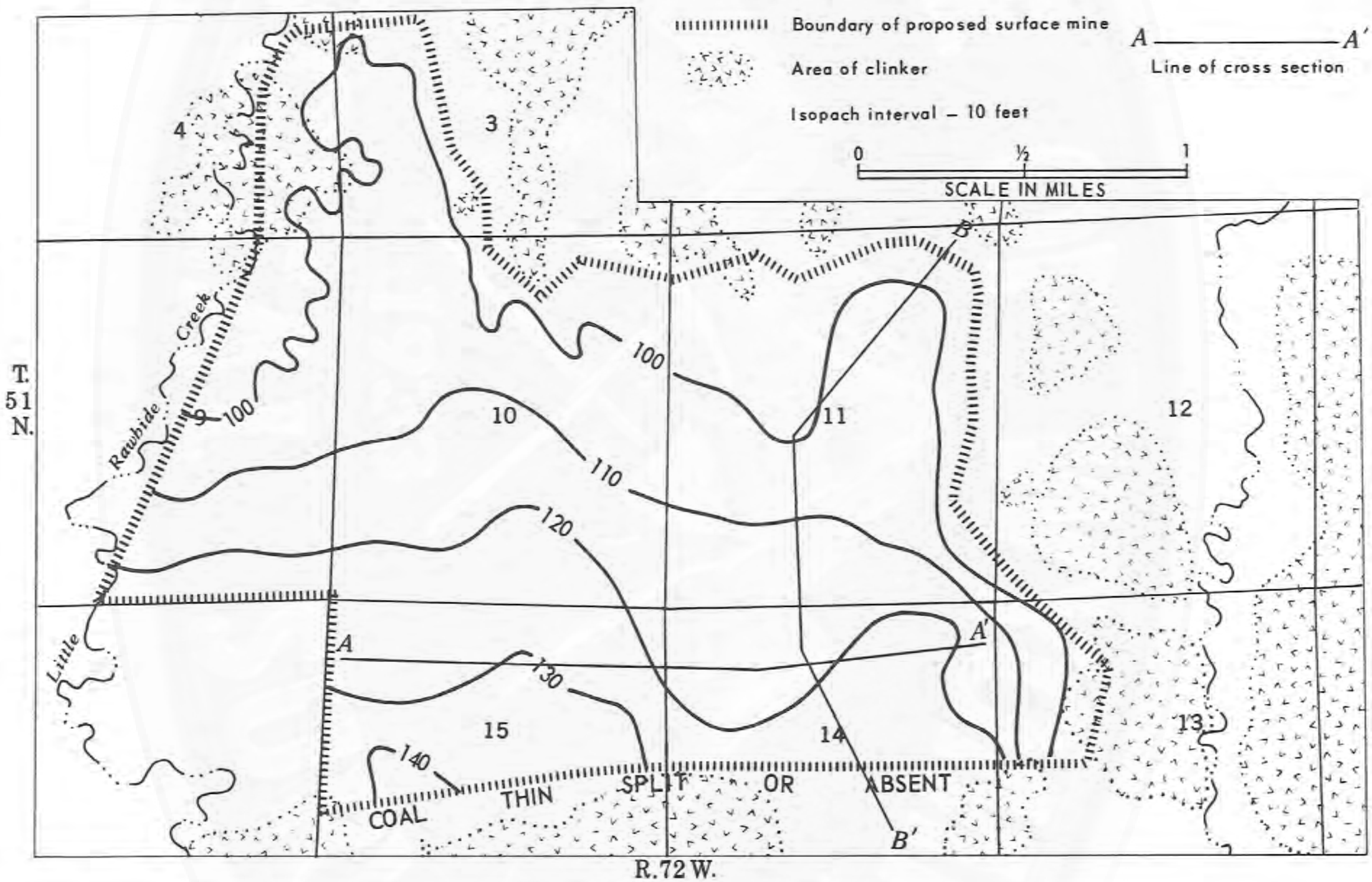

Figure 5. Thickness of the Wyodak-Anderson coal bed at the Rawhide mine (adapted from U. S. Department of Agriculture, et. al., 1974).

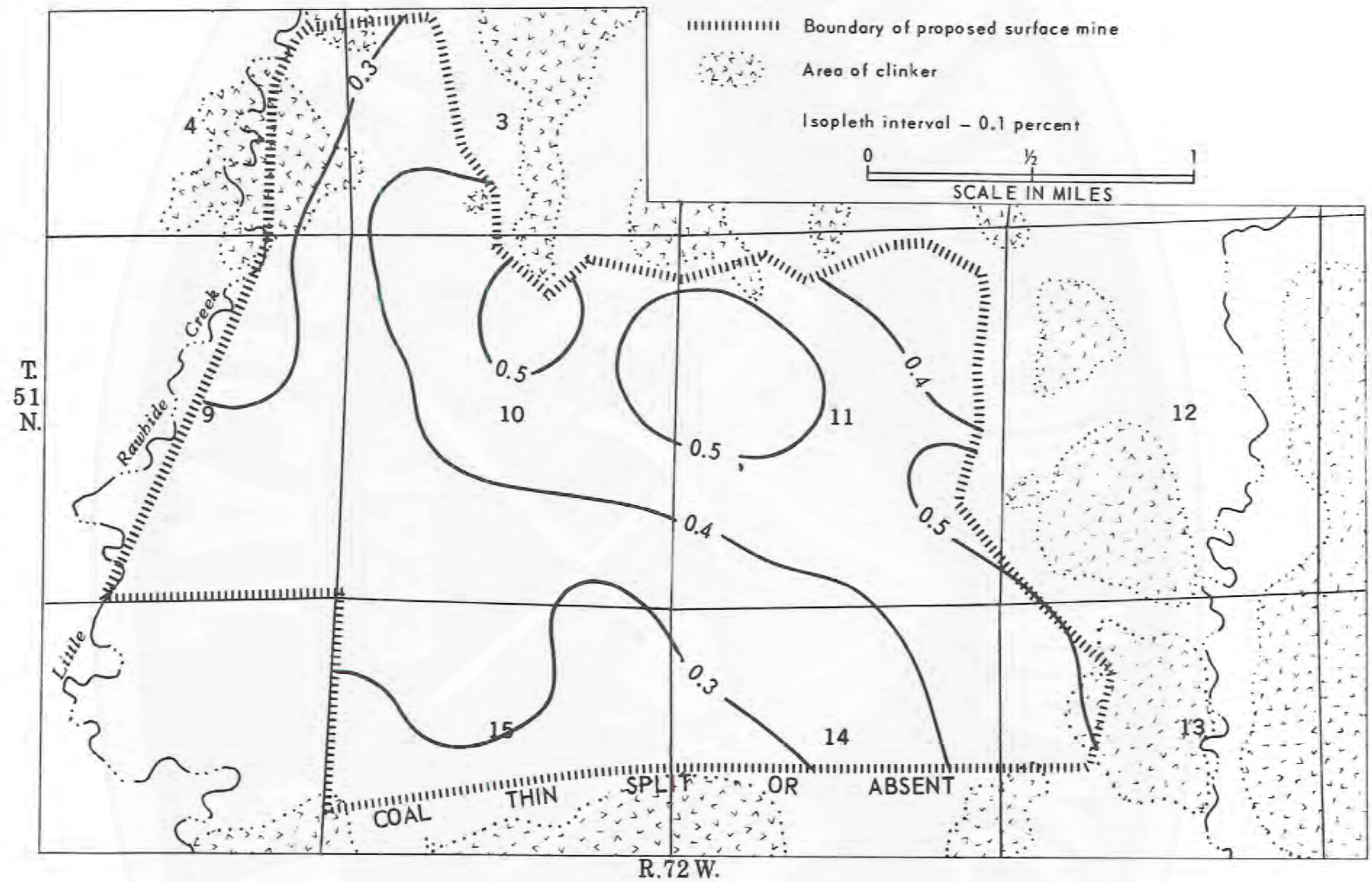

Figure 6. Distribution of sulfur content in the Wyodak-Anderson coal bed at the Rawhide mine (adapted from U. S. Department of Agriculture, et. al., 1974).

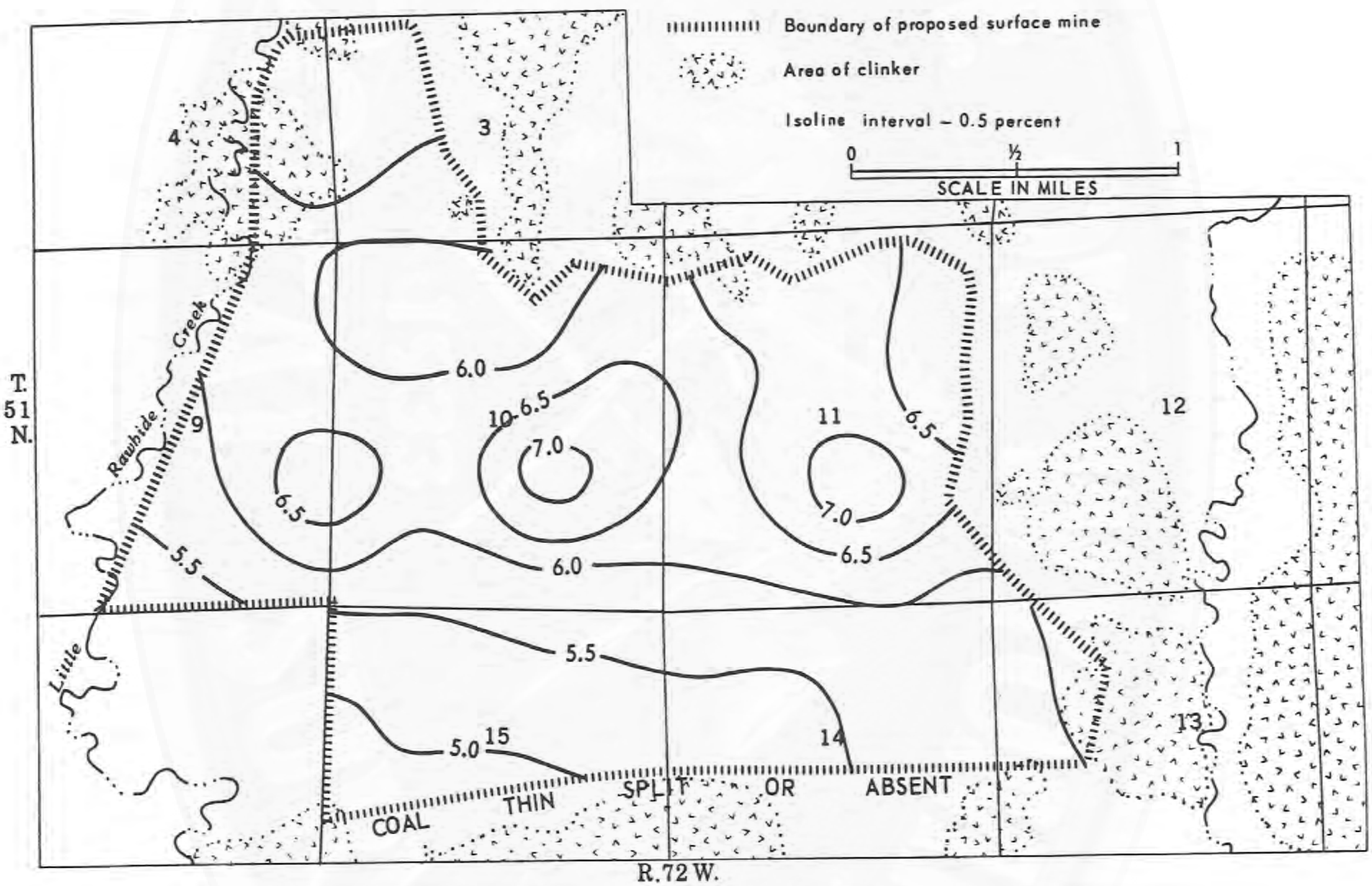

Figure 7. Distribution of ash content in the Wyodak-Anderson coal bed at the Rawhide mine (adapted from U. S. Department of Agriculture, et. al., 1974).

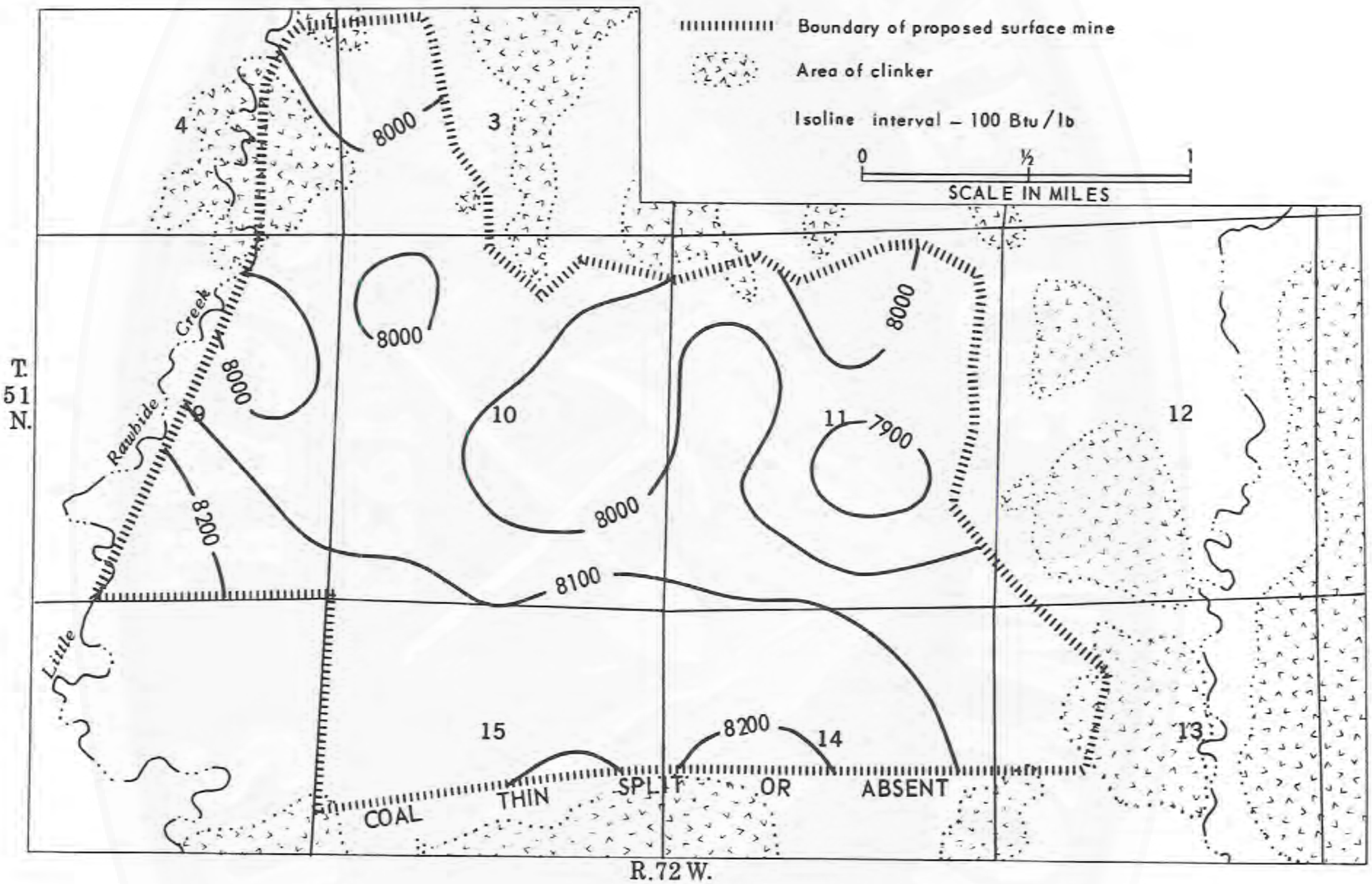

Figure 8. Distribution of the heat value (Btu/lb.) of the Wyodak-Anderson coal bed at the Rawhide mine (adapted from U. S. Department of Agriculture, et. al., 1974).

Table 2. Analyses of selected trace elements in the Wyodak-Anderson coal bed at the Rawhide mine (values in parts per million on a whole-coal basis) (adapted from U. S. Department of Agriculture, et. al., 1974).

	Sample Number							
ELEMENT	NRH 58 1/	NRH 62 1/	NRH 76 1/	D-279 1/	D-281 2/	D-281 3/	D-286 2/	D-286 3/
Arsenic	1.8	<0.33	1.1	1.5	0.65	< 0.20	2.9	0.29
Boron	29.	3.6	32.	25.	2.8	3.2	25.	28.
Fluorine	200.	2.6	131.	170.	5.0	1.5	7.5	150.
Lead	1.9	0.51	0.93	1.6	0.54	0.41	1.6	0.54
Mercury	< 0.007	< 0.006	0.28	0.006	< 0.005	< 0.005	0.28	0.23
Selenium	0.18	0.06	0.14	0.15	0.10	0.04	0.31	0.06
Uranium	1.3	0.7	1.5	1.1	1.1	0.48	1.1	1.4
Vanadium	19.	8.3	13.5	16.0	13.0	5.8	13.	11.

1) Composite coal sample of upper (Roland) and lower (Smith) beds.

2 Composite coal sample of upper (Roland) bed.

3 Composite coal sample of lower (Smith) bed.

Table 3. Coal reserves of Anderson (Carter's Roland) and Canyon (Carter's Smith) coal beds on the Rawhide lease, Campbell County, Wyoming (adapted from U. S. Department of Agriculture, et. al., 1974).

Location	Lower (Smith) Bed 1/ Acres	Lower (Smith) Bed 1/ Coal in Place	Upper (Roland) Bed Acres	Upper (Roland) Bed Coal in Place	Total Coal in Place 2/	Recoverable Coal 3/	Stripping Ratio 4/
MINE BLOCK AREA							
T. 51 N., R. 72 W.							
Section 3	115	12,280	91	5,445	17,725	15,952	0.62
Section 4	29	3,388	29	1,443	4,831	4,348	0.50
Section 9	272	37,812	272	12,600	50,412	45,371	0.92
Section 10	570	75,214	535	28,707	103,921	93,529	1.34
Section 11	540	67,303	518	23,762	91,065	81,959	1.29
Section 12	20	1,115	0	0	1,115	1,004	0.97
Section 13	63	8,054	51	1,726	9,780	8,802	0.78
Section 14	240	40,627	240	8,974	49,601	44,640	0.78
Section 15	288	52,551	288	12,453	65,004	58,504	0.52
Sub-total	2,137	298,344	2,024	95,110	393,454	354,109	1.01 5/
REMAINDER OF LEASE AREA							
T. 51 N., R. 72 W.							
Section 4	361	34,822	343	21,485	56,307	50,676	1.14
Section 5	430	45,124	309	24,564	69,688	62,719	1.19
Section 6	449	50,376	597	36,493	86,869	78,182	1.46
Section 9	381	47,075	381	22,408	69,483	62,535	1.23
Section 14	0	0	121	4,590	4,590	4,131	2.29
Section 15	0	0	121	7,713	7,713	6,942	1.38
T. 52 N., R. 72 W.							
Section 31	81	9,607	81	7,167	16,774	15,096	1.36
Section 33	295	30,581	243	17,076	47,657	42,891	0.87
Sub-total	1,997	217,585	2,196	141,496	359,081	323,172	1.24 5/
GRAND TOTAL	4,134	515,929	4,220	236,606	752,535	677,281	1.12 5/

1/ Basal 3 feet of bed, which will not be mined, are excluded from estimates.
2/ Assuming 1,770 short tons of coal per acre foot.
3/ Assuming 90 percent recovery of coal in place.
4/ Cubic yards of overburden per ton of recoverable coal.
5/ Weighted average.

Source: Carter Oil Company

that Carter already has contracts for 210 million tons of the reserves for delivery between 1977 and 2011.

While Rawhide's production in 1977 was 1.1 million tons, 1978 production more than doubled to 2.6 million tons. Production in 1979 increased to 3.6 million tons. Contracted annual production is currently estimated at a maximum of 7.8 million tons per year by 1984. Table 4 lists all of Rawhide's existing coal contracts (Glass, 1980). Anticipated new demand has already prompted Carter to seek permits that will allow them to double Rawhide's present capacity of 12 million tons per year.

MINING METHODS

Specht and Bryant (1979) describe the mining methods at Rawhide:

> *The mining scheme at Rawhide is primarily a truck-shovel operation. The overburden is removed by a BE-295 electric shovel with a 22 yard bucket. Its truck fleet consists of six Mark-36 rear dump trucks with a capacity of 170 tons. Auxiliary equipment for overburden removal include two L-800 front end loaders with 13 yard buckets and three Cat 633-C scrapers. Coal from the upper seam is mined by a L-800 front end loader, but will be replaced in the near future by a P&H 1900 electric shovel with a 15 yard bucket. The upper 65 feet of the lower seam is being mined by a B-E 295B electric shovel with a 35 yard bucket and a 65 foot boom. The remaining portion of the lower seam is being removed by a Marion 195M dragline with a 22 yard bucket. All three pieces are served by a fleet of BD-180's, bottom dump tractor-trailer type trucks with 180 tons capacity.*

Table 4. Rawhide's coal contracts (Glass, 1980)

BUYER INFORMATION		CONTRACT SPECIFICATIONS							
Company Name	Plant (name, location, capacity, annual fuel requirement)	Total Tonnage Contracted	Average Tonnage Per Year	Duration of Contract	Startup and Completion	FOB Mine Price Per Ton	Delivered Price Per Ton	Delivered Price Cents/ MMBTU	Miscellaneous Comments
Indiana and Michigan Electric Power (AEP)	?Tanners Creek Plant, Lawrenceburg, IN 1015 MW; 2.0 myn tons/year On line in 1977	60 myn tons	2.0 myn tons	30 years	1977-2006		$15.74[1] (1977)	72.1¢	Contract may not be for this plant although some coal shipped in 1977; shipped through Cook barge terminal at Metropolis, IL; maybe going to other AEP plants; contract announced in 1974 did not specify plant name
Indiana and Michigan Electric Power (AEP)	?Project 2602 No. 1, ? location, ?IN 1300 MW; 3.0 myn tons/year Startup in 1983	75 myn tons[2]	3.0 myn[2] tons	30 years[2]	1982-2011[2]				May not be part of 1974 contract but this plant could account for committed tonnage
Indiana and Michigan Electric Power (AEP)	?Unspecified plant or plants	15 myn tons[2]							Balance of tonnage committed in 1974 contract; could also be used to extend length of other contracts
Iowa Public Service Co.	George Neal No. 4 (Sergeant Bluff) Salix, IA 576 MW; 2.0 myn tons/year Startup in 1979	40 myn tons	2.0 myn tons	20 years	1979-1998				Five year contract with 15 year option; contract announced in 1978; plant jointly owned by Iowa Public Service Co. and Corn Belt Coop.(278 MW), Interstate Power Co. (100 MW), Northwestern Public Service Co. (50 MW), Northwest Iowa Power Coop. (100 MW) and various municipalities; 1979 rail rate $10.69
Kansas City Board of Public Utilities	Nearman No. 1, Kansas City, KS 235 MW; 0.8 myn tons/year Startup in 1980	20 myn tons	0.8 myn tons	25 years	1980-1999				Contract negotiated by Western Fuels Assoc., Inc. and announced in 1978; Unit 2 (310 MW) planned for 1986, but coal supplier unknown

Notes: [1] FERC data [2] Estimated

Table 4. Rawhide's coal contracts (continued)

BUYER INFORMATION		CONTRACT SPECIFICATIONS							
Company Name	Plant (name, location, capacity, annual fuel requirement)	Total Tonnage Contracted	Average Tonnage Per Year	Duration of Contract	Startup and Completion	FOB Mine Price Per Ton	Delivered Price Per Ton	Delivered Price Cents/MMBTU	Miscellaneous Comments
SPOT SALES									
Tennessee Valley Authority	Unspecified plants	0.2 myn tons[2]		short	1978-1979				Spot sale during strike
Union Electric Co.	?Sioux Plant, West Alton, MO 904 MW; 2.0 myn tons/year On line			short	1978-1979		\$22.30[1] (1978)	136.0¢	Spot sale during strike

Figure 9 shows the current layout of the mine while Figure 10 depicts the mining procedures.

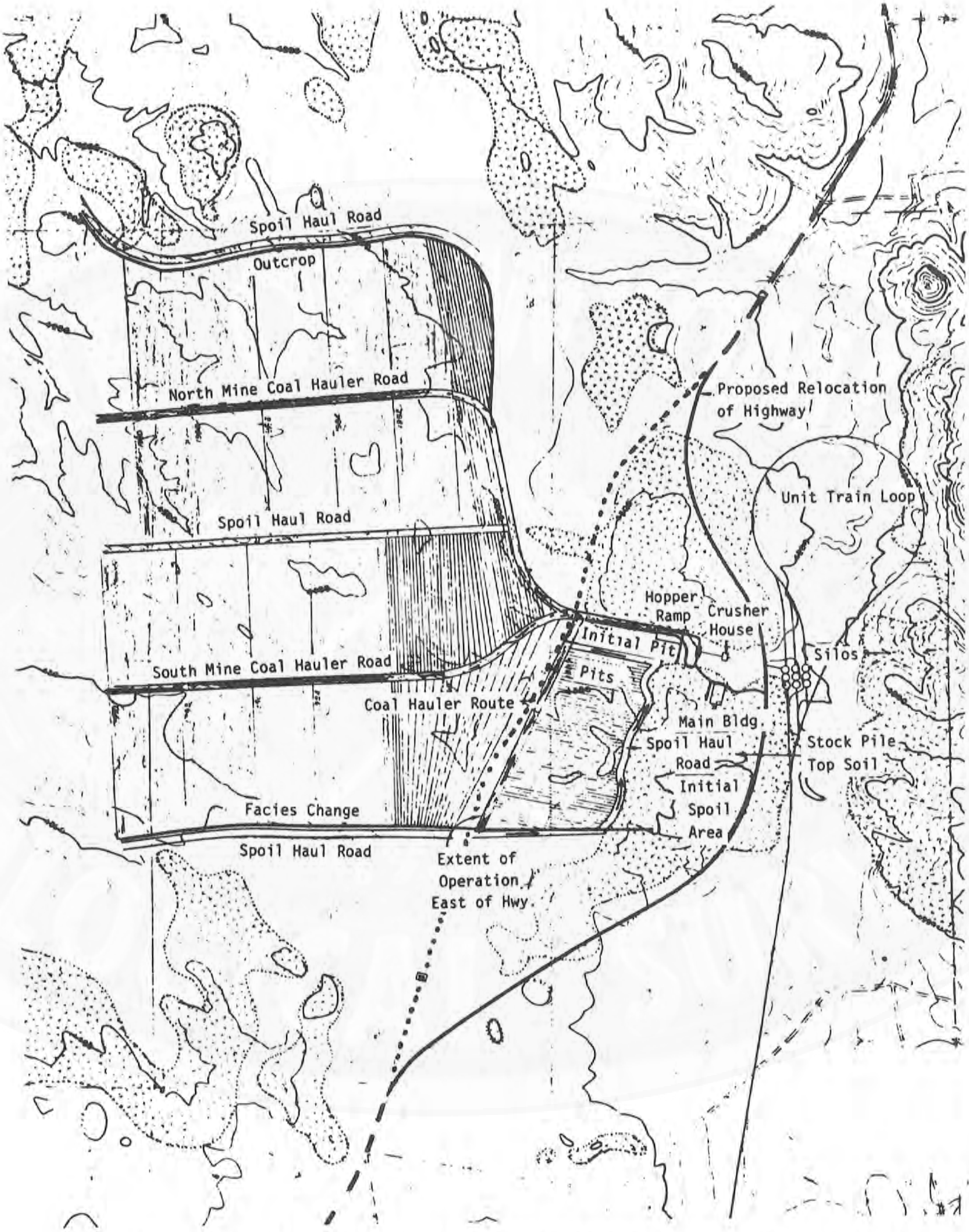

Figure 9. Rawhide mine plan showing layout of surface facilities (adapted from U. S. Department of Agriculture, et. al., 1974).

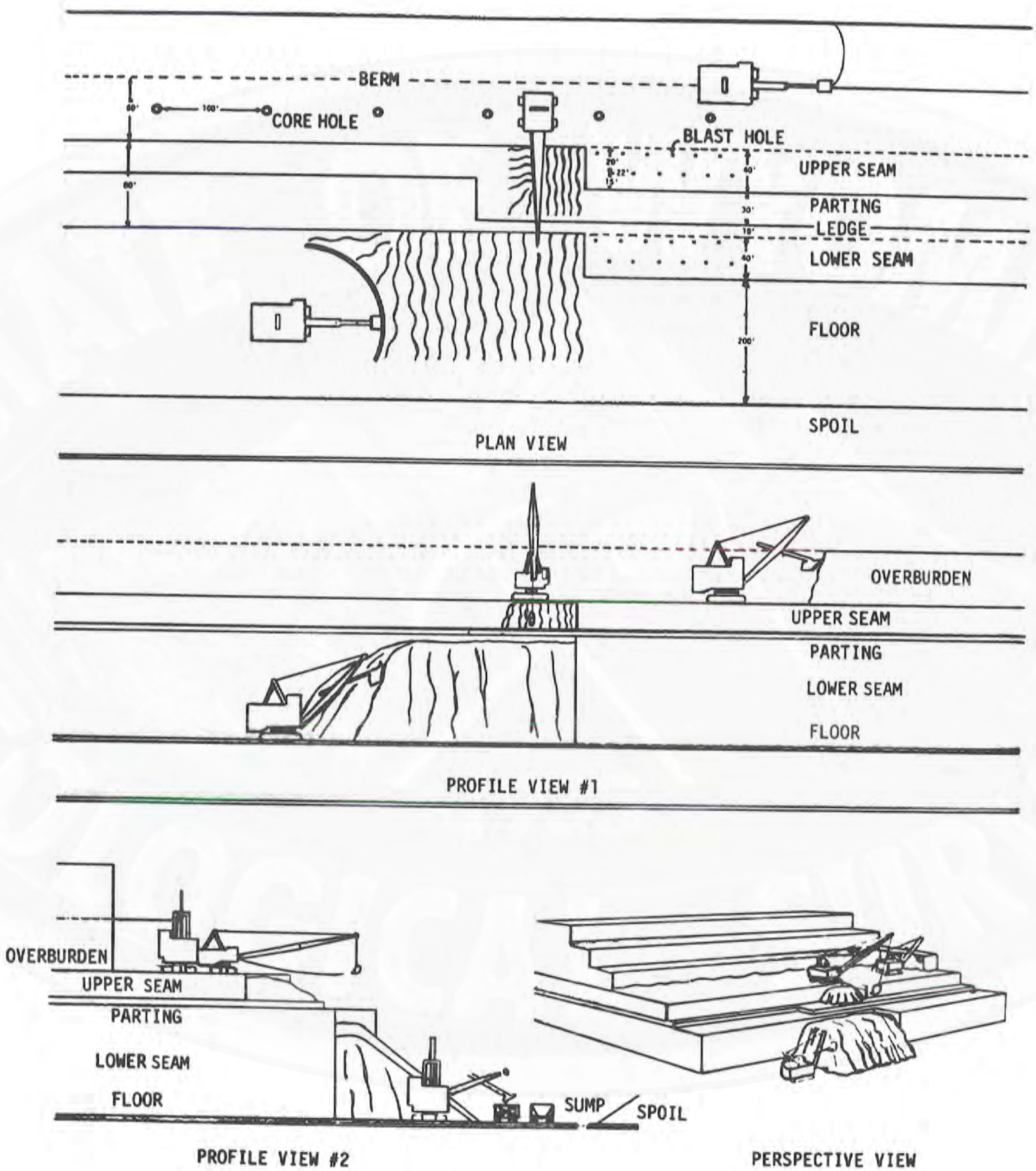

Figure 10. Schematic drawings of the mining methods used at the Rawhide mine (adapted from U. S. Department of Agriculture, et. al., 1974).

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GEOLOGIC MAP EXPLANATION FOR PLATE I

NORTHEASTERN WYOMING

QUATERNARY

Qal	Alluvial deposits
Qs	Wind-blown sands
Qg	Glacial deposits
Qls	Landslide deposits

TERTIARY

Tmo	Miocene and Oligocene rocks (Miocene rocks chiefly light-gray sandstone; Oligocene rocks chiefly white tuffaceous claystone and siltstone)
Twr	White River Formation (white to pale-pink blocky tuffaceous claystone and lenticular arkosic conglomerate)
Tw	Wasatch Formation (Drab-colored to variegated claystone and shale, drab-colored sandstone, and numerous coal beds)
Twm	Moncrief member (Conglomerates of Precambrian rock fragments, sandstones, and drab shale)
Twk	Kingsbury member (Conglomerate of Paleozoic rock fragments, sandstone, and variegated claystone)
Tf	Fort Union Formation (Light colored massive sandstone, drab-colored shale and coal)
Tftr	Tongue River member
Tfl	Lebo member
Tft	Tullock member

SOUTHEASTERN WYOMING

QUATERNARY

Qal	Alluvial deposits
Qs	Wind-blown sands
Qg	Glacial deposits
Qls	Landslide deposits

TERTIARY

To	Ogallala Formation (light-colored limy tuffaceous conglomerate, sandstone, and claystone)
Tm	Miocene rocks (White massive soft tuffaceous sandstone and white marl; coarse-grained arkosic sandstone and conglomerate in lower part)
Tmo	Miocene and Oligocene rocks (Miocene rocks chiefly light-gray, soft sandstone; Oligocene rocks chiefly white tuffaceous claystone and siltstone)
Tbr	Brule Formation (Pale pink to white blocky claystone)
Twr	White River Formation (White to pale-pink blocky tuffaceous claystone and lenticular arkosic conglomerate)
Tc	Chadron Formation (Light-gray to dark-red claystone, sandstone, and lenticular conglomerate)
Tw	Wasatch Formation (Drab-colored sandstone, drab-colored to variegated claystone and shale)

CRETACEOUS

Kl Lance Formation (Brown and gray sandstone and shale; thin coal and carbonaceous shale beds)

Khc Hell Creek Formation (Brown and gray sandstone and shale; thin coal and carbonaceous shale beds)

Klf Lance Formation and Fox Hills Sandstone (Includes Bearpaw Shale in places)

Kfh Fox Hills Sandstone (Light-colored sandstone and gray shale containing marine fossils)

Kmv Mesaverde Formation (Light-colored massive to thin-bedded sandstone, gray sandy shale, and coal; Parkman sandstone member at base; Teapot sandstone member near top)

Kp Pierre Shale (Dark-gray concretionary marine shale)

Kc Cody Shale (Dark-gray marine shale with numerous bentonite beds; Shannon sandstone member 2000 feet above base and Sussex sandstone member 2500 feet above base)

Kn Niobrara Formation (Light-colored limestone and gray to yellow, speckled limy shale)

Tf Fort Union Formation (Brown to gray sandstone, gray to black shale, carbonaceous shale, and thin coal beds)

CRETACEOUS

Kl Lance Formation (Brown and gray sandstone and shale; thin coal and carbonaceous shale beds)

Kfh Fox Hills Sandstone (Light-colored sandstone and shale containing marine fossils)

Kmv Mesaverde Formation (Gray to tan sandstone and sandy shale; some coal beds; Pine Ridge sandstone member at top)

Ks Steele Shale (Gray soft marine shale with numerous bentonite beds and thin lenticular sandstones)

Kc Cody Shale (Gray soft marine shale with many lenticular sandstone beds and some bentonite beds)

Kn Niobrara Formation (Light-colored limestone and gray to yellow, speckled limy shale)

Kf Frontier Formation (Gray shale and sandstone; Wall Creek sandstone member at top)

Kft Frontier Formation, Mowry and Thermopolis shales

Kf Frontier Formation (Gray shale and sandstone; Wall Creek sandstone member at top)

Kft Frontier Formation, Mowry and Thermopolis shales (Mowry Shale is black, hard, siliceous, and weathers silvery gray; Thermopolis Shale is soft, black shale with Muddy sandstone member 150-250 feet above base)

Kmt Mowry and Thermopolis shales

CRETACEOUS-JURASSIC

KJm Cloverly and Morrison formations (Cloverly Formation is light-gray sandstone and lenticular chert pebble conglomerate interbedded with variegated bentonitic claystone; the underlying Morrison Formation consists of dully variegated siliceous claystone with nodular limestone and gray silty sandstone lenses)

JURASSIC

Js Sundance Formation (Greenish-gray glauconitic sandstone and shale underlain by red and gray non-glauconitic sandstone and shale)

Ju Jurassic rocks, undivided (Includes Sundance and Gypsum Springs formations)

Kmt Mowry and Thermopolis shales (Mowry Shale is black and gray, weathers silvery gray, hard, contains thin bentonite beds and abundant fish scales; underlain by Thermopolis Shale with Muddy sandstone member 50-200 feet above base)

CRETACEOUS-JURASSIC

KJm Cloverly and Morrison formations (See description to left)

KJms Cloverly, Morrison, and Sundance formations (Sundance Formation is greenish-gray glauconitic sandstone and shale underlain by red and gray non-glauconitic sandstone and shale)

JURASSIC

Js Sundance Formation (See description to left)

Ju Jurassic rocks, undivided (Includes Sundance Formation and Nugget Sandstone; Nugget Sandstone is gray to dull-red massive and coarsely bedded sandstone)

TRIASSIC

TRu Triassic rocks, undivided (Includes Chugwater and Dinwoody formations; Chugwater Formation is red shale and red siltstone with thin gypsum partings near base)

TRIASSIC-PERMIAN

TRPu Triassic and Permian rocks, undivided (Includes Chugwater Formation and red siltstones and gypsum beds equivalent to the Dinwoody and Phosphoria formations of areas to the west)

PERMIAN

Pp Phosphoria Formation (Cherty gray and lavender dolomite interbedded with red shale and gypsum)

PERMIAN-CARBONIFEROUS

CARBONIFEROUS

Cta Tensleep Sandstone and Amsden formation (Gray sandstone and thin limestone and dolomite beds; basal part contains red and green shale; Darwin sandstone member at base)

Cm Madison Limestone (Blue-gray massive cavernous cherty limestone and dolomite)

TRIASSIC

TRu Triassic rocks, undivided (Includes Jelm and Chugwater formations)

TRc Chugwater Formation (Red shale and red siltstone with thin gypsum partings near base)

TRIASSIC-PERMIAN

TRPu Triassic and Permian rocks, undivided (See description to left)

PERMIAN

Pp Phosphoria Formation (See description to left)

Pu Permian rocks, undivided

PERMIAN-CARBONIFEROUS

PCh Hartville Formation (In descending order: red and white sandstone, gray dolomite and limestone, red shale, and red and gray sandstone)

CARBONIFEROUS

Cc Casper Formation (Gray and tan thick-bedded sandstone, underlain by interbedded sandstone and pink and gray limestone)

Cta Tensleep Sandstone and Amsden Formation (See description to left)

CARBONIFEROUS-CAMBRIAN

ORDOVICIAN-CAMBRIAN

O€u Ordovician and Cambrian rocks, undivided

PRECAMBRIAN

p€u Precambrian rocks, undivided

Cm Madison Limestone (Blue-gray massive cavernous cherty limestone and dolomite; arkosic sandstone present in places at base may be Cambrian age)

Cg Guernsey Limestone (Blue-gray massive cherty limestone and dolomite. Locally includes dolomite and sandstone of Devonian age)

CARBONIFEROUS-CAMBRIAN

C€mu Madison Limestone and Cambrian rocks, undivided

ORDOVICIAN-CAMBRIAN

PRECAMBRIAN

p€u Precambrian rocks, undivided

Adapted from Geologic Map of Wyoming by J. D. Love, J. L. Weitz, and R. K. Hose, U. S. Geological Survey, 1955.