Genesis of thick coal deposits and their unique angular relationships:

Powder River Basin, Wyoming

Nick R. Jones

WSGS

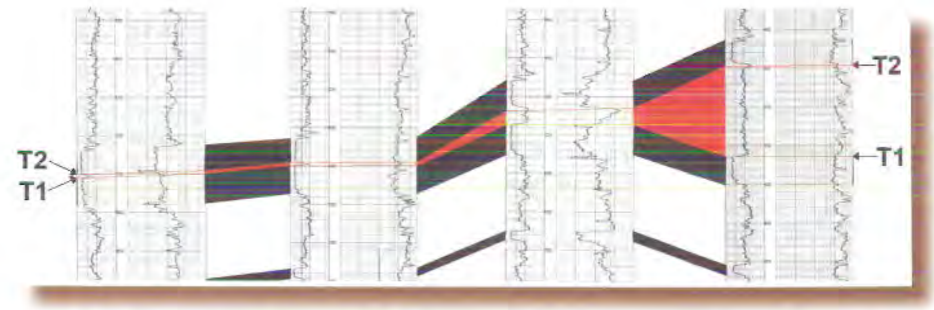
Wyoming State Geological Survey

Report of Investigations No. 60

2010

WSGS

Director and State Geologist Ronald C. Surdam



Detailed cross section showing the distinct parting geometry between the top of the basal coal (T1) and the base of the overlying coal (T2). This geometry is the result of active basement block faulting during the Paleocene. From Figure 37 (p. 46).

Edited by:
David A. Copeland
Robert W. Waggener
Tamara T. Linse

Design by:
Brendon B. Orr
Robert W. Waggener

Illustration assistance by:
James R. Rodgers

Layout by:
Brendon B. Orr

First printing of 500 copies by Pioneer Printing, July 2010.

Genesis of thick coal deposits and their unique angular relationships, Powder River Basin, Wyoming, by Nick R. Jones. This report is based on the master's thesis by Jones, M.S. 2009, Department of Geology and Geophysics, University of Wyoming.

Wyoming State Geological Survey (WSGS) Report of Investigations No. 60, 2010.
ISBN 978-1-884589-53-9

Cover: Bald cypress trees in Pointe Lake, Louisiana. This is an example of a wetland system similar to those that existed in Wyoming during the Paleocene – a period of time when coals were formed across the state, including in the Powder River Basin. *Photo by Nick R. Jones, WSGS (2007).*

Genesis of thick coal deposits and their unique angular relationships:

Powder River Basin, Wyoming

Wyoming State Geological Survey
Report of Investigations No. 60
2010

Nick R. Jones

TABLE OF CONTENTS

PLATES

ABSTRACT

Tertiary coal deposits in northeastern Wyoming's Powder River Basin (PRB) contain the most abundant, thick, low-sulfur, low-ash, minable coal reserves in the United States. Several of these coal deposits exceed 100 feet in thickness, and consequently their formation has been of great interest to geologists and others. Several models have been proposed to explain the origin of these thick coal deposits. These models attribute the development of accommodation and the nature of coal splitting (parting geometry) to sedimentary processes (differential compaction, channel switching, and crevasse splay deposits) within specific depositional environments (raised mires, deltas, and basin-wide wetlands). Most are based on peat-to-coal compaction ratios ranging from 3:1 to 20:1 (3–20 feet of peat compacts to form 1 foot of coal).

This study proposes an alternate hypothesis that explains the genesis of thick Tertiary coal deposits on the basis of (1) chronostratigraphic correlation (sequence stratigraphy) of coal beds, (2) basement-related structural influence on differential development of accommodation within the basin, and (3) the coalification process – not compaction. A 2-D structural reconstruction model illustrates the structural development of accommodation, alternating periods of clastic and organic deposition, and the formation of stacked coal beds and accurate parting geometries. The model is based on four assumptions: (1) the top of each coal represents a chronostratigraphic surface; (2) development of accommodation is syndepositional with and controlled by basement faulting; (3) syndepositional and post-depositional compaction of organic and clastic sediments is minimal; and (4) thick coal deposits comprise numerous thin coal beds that formed from an incompressible organic-rich hydrogel. Plates A–A', B–B', and C–C' (**Plates I–III**) illustrate the unique subsurface geometry of the coal deposits in the PRB. A structural reconstruction analysis, performed using cross section A–A', illustrates the application of the new model.

ARCUATE

INTRODUCTION

The coal-bearing Tongue River Member is the uppermost member of the early Tertiary (Paleocene) Fort Union Formation in Wyoming's PRB. It is composed of fluvial, lacustrine, and mire deposits (*mire* is the generic term for wetlands: swamps, marshes, and bogs) consisting of interbedded shale, mudstone, claystone, siltstone, and sandstone alternating with carbonaceous shale and coal.

The Tongue River Member contains the most abundant deposits of thick, mineable, low-ash, low-sulfur subbituminous coal in the contiguous United States – if not the world. In 2008, coal production from 13 active coal mines accounted for approximately 40 percent of annual U.S. coal production and set a new annual Wyoming record of 451 million tons (Mine Safety and Health Administration, 2009). This coal is produced from the Tongue River Member, where the coal lies within 500 feet of the surface.

These coal deposits also contain abundant coalbed natural gas (CBNG). At 65 cubic feet of CBNG per ton of in-place coal, the CBNG resource in the Wyoming PRB is estimated to be approximately 37 trillion cubic feet (De Bruin, 2009). This is enough natural gas to meet the energy needs of approximately 12 million homes for 37 years.

In 2008, approximately 535 billion cubic feet of CBNG and more than 500 million barrels of water were collectively produced (Wyoming Oil and Gas Conservation Commission, 2009) from 24 unique coal deposits in 10 Tongue River Member coal zones that occur in the Wyoming PRB (Jones, 2008).

Since drilling started in 1987, approximately 27,000 CBNG wells have been drilled, logged, and completed, resulting in a wealth of subsurface information on the coal-bearing rocks in the PRB. Well logs selected from this data set were used to identify and develop a coal occurrence database. This database was used to correlate and model coal deposits in the basin to better understand the coal stratigraphy and its distribution in the subsurface. This was part of a basin-wide study related to produced CBNG water in research conducted by the Wyoming State

Geological Survey (WSGS) as part of a larger basin-wide hydrologic and geologic study (Copeland and Ewald, 2008). Data for the coal model were interpreted, correlated, and modeled by the author and WSGS staff (Jones, 2008).

PURPOSE AND SCOPE

During the last 40 years, the Tertiary coal beds in the PRB have been the subject of many geologic investigations relating to their origin, stratigraphic distribution, and structural geometry. Information collected during these investigations has led to various hypotheses about how these coals formed – especially the extremely thick coal deposits that distinguish this resource. The objective of this study is to present a new model to explain the genesis and the unique structural geometry of the thick coal deposits in the Tongue River Member of the Fort Union Formation in the PRB. Research for this study was conducted between 2007 and 2009 and included fieldwork, well log analysis, and correlation (N.R. Jones, 2009). Intervals of subbituminous coal containing combinations of high-ash layers, bone coal (a hard, coaly material containing less than 50 percent carbon), rooted zones, and partings composed of clastic material were used together with concepts of sequence stratigraphy to identify buried regional paleo-surfaces within thick coals.

LOCATION

The research area for this study is the Wyoming portion of the PRB in Campbell County. Three cross sections (**Plates I, II,** and **III**) were constructed within this county on the basis of the resolution, distribution, density, and depth of available well logs (**Figure 1**). Cross section A–A′, in northwestern Campbell County, is approximately 9 miles long and trends southeast from sec. 34, T. 56 N., R. 76 W. to sec. 27, T. 55 N., R. 75 W. (**Plate I**). Cross section B–B′, in west-central Campbell County, is approximately 10 miles long and trends south-southeast from sec. 2, T. 49 N., R. 76 W. to sec. 16, T. 48 N., R. 75 W. (**Plate II**). A third generalized cross section, C–C′, constructed across west-central Campbell County, is approximately 40 miles long and trends north-northeast from sec. 29, T. 46 N., R. 76 W. to sec. 21, T. 50 N., R. 72 W. (**Plate III**).

GENERAL OBSERVATIONS

The significant economic importance of these coal deposits, due to their extraordinary thickness and regional extent, has led to numerous studies by many researchers. The earliest comprehensive field studies on Tongue River coal deposits began in 1907 by U.S. Geological Survey (USGS) geologists (Taff, 1909). Beginning with the earliest studies, one question that puzzled geologists was the processes by which the thick deposits formed. Not only are these deposits more than 100 feet thick, they also split into several different coal sequences that further split into individual coal beds. The geometry of the splitting also puzzled investigators. The thickness of the clastic material (the parting) within a split coal deposit may increase longitudinally from less than an inch to more than 100 feet and pinch out in less than 2 miles; furthermore, the upper coal may ramp up in a convex manner above the parting where the lower coal remains parallel to the structural dip of the Tongue River Member (**Figure 2**).

The combined thickness of coals where they split and their combined thickness where they coalesce are generally equal, and where one of the coals is thicker than the other their relative thicknesses where they are separated by the parting remain uniform (**Figure 3a**).

Presently, there is no consensus regarding a process that produces lenticular partings at the scale observed in the Tongue River Member. Previous research in the northwestern PRB in Wyoming and Montana attributed the splitting of coal deposits to structural controls not yet recognized (Sholes and Cole, 1981). Normal faults in this area of the PRB mapped by Law and Grazis (1972) were associated with normal faults in Montana's western PRB and were interpreted as surface expressions of left-lateral movement along basement wrench faults (Robinson and Barnum, 1986). In the southeastern basin, splits were attributed to faulting and paleostructures related to basement faulting (Denson et al., 1978a, b). Others attributed major splitting of thick coal deposits to overbank deposits, compaction of peat, and differential compaction of underlying sediments (Flores 1981, 1986; Ayers and Kaiser, 1984; Pocknall and Flores, 1987; Flores and Moore, 1994).

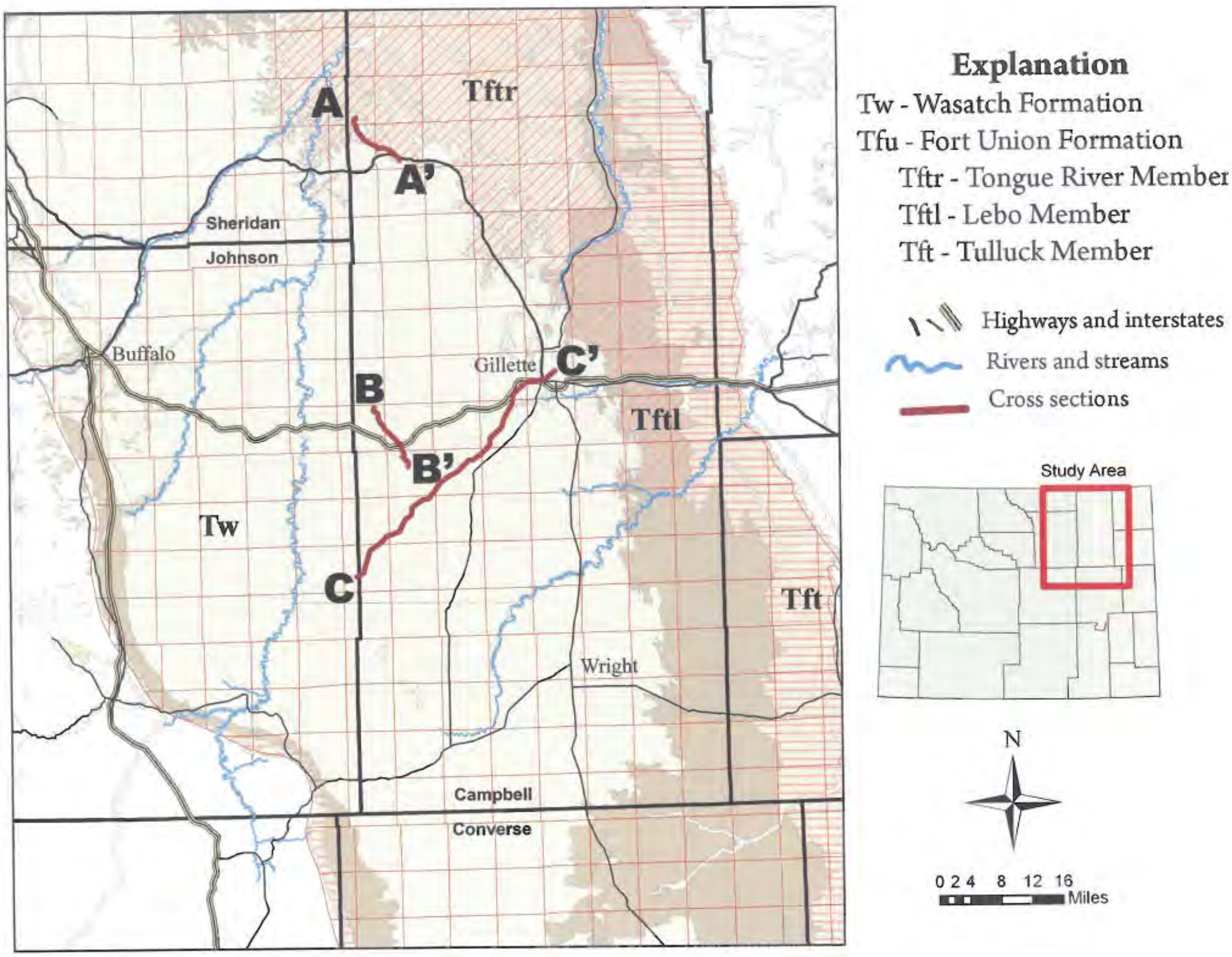


Figure 1. Map of study area showing locations of cross sections. *Illustration from N.R. Jones (2009).*

At other locations in the basin where the geometry of a parting is wedge shaped, the thickness of one or both of the interrelated (stratigraphically adjacent) coals "pinches out" (thins to zero) some distance from the split (**Figures 3b** and **3c**). These partings and bed geometries are considered to be the result of alternating wetland facies and fluvial-lacustrine facies (Flores 1981, 1986; Ayers and Kaiser, 1984; Pocknall and Flores, 1987; Flores and Moore, 1994). Regardless of their shape, partings between two interrelated coals typically consist of shale, mudstone, siltstone, and sandstone but vary in composition from location to location in the basin. This parting material is widely accepted as consisting of stacked fluvial and lacustrine deposits.

The contact between the top of a parting and the base of the overlying coal and the contact between the bottom of the parting and the top of the underlying coal are clearly recognizable surfaces that serve as stratigraphic horizons (**Figure 4**) (N.R. Jones, 2009). Where the thickness of a parting goes to zero, the overlying and underlying coals merge, and the contact between them continues into the combined coal (**Figure 5**). Tracing this surface beyond the merge point of the two coals, however, can be difficult and requires detailed field observation, core analysis, and access to exposed faces of coal in mine highwalls such as shown in **Figure 5**.

This subtle and often difficult-to-recognize layer is an oxidized coal interval that ranges in thickness from a

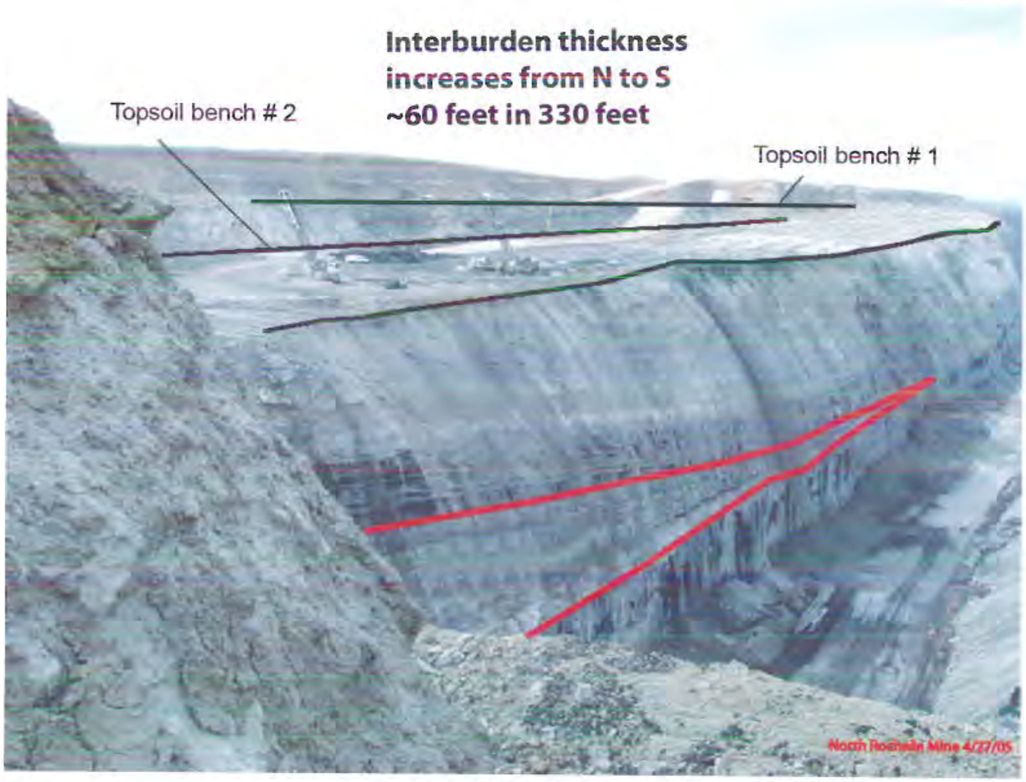


Figure 2. Photo showing major split (highlighted in red) and development of parting between Wyodak coals. Note the increase in interburden thickness. *Photo by Tim Rohrbacher, U.S. Geological Survey, circa 1990, and used with permission.*

few inches to several feet and can be considered to be a paleosol. The paleosols within the coal deposit represent hiatuses that indicate an absence of the overlying peat deposit and subaerial exposure of the surface of the underlying, previously deposited organic material. The oxidized layers (P0 through P12, **Figure 5**) are heterogeneous and consist of claystone, gypsum, weathered coal, bone coal, rooted zones, and high concentrations of the coal maceral fusain, a charcoal that is produced from burning coal (Moore, 1994; N.R. Jones, 2009; Jones et al., 2009). The ash content (the inorganic noncombustible material in coal) is much higher (>6 percent) at the base of the coal directly above an oxidized layer (between P0 and P1, **Figure 5**).

Different interpretations have been developed on the basis of these observations. There are several questions to consider concerning the interpretation of these coals, and how they are addressed has led to the new interpretations discussed in subsequent sections of this report. Four questions that field investigators have focused on are (1) what type or types of wetland environments produced such thick coal deposits; (2) what were the mechanisms that produced sufficient accommodation; (3) what were the processes that caused splits to occur; and (4) why is the ash content in these coal deposits so low? This author poses another question: How did the unique angular relationships between stratigraphically adjacent coal deposits develop?

STRUCTURAL SETTING

The PRB is an elongate, north–south, asymmetric synclinal trough that formed during compartmentalization of the Cretaceous foreland east of the Wyoming Overthrust Belt. The axis of the basin is located west of the basin's geographic center and trends north-northwest into Montana (Curry, 1971). The basin is bounded on the west by the Bighorn Mountains, on the north by the Grass Creek Anticline and Miles City Arch in Montana, on the east by the Black Hills, and on the south by the Hartville Uplift, Laramie Mountains, and Casper Arch.

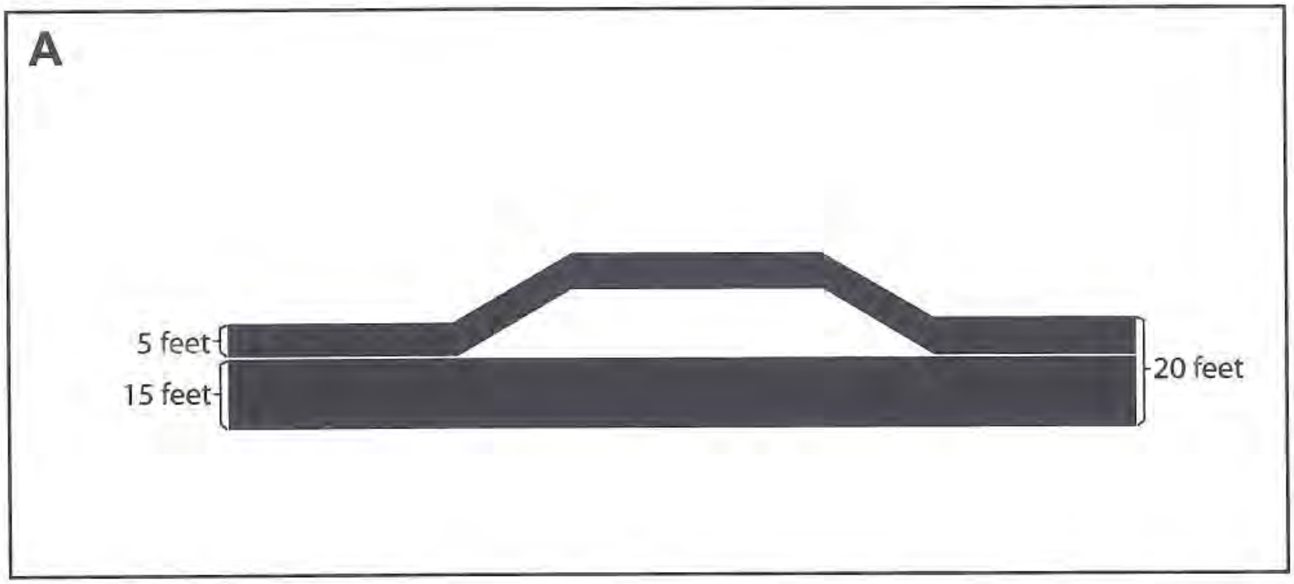


Figure 3a. Continuity of coal thickness across a lenticular-shaped parting. *Illustration from N.R. Jones (2009).*

Initial compartmentalization of the Cretaceous foreland began approximately 100 million years ago (Ma) and is attributed to the formation and eastward migration of intrabasinal highs and lows in response to eastward tectonic propagation from the Overthrust Belt west of the PRB (Steidtmann, 1993). This age determination is also evident from channel patterns mapped in the Lower Cretaceous Muddy Sandstone (Dolson et al., 1991) and from biostratigraphic work on condensed sections on paleotopographic highs in areas now occupied by swells, arches, and uplifts (Merewether, 1983; Merewether and Cobban, 1986).

Initial development of the PRB occurred between 75 and 80 Ma during the transition between the Sevier and Laramide orogenies (Beck et al., 1988; Tikoff and Maxson, 2001). The most significant development of the basin was in the late Paleocene and early Eocene during a period of heightened Laramide activity. Evidence for this occurs along the western margin of the basin as a syntectonic sequence that coarsens upward from the uppermost part of the Tongue River Member into the early Eocene Kingsbury and Moncrief Conglomerate Members of the overlying Wasatch Formation (Hoy and Ridgeway, 1997). The changing composition of this sequence indicates final unroofing of Mesozoic strata and initiation of the sequential unroofing of the more competent Paleozoic strata from the Bighorn basement block. During this period in the Laramide, it is likely that fault reactivation in the basement occurred along pre-existing zones of weakness; the present-day surface expressions of these zones are called *lineaments* (**Figure 6**). Following this unroofing sequence, the Precambrian basements of the Bighorn and Black Hills blocks were exposed, and because of the more competent nature of these rocks, uplift outpaced erosion, which resulted in significant relief between the tops of the rising blocks and the surface of the basin (Whipkey et al., 1991).

STRATIGRAPHIC SETTING

The Tongue River Member was deposited during a brief (4-million-year) period between 63 and 59 Ma (Lisenbee and DeWitt, 1993) and is subdivided into two stratigraphic facies: (1) a lower meandering fluvial facies characterized by meander-belt lithofacies and thick coals deposited in swamp environments and (2) an upper anastomosed fluvial facies characterized by lacustrine, lacustrine-delta, and crevasse-splay lithofacies and thin coals deposited in lake-margin swamp environments (Flores 1981, 1986; Pocknall and Flores, 1987; Flores and Moore, 1994). Ayers and Kaiser (1984) characterized the stratigraphic facies

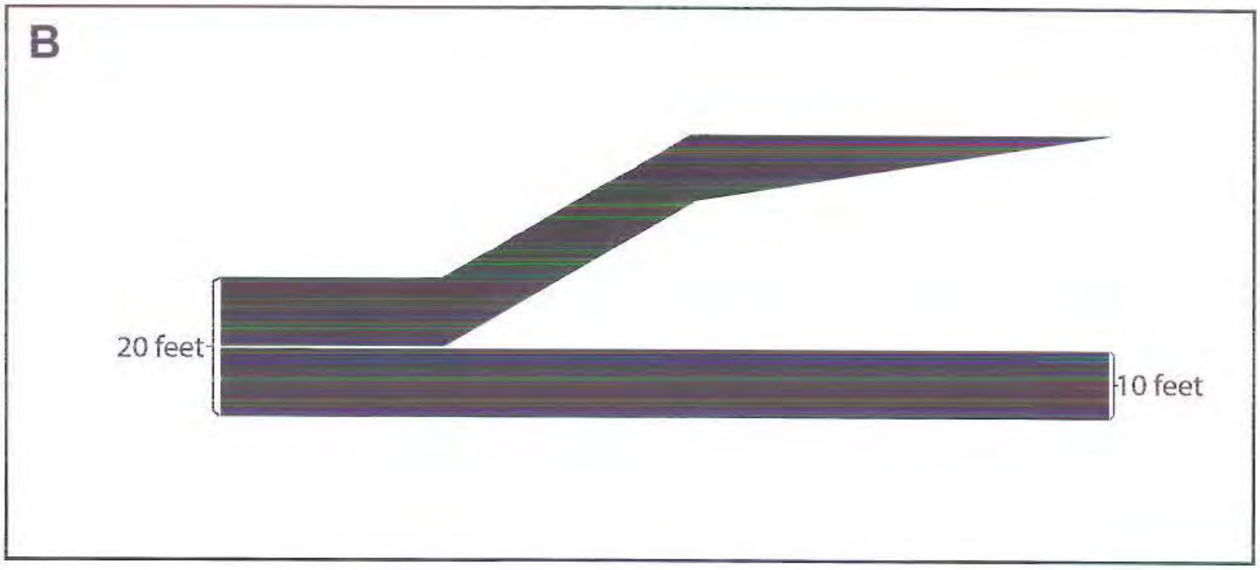


Figure 3b. Pinch-out of coal deposit some distance from a wedge-shaped split. *Illustration from N.R. Jones (2009).*

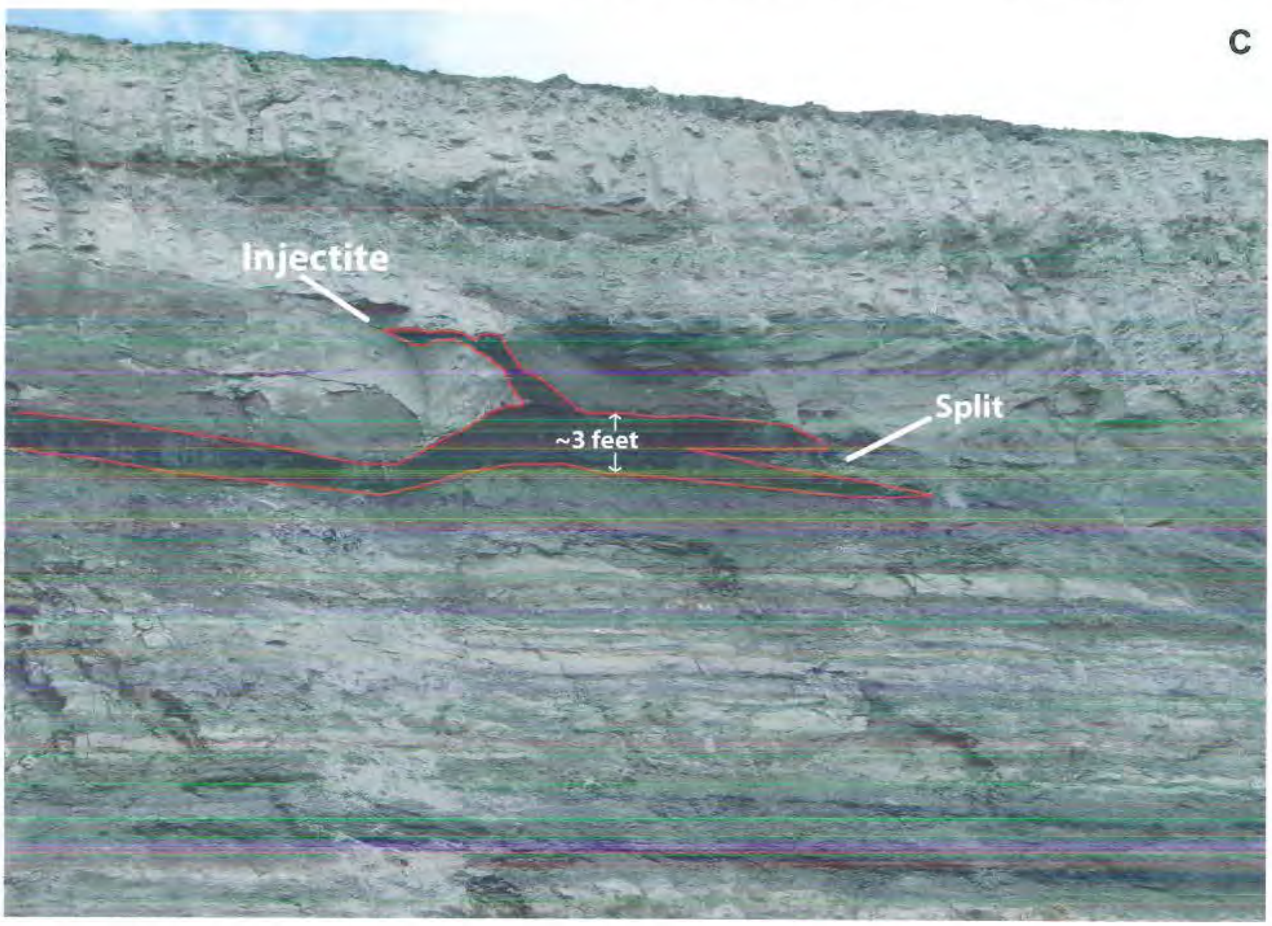


Figure 3c. Photo showing termination of coal bed and splitting resulting from facies change. The injectite is a result of soft sediment deformation caused by loading of the hydrophilic gel called *gytta*, the precursor of coal. *Photo from N.R. Jones (2009).*

of the Tongue River as transitional from fluvial-deltaic facies along the basin margin, to an interdeltaic swamp facies, to a lacustrine facies within the basin.

Moore (1994) analyzed compositional variations in the cores of three stratigraphically adjacent Paleocene coals and determined that the stratigraphically adjacent coal beds represent a stacked mire sequence disrupted by channel-overbank deposits.

More recently, the author divided the Tongue River Member into seven coal zones on the basis of distinct stratigraphic intervals containing coal sequences identifiable in well data. The coal zones are (1) Roland, (2) Wyodak Rider, (3) Upper Wyodak, (4) Lower Wyodak, (5) Cook, (6) Wall, and (7) Basal Tongue River (Jones, 2008) (**Table 1**).

STRUCTURAL VS. DEPOSITIONAL INFLUENCES ON ACCOMMODATION

The current consensus is that throughout the Paleocene, development of *accommodation* (the available space for sediments to accumulate) and the rate of basin fill were in equilibrium, so that erosion of sediments kept pace with uplift. During this time, the PRB was a *perimeter* basin with gentle structural relief along its flanks (Dickinson et al., 1988). In order to explain how extraordinarily thick deposits of coal developed, previous interpretations focused on rates of peat accumulation coincident with rates of subsidence. These interpretations assumed that accommodation developed due to (1) regional subsidence at a rate of 0.5 foot per thousand years (Ayers and Kaiser, 1984), (2) differential compac-

Figure 4. Photo showing distinct stratigraphic horizons at the top and base of coals and increasing thickness of the clastic material between the coal beds – "the interburden or parting material." The dip of the lower coal is parallel to the structural dip of the Fort Union Formation. *Photo from N.R. Jones (2009).*

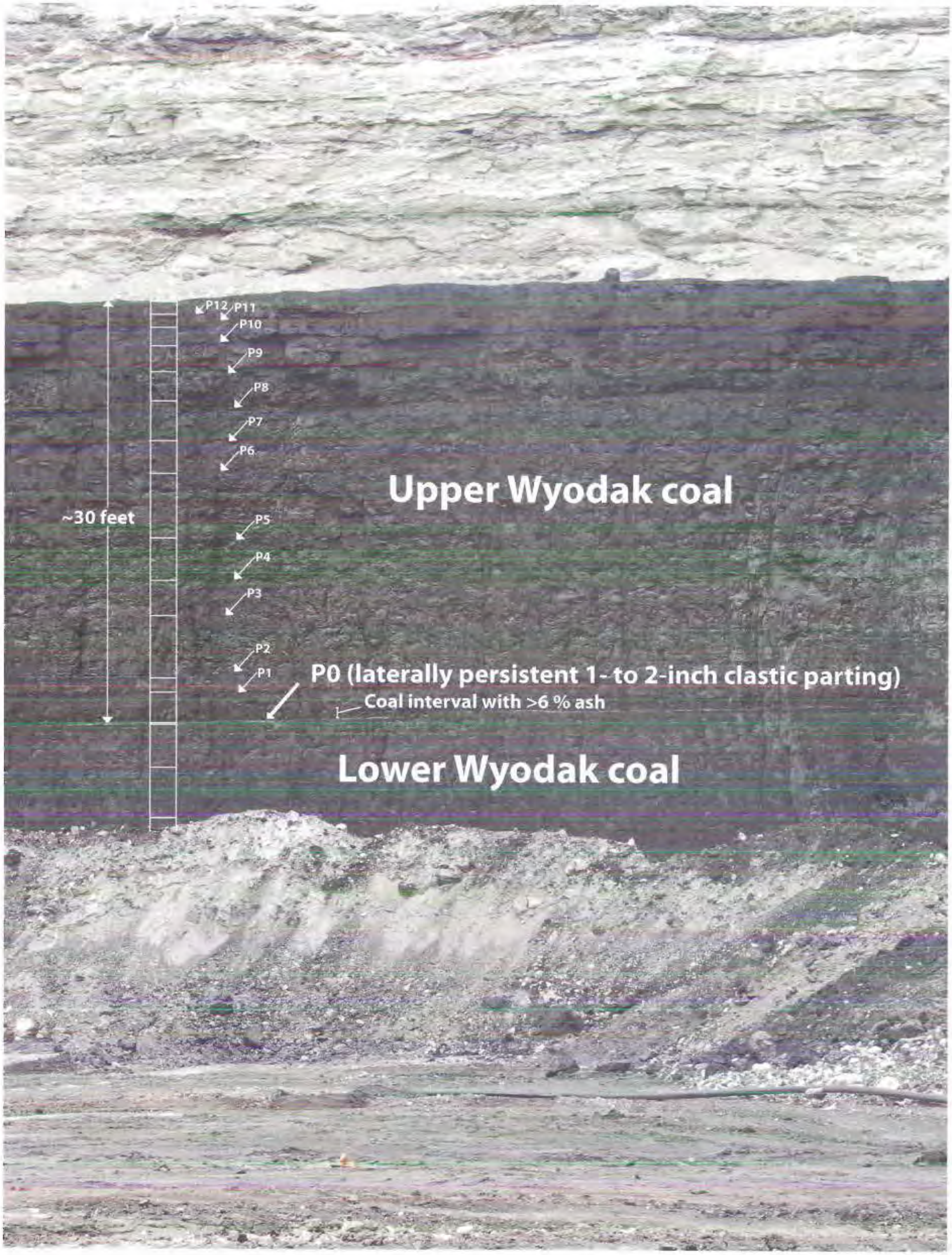


Figure 5. Photo showing distinct stratigraphic horizons within and between the two major Wyodak coals where the parting material between them is minimal. *Photo from N.R. Jones (2009).*

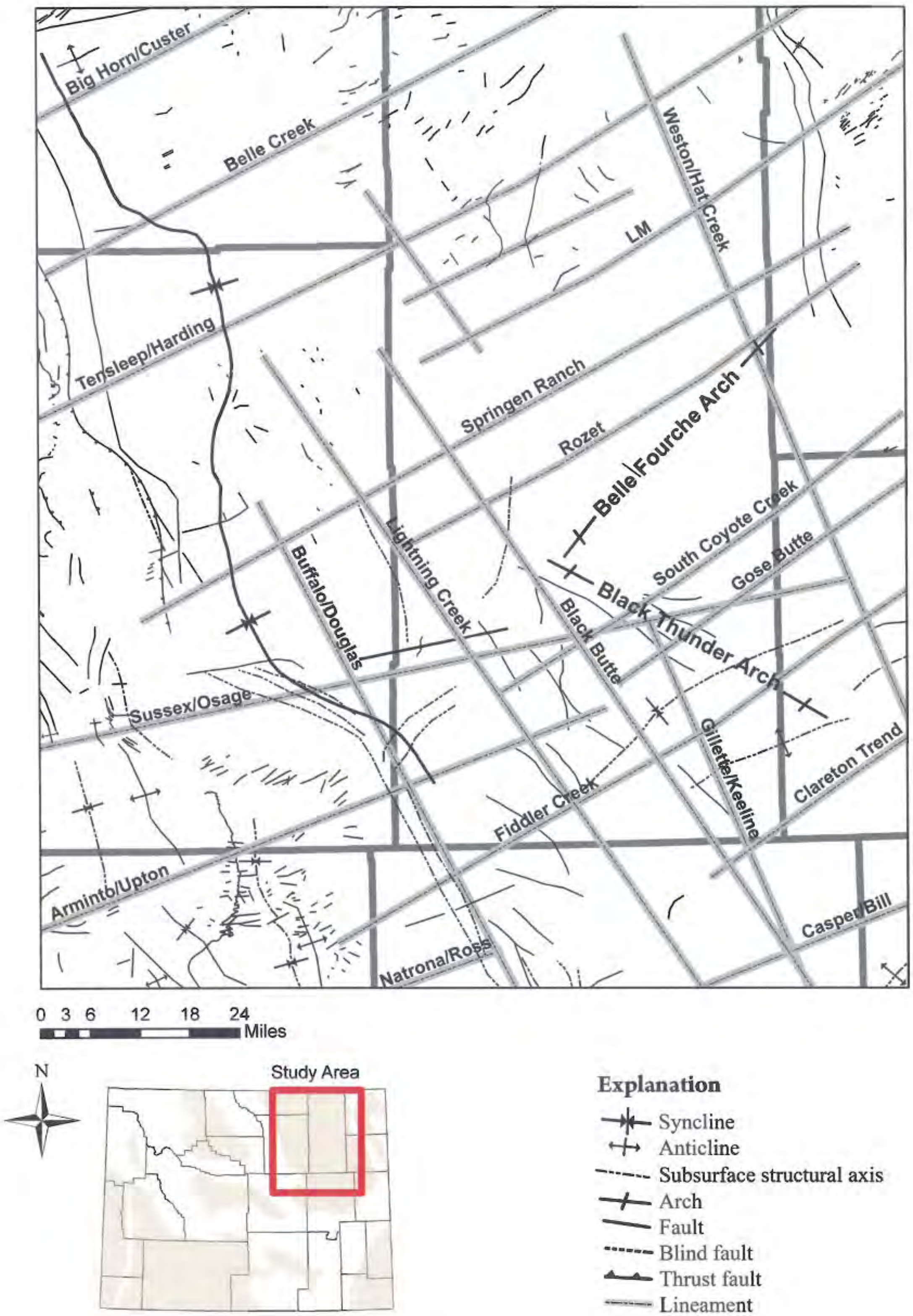


Figure 6. Generalized structure map of the Powder River Basin denoting subsurface structures, blind faults, and lineaments. *Illustration compiled from Denson et al. (1978a, b), Marrs and Raines (1984), and Martinsen (2003a, b; 2008).*

Table 1. Coal stratigraphy of Tertiary rocks in the Powder River Basin. Number of wells represents the total number of wells wherein a coal deposit was identified; coal zone refers to a distinct stratigraphic horizon that contains packages of interrelated coal deposits; acres indicates the modeled subsurface extent of a coal bed; million tons indicates the modeled value of in-place coal resources for each coal deposit. Summed coal resources in this table are approximately 1.1 trillion tons. *Table modified from Jones (2008).*

Formation	Maximum thickness	Number of wells	Coal bed name	Coal zone	Acres	Million tons
WASATCH	40	41	Ulm	Upper Wasatch	87,684	4,125
	54	164	Buffalo Cameron (Lake De Smet)		468,400	12,416
	147	251	Murray (Lake De Smet)		766,503	13,123
	212	377	Ucross (Lake De Smet)		814,184	19,736
	25	431	Felix Rider	Felix	1,412,514	13,269
	47	631	Upper Felix		1,531,376	18,992
	77	1517	Felix		2,103,350	40,391
	75	431	Arvada	Lower Wasatch	904,397	21,899
	45	485	Unnamed		162,702	4,352
FORT UNION	39	1185	Upper Roland	Roland	402,998	11,121
	93	2849	Roland of Baker		1,208,048	37,110
	58	1615	Roland of Taff		1,127,022	37,087
	107	525	Smith Rider	Wyodak Rider	668,384	26,400
	216	2311	Smith / Big George		1,791,288	147,573
	100	603	Lower Smith		1,703,440	37,848
	52	382	Anderson Rider	Upper Wyodak	1,032,257	29,952
	208	2856	Anderson		3,789,227	225,800
	167	1015	Lower Anderson		2,998,382	97,312
	38	270	Canyon Rider	Lower Wyodak	335,146	9,114
	205	1131	Canyon		1,689,675	79,848
	145	903	Cook	Cook	1,788,301	76,430
	38	172	Lower Cook		638,128	16,420
	139	996	Wall	Wall	1,862,080	73,112
	58	494	Lower Wall		3,177,455	54,701
	50	586	Pawnee		1,097,580	30,996
	45	374	Moyer	Basal Tongue River	1,250,938	39,498

tion of underlying sediments in response to loading (assumed in all models), and (3) auto-compaction of peat based on compaction ratios between 3:1 (3 feet of peat compacting to form 1 foot of coal) and 10:1 (Flores 1981, 1986; Ayers and Kaiser, 1984; Flores and Moore, 1994; Kent, 1986; Pocknall and Flores, 1987; Moore and Shearer, 1993).

Accepted structural influences on the development of accommodation in the PRB during the Paleocene are a combination of (1) regional subsidence related to basin formation, (2) structural deformation in the basin in response to the uplift of adjacent basement blocks, and (3) basin subsidence resulting from the movement of the underlying basement blocks (Slack, 1981; Martinsen and Marrs, 1985).

Postulated depositional influences that created accommodation in the PRB during the Paleocene are changes in base level, aggrading river systems, and compaction of sediments in response to loading. During this time, sedimentation kept pace with available accommodation, causing the available space to fill with deposits such as organic accumulations, fining-upward sequences of overbank-crevasse splays, fine-grained lacustrine sediments, and medium- to coarse-grained channel and fluvial-deltaic sediments.

WETLANDS

Important research for this study included fieldwork and the study of present-day subtropical wetland environments along the east coast of the U.S. from the Carolinas south to Georgia and Florida, as well as southern Louisiana. Wetlands that were visited and studied include the Great Dismal Swamp in Virginia; back beach barrier island wetlands along the Outer Banks off the coast of North Carolina; the Okefenokee Swamp in Georgia; the Corkscrew, Big Cypress, and Mangrove swamps and the Everglade marshes in Florida; the upper and lower delta plain along the Mississippi River; and the Atchafalaya Basin and Pointe Lake in southern Louisiana. Throughout this fieldwork, ecologists, botanists, and naturalists contributed much information about subtropical wetland environments.

These wetland environments occur in areas with a subtropical climate, are at or near sea-level, and are flat lying. Variations in daily temperature are minimal, and precipitation exceeds 50 inches per year. They are similar to the paleo-wetlands of the early Tertiary in the PRB (McClurg, 2009).

Notable wetland characteristics that influence the nature of organic accumulation include the level of the water table, water chemistry, ecological heterogeneity (the diversity of ecosystems in wetland environments), flow velocity, and seasonal fluctuations in temperature. The three most important characteristics are fluctuations in the level of the water table, water chemistry, and ecological heterogeneity. These three factors significantly influence the composition and accumulation of organic material in wetland ecosystems.

The most significant influence on organic accumulations in wetland systems is the level of the water table. Wetlands are low, flat-lying environments wherein deposition of organic material occurs parallel to the surface of the water table. Organic detritus that is shed onto the floor of a wetland in subaerial conditions rapidly succumbs to nearly complete oxidation and decay. Residence time for this material under these conditions is short, and the released nutrients are recycled back into the mega flora. If this material accumulates in anoxic subaqueous conditions, oxidation and decay are restricted, and available nutrients in the material are consumed by anaerobes. Under these conditions, the residence time for the material is long, and nutrient cycling is restricted, which results in a thickening accumulation of organic-rich hydrogel relative to available accommodation (the space available for sediments to be deposited).

Water chemistry – specifically pH and dissolved oxygen – is also an important factor affecting the characteristics of accumulating organic material in wetlands. Subaqueous decay of dead organic material consumes oxygen and produces acids. As the available dissolved oxygen is consumed and the pH of the waters in the wetland is depressed, the rate of microbial activity is affected. Water chemistry combined with low nutrient levels retards the biogenic decay of accumulated organic material. Increased acidity also affects the color of the water by staining it a brown to black tea-color, hence the term "black-water swamp." When swamp waters mix with the turbid water of a flowing channel or an open body of water, rapid settling of suspended particles occurs at the mixing interface via a process called *flocculation*. Flocculation occurs at the margin of wetlands. This process inhibits the intrusion and mixing of clastic material with accumulating organics. This occurs immediately behind the turbid water/black-water interface. A result of this process is low-ash coal (McClurg, 1988, 2009) (**Figure 7**).

The various interrelated ecosystems within wetlands include flooded meadows, flooded prairies, shallow bodies of open water, and densely vegetated flooded forests (**Figures 8** and **9**). Due to changes in the level of the water table, these ecosystems can shift position within a wetland and result in variations in the nature of the organics that are deposited and also the nature of hydrophilic gel that accumulates.

Figure 7. Aerial photo showing the mixing interface and zone of flocculation between swamp waters and turbid waters in the Atchafalaya Basin, southern Louisiana. This buffering prevents clastic material in the turbid waters from mixing with organic material in the swamp and results in low-ash coal deposits. *Photo from N.R. Jones (2009).*

PREVIOUS WORK

There are four notable models of how thick deposits of low-ash coal formed in the Tongue River Member of the Fort Union Formation in Wyoming's PRB. For the purpose of discussion, these models are termed (1) fluvial systems and raised mires (Flores, 1981, 1986; Pocknall and Flores, 1987; Flores and Moore, 1994), (2) lacustrine-interdeltaic systems and discharge of groundwater (Ayers and Kaiser, 1984), (3) the "teeter-board" hypothesis (Kent, 1986), and (4) basin-wide wetlands and shallow lacustrine systems (McClurg, 1988).

Key factors in these models include the nature of the mires in which the peat accumulated, the accommodation indicated by the accumulation of peat, the alleged great compaction of peat in coal formation, the paucity of clastic sediments that resulted in low-ash coal, and the intermittent accumulations of clastic sediment that split the coal.

FLUVIAL SYSTEMS AND RAISED MIRES

Flores (1981) divided the Tongue River Member into two stratigraphic facies: an upper anastomosed (braided) fluvial facies (**Figure 10a**) and a lower meandering fluvial facies (**Figure 10b**). The upper anastomosed facies is characterized by lacustrine, lacustrine-delta, and crevasse-splay lithofacies and thin coals that were deposited in lake-margin swamp environments. The lower meandering facies is characterized by meander-belt lithofacies and thick coals deposited in swamp environments. The major drainage for the basin during these periods was a major, north-flowing, basin-axis, trunk channel.

The thin coals of the upper facies formed from thin accumulations of peat in low-lying swamps that developed along the margins of flood-basin lakes. Laterally persistent clastic partings between thin coal beds are interpreted to have resulted from differential compaction of lake sediments. These sediments were depos-

Figure 8. Photos showing the ecological heterogeneity of swamp environments. **A**, Flooded forest in Pointe Lake, Louisiana; **B**, densely vegetated region within the Corkscrew Swamp, Florida; **C**, flooded forest in the Big Cypress Swamp, Florida; **D**, flooded meadow in the Okefenokee Swamp, Georgia; **E**, flooded meadow in front of a flooded forest in the Okefenokee Swamp, Georgia. *Photos from N.R. Jones (2009).*

Figure 9. Aerial photos showing the ecological diversity of marsh and marsh/swamp environments. **A**, Coastal marshes along the lower Mississippi River Delta; **B**, boundary between the upper and lower delta plains of the Mississippi River Delta. Note: Variations in the level of the water table can shift the locations of adjacent wetland environments. *Photos from N.R. Jones (2009).*

Figure 10. A, Block diagrams illustrating anastomosing streams and raised swamps. *Illustration from Flores (1986).* **B**, Block diagrams illustrating meandering streams, crevasse splays, and channel avulsion. *Illustration from Flores (1986).*

ited over the top of the drowned lake-margin peat swamp and from increased loading because of sediment deposited in crevasse splays and lacustrine deltas.

The thick coals of the upper facies formed from peat that accumulated in raised mires. *Raised mires* are peat deposits that develop above the local fluvial drainage level (surface water table) and are protected from detrital influx during periods of excessive flooding. This concept of raised mires is used to explain two factors: development of significant accommodation and the low ash content of the coals. Local drainage patterns governed the distribution of swamp vegetation, differential decay, and accumulation of organic matter. Partings consisting of sandstone, siltstone, shale, and mudstone that occur throughout a singularly thick coal bed are interpreted to be overbank deposits of adjacent fluvial channels. Raised mires exist today in parts of Indonesia that develop thicknesses as much as 30 feet above the surface water table.

Individual splits in coals may result from either syndepositional processes or syntectonic processes. Syndepositional processes encompass depositional environments (e.g., rivers, lakes, fans, and deltas), differential compaction of sediments, and autocompaction of peat. The syntectonic processes are folding and growth faulting.

Compaction of peat is assumed at a conservative ratio of 3:1 (3 feet of peat is compacted to produce approximately 1 foot of coal). This ratio accounts for syndepositional autocompaction of peat.

LACUSTRINE-INTERDELTAIC SYSTEMS AND DISCHARGE OF GROUNDWATER

Ayers and Kaiser (1984) concluded that the PRB had originated as a structural and depositional basin by early to middle Paleocene. As the basin rapidly subsided, a large lake (Lake Lebo, named for the middle Lebo Shale Member of the Fort Union Formation) formed along the axis of the basin. Lake Lebo was subsequently filled in with clastic sediments transported into the lake by peripheral fluvial-deltaic systems (**Figure 11**).

These sediments came from the east as elongate river deltas transporting mixed bed-load sediments from the ancestral Black Hills, from the southwest as mixed bed-load streams flowing from what is today the Wind River Basin, and from the northwest as elongate river deltas transporting mixed suspended to mixed bed-load sediments from what is today the Bull Mountain Basin in Montana (**Figure 11**).

Basin subsidence commenced following deposition of the lower Tullock Member of the Fort Union

Figure 11. Paleo-reconstruction of middle to late Paleocene lacustrine-interdeltaic systems in the Powder River Basin. *Illustration from Ayers and Kaiser (1984).*

Formation and proceeded at a rapid rate throughout deposition of the middle Lebo Shale Member and upper Tongue River Member of the Fort Union. The rate of subsidence is generally estimated to have been approximately 0.5 foot per 1,000 years, a rate typical of Laramide basins in Wyoming during the Paleocene.

According to Ayers and Kaiser (1984), there is no evidence for a basin-axis fluvial system, as suggested by previous research (Flores 1981, 1986), as sand percentages are lowest along the axis of the basin.

Ayers and Kaiser's model is based on the relationship between the framework elements (deltas and interdeltaic systems along a lake margin, as delineated by sand percentages) and on persistent paleo-swamp environments similar to those related to the lignite deposits along the Gulf Coast of Texas. The thick coals developed in inferred distal deltaic and interdeltaic locations within the basin.

Major peat-forming swamps were initiated at the distal end of the lacustrine deltaic network, where the hydraulic gradient in combination with flow barriers forced surface discharge of groundwater upward toward the surface through the peat. This process was sufficient to maintain water levels at or near the land surface, creating conditions favorable for peat accumulation. This concept of forced surface discharge of groundwater is used to explain two factors: the development of accommodation and the low ash content of the resulting coals.

Studies on rates of modern peat accumulation suggest a mean peat accumulation rate in the PRB peat swamps of approximately 5.6 feet per 1,000 years. Using this rate and assuming a 5:1 compaction ratio for the transformation of peat into subbituminous coal, Ayers and Kaiser determined that a coal bed 100 feet thick would require approximately 500 feet of peat to accumulate over an 89,000-year period. They concluded that this duration of peat accumulation far exceeds the natural length of time between cycles of avulsion and channel switching in major fluvial systems; therefore, thick coals in the PRB were not deposited in a fluvial dominated system, as proposed by previous research (Flores, 1981, 1986; Ayers and Kaiser, 1984; Ayers, 1986).

THE 'TEETERBOARD' HYPOTHESIS

Kent (1986) suggests that the Laramide Orogeny – specifically, subsidence along the western PRB in conjunction with active Laramide uplift of the Black Hills and Bighorn blocks and the effect it had on the eastern, northeastern, and far western areas of the PRB – resulted in prolonged periods of optimum conditions for deposition of thick beds of peat.

This model proposes a migrating fulcrum area between areas of subsidence in the west and uplift in the east. The fulcrum area, juxtaposed between the moving areas, was in dynamic equilibrium and would migrate in response to pronounced uplift in the east or subsidence in the west. Organic material accumulated in the fulcrum area across a west-tilted paleoslope: subsidence in the area west of the fulcrum was in balance with the accumulation of organic material, and this balance resulted in thick deposits of peat. When the fulcrum migrated to the west in response to uplift of the Black Hills block, clastic material was shed onto the area east of the migrating fulcrum, burying and preserving the thick beds of accumulated peat, while in the west, clastic material was shed from the uplifting Bighorn block into the basin and deposited in areas west of the fulcrum. Again, when pronounced subsidence in the western basin caused the fulcrum to migrate to the east, the influx of clastic sediment from the west would arrest peat formation and would bury and preserve thick beds of accumulated peat.

Kent's model emphasizes a compaction coefficient of peat to coal of approximately 3:1. This 3:1 ratio is based on water loss and varies inversely with the specific moisture content of the rank of coal involved.

BASIN-WIDE WETLANDS AND SHALLOW LACUSTRINE SYSTEMS

McClurg (1988) concluded that the anomalously thick, low-ash, low-sulfur coal deposits in the PRB are the result of a series of interacting, basin-wide, lacustrine/swamp ecosystems that developed intermittently in a subsiding basin. A small-scale modern analogue of the type of wetland ecosystem described by McClurg is the Okefenokee Swamp in southeastern Georgia (**Figure 12**).

The process by which thick coal deposits split into several thinner coal beds is a function of periodic fluctuation of the water table. The margins of the swamp recede in much the same fashion as the margins of a lake during times of drought, and when the water table rises, the margin of the swamp expands. The result of a fluctuating water table is the deposition of a sequence of interfingered organic, organoclastic, and clastic sediments. When the water table rises to a level not supportive of species of rooted wetland flora, the swamp drowns and becomes a shallow body of open water.

Deposition of clastic sediment into a large, low-energy swamp is limited to a narrow band along the margin of the swamp, where the river water meets the swamp and the clay load of the river water flocculates and settles out of suspension. This buffering at the fluctuating margin of the swamp produces localized sequences of interfingered clastic and organic sediments (splits), and it limits clastic deposition within the swamp, favoring the formation of low-ash coal.

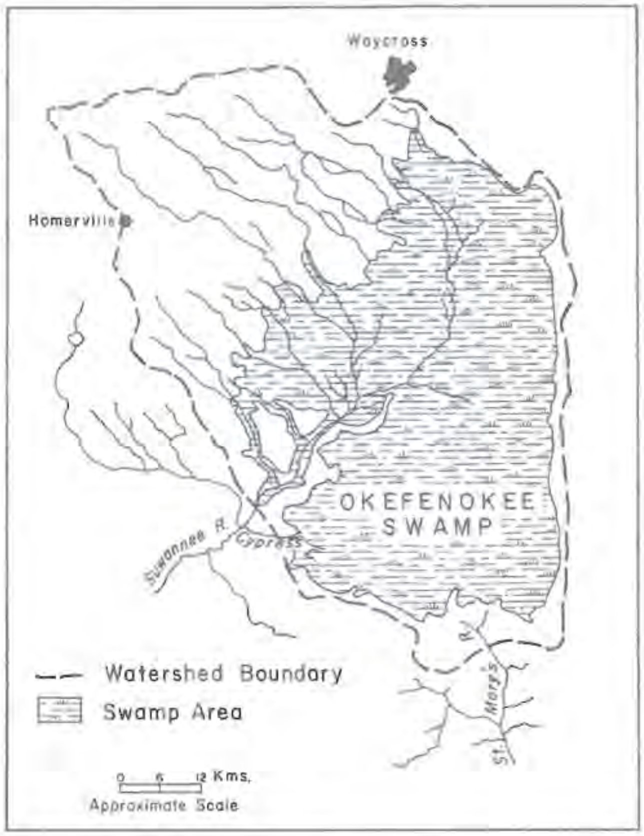


Figure 12. Map of the Okefenokee Swamp, a small-scale modern depositional analogue of Paleocene depositional environments in the Powder River Basin. *Illustration from Rykiel (1984).*

DISCUSSION

Four key points addressed in these four models explain (1) the types of wetland facies capable of producing thick coal deposits, (2) mechanisms and processes that result in low-ash coal, (3) the development of accommodation, and (4) processes that produce splits and partings in and between coal beds.

There is disagreement among the aforementioned models of Flores (1981, 1986), Pocknall and Flores (1987), Flores and Moore (1994), Ayers and Kaiser (1984), and McClurg (1988), as each model suggests a different type of wetland facies. The studies of Flores and colleagues suggest fluvial systems and raised mires based on the modern analogue of wetlands in parts of Indonesia. Ayers and Kaiser found no lithologic evidence to support a trunk channel system and conclude that the dominant facies was a lacustrine-interdeltaic system on the basis of analogues of the Gulf Coast lignites in Texas. McClurg (2009) suggests basin-wide wetlands and lacustrine systems based on the modern analogues of the Okefenokee Swamp in North America and also more recently of the Pantanal wetlands in South America.

The basin-wide wetlands and shallow lacustrine systems model of McClurg is the only model discussed in this report that recognizes physical buffering of fine-grained inorganic material along the margins of wetlands as a process that produces low-ash coal. Raised ombrotrophic (rain-fed) mires, as described in the model of Flores and others, develop above the water table and result in low-ash coal because they are not susceptible to mixing of clastic and organic material during seasonal flooding. The lacustrine-interdeltaic system of Ayers and Kaiser suggests discharge of groundwater from beneath the wetland system, a process that prevents clastic material from entering a wetland.

Apart from any specific wetland facies and processes that result in low-ash coal, Kent's (1986) teeterboard hypothesis is the only model discussed in this report that addresses the interplay between uplift and subsidence that may have occurred in the developing basin. The raised mires model by Flores and colleagues and the lacustrine-interdeltaic model by Ayers and Kaiser see the development of accommodation solely as a function of basin subsidence. The basin-wide wetland model by McClurg is the only model known by this author to emphasize that accommodation, in addition to subsidence, can also develop by increasing the surface water table. The raised mires model and the lacustrine-interdeltaic model suggest differential compaction of clastic sediments and peat as additional components of accommodation where thick coal deposits occur. None of the models, however, consider differential development of accommodation in localized areas in the PRB during the Tertiary; rather, accommodation is attributed to subsidence of the entire basin or to subsidence alternating between the east side and west side of the basin.

There is consensus among the models that splits in coal likely result from overbank deposits where wetlands are associated with fluvial systems along facies interfaces; however, McClurg's basin-wide wetlands and shallow lacustrine systems model suggests that the size of a wetland at any time is a function of the water table. If the water table drops, the size of the wetland is reduced and so is the amount of available accommodation. As the water table slowly rises and the size of the wetland expands, accommodation is created. The organics produced in the wetland accumulate above the clastics that accumulated during wetland margin recession, producing a split; however, if the water table rises too much or too quickly, the wetland becomes a lake wherein pelagic sedimentation occurs.

Sequence Stratigraphy

Sequence stratigraphy is a subdiscipline of stratigraphy used to divide sedimentary basin fill into genetic packages bounded by unconformities and their correlative conformities. The difference between sequence stratigraphic correlation and lithostratigraphic correlation is that sequence stratigraphy is based on correlation of lithologic facies in time as opposed to correlation of similar lithologic types (Emery and Myers, 1996). The time component of sequence stratigraphy makes it possible to identify laterally time-equivalent facies and to mark changes in base level and sediment supply that result in progradational sequences, aggradational sequences, and retrogradational sequences. Because base level and sediment supply are independent variables, the effect of one can overprint the effect of the other. For example, if base level remains constant and sediment supply is reduced, the result is a retrogradational sequence, but if sediment supply is accelerated, the result is a progradational sequence.

STACKED MIRE SEQUENCES

Petrographic analyses of the Paleocene Anderson-Dietz 1 coal bed in the western PRB of southeastern Montana (equivalent to the Wyodak coal in the eastern PRB of Wyoming) indicate the presence of laterally extensive layers of oxidized organic material within this thick coal deposit (Moore and Shearer, 1993; Moore, 1994). On the basis of compositional variations in coal above, below, and within the oxidized zone, Moore determined that the oxidized layers represent periods when the organic material was subaerially exposed. Moore then determined that each oxidized layer represents a period between accumulations of peat and concluded that the thick Anderson-Dietz 1 coal bed is actually composed of several stacked mire sequences.

The paradigm underlying Moore's conclusion is that thick coal deposits in the PRB are not the result of organics that accumulated in a single, long-lived, stable wetland; rather, these thick coal deposits are composed of numerous, stratigraphically adjacent coal beds that developed intermittently between periods of organic deposition and periods of non-deposition and weathering. Where these discrete horizons thicken and become lenticular or wedge-shaped partings indicates an angular relationship between the two genetic packages of coal at that location (**Figure 13**).

Furthermore, evidence for paleosols – including *fusain layers* (discrete horizons of oxidized coal), rooted zones, and evaporite deposits within and between coal deposits – indicates that subaqueous accumulation of organic material was intermittently interrupted. The regional extent of these variably thick paleosols suggests that basin-wide changes in the level of the water table likely occurred. It can also be suggested that these paleosols denote significant gaps in time between subaqueous intervals and mark hiatuses between the accumulations of organic material in wetlands.

STRUCTURAL INFLUENCES

The PRB formed as a result of the Laramide Orogeny, which was characterized by thick-skinned deformation expressed as basement-involved uplifts. The effect of the Laramide was compartmentalization of the Cretaceous foreland into a series of continental sedimentary basins bounded by Precambrian uplifts. The PRB is one of eight intermontane basins bounded by Laramide uplifts within the Wyoming portion of the Rocky Mountain foreland province (**Figure 14**). During the Laramide, basement block faulting controlled the geometry of sedimentary deposits in the basins (Blackstone, 1990). Sedimentation in these basins was most likely governed by syntectonic processes associated with fault reactivation along zones of pre-existing fractures and inherited planes of weakness. Surface expressions of these basement fracture systems appear as linear features termed lineaments (Hoppin, 1974); see **Figure 6**.

TIMING OF LARAMIDE DEFORMATION AND BASIN DEVELOPMENT

Prior to deposition of latest Cretaceous and early Tertiary continental deposits, the region that is now the PRB was in the central part of the Great Interior Seaway that occupied the greater Cretaceous foreland basin. The foreland extended across Wyoming and Nebraska and from the present-day Gulf Coast north across the U.S. and Canada to the Arctic Ocean (**Figure 15**). By earliest Tertiary (Paleocene) time, only a remnant of the Cretaceous Interior Seaway, the Cannonball Sea, occupied part of eastern Montana, all of western North Dakota, and the northwest part of South Dakota in what is today the Williston Basin (Dickinson et al., 1988; Hartman and Kirkland, 2002) (**Figure 16**).

Compartmentalization of the Cretaceous foreland basin in Wyoming and structural initiation and development of the PRB began as early as 100 Ma (Dolson et al., 1991; Steidtmann, 1993) and continued throughout the Laramide between 75 and 55 Ma (Beck et al., 1988; Tikoff and Maxson, 2001). Most of the deformation associated with the Bighorn uplift, however, occurred during the Eocene (55–35 Ma) (Dickinson et al., 1988; Hoy and Ridgeway, 1997).

Deposition of early Tertiary sediments in the PRB coincided with development of the adjacent Bighorn and Black Hills uplifts. Mesozoic rocks were shed into the basin during the Paleocene unroofing of the adjacent uplifting blocks (Whipkey et al., 1991; Crowley et al., 2002). Prior to development of the Casper Arch (a topographic high southwest of the PRB), fluvial systems from the west transported sediment northeast across this nascent feature (Dickinson et al., 1988). The composition of coarse-grained material in the uppermost Fort Union

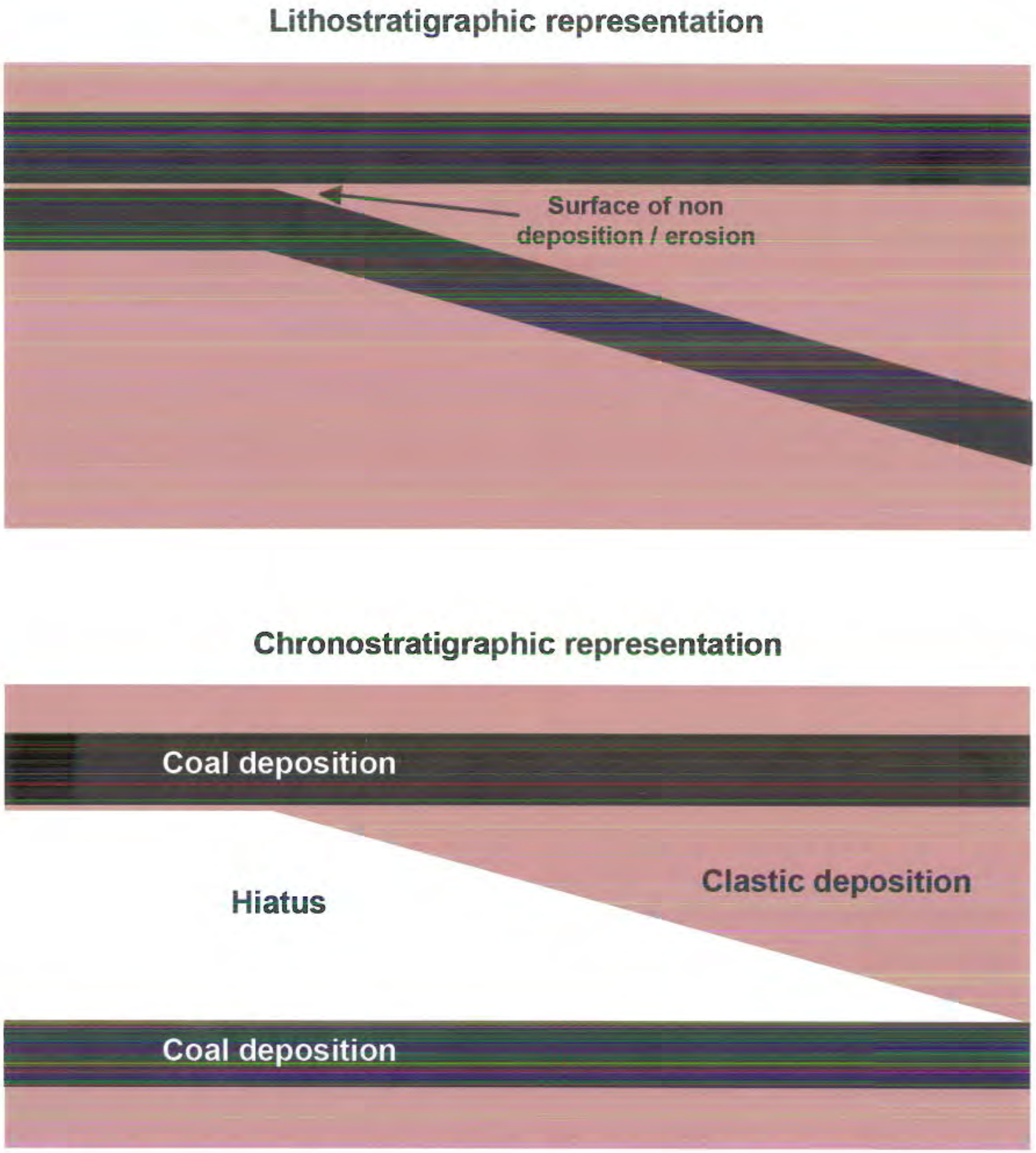


Figure 13. Lithostratigraphic and chronostratigraphic representations of a major split between thick coal deposits. *Illustration from N.R. Jones (2009).*

Formation (above the coal-bearing interval) and in the conglomeratic members in the overlying lower Wasatch Formation (Eocene) indicates that Paleozoic and Precambrian material was exposed in the cores of the uplifts by that time (Curry, 1971; Dickinson et al., 1988; Whipkey et al., 1991). Development of topographic relief between the basin and adjacent uplifts most likely increased when the unroofing sequence exposed older, more competent Paleozoic strata and the underlying Precambrian granite. This period of accelerated development of topographic relief occurred after deposition of coal in the Fort Union Formation and during deposition of the Wasatch Formation (Dickinson et al., 1988; McClurg, 2009). Paleocurrent evidence suggests that, as the basin developed, the basin axis migrated approximately

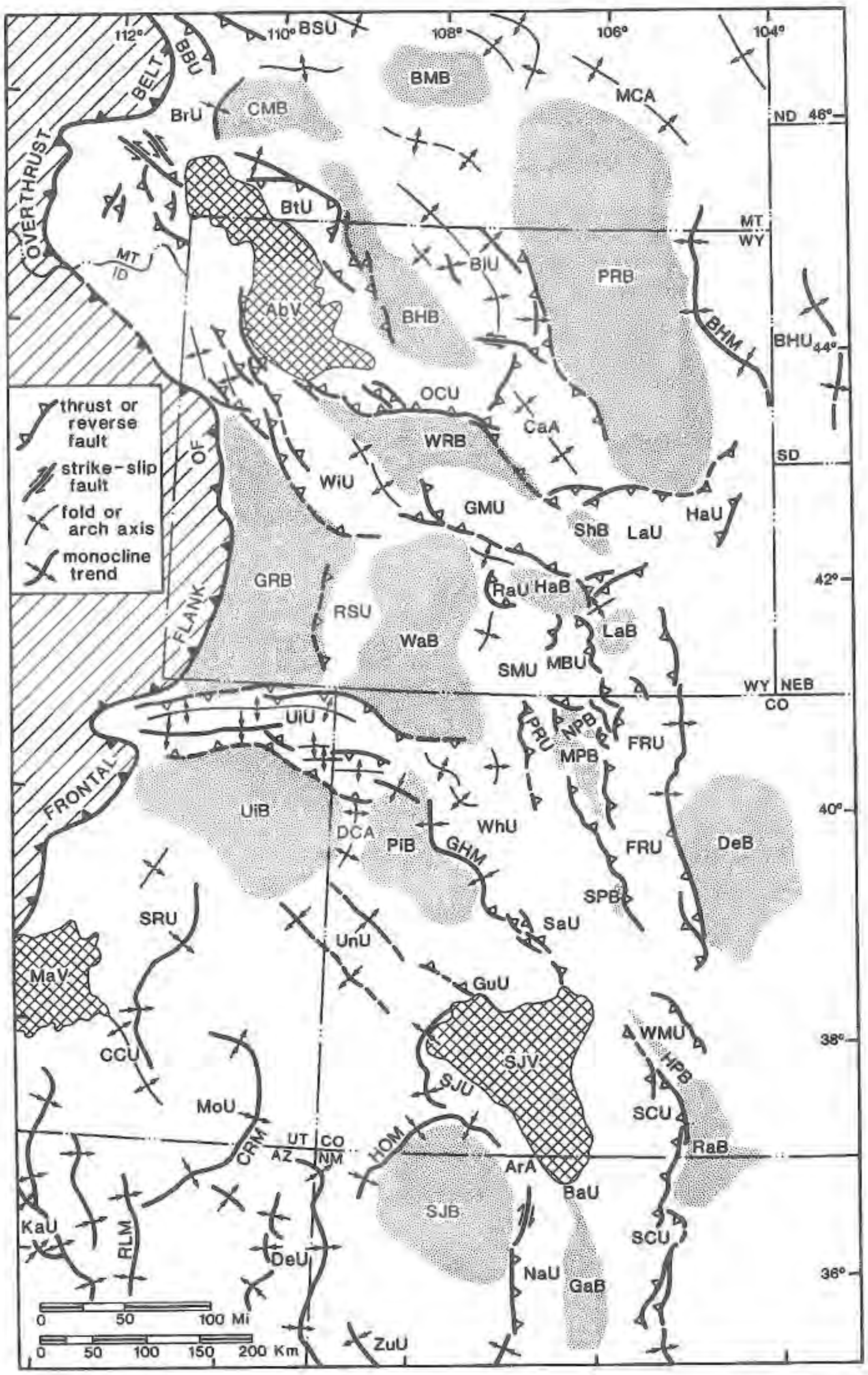


Figure 14. Map showing continental basins and regional structure in the central Rocky Mountains that developed as a result of the Laramide Orogeny. Wyoming sedimentary basins (stippled): PRB, Powder River Basin; BHB, Bighorn Basin; WRB, Wind River Basin; ShB, Shirley Basin; HaB, Hanna Basin; LaB, Laramie Basin; GRB, Green River Basin; WaB, Washakie Basin; Abv, Absaroka Volcanics. *Illustration from Dickinson et al. (1988).*

Figure 15. Illustration showing extent of Cretaceous Interior Seaway (in blue). *Illustration modified from Williams and Stelck (1975).*

45 miles westward between Tongue River time and Wasatch time (Seeland, 1992, 1993).

Significant angular relationships exist between and within Eocene, late Paleocene, and middle Paleocene coals in the central and southern PRB (**Figure 17**). Such an angular relationship can be seen in the north pit at the North Antelope Rochelle Mine in southern Campbell County (**Figure 18**).

This study proposes that angular relationships represent the variable accommodation that developed as a result of basement block faulting during the latter part of the Paleocene.

Basement Block Faulting

The most distinct expressions of movement related to basement block faulting are the Precambrian-cored mountains that surround the Laramide basins. These mountain ranges are the result of large-scale, basement-involved uplifts that were initiated as early as 100 Ma and are attributed to the formation and migration of intrabasinal highs that propagated eastward across the Cretaceous foreland basin (Steidtmann, 1993). Significant topographic development most likely occurred during the Laramide Orogeny, a period of thick-skinned deformation (75–50 Ma) (Beck et al., 1988; Tikoff and Maxson, 2001). Major faults developed along pre-existing zones of weakness, and movement along them most likely occurred in stages or pulses. The episodic nature of these movements is inferred from coarsening-upward sequences in Paleocene deposits including the Tullock Member and uppermost part of the Tongue River Member of the Fort Union Formation and basal Eocene conglomerates in the Kingsbury and Moncrief Members of the Wasatch Formation (Hoy and Ridgeway, 1997).

The large-scale deformation in the Rocky Mountain foreland during the Laramide resulted in the development of the Black Hills, Bighorn Mountains, and Wind River Range. The axes of these mountains are spaced at a semi-regular frequency, about 118 miles apart, indicating a discernable pattern that has been attributed to the coupling and decoupling of lithospheric layers (Tikoff and Maxson, 2001).

Smaller-scale deformation related to block faulting along the eastern flank of the Bighorn block (Precambrian core of the Bighorn Mountains) resulted in development of footwall growth synclines. These synorogenic, syntectonic features developed in stages (Hoy and Ridgeway, 1997) and allowed differential development of accommodation along the footwall of the growth fault. This created the accommodation along the western edge of the PRB wherein uppermost Paleocene coarsening-upward sequences and basal Eocene conglomerates were deposited.

The range of scales and timing of basement block faulting in this region during the Laramide led the author to consider the possible effects of basement block faulting within the interior of the basin. Within the PRB, rectilinear features (*lineaments*, a linear topographic feature of regional extent that is believed to reflect crustal structure) (Hobbs et al., 1976) have been mapped using satellite and aerial photography (Marrs and Raines, 1984; Martinsen and Marrs, 1985; Michael and Merin, 1986). These features are thought to be the surface expression of zones of regional structural discordance that have a long history of repeated movement

Figure 16. Illustration showing remaining extent of Cretaceous–Tertiary Cannonball Sea. *Illustration modified from N.R. Jones (2009).*

(Hoppin, 1974). In the PRB, there are two distinct sets of lineaments: one set trending northeast, the other trending northwest (Marrs and Raines, 1984).

Differential uplift related to basement block faulting within the PRB that is associated with the Black Hills uplift is attributed to the movement of basement blocks delineated by lineaments. One result of this movement is the subtle northeast-trending structure, the Belle Fourche Arch, that separates the Little Powder River and Belle Fourche River drainages (Slack, 1981).

INFLUENCES OF LINEAMENTS ON SEDIMENT DISTRIBUTION

Understanding the paleotectonic role of lineaments and their geometry helps in predicting the distribution and thickness of sedimentary rocks (Shurr, 1982; Martinsen and Marrs, 1985). An important concept regarding the paleotectonic role of lineaments and their influence on surface topography and sediment distribution is that periodic adjustments between basement blocks can result in bilateral motion, wherein the direction of offset and relative motion is periodically reversed (Martinsen, 2003a, 2003b).

Periodic movement of basement blocks below the PRB has influenced deposition and has structurally affected strata after deposition. These readjustments likely affected Paleozoic and Mesozoic sediments (Hoppin, 1974; Slack, 1981; Shurr, 1982; Marrs and Raines, 1984; Martinsen and Marrs, 1985; Michael and Merin, 1986; Martinsen, 2003a, 2003b). The syntectonic effects of local deformation associated

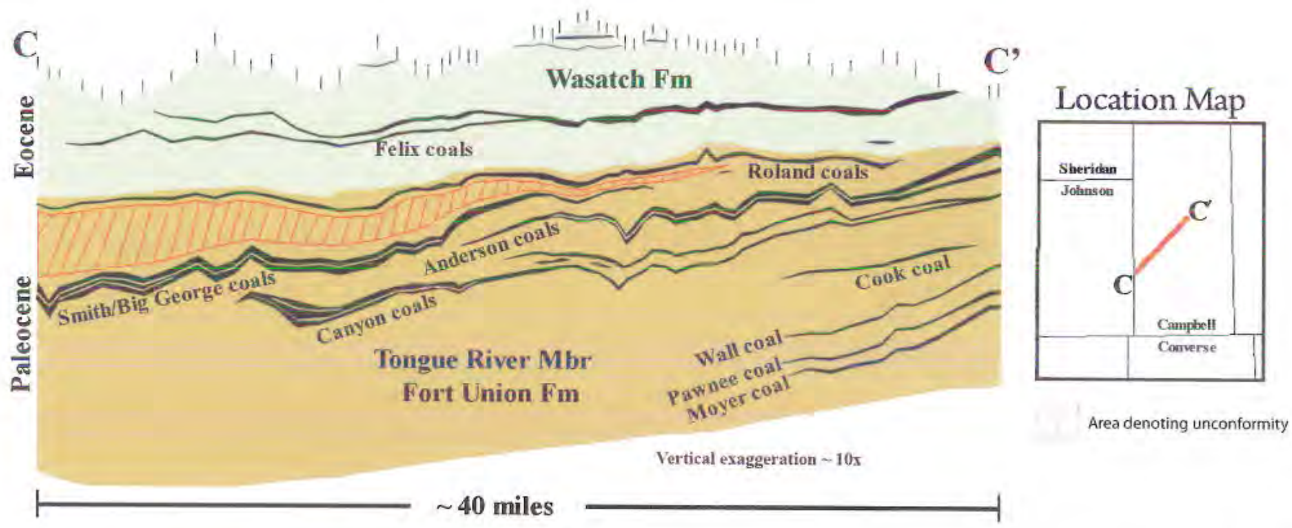


Figure 17. Location map and cross section showing angular relationship between the Roland coal zone (Roland of Baker and Roland of Taff coal beds) and the lower Wyodak Rider coal zone (Smith Rider and Smith/Big George coal beds). *Illustration from N.R. Jones (2009).*

with lineaments during the late Cretaceous may also have persisted throughout the Tertiary. Recurrent episodes of displacement along basement block boundaries were likely very subtle – about 10 feet – enough to shift fluvial systems, stabilize shorelines (Martinsen and Marrs, 1985), and develop, drain, or drown wetland systems.

Paleotectonic studies of Cretaceous hydrocarbon accumulations in the PRB have identified differential vertical uplift associated with the Belle Fourche Arch (Slack, 1981), expressed as numerous northeast-trending structural lineaments. Offsets in the Black Hills monocline, well-defined linear topographic escarpments, and linear drainage patterns are examples of these structural lineaments (Shurr, 1982). Paleotectonic channel deposits in the Lower Cretaceous Muddy Sandstone were controlled by vertical displacement along lineaments in the PRB (Slack, 1981). The distribution of sands that contain oil and gas reservoirs in the Upper Cretaceous Teapot and Shannon Sandstones is also related to lineaments (Martinsen, 2003a, 2003b) (**Figure 19**). Martinsen (2003a, 2003b) also documented how differential accommodation associated with basement blocks influenced the deposition and preservation of Cretaceous shales in the PRB and resulted in the formation of several scales of depositional (erosional) remnants.

Differential development of accommodation in the PRB during Tongue River time in the Paleocene was coincident with the Laramide Orogeny. More specifically, the accommodation where thick coal deposits formed can be attributed to the recurrent movement of basement blocks. Isopach maps of selected coal deposits in the Tongue River Member of the Fort Union Formation (Jones, 2008; N.R. Jones, 2009) were compared with the distribution of lineaments in the PRB (**Figures 20** through **25**). Noticeable trends in coal thickness distribution coincide with several lineaments throughout the basin. Key northeast- and northwest-trending lineaments that controlled coal distribution are noted below each figure.

Figure 26, an isopach map showing the summed coal thicknesses of the selected Tongue River coals, clearly relates key lineaments with coal distribution and thickness. Apart from the Lake De Smet coal deposit, there are two other areas within the PRB where thick coal deposits occur. These areas are bounded by northeast- and northwest-trending lineaments. The first is in south-central Campbell County east of the Lightning Creek lineament and

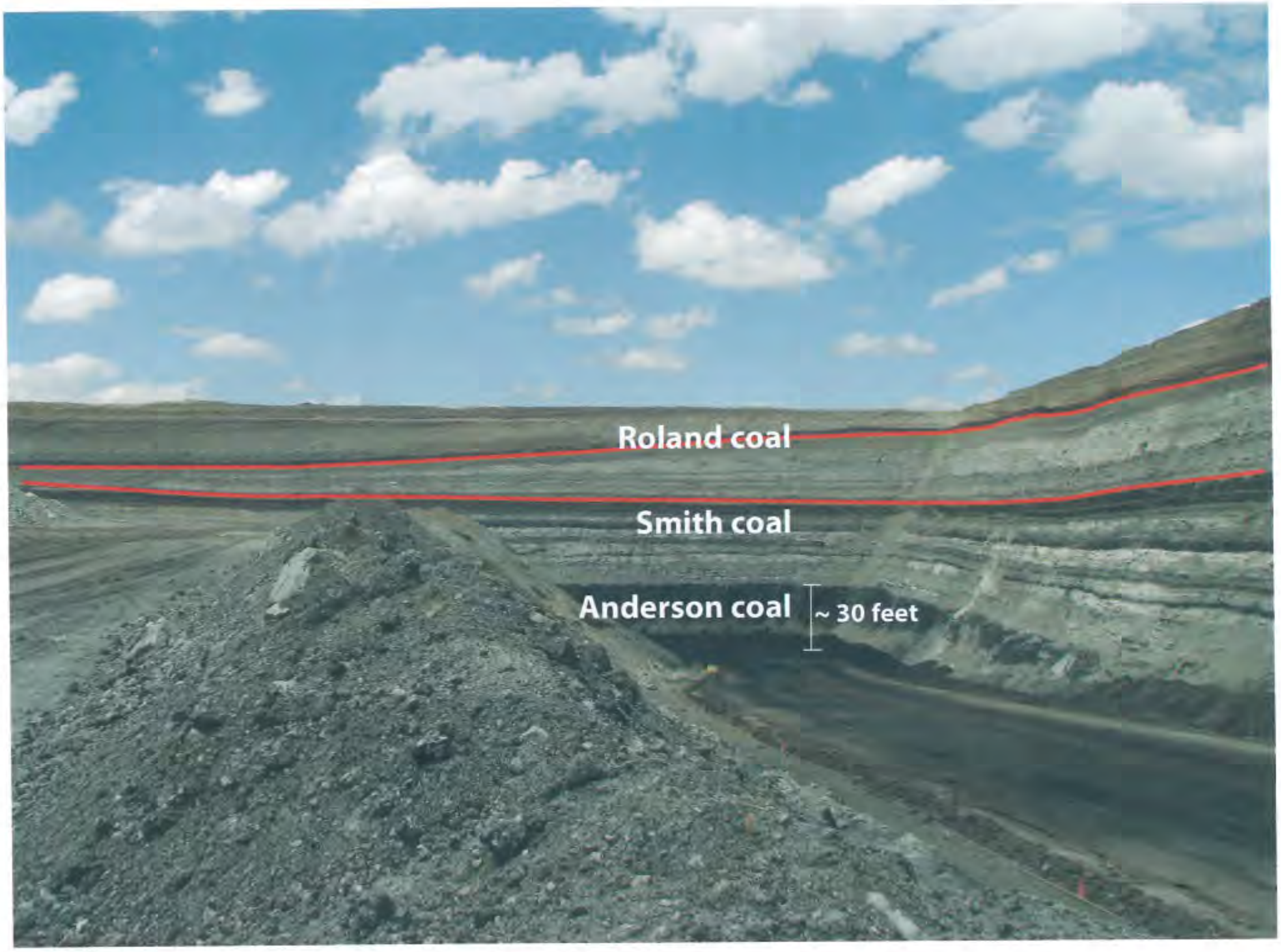


Figure 18. Highwall at the North Antelope Rochelle Mine showing the angular relationship between the Roland coal zone (Roland of Baker and Roland of Taff coal beds) and the underlying Wyodak Rider coal zone (Smith Rider and Smith/Big George coal beds). *Photo from N.R. Jones (2009).*

bounded by the northeast-trending Rozet and Gose Butte lineaments – this area coincides with the distribution of the thickest parts of the Upper and Lower Wyodak coal deposits. The second area of thick coal is in eastern Johnson County and western Campbell County; it is also east of the Lightning Creek lineament and is bounded by the northeast-trending Springen Ranch and Tensleep/Harding lineaments and coincides with the thickest part of the Wyodak Rider coal deposit.

Recurrent movement along basement faults resulted in stacked organic deposits, alternating organic and clastic deposits, and heterogeneous clastic deposits. The shedding of floral litter in a wetland results in layers of peat, and the bacterial reduction of peat is a subaqueous process sensitive to surface hydrologic changes. Subtle changes in surface topography resulting from structural movement of basement blocks disrupt this process by changing the water table, shifting fluvial systems, and effecting the stabilization of shorelines. These changes can either hinder or enhance wetland productivity of floral litter and its biogenic alteration.

An important factor regarding three of the aforementioned models is the concept of *peat compaction*. The raised mires model, the interdeltaic wetlands model, and the teeterboard tectonic model assume that tremendous amounts of accommodation are necessary to allow for great thicknesses of peat to accumulate. Thus, these models are based on the

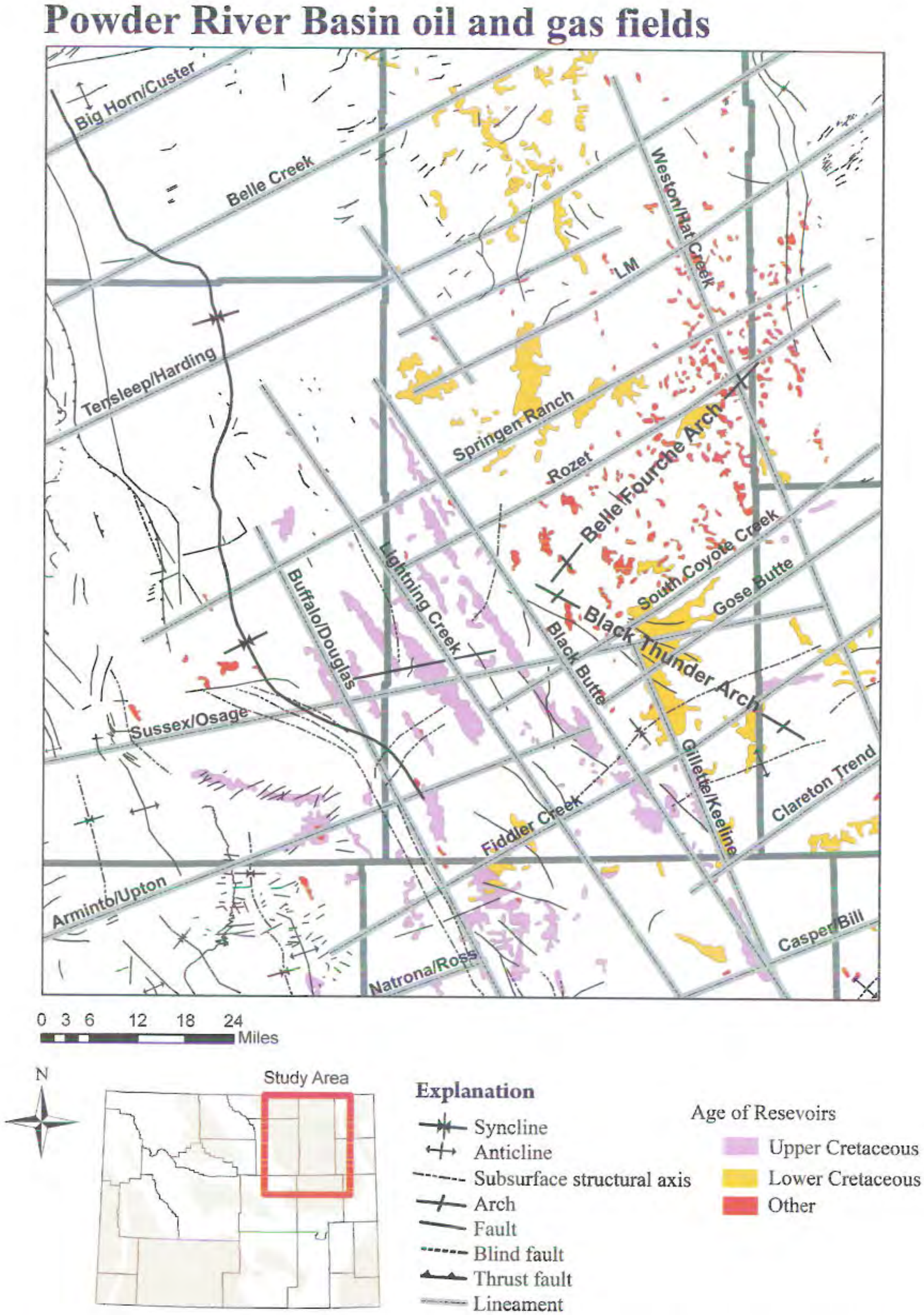


Figure 19. Distribution of oil and gas fields in the Powder River Basin, overlain on Figure 6. *Illustration modified from De Bruin (2007).*

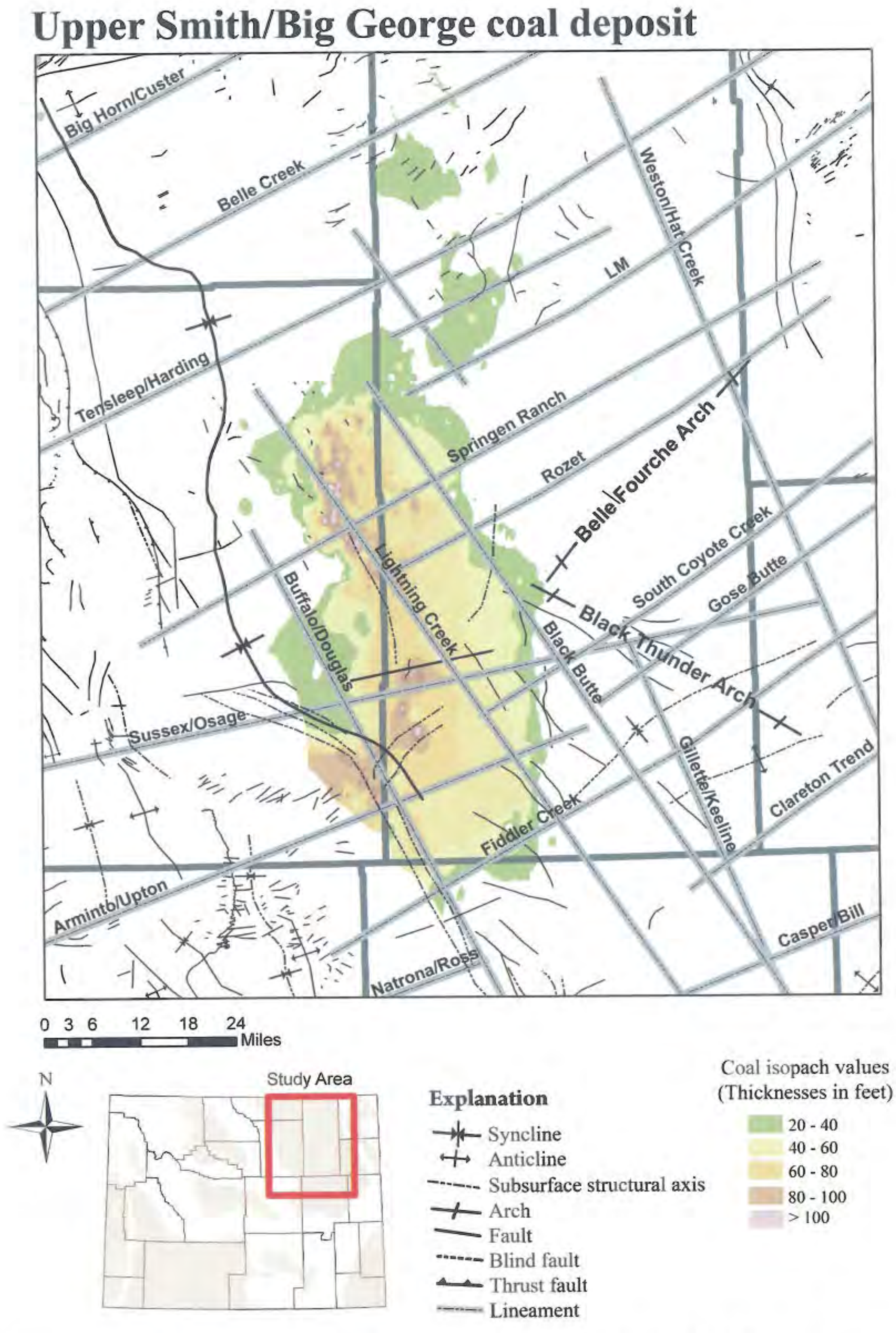


Figure 20. Isopach map of the upper Smith/Big George coal deposit in the Wyodak Rider coal zone, overlain on Figure 6. Thickness distribution of this deposit is controlled by the northwest-trending Buffalo/Douglas, Lightning Creek, and Black Butte lineaments and by the northeast-trending Fiddler Creek, Arminto/Upton, Sussex/Osage, Rozet, Springen Ranch, LM, and Tensleep/Harding lineaments. *Illustration modified from N.R. Jones (2009).*

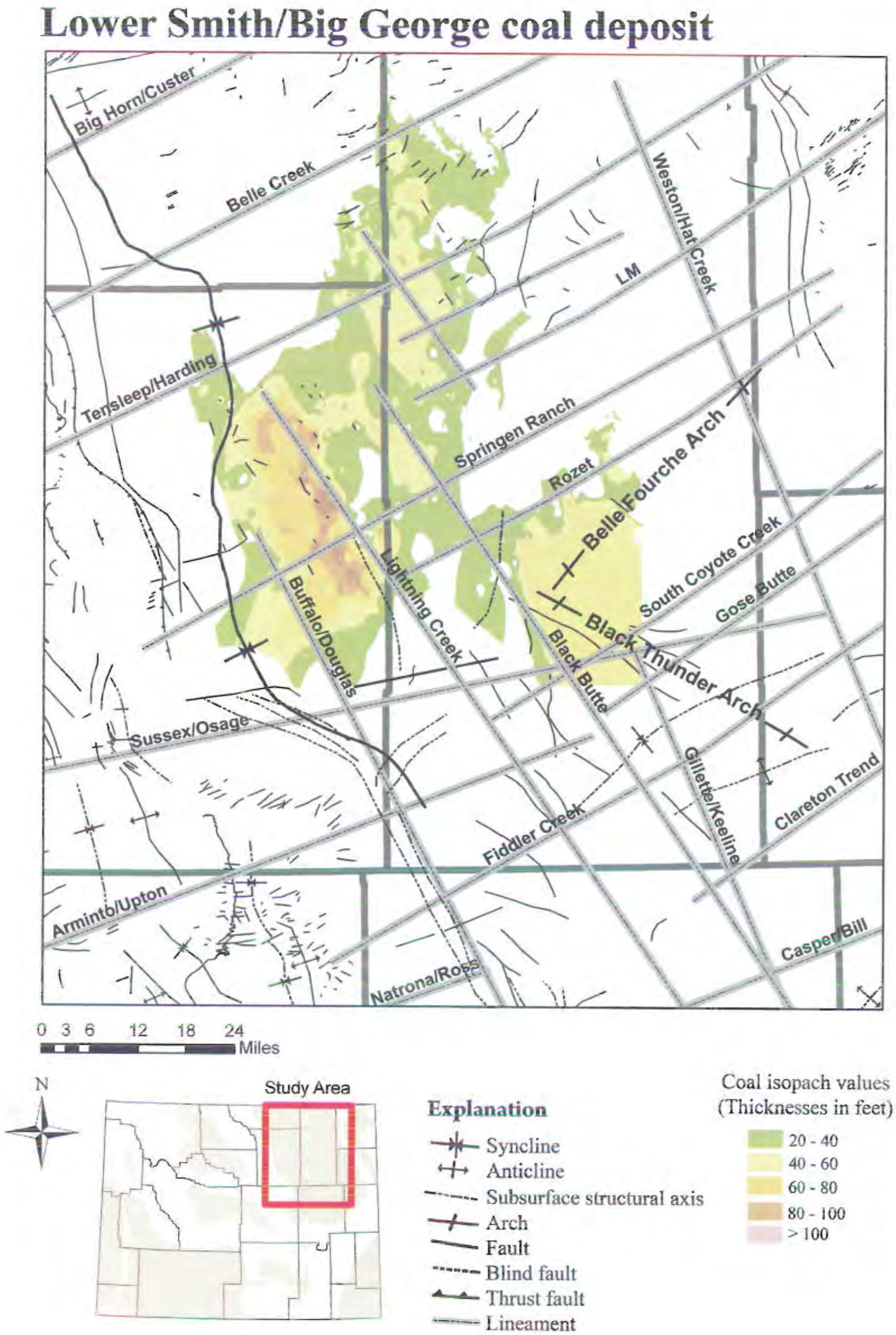


Figure 21. Isopach map of the lower Smith/Big George coal deposit in the Wyodak Rider coal zone, overlain on Figure 6. Thickness distribution of this deposit is controlled by the northwest-trending Buffalo/Douglas, Lightning Creek, and Black Butte lineaments and by the northeast-trending Gose Butte, Sussex/Osage, South Coyote Creek, Rozet, Springen Ranch, and Tensleep/Harding lineaments. *Illustration modified from N.R. Jones (2009).*

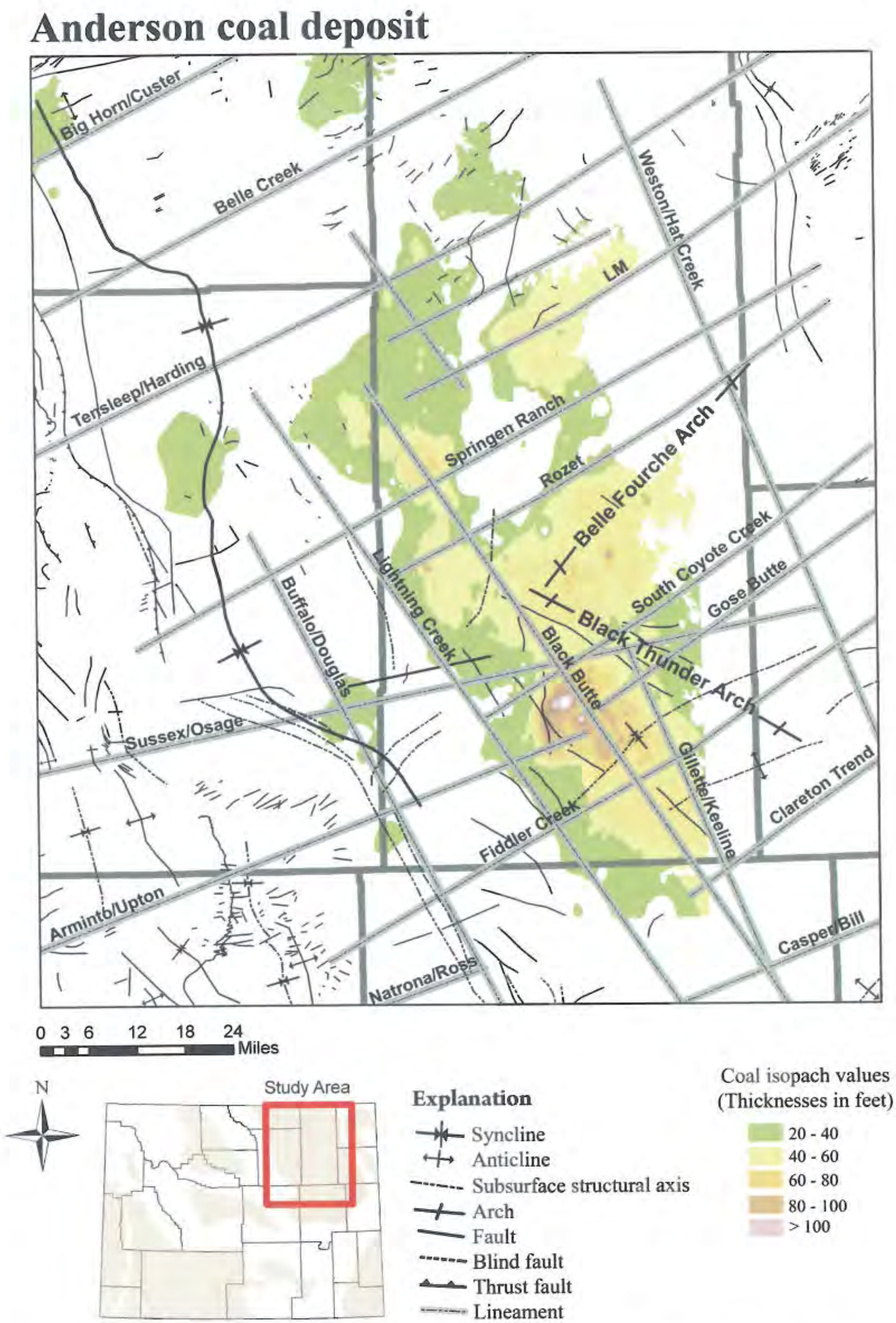


Figure 22. Isopach map of the Anderson coal deposit in the Upper Wyodak coal zones, overlain on Figure 6. Thickness distribution of this deposit is controlled by the northwest-trending Lightning Creek, Black Butte, and Gillette/Keeline lineaments and by the northeast-trending Clareton Trend, Fiddler Creek, Arminto/Upton, Gose Butte, Sussex/Osage, South Coyote Creek, Rozet, Springen Ranch, LM, and Tensleep/Harding lineaments and in the far northwest by the Big Horn/Custer Lineament. *Illustration modified from N.R. Jones (2009).*

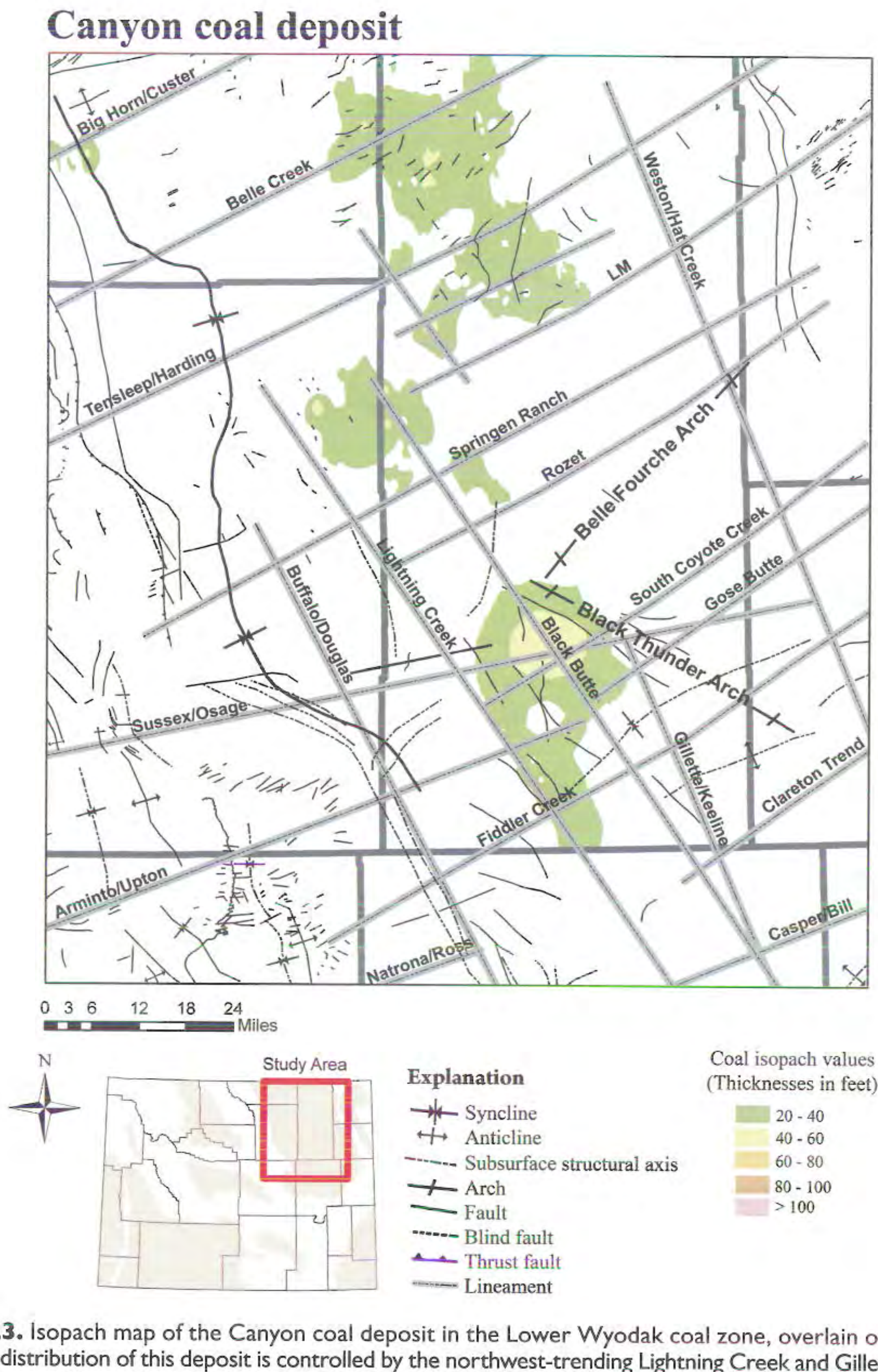


Figure 23. Isopach map of the Canyon coal deposit in the Lower Wyodak coal zone, overlain on Figure 6. Thickness distribution of this deposit is controlled by the northwest-trending Lightning Creek and Gillette/Keeline lineaments and by the northeast-trending Fiddler Creek, Arminto/Upton, Gose Butte, Sussex/Osage, Rozet, Springen Ranch, LM, Tensleep Harding, and Bell Creek lineaments. *Illustration modified from N.R. Jones (2009).*

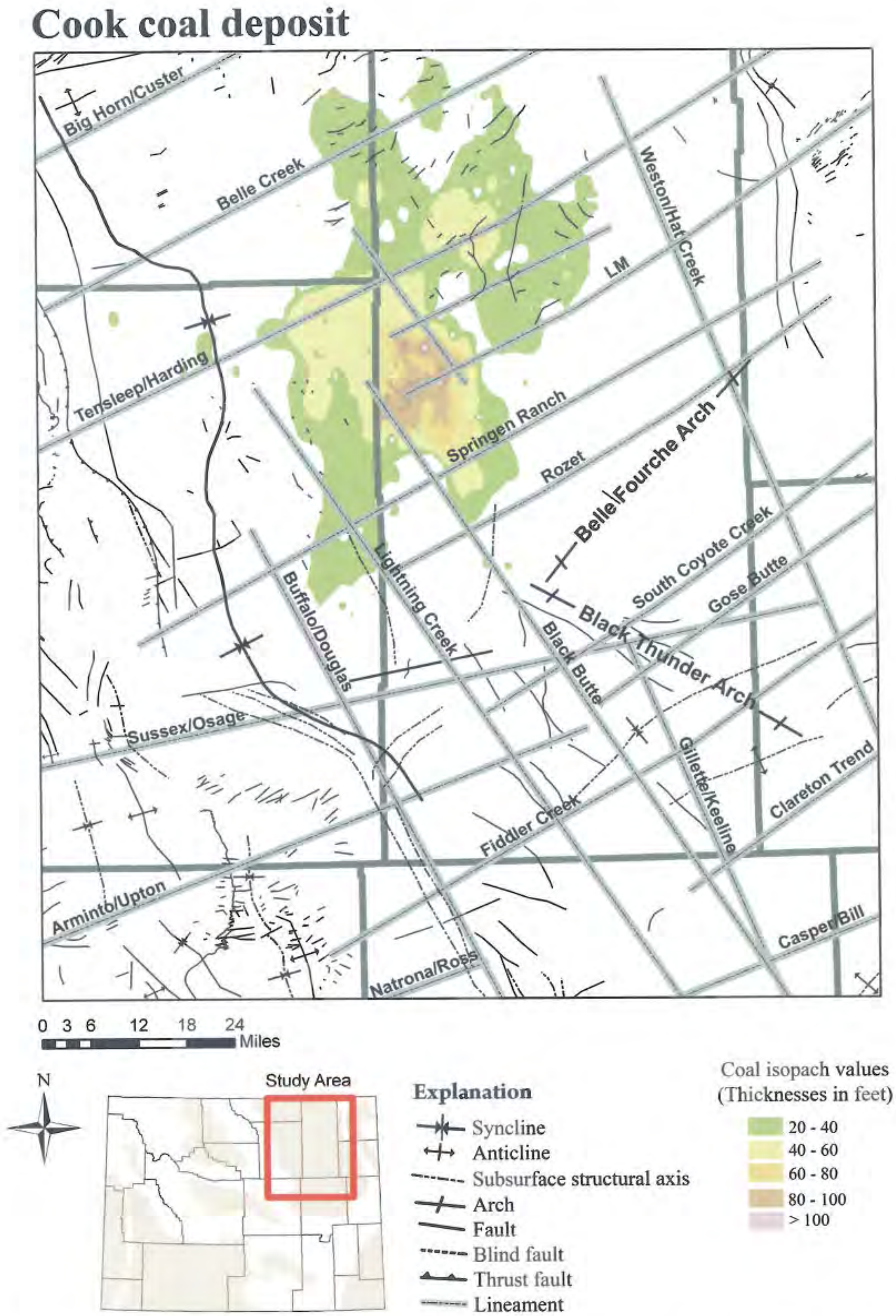


Figure 24. Isopach map of the Cook coal deposit in the Cook coal zone, overlain on Figure 6. Thickness distribution of this deposit is controlled by the northwest-trending Lightning Creek, Black Butte, and Gillette/Keeline lineaments and by the northeast-trending Rozet, Springen Ranch, Tensleep Harding, and Bell Creek lineaments. *Illustration modified from N.R. Jones (2009).*

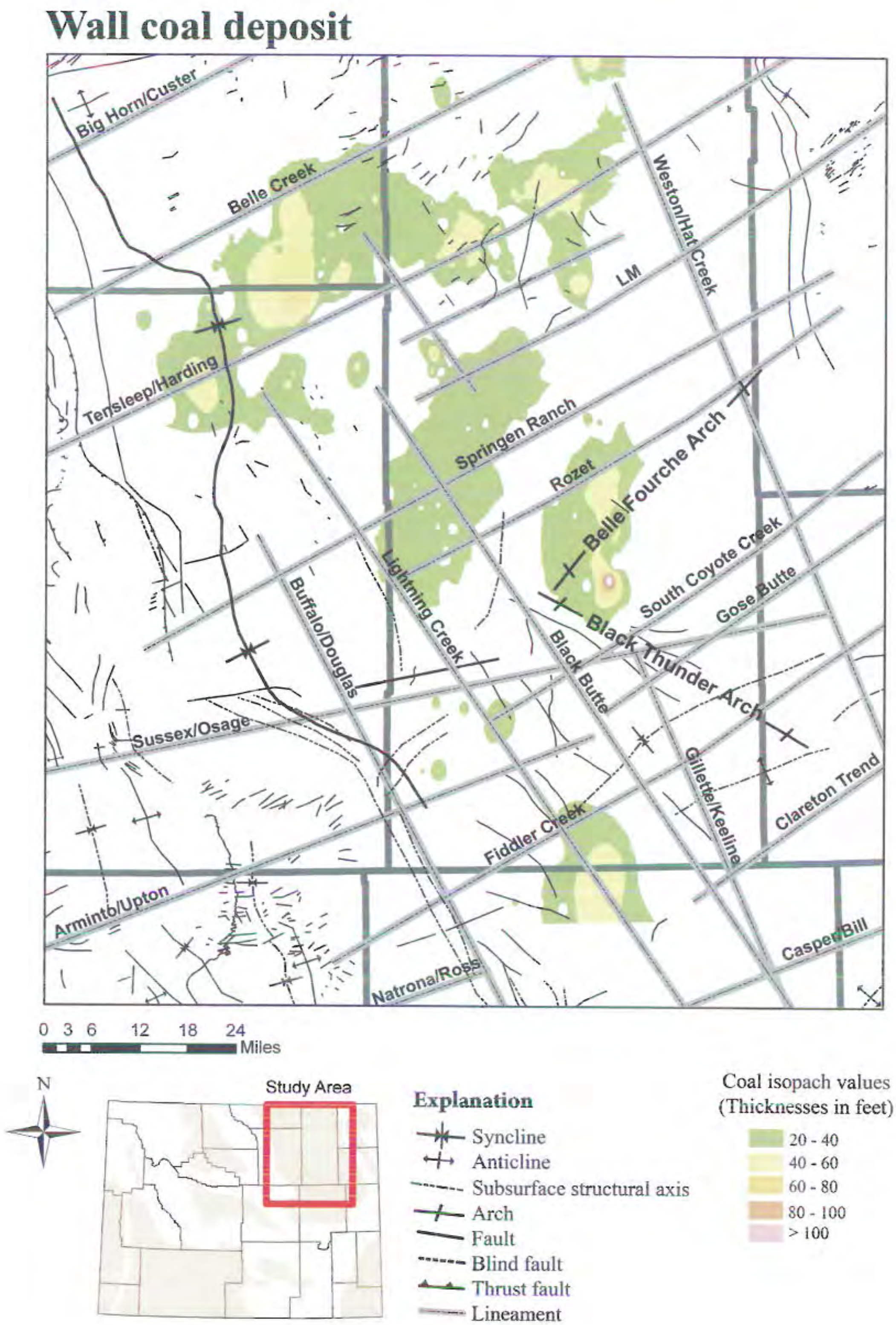


Figure 25. Isopach map of the Wall coal deposit in the Wall coal zone, overlain on Figure 6. Thickness distribution of this coal deposit is controlled by the northwest-trending Lightning Creek and Black Butte lineaments and by the northeast-trending Fiddler Creek, South Coyote Creek, Rozet, Springen Ranch, Tensleep/Harding, and Bell Creek lineaments. *Illustration modified from N.R. Jones (2009).*

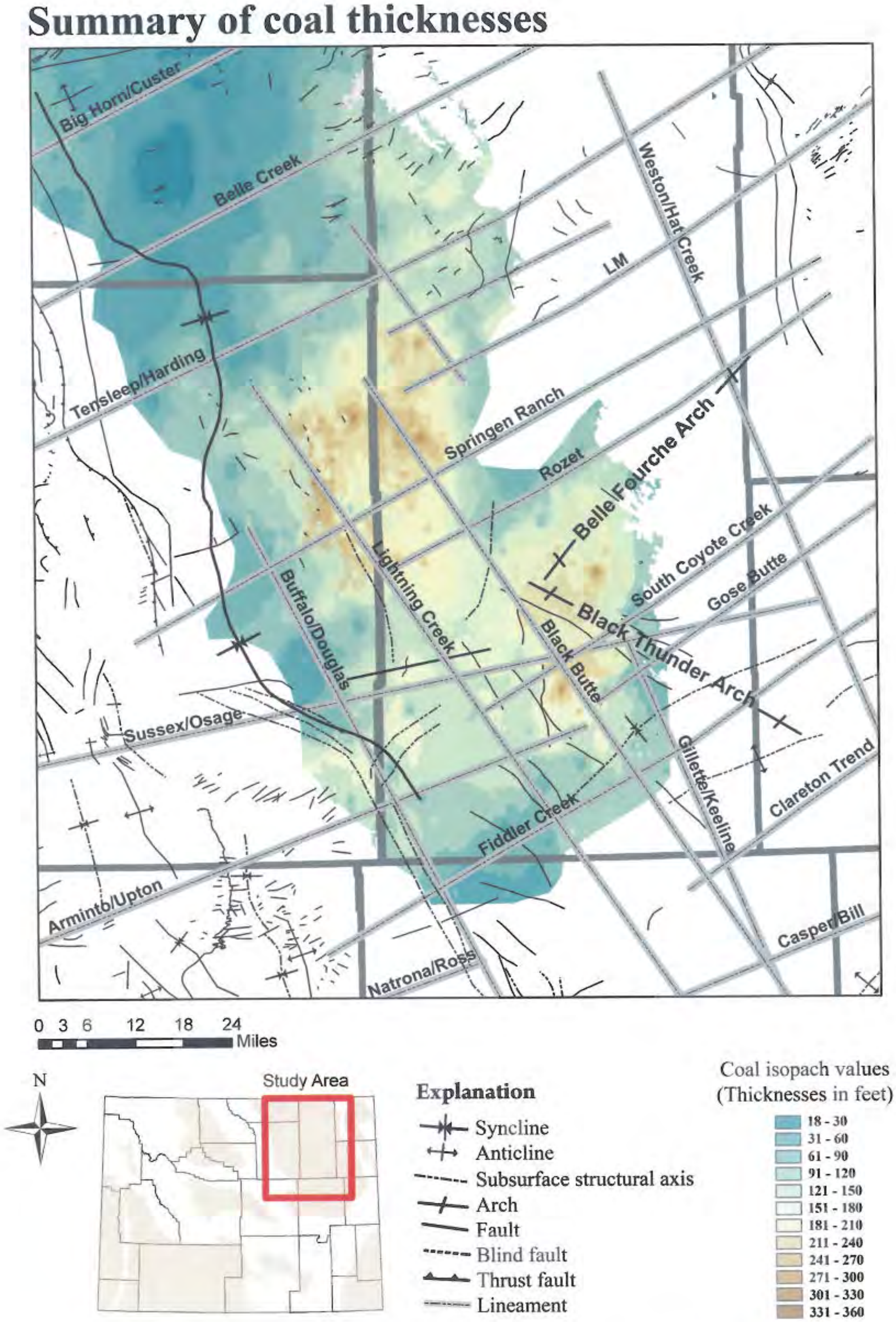


Figure 26. Isopach map representing summed coal thicknesses (upper Smith/Big George, lower Smith/Big George, Anderson, Canyon, Cook, and Wall coals) and thickness distribution coincident with distribution of lineaments, as shown on Figure 6. Note: The area of summed coal thickness is restricted to extent of the Smith/Big George boundary. *Illustration modified from N.R. Jones (2009).*

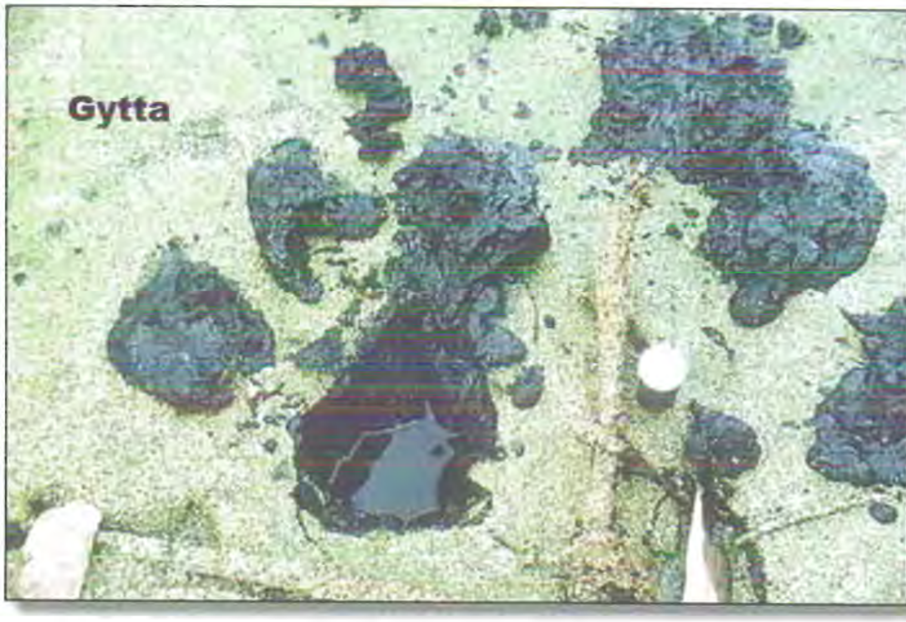


Figure 27. Exhumed organic-rich hydrogel, called *gytta* (black), along with algae and duckweed (green). Gytta is a product of biogenic decay and develops below the water table in wetlands. (Quarter for scale.) *Photo by James E. McClurg, University of Wyoming, circa 1988, and used with permission.*

concept of peat-to-coal compaction ratios wherein a given amount of peat is compressed to form a given thickness of coal. Although these models explain various mechanisms for the development of accommodation, they do not take into account the actual process of coalification.

COALIFICATION

Peat consists of partially decayed plant matter that accumulates on the bottom of a mire (*mire* is the generic term for any wetland). Coalification is the slow alteration of that plant matter into coal, and it proceeds in two phases. In the first – biogenesis – plant matter is biogenically changed into serial forms of peat, culminating in a dark-colored hydrogel (complex hydrophilic gel) termed *gytta* (**Figure 27**). The second phase is thermogenesis, where the gytta is changed by heat into one of the serial ranks of coal. It is a common misconception that coal forms by compaction of partially degraded organic material (Francis, 1954; McClurg, 1988, 2009; Jones, 2008; Jones et al., 2009). Although lithostatic pressure does force pore-space closure and the evacuation of free water during the early stages of burial, lithostatic pressure actually retards the coalification process (Francis, 1954; Tatsch, 1980).

Contrary to the concept of compaction of peat, it is the biogenic reduction and alteration of the peat (as it becomes gytta) that results in net volumetric loss from the original organic material (McClurg, 2009). Well-preserved coalified woody plant material such as coalified tree limbs found in coal deposits and in clastic sediments generally shows no evidence of compaction (**Figure 28**). Those that do likely formed as a result of subaerial exposure and fungal attack, wherein woody tissues of the plant are broken down prior to burial, making the floral remains more susceptible to compression. The compaction of subaqueous organic material in a wetland only occurs within the uppermost few inches of the peat column, not at depth. Evidence that supports this includes sedimentary structures, fossil tracks in coal, and in-place coalified and fossilized tree stumps (Nadon, 1998). Fossil tracks that occur in coal provide evidence that the animals making those tracks were walking on the exposed surface of the gytta, not on the surface of the peat (**Figure 29**).

BIOGENESIS

The vertical succession of accumulating peat (the peat column) comprises a sequence of three zones that represent successive levels of aerobic and anaerobic bac-

Figure 28. Photo of well-preserved coalified tree limb in a clastic matrix that illustrates that the compaction of organics does not occur in the transition from peat to gytta to coal. This coalified specimen formed in the parting material above the Anderson coal bed. This specimen is from the southern pit of the North Antelope Rochelle Mine. *Photo modified from N.R. Jones (2009).*

terial decay. From top to bottom, these are the *fibric* (identifiable plant fragments and dense root systems), the *humic* (few identifiable plant fragments), and the *sapropelic* (dominantly microscopic plant fragments) (**Figure 30**). The end result of biogenic processes through these zones is the dark-brown to black hydrogel gytta (Thiessen, 1925; Francis, 1954; McClurg, 2009; N.R. Jones, 2009; Jones et al., 2009).

The uppermost few inches of the peat column contain abundant free oxygen that supports aerobic bacteria; below it, little or no free oxygen is available, it having been consumed by the aerobic bacteria. This allows anaerobic bacteria to take over. Closure of pore space occurs in the uppermost few inches, and decay happens most rapidly in the upper 8 to 11 inches of the fibric zone, where plant structures are rapidly broken down by aerobic bacteria (Fenton, 1980; Johnson et al., 1990). Mature peat is composed primarily of woody plant fragments embedded in a dark-brown to black mud, called gytta. Gytta generally begins to develop within a foot of the surface, and the ratio of gytta to plant fragments increases with depth in the peat column (Thiessen, 1925). It is the gytta that is buried and preserved, not the peat. This results in an accumulation of gytta at the base of the peat column.

During biogenesis, the availability of nutrients in the peat column decreases with depth. The decay produces gasses such as hydrogen sulfide (H_2S) and methane (CH_4) as well as tannic and humic acids. As the biogenic decay of the peat progresses, the concen-

Figure 29. Photo of dinosaur track (outlined in red) in the roof of the Deer Creek underground coal mine in Utah. (Coal is sprayed with calcium carbonate for dust suppression.) For scale, the plates in the roof are 4x8 inches. *Photo by Michael Vanden Berg, Utah Geological Survey, 2004, and used with permission.*

tration of the tannic and humic acid increases, which reduces the pH of the surface water to between 3.0 and 2.5. Elevated concentrations of tannic and humic acid stain the stagnant water in mires brown (tea-colored) to black ("black-water"). As the acid concentration increases and available nutrients are depleted, conditions in the lower part of the peat column become intolerable to bacteria, and the biogenic process ceases.

The end product of the bacterial reduction of accumulated plant matter is the dark brown to black, semi-amorphous, organic-rich gel gytta. This material contains between 70 and 90 percent moisture (Odell and Hood, 1926; Tatsch, 1980). "The water exists in a form not like the water in a wet sponge but rather like that in jelly" (Odell and Hood, p. 8). Gytta is the precursor of coal. As biogenesis progresses over time, the gytta zone increases in thickness, while the combined thickness of the upper three zones in the peat column above the gytta remains fairly constant; however, peat is readily oxidized and prone to erosion when dry and is quite often not preserved. The thickness of a coal bed generally corresponds to the final thickness of the gytta layer.

THERMOGENESIS

The second phase in coalification is the heat-driven process, *thermogenesis*. This thermochemical process slowly converts gytta to coal through sequential levels of thermal maturation by progressively driving off bonded water and volatiles, and concentrating available carbon. As the bonded water is driven off by heat, the initial volume of gytta is maintained in two phases: a thermo-plastic resin (solid phase) and pore-water (liquid phase). As the gytta separates into the two phases, dehydration of the solid phase produces desiccation (cracking), and endogenic (primary) cleats in young lignite develop (Francis, 1954).

Thermal maturation is a function of time and temperature. Thermogenesis also releases gasses such as hydrogen, oxygen, nitrogen, and methane. In order for gytta to be thermogenically converted to coal, subsurface temperatures must reach at least 212°F (100°C) for millions of years. These temperatures are generated by several geologic processes: (1) the natural geothermal gradient of the earth (the temperature increases approximately 1°F per 60 feet of depth) maintained by the insulating effect of thick layers of sediment above the proto-coal, (2) by naturally

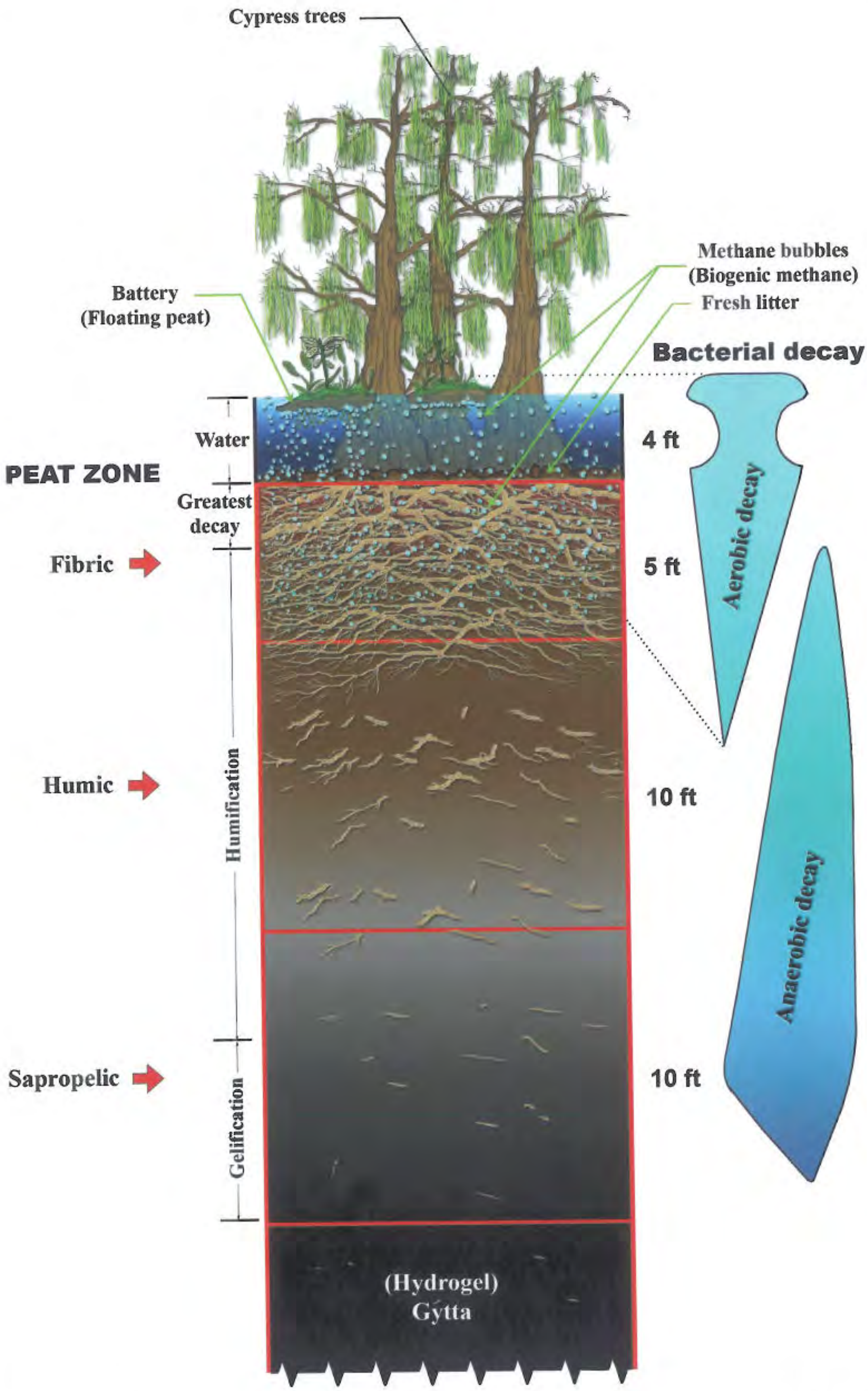


Figure 30. Columnar representation of a peat column. Numbers along the right side of the column represent generalized interval thickness. *Illustration modified from Jones et al. (2009).*

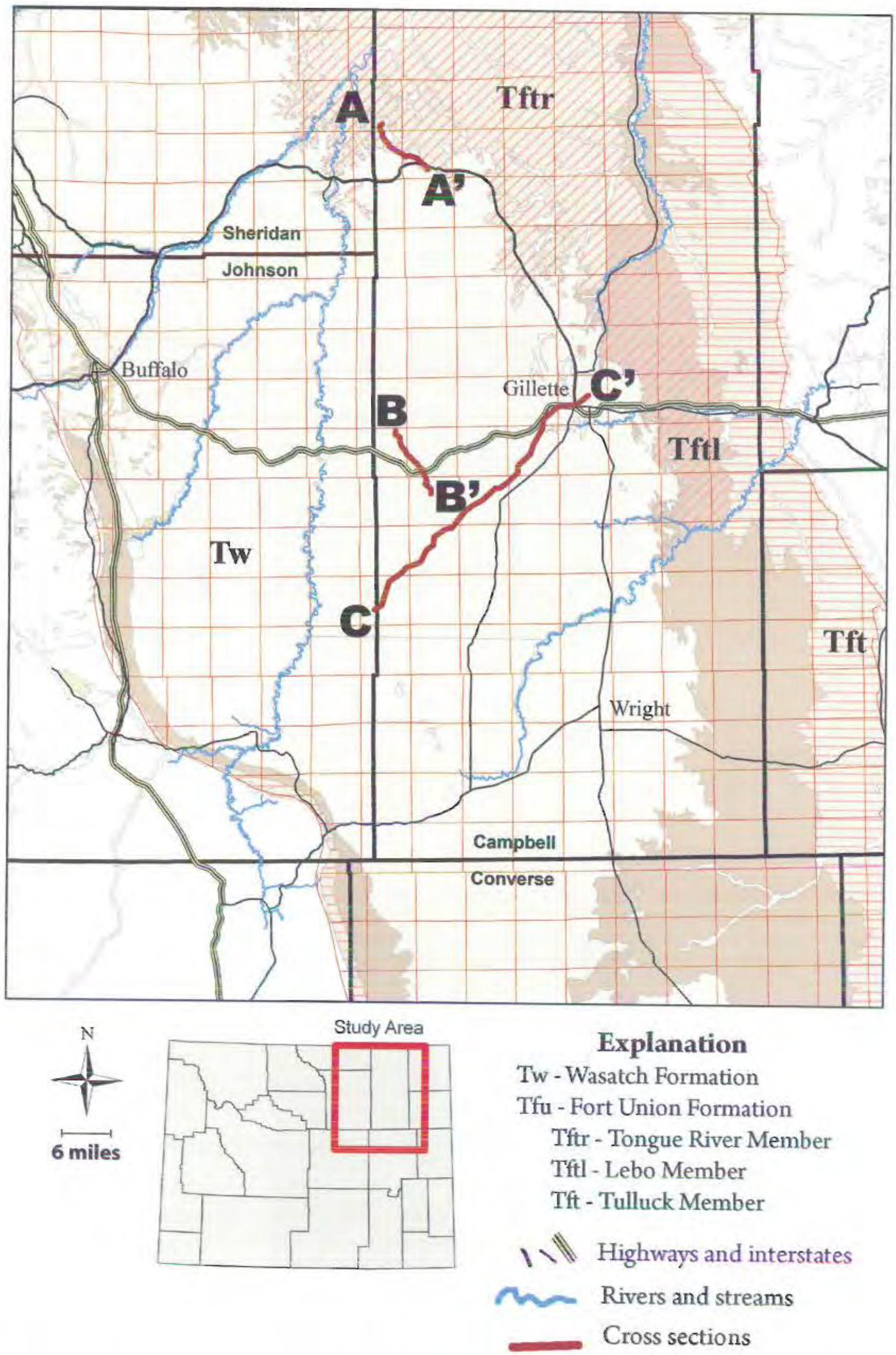


Figure 31. Map of study area showing locations of cross sections. *Illustration from N.R. Jones (2009).*

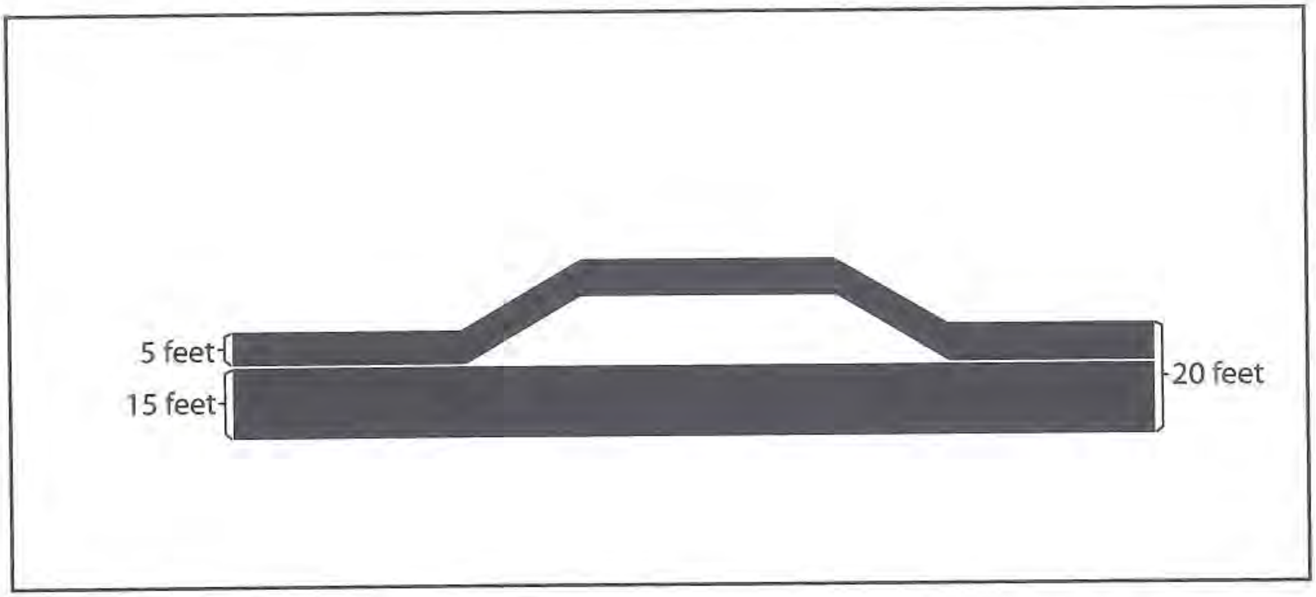


Figure 32. Generalized cross-sectional geometry of parting between two coals. *Illustration from N.R. Jones (2009).*

occurring fires in stratigraphically adjacent coal beds (Jones, 2008), and (3) sometimes, but rarely, by the emplacement of igneous rocks (intrusive and extrusive).

METHODS

Three cross sections in Campbell County (**Plates I, II**, and **III**) were constructed on the basis of the resolution, distribution, density, and depth of available well logs (**Figure 31**). Cross section A–A′, in northwest Campbell County, is approximately 9 miles long and trends southeast from sec. 34, T. 56 N., R. 76 W. to sec. 27, T. 55 N., R. 75 W. (**Plate I**). Cross section B–B′, in west-central Campbell County, is approximately 10 miles long and trends south-southeast from sec. 2, T. 49 N., R. 76 W. to sec. 16, T. 48 N., R. 75 W. (**Plate II**). Cross section C–C′, crossing west-central Campbell County, is approximately 40 miles long and trends north-northeast from sec. 29, T. 46 N., R. 76 W. to sec. 21, T. 50 N., R. 72 W. (**Plate III**).

The three cross sections were located to illustrate the unique cross-sectional geometry of correlated early Tertiary coals in the PRB. The cross sections all show the same key interval of several thick coal deposits that have distinct partings and structural geometry.

Cross section A–A′ was selected for reconstruction analysis (a paleo-deformational reconstruction sequence) to illustrate the sequence of events that produces lenticular partings between two coals, where the upper coal deposit is convex upward and the underlying coal is relatively flat lying - parallel to the local dip of the Tongue River Member at that location (**Figure 32**).

DATA DENSITY AND RESOLUTION

Coalbed natural gas (CBNG) development in the PRB during the last decade has resulted in a wealth of high-resolution subsurface geophysical information. This new information pertains directly to Paleocene- and Eocene-age coal deposits. Between 1987 and 2008, approximately 27,400 CBNG wells were drilled in the Wyoming PRB. Initial well spacing in the basin was 40 acres; in 2000, the spacing was increased to 80 acres. Coal beds 10 feet thick or thicker were targeted for methane production. Because of the complexity of the coal stratigraphy and inconsistencies in coal bed nomenclature, there are instances where wells are spaced less than 40 acres apart and are actually producing from the same coal. In most cases, however, wells drilled close to each other target coals at different geologic horizons. The result of the CBNG activity in the PRB is a high density of well log measurements that geophysically identify coal type lithology.

Vertical resolution on well logs for oil and gas wells is 10 feet (paper scale is 2 inches per 100 feet), while CBNG well logs have a vertical resolution of 2 feet (paper scale – 5 inches per 100 feet) (**Figure 33**). This difference in vertical resolution is important because thin, laterally persistent partings in and between coals cannot be identified on well logs with the larger 10-foot resolution. The parting thickness between two coals is commonly below the vertical resolution of the log scale on conventional oil and gas wells. Where the parting thickness is sufficient for detection, the parting appears as a split developing in a single coal bed; however, thin partings can be identified on CBNG wells, making it possible to accurately identify and map their extent in the subsurface.

Coal studies in the PRB that occurred prior to CBNG activity used only paper copies of well logs, and, in most cases, these logs were from oil and gas well logs with the larger vertical scale of 10 feet. In addition to the limitations of the larger scale, many oil and gas geophysical measurements, including gamma and density, were not logged through the Tertiary or not logged at all due to cost or to borehole stability problems requiring surface casing set to below thick coal zones (Martinsen, 2008).

Prior to the Wyoming Oil and Gas Conservation Commission Web site, paper copies of well logs were either purchased from industry or obtained by visiting well log repositories at the commission's building in Casper or the WSGS in Laramie. If the well was drilled on federal land, well logs were examined and copied at Bureau of Land Management (BLM) offices around the state.

DATA COLLECTION AND INTERPRETATION

Log data from conventional oil and gas and CBNG wells in the PRB used in this study were collected via the internet from the Wyoming Oil and Gas Conservation Commission Web site. Selected geophysical logs were downloaded to construct each cross section. Well data were selected from a coal occurrence database developed by this author and other WSGS staff. This coal occurrence database was developed as part of a basin-wide study on coal occurrence and distribution in the PRB (Jones, 2008). Work on the database began in the fall of 2004 and was completed in the winter of 2007. The resulting coal occurrence database includes 49,859 coal picks (depths to the tops and bases of coals) from 8,659 CBNG and conventional oil and gas wells. In addition to data generated by the WSGS, the database also includes coal occurrence data from the Fort Union Coal Assessment Team (1999), from Flores et al. (1999), and from this author's work in cooperation with the USGS Coal Resource Team between 2003 and 2008.

A subset of the database consisting of 4,158 wells containing 25,409 coal tops and bases was selected for correlation of coal beds in the PRB. The purposes of using a subset of the collected bore-hole data are (1) to incorporate wells with associated water quality data, (2) to expedite work by reducing the number of correlations, and (3) to develop an even distribution of representative well data throughout the basin (**Figure 34**).

Interpreting well logs involved viewing digital image files of geophysical logs using computers. Data were compiled and recorded by assigning a "depth to top" and "depth to base" for each identifiable coal signature within each log. These data were then entered into a coal occurrence database spreadsheet.

Coals were identified on geophysical logs showing (1) a low gamma-ray response (less than 20 gAPI [American Petroleum Institute gamma-ray units]), (2) a low-density response (less than 1.4 grams per cubic centimeter), (3) a high-resistivity response (greater than 50 ohm-meters), and (4) a low-conductivity response (less than 5 millimhos per meter). Where coal geophysical signatures on a log were questionable, coal type responses on adjacent logs were used to verify the interpretation.

Quality control of the data comprised verification of borehole location and elevation and review of coal picks from well logs where necessary. In order to verify borehole locations and surface elevations for well sites, the wells were spatially plotted using their surveyed latitude and longitude (Lat-Long) coordinates. The surveyed locations were then checked using each well's reported Public Land Survey

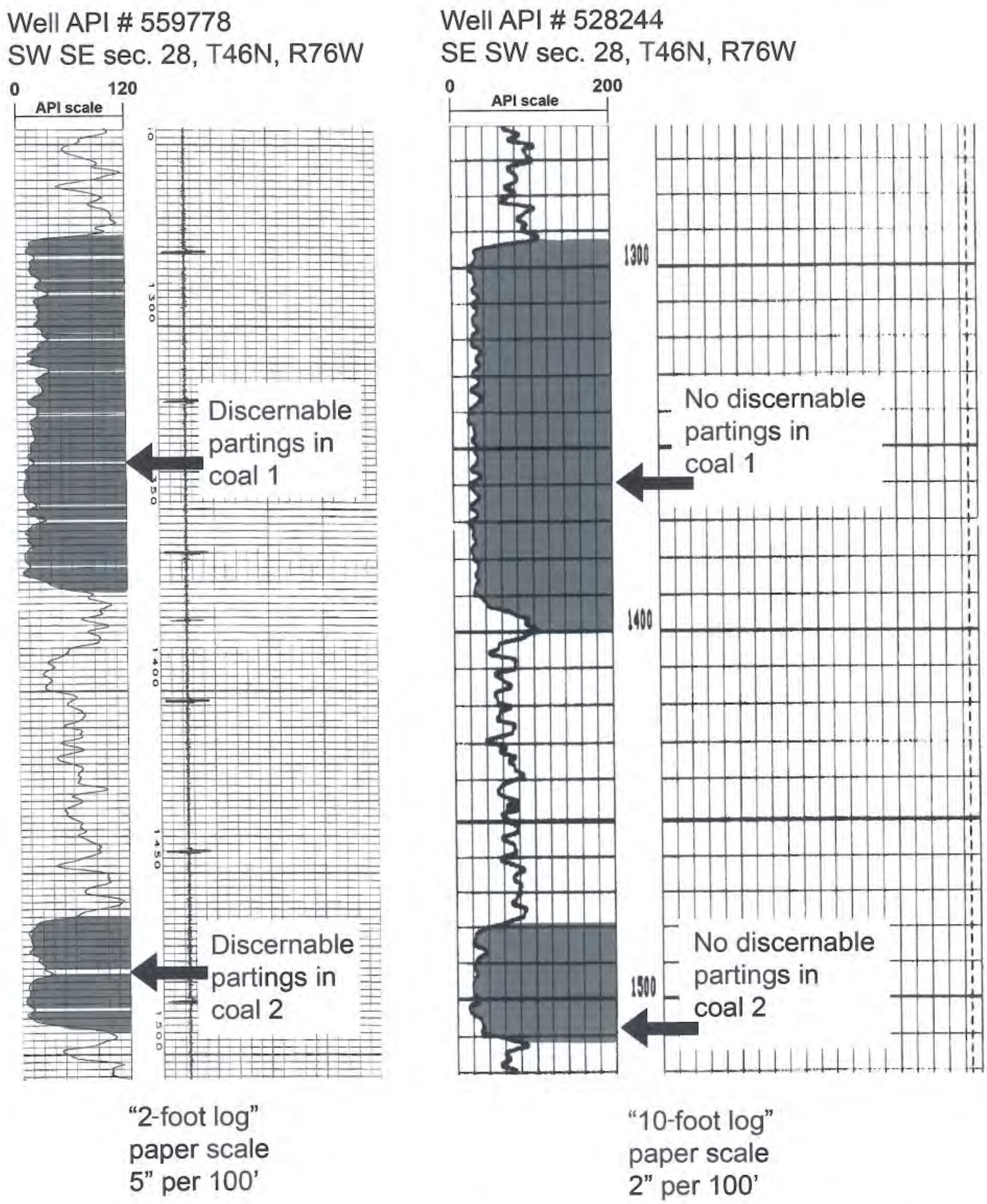


Figure 33. A comparison of two gamma-ray well logs located approximately 0.2 miles apart showing the same stratigraphic interval. The log on the left is from a coalbed natural gas (CBNG) well and has a higher resolution of 5 inches per 100 feet. The log on the right is from a conventional oil well with a lower resolution of 2 inches per 100 feet. Note the discernable high-ash/clastic partings detected by the gamma-ray log on the CBNG well. On a gamma-ray log, coals are identified as having less than 20 gAPI units, and partings are identified by a gamma-ray response greater than 20 gAPI units. *Illustration modified from N.R. Jones (2009).*

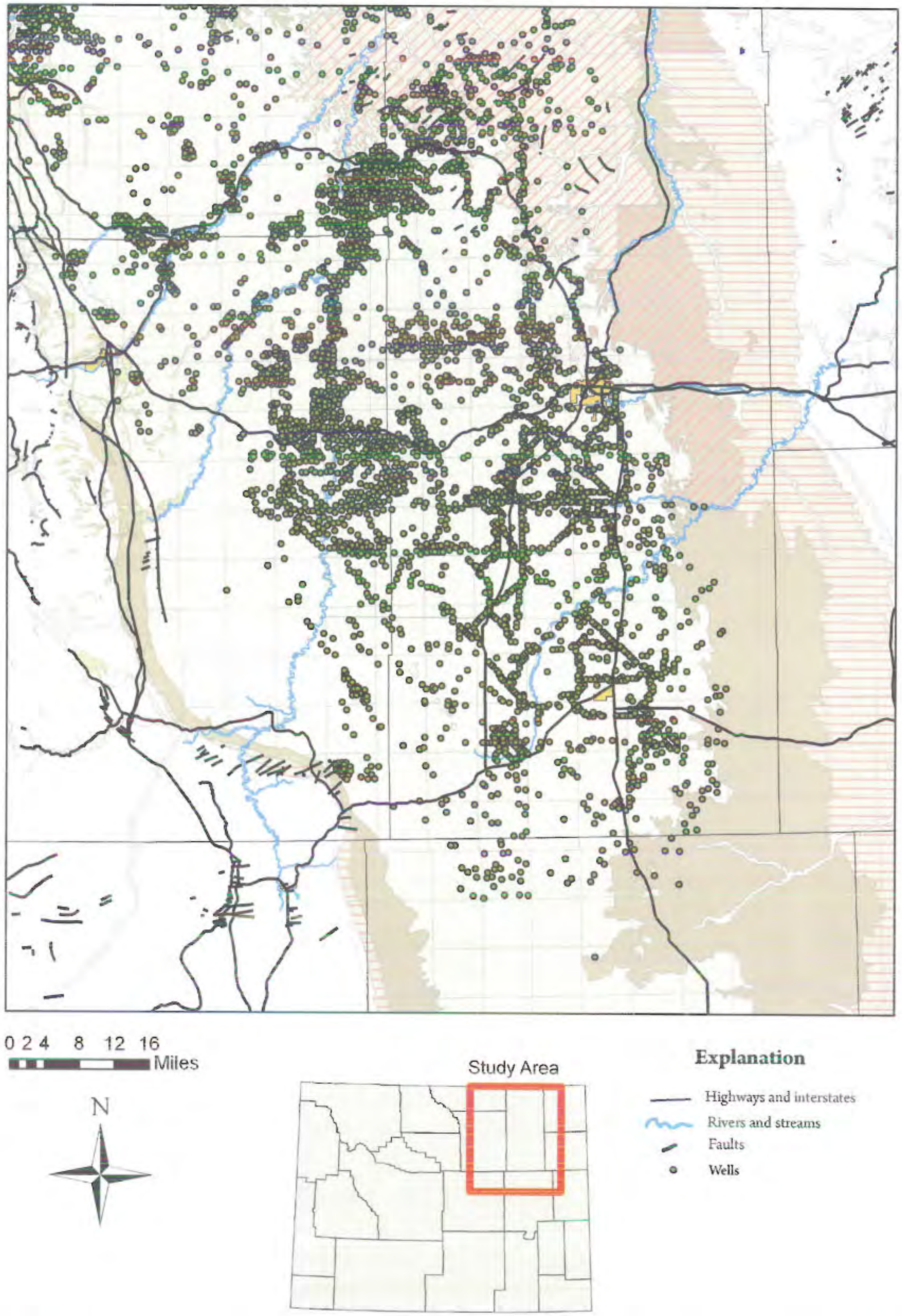


Figure 34. Distribution of correlated geophysical well data used for the basin-wide coal study in the Powder River Basin. *Illustration modified from N.R. Jones (2009).*

System (PLSS) legal location, which included section, township, range, and elevation. The legal PLSS location was checked against its plotted (Lat-Long) location using ArcGIS® software and geospatial data layers. The data layers include elevation grids and PLSS grids. Wells that plotted in the incorrect section, township, or range and wells with elevations more than 50 feet above or below the elevation grid were reviewed and corrected or were excluded from the database.

RockWorks™ computer software was used for the stratigraphic correlation of coal beds based on elevation and to generate and display representative coal occurrence data for selected logs in a cross-sectional profile. The displayed coal occurrence data were then correlated between adjacent logs by assigning codes to correlative beds (**Figure 35**).

Characteristics used for correlating individual coal beds were relative equivalence of elevation on adjacent logs and coal bed position within a stratigraphic sequence of other coal beds. After codes were assigned to correlative beds, the cross section was regenerated. This method allowed for the correlation of coals between numerous adjacent wells during each work session. After correlations were completed within a small region of the well data, the correlation was extended outward to include more wells within a predetermined area. In all work sessions, wells that had been previously correlated were included at the beginning and end of each new cross section to ensure consistency in the use of coding and for closure of correlations from area to area.

Fieldwork for this project included the evaluation of outcrops and the study of modern depositional environments. Numerous coal-bearing rocks were studied across Wyoming, including those exposed in outcrops in the Hanna, Green River, Wind River, Bighorn, and Powder River basins and the Hams Fork area. Fieldwork included mine visits, discussions with mine geologists, sediment and coal sampling, photo-documentation, and paleoenvironment (depositional facies) reconstruction. Following these trips, modern subtropical wetland systems were studied – including the Great Dismal Swamp, Okefenokee Swamp, Big Cypress Swamp, Florida Everglades, Mississippi Delta, and Atchafalaya Basins. Fieldwork in these wetlands included sediment and peat sampling, pH measurements of swamp waters, photo-documentation, and discussions with the field instructor (geologist and University of Wyoming [UW] Professor Emeritus James E. McClurg), local wetland ecologists, and colleagues.

RECONSTRUCTION ANALYSIS

Cross section A–A′ (**Plate I**) was selected for reconstruction analysis because it was best suited to model the effects of differential development of accommodation in the interior of a basin as a result of episodic deformation related to reactivation of basement faults. This cross section is constructed from closely spaced wells that clearly show coal type log responses for five key coals across the entire section. Thin coals were excluded from the model in order to simplify the sequence of events.

Log data for the cross section were selected from the WSGS coal occurrence database for the PRB (Jones, 2008). Output from RockWorks™ software was utilized to construct a sequence of cross sections that used the tops of sequential coal deposits as datums. This was done to show the structural deformation of coal deposits that occur below the datum. The result of the reconstruction analysis is a model that illustrates the sequence of syndepositional and syntectonic events in cross section that produces thick (>60 feet) coal deposits. The cross-sectional model is set to a vertical exaggeration scale of approximately 5 to 1.

RESULTS

The model resulting from this simple reconstruction analysis clearly illustrates the sequence of events that produces the unique structural geometry of thick coal deposits in the Tongue River Member of the Fort Union Formation (**Figure 36**). The model illustrates how two distinct, relatively thick (>30 feet) coal deposits of different ages can coalesce (merge) about a detectable thin parting, producing a singularly thick deposit of coal between 60 and 70 feet thick. It can be inferred from the model that syndepositional development of accommodation is the result of recurrent deformation and not from the compaction, autocompaction, or differential compaction of peat or the

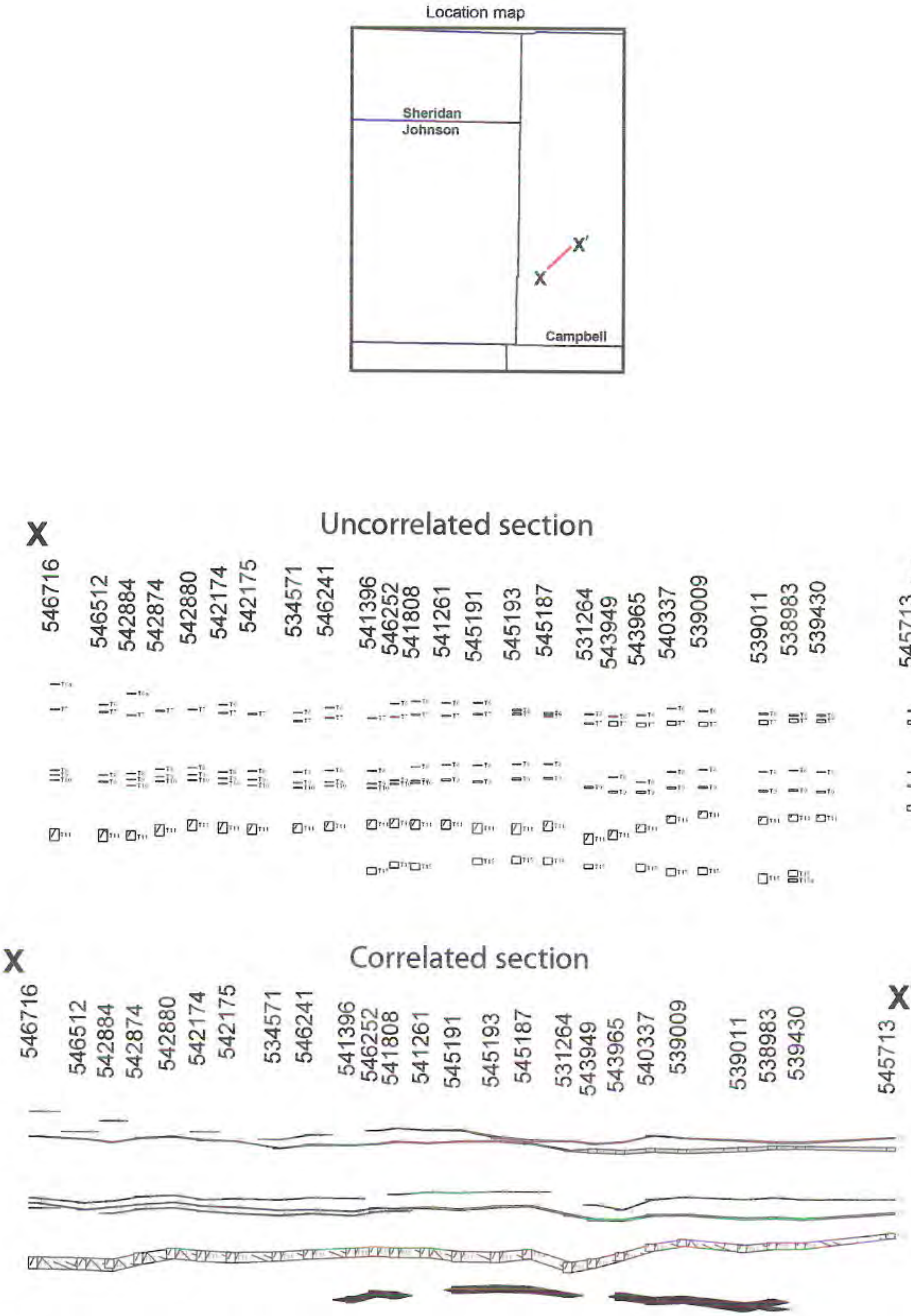


Figure 35. Representative illustration showing uncorrelated coal picks from well logs (top) and resulting interpretation of coal correlations in a final section (bottom). *Illustration from N.R. Jones (2009).*

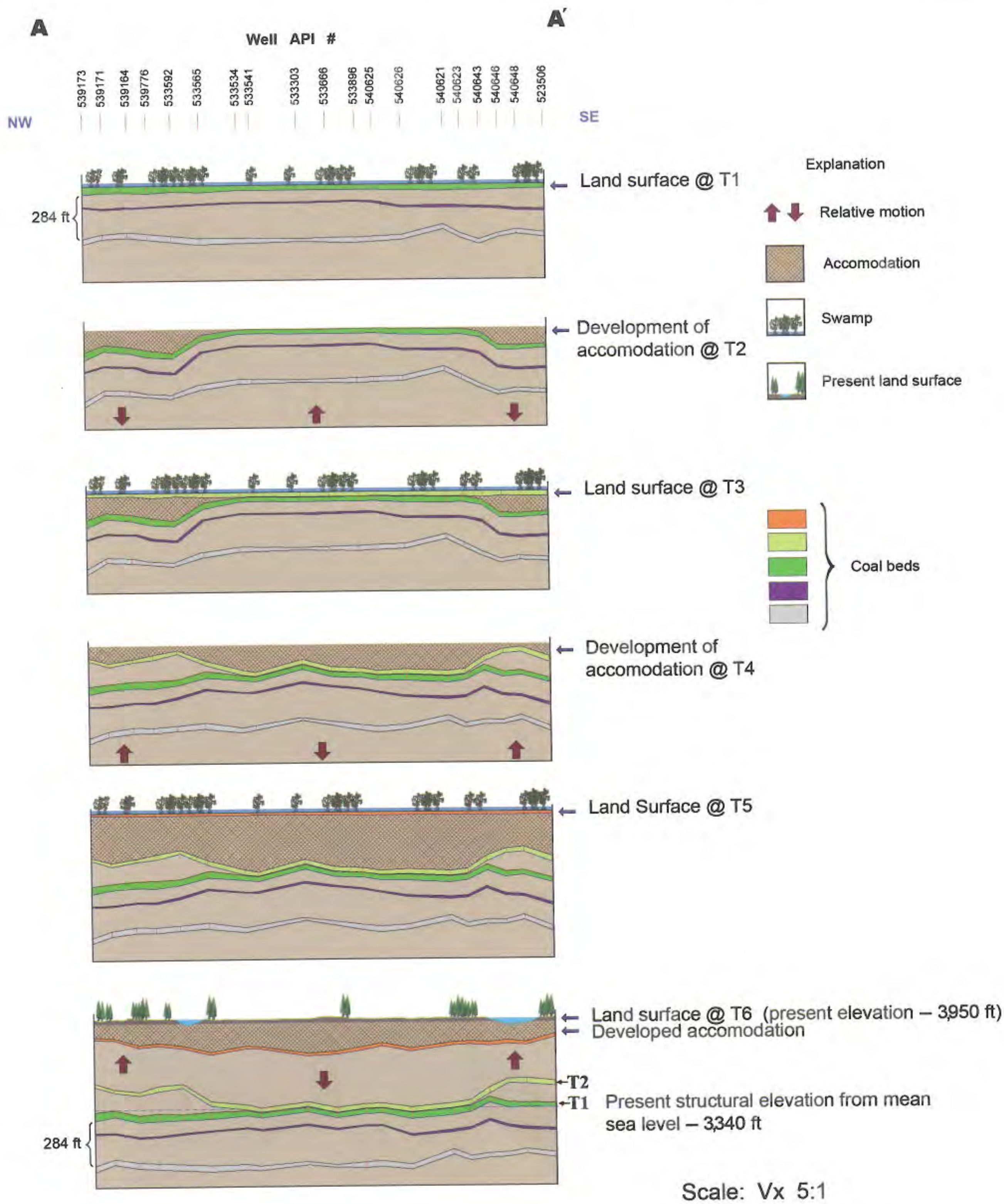


Figure 36. Model of sequential differential development of accommodation that results in the unique geometry of coal deposits and how they coalesce and split in the Tongue River Member of the Fort Union Formation, Powder River Basin. *Illustration modified from N.R. Jones (2009).*

underlying rocks. Four key assumptions are critical to this model: (1) the top of each coal represents a time line, (2) development of accommodation is syndepositional and controlled by basement faulting, (3) there is no syndepositional compaction of organic and/or clastic sediments, and (4) the two thick coals that coalesce comprise several stacked, thin (1- to 3-foot thick) coals that formed from the accumulation and thermal maturation of gytta below a peat column.

INTERPRETATION OF RESULTS

T1 (time one) represents the land surface during deposition and accumulation of gytta at the base of the peat column. Between T1 and T2, accommodation for sediment develops on the outer edges of the wetland, the area in the middle drains, and the peat is oxidized and eroded, subaerially exposing the top of the underlying gytta. Evidence that supports subaerial exposure of the gytta includes thin paleosols such as fusain layers (discrete horizons of oxidized coal), evaporate minerals (gypsum, anhydrite, etc.), different ash content of the coal above and below the thin oxidized surfaces, casts or imprints of animal tracks, and rooted zones. During this period, the areas of accommodation fill with clastic sediment composed of lacustrine and fluvial deposits. By T3, clastic sedimentation has filled in the available accommodation, the water table rises, and another wetland develops. On the outer edges, more gytta accumulates above the previous deposit, separated by approximately 200 feet of clastic sediment, while in the middle, the two are separated by only a thin oxidized layer of gytta. Between T3 and T4, the direction of the relative motion that created the initial accommodation reverses, resulting in more accommodation in the middle than on the edges. The reversal in the direction of the relative motion affects where accommodation develops: it is this process that produces the unique convex geometry of the interburden between thick coals. By T5, the deposits of gytta are more deeply buried and become more thermogenically mature. Between T5 and T6, the sequence that occurred between T3 and T4 is repeated. This results in the present structural geometry of the coals.

The top and bottom of a parting in a coal deposit are surfaces that mark periods between wetland facies, and the spacing of these chronostratigraphic surfaces (time lines) represent equal amounts of time (**Figure 37**). These time lines are important because they indicate that thick coal deposits did not form from a singularly thick deposit of peat and that a thick coal deposit actually formed from numerous, stacked, thinner accumulations of gytta.

Evidence that further supports the concept of differential development of accommodation is the presence of clastic packages that progressively pinch-out and onlap onto the lower coal along the margin of the split (**Figure 38**). The presence of onlap illustrates that there was a hiatus between organic accumulations during the period when the area of accommodation aggraded with clastic material.

DISCUSSION

Wetlands are governed by the water table and therefore have little or no discernable surface topography.

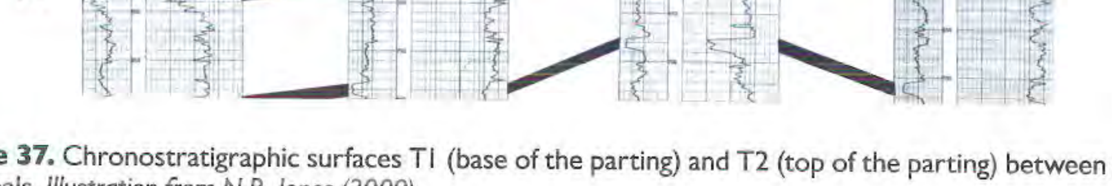


Figure 37. Chronostratigraphic surfaces T1 (base of the parting) and T2 (top of the parting) between two distinct coals. *Illustration from N.R. Jones (2009).*

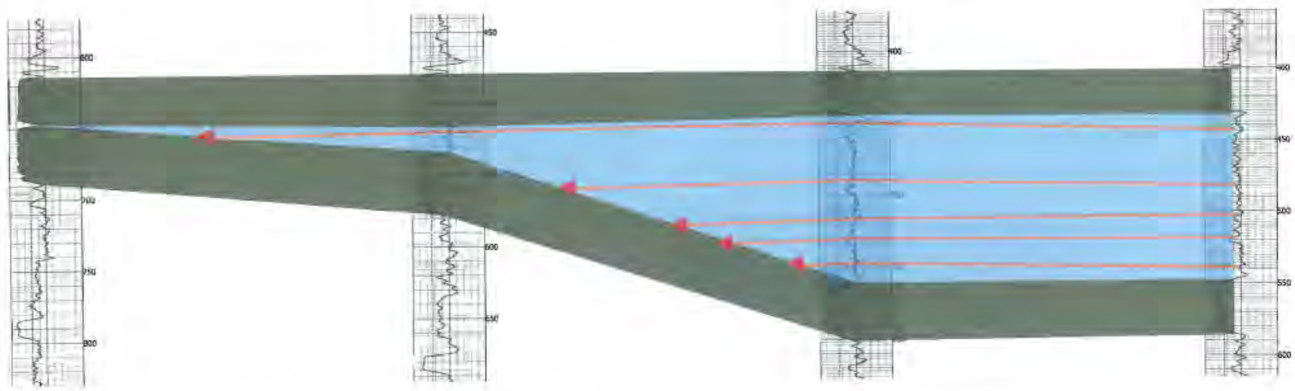


Figure 38. Cross section showing onlap. Datum is set to the top of the upper coal. Red arrows denote location and direction of onlap. Note: This figure was modified from Figure 37. Log signatures are gamma-ray responses. *Illustration from N.R. Jones (2009).*

A swamp is basically a shallow lake with trees growing in it, and a marsh is a flooded grassland (N.R. Jones, 2009; R.W. Jones, 2009; McClurg, 2009). A factor not addressed in the models of Flores and Ayers is localized deformation in the PRB attributable to tectonically active episodes in the Laramide Orogeny during the early Tertiary. Instead, these researchers explain differential coal thickness and interburden thickness as being influenced by differential compaction of underlying sediments, autocompaction of peat, and syndepositional processes such as channel switching and overbank deposits. Kent's teeterboard model of a migrating fulcrum in response to tectonic development of the PRB and the Black Hills explains why peat developed where it did and how it was buried, but it does not explain the differential interburden thickness that exists between adjacent coal beds.

IMPLICATIONS

Considering the effect of syntectonic deformation and its influence on Cretaceous-age fluvial sandstones, it is not impractical to assume that pre-existing structural controls on deposition were periodically reactivated during deposition of the Tongue River Member of the Fort Union Formation in the Tertiary. Succinctly, the new model explains unique coal bed geometry and differential interburden thickness to be the result of syntectonic deposition of clastic sediments that occurred intermittently between periods of organic accumulation. Following accumulation of organics (peat and gytta), local Laramide deformation in the nascent PRB created topographic highs and lows and was synchronous with the transition from a low-energy system of basin-wide blackwater swamps to a higher-energy system of rivers, streams, and lakes (**Figure 39**).

Well-documented crevasse splays, channel deposits, and lacustrine deposits noted between stratigraphically adjacent coals were most likely deposited during cyclic periods of local deformation caused by the differential displacement of adjacent Laramide basement blocks coincident with basin subsidence and regional deformation. These episodes resulted in differential interburden thickness – splits between sequential coal beds and those stacks of sequential coal beds that appear to be continuous. Splitting under these circumstances can be attributed to growth faulting due to reactivation of basement faults. This resulted in gentle downwarping of sections of accumulated organic material followed by deposition of non-organic material. After such a low area fills to the level not affected by downwarping, organic accumulation recommences (Thomas, 1992).

Another implication of this model is that localized deformation within the basin's interior can be associated with recurrent basement block faulting. This means that each structurally affected coal deposit can be used to help better constrain the sequencing of episodes of deformation during the Laramide Orogeny.

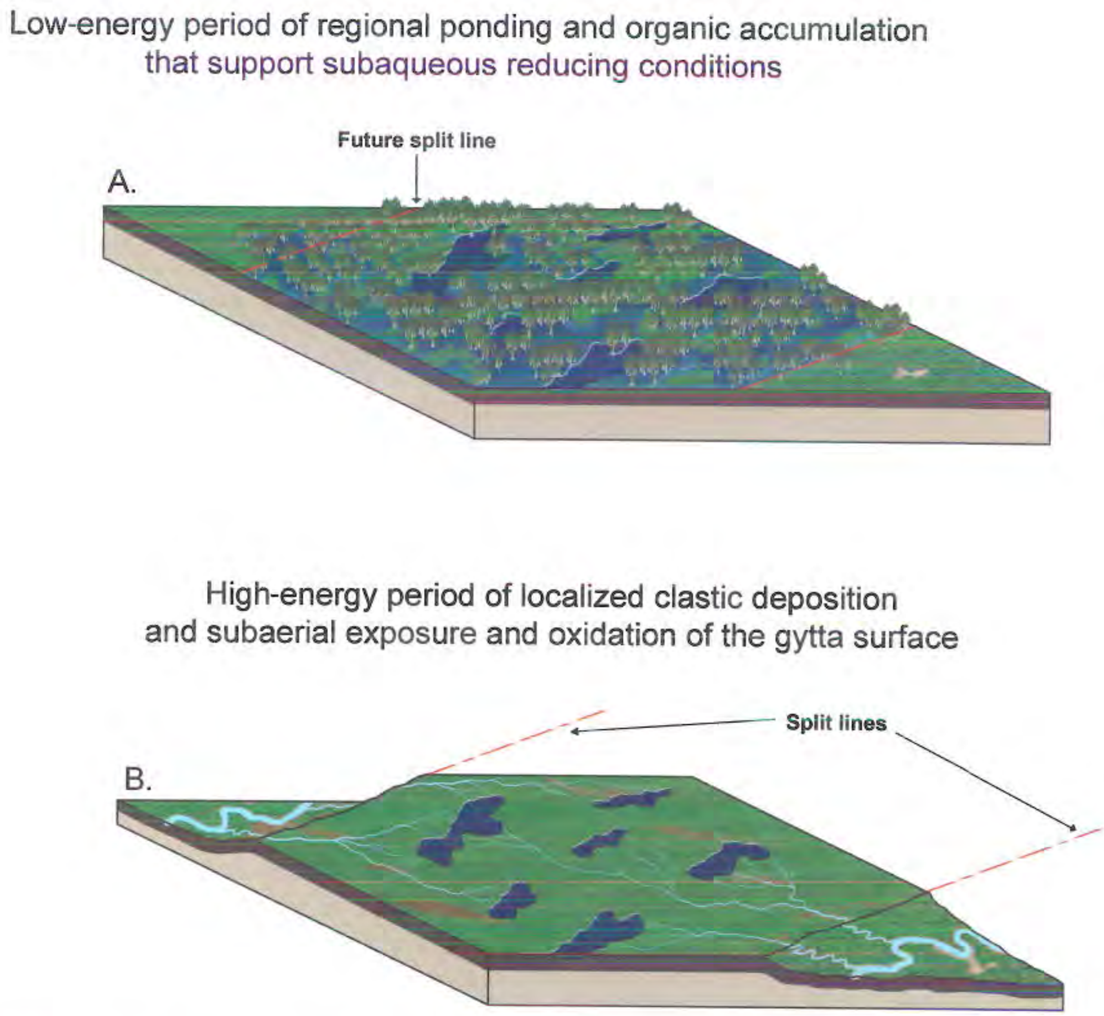


Figure 39. Block diagrams showing generalized surface topography (A.) before and (B.) after development of differential accommodation due to fault reactivation of basement blocks. Movement along the faults is expressed on the surface by lineaments called split lines. *Illustration from N.R. Jones (2009).*

CONCLUSIONS

The presence of oxidized layers, splits, and partings within thick coals indicates that establishment of basin-wide wetlands and deposition of organics was intermittent. High-energy, sediment-laden fluvial systems and low-energy mires and lacustrine systems were not coeval during latest Paleocene and early Eocene time. Additionally, wetlands in the basin developed over broad areas with relatively flat topography; any inherited relief within the wetland likely resulted in *wants* (areas of non-coal within the overall deposit). During that time, the distribution and thickness of coal deposits in the basin were controlled by differential development of accommodation attributable to intrabasinal tectonics. Parting geometry and angular relationships between coals laterally adjacent to thick sequences of stacked coal deposits resulted from intermittent, syndepositional, recurrent movement along zones of weakness in basement rocks. Intermittent periods of (1) dewatering, erosion, and oxidation of peat, (2) subaerial exposure of gytta, and (3) deposition of clastic material in areas of newly created accommodation within the nascent basin coincide with movement along zones of weakness in basement blocks.

SUGGESTIONS FOR FUTURE WORK

With the abundance of available subsurface borehole data from the PRB, future work in the basin could include (1) a basin-wide revision in correlations of individual coals based on identifiable partings within them, (2) a more detailed association of thick coals and coal splitting associated with lineaments, (3) detailed mapping of subsurface structures and angular unconformities within early Tertiary rocks in the interior of this and other Laramide basins in the Rocky Mountains, (4) comparisons of water-to-gas ratios from producing CBNG wells among areas of the basin where subsurface coal bed geometry was likely influenced by fault reactivation of basement rocks, and (5) evaluation of the interplay between large-scale and small-scale structural dynamics and their influence on subsurface basin structure and basin paleotopography.

Acknowledgments

The author acknowledges several people for their help with this report. I thank my thesis adviser, Randi Martinsen, senior lecturer, UW Department of Geology and Geophysics. Geologist and UW Professor Emeritus Jim McClurg shared his expertise of coal and wetlands during field trips and insightful discussions. Ed Heffern, a geologist with the BLM in Wyoming, reviewed this report and shared insightful comments and suggestions. Geologist Chris Carroll (Colorado Geological Survey) also reviewed the manuscript and offered valuable information. Geologists of the USGS Coal Resource Team (James Luppens, Lee Osmonson, Dave Scott, Jon Haacke, and Tim Rohrbacher) offered suggestions and comments. WSGS geologists Richard Jones, Wayne Sutherland, and Robert Gregory allowed me to share and discuss ideas with them. I thank Jim Rodgers, WSGS petroleum engineer, for his assistance in generating many of the figures in this report. Dave Copeland, WSGS contract editor, provided advice and valuable technical editing assistance. Tamara Linse (consulting technical editor), Robert Waggener (WSGS editor in chief), and Brendon Orr (consulting graphic designer) also provided editorial assistance. I have great appreciation and gratitude for the late Robert "Bob" Lyman, my former supervisor and mentor at the WSGS, who offered great encouragement and support early in my career.

References Cited

Ayers, W.B., Jr., 1986, Lacustrine and fluvial-deltaic depositional systems, Fort Union Formation (Paleocene), Powder River Basin, Wyoming and Montana: American Association of Petroleum Geologists Bulletin, v. 70, no. 11, p. 1,651–1,673.

Ayers, W.B., Jr., and Kaiser, W.R., 1984, Lacustrine-interdeltaic coal in the Fort Union Formation (Paleocene), Powder River Basin, Wyoming and Montana, *in* Rahmani, R.A., and Flores, R.M., eds., Sedimentology of coal and coal-bearing sequences: International Association of Sedimentologists Special Publication 7, p. 61–84.

Beck, R.A., Vondra, C.F., Filkens, J.E., and Olander, J.D., 1988, Synorogenic sedimentation and Laramide basement thrusting, Cordilleran foreland - Timing of deformation, *in* Schmidt, C.J., and Perry, W.J., Jr., eds., Interaction of the Rocky Mountain Foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 465–487.

Blackstone, D.L., Jr., 1990, Rocky Mountain foreland structure exemplified by the Owl Creek Mountains, Bridger Range and Casper Arch, central Wyoming, *in* Wyoming sedimentation and tectonics: Wyoming Geological Association Guidebook, 41st Annual Field Conference, p. 151–166.

Copeland, D.A., and Ewald, M.L., eds., 2008, Water associated with coal beds in Wyoming's Powder River Basin – Geology, hydrology, and water quality: Wyoming State Geological Survey Exploration Memoir No. 2, 344 p.

Crowley, P.D., Reiners, P.W., Reuter, J.M., and Kaye, G.D., 2002, Laramide exhumation of the Bighorn Mountains, Wyoming - An apatite (U-Th)/He thermochronology study: Geology, v. 30, no. 1, p. 27–30.

Curry, W.H., III, 1971, Laramide structural history of the Powder River Basin, Wyoming, *in* Renfro, A.R., Madison, L.V., Jarre, G.A., and Bradley, W.A., eds., Symposium on Wyoming tectonics and their economic significance: Wyoming Geological Association Guidebook, 28th Annual Field Conference, v. 18, p. 332–406.

De Bruin, R.H., 2007, Wyoming oil and gas map: Wyoming State Geological Survey Map Series MS-55.

De Bruin, R.H., 2009, Wyoming State Geological Survey, personal communication.

Denson, N.M., Dover, J.H., and Osmonson, L.M., 1978a, Lower Tertiary coal bed distribution and coal resources of the Reno Junction-Antelope Creek area, Campbell, Converse, Niobrara, and Weston counties, Wyoming: U.S. Geological Survey Map MF-960, 1:125,000.

Denson, N.M., Dover, J.H., and Osmonson, L.M., 1978b, Structure contour and isopach maps of the Wyodak-Anderson coal bed in the Reno Junction-Antelope Creek area, Campbell and Converse counties, Wyoming: U.S. Geological Survey Map MF-961, 1:125,000.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Janecke, S.U., Lundin, E.R., McKittrick, M.A., and Olivares, M.D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: Geological Society of America Bulletin, v. 100, no. 7, p. 1,023–1,039.

Dolson, J., Muller, D., Evetts, M.J., and Stein, J.A., 1991, Regional paleotopographic trends and production, Muddy Sandstone (Lower Cretaceous), central and northern Rocky Mountains: American Association of Petroleum Geologists Bulletin, v. 75, no. 3, p. 409–435.

Emery, D., and Myers, K.J., eds., 1996, Sequence stratigraphy: Malden, Massachusetts, Blackwell Publishing Company, p. 297.

Fenton, J.H.C., 1980, The rate of peat accumulation in Antarctic moss banks: Journal of Ecology, v. 68, no. 1, p. 211–228.

Flores, R.M., 1981, Coal deposition in fluvial paleoenvironments of the Paleocene Tongue River Member of the Fort Union Formation, Powder River area, Powder River Basin, Wyoming and Montana, *in* Ethridge, F.G., and Flores, R.M., eds., Recent and ancient nonmarine depositional environments – Models for exploration: Society of Economic Paleontologists and Mineralogists Special Publication 31, p. 169–190.

Flores, R.M., 1986, Styles of coal deposition in Tertiary alluvial deposits, Powder River Basin, Montana and Wyoming, *in* Lyons, P.C., and Rice, C.L., eds., Paleoenvironmental and tectonic controls in coal-forming basins in the United States: Geological Society of America Special Paper 210, p. 79–104.

Flores, R.M., and Moore, T.A., 1994, Mechanisms of splitting of the Anderson-Dietz coal bed in the Decker area, Montana – A synthesis, *in* Flores, R.M., Mehring, K.T., Jones, R.W., and Beck, T.L., eds., Organics and the Rockies field guide: Wyoming State Geological Survey Public Information Circular No. 33, p. 153–161.

Flores, R.M., Ochs, A.M., Bader, L.R., Johnson, R.C., and Vogler, D., 1999, Framework geology of the Fort Union coal in the Powder River Basin, Chapter PF, *in* Fort Union Coal Assessment Team, 1999 resource assessment of selected Tertiary coal beds and zones in the northern Rocky Mountains and Great Plains region: U.S. Geological Survey Professional Paper 1625-A, 40 p.

Fort Union Coal Assessment Team, 1999, 1999 resource assessment of selected Tertiary coal beds and zones in the northern Rocky Mountains and Great Plains region: U.S. Geological Survey Professional Paper 1625–A, 58 p.

Francis, W., 1954, Coal – Its formation and composition: London: London, Edward Arnold Publishing, 567 p.

Hartman, J.H, and Kirkland, J.I., 2002, The brackish and marine mollusks of the Hell Creek Formation, North Dakota – Evidence for a persisting seaway, *in* Hartman, J.H., Johnson, K.R., and Nichols, D.J., eds., The Hell Creek Formation and the Cretaceous-Tertiary boundary in the northern Great Plains – An integrated continental record of the end of the Cretaceous: Geological Society of America Special Paper 361, p. 271–296.

Hobbs, B.E., Means, W.D., and Williams, P.F., 1976, An outline of structural geology: New York, John Wiley & Sons, Inc., 571 p.

Hoppin, R.A, 1974, Lineaments – Their role in tectonics of central Rocky Mountains: American Association of Petroleum Geologists Bulletin, v. 58, no. 11, p. 2,260–2,273.

Hoy, R.G., and Ridgeway, K.D., 1997, Structural and sedimentological development of footwall growth synclines along an intraforeland uplift, east-central Bighorn Mountains, Wyoming: Geological Society of America Bulletin, v. 109, no. 8, p. 915–935.

Johnson, L.C., Damman, A.W.H., and Malmer, N., 1990, Sphagnum macrostructures as an indicator of decay and compaction in peat cores from an ombrotrophic south Swedish peat bog: Journal of Ecology, v. 78, no. 3, p. 633–647.

Jones, N.R., 2008, Coal bed nomenclature and distribution, *in* Copeland, D.A., and Ewald, M.L., eds., Water associated with coal beds in Wyoming's Powder River Basin – Geology, hydrology, and water quality: Wyoming State Geological Survey Exploration Memoir No. 2, p. 45–108.

Jones, N.R., 2009, Paradigm in the genesis of thick coal deposits and their unique angular relationships – A result of differential development of accommodation in the Powder River Basin, Wyoming: M.S. thesis, Department of Geology and Geophysics, University of Wyoming, 83 p., 3 pl.

Jones, N.R., McClurg, J.E., and Quillinan, S.A., 2009, Wyoming coal: Wyoming State Geological Survey Public Information Circular No. 44, 28 p.

Jones, R.W., 2009, Wyoming State Geological Survey, personal communication.

Kent, B.H., 1986, Evolution of thick coal deposits in the Powder River Basin, northeastern Wyoming, *in* Lyons, P.C., and Rice, C.L., eds., Paleoenvironmental and tectonic controls in coal-forming basins in the United States: Geological Society of America Special Paper 210, p. 105–122.

Law, B.E., and Grazis, S.L., 1972, Preliminary geologic map and coal resources of the Decker quadrangle, Big Horn County, Montana: U.S. Geological Survey Open-File Report 72-0220, three sheets.

Lisenbee, A.L., and DeWitt, E., 1993, Laramide evolution of the Black Hills uplift, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Memoir No. 5, p. 374–412.

Love, J.D., and Christiansen, A.C., 1985, Geologic map of Wyoming: U.S. Geological Survey Map, scale 1:500,000, colored, 3 sheets.

Marrs, R.W., and Raines, G.L., 1984, Tectonic framework of Powder River Basin, Wyoming and Montana, interpreted from Landsat imagery: American Association of Petroleum Geologists Bulletin, v. 68, no. 11, p. 1,718–1,731.

Martinsen, R.S., 2003a, Depositional remnants, part 1: Common components of the stratigraphic record with important implications for hydrocarbon exploration and production: American Association of Petroleum Geologists Bulletin, v. 87, no. 12, p. 1,869–1,882.

Martinsen, R.S., 2003b, Depositional remnants, part 2: Examples from the Western Interior Cretaceous basin of North America: American Association of Petroleum Geologists Bulletin, v. 87, no. 12, p. 1,883–1,909.

Martinsen, R.S., 2008, senior lecturer and thesis adviser, Department of Geology and Geophysics, University of Wyoming, personal communication.

Martinsen, R.S., and Marrs, R.W., 1985, Comparison of major lineament trends to sedimentary rock thicknesses and facies distribution, Powder River Basin, Wyoming: Fourth Thematic Conference - Remote sensing for exploration geology, Environmental Research Institute, Ann Arbor, Michigan, 11 p.

McClurg, J.E., 1988, Peat forming wetlands and the thick Powder River Basin coals: Wyoming Geological Association Guidebook, 39th Field Conference, p. 229–236.

McClurg, J.E., 2009, professor emeritus, Department of Geology and Geophysics, University of Wyoming, personal communication.

Merewether, E.A., 1983, The Frontier Formation and mid-Cretaceous orogeny in the foreland of southwestern Wyoming: The Mountain Geologist, v. 20, no. 4, p. 121–138.

Merewether, E.A., and Cobban, W.A., 1986, Biostratigraphic units and tectonism in the mid-Cretaceous foreland of Wyoming, Colorado, and adjoining areas, *in* Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 443–468.

Michael, R.C., and Merin, I.S., 1986, Tectonic framework of Powder River Basin, Wyoming and Montana, interpreted from Landsat imagery - Discussion: American Association of Petroleum Geologists Bulletin, v. 70, no. 4, p. 453–455.

Mine Safety and Health Administration, 2009, Mine Safety and Health Administration Web site: *at* www.msha.gov (accessed 2006–2009).

Moore, T.A., 1994, Organic compositional clues to a stacked mire sequence in the Anderson-Dietz 1 coal bed (Paleocene), Montana, *in* Flores, R.M., Mehring, K.T., Jones, R.W., and Beck, T.L., eds., Organics and the Rockies field guide: Wyoming State Geological Survey Public Information Circular No. 33, p. 163–172.

Moore, T.A., and Shearer, J.C., 1993, Processes and possible analogues in the formation of Wyoming's coal deposits, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Memoir No. 5, p. 874–896.

Nadon, G.C., 1998, Magnitude and timing of peat-to-coal compaction. Geology, v. 26, no. 8, p. 727–730.

Odell, W.W., and Hood, O.P., 1926, Possibilities for the commercial utilization of peat: U.S. Bureau of Mines Bulletin 253, p. 160.

Pocknall, D.T., and Flores, R.M., 1987, Coal palynology and sedimentology in the Tongue River Member, Fort Union Formation, Powder River Basin, Wyoming: Society of Economic Paleontologists and Mineralogists, Palaios, v. 2, no. 2, p. 133–145.

Robinson, L.N., and Barnum, B.E., 1986, Southeastern extension of the Lake Basin fault zone in south-central Montana - implications for coal and hydrocarbon exploration: The Mountain Geologist, v. 23, no. 2, p. 37–44.

Rykiel, E.J., Jr., 1984, General hydrology and mineral budgets for the Okefenokee Swamp - Ecological significance, *in* Cohen, A.D., Casgrande, D.J., Andrejko, M.J., and Best, G.R., eds., The Okefenokee Swamp, Wetland Surveys, p. 212-228.

Seeland, D.A., 1992, Depositional systems of a synorogenic continental deposit - The upper Paleocene and lower Eocene Wasatch Formation of the Powder River Basin, northeast Wyoming: U.S. Geological Survey Bulletin 1917-H, 20 p.

Seeland, D.A., 1993, Origin of thick lower Tertiary coal beds in the Powder River Basin, Wyoming and Montana – Some paleogeographic constraints: U.S. Geological Survey Bulletin 1917-Q, 13 p.

Sholes, M.A., and Cole, G.A., 1981, Depositional history and correlation problems of the Anderson-Dietz coal zone, southeastern Montana: The Mountain Geologist, v. 18, no. 2. p. 35–45.

Shurr, G.W., 1982, Geological significance of lineaments interpreted from Landsat images near the northern Black Hills, *in* Christopher, J.E., and Kaldi, J., eds., Fourth International Williston Basin Symposium Proceedings: Saskatchewan Geological Society Special Publication 6, p. 313–320.

Slack, P.B., 1981, Paleotectonics and hydrocarbon accumulation, Powder River Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 65, no. 4, p. 730–743.

Steidtmann, J.R., 1993, The Cretaceous foreland basin and its sedimentary record, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Memoir No. 5, p. 250–271.

Taff, J.A., 1909, The Sheridan coal field, Wyoming: U.S. Geological Survey Bulletin 341, p. 123–150.

Tatsch, J.H., 1980, Coal deposits – Origin, evolution, and present characteristics; an analysis of the present coal deposits in terms of the geometrical, mechanical, thermal and chemical aspects of the Earth's behavior during the past 4.6 billion years: Sudbury, Massachusetts, Tatsch Associates, 590 p.

Thiessen, R., 1925, The microscopic constitution of coal, *in* Ross, C.A., and Ross, R.P., Geology of coal, Benchmark Papers v. 77: Stroudsburg, Pennsylvania, Hutchinson Ross Publishing Company, p. 244–305.

Thomas, L., 1992, Handbook of practical coal geology: Chichester, England, John Wiley & Sons, Inc., 338 p.

Tikoff, B., and Maxson, J., 2001, Lithospheric buckling of the Laramide foreland during Late Cretaceous and Paleogene, western United States: Rocky Mountain Geology, v. 36, no. 1, p. 13–35.

Whipkey, C.E., Cavaroc, V.V., and Flores, R.M., 1991, Uplift of the Bighorn Mountains, Wyoming and Montana – A sandstone provenance study: U.S. Geological Survey Bulletin 1917-D, 20 p.

Williams G.D., and Stelck, C.R., 1975, Speculations on the Cretaceous paleogeography of North America, *in* Caldwell, W.G.E., ed., The Cretaceous System in the Western Interior of North America: Geological Association of Canada Special Papers 11, p. 1–29.

Wyoming Oil and Gas Conservation Commission, 2009, Wyoming Oil and Gas Conservation Commission Web site: *at* http://wogcc.state.wy.us

Appendix

Well information for cross section A-A'

API No.	Elevation	Longitude	Latitude	Range	Township	Section
539173	4061	-105.992331	44.791110	76	56	34
539171	4040	-105.997657	44.787380	76	56	34
539164	3994	-105.997972	44.780304	76	56	34
539776	3985	-105.991760	44.777242	76	55	3
533592	3991	-105.991919	44.770495	76	55	3
533565	3957	-105.987255	44.763336	76	55	10
533534	3964	-105.977300	44.755900	76	55	11
533541	3957	-105.976706	44.752260	76	55	11
533303	3972	-105.961400	44.745000	76	55	13
533666	3964	-105.951299	44.741413	76	55	13
533896	3966	-105.941202	44.737624	75	55	18
540625	3999	-105.936742	44.734220	75	55	19
540626	3996	-105.925477	44.734703	75	55	19
540621	4123	-105.909616	44.731426	75	55	20
540623	4033	-105.904678	44.728277	75	55	20
540643	3975	-105.899125	44.724749	75	55	21
540646	3967	-105.893839	44.721121	75	55	28
540648	3953	-105.888584	44.717634	75	55	28
523506	4000	-105.882854	44.711013	75	55	28

(accessed 2003–2009).

Well information for cross section B-B'

API No.	Elevation	Longitude	Latitude	Range	Township	Section
551153	4550	-105.962790	44.251210	76	49	2
552265	4543	-105.964270	44.245540	76	49	2
505482	4464	-105.952585	44.240323	76	49	12
505444	4568	-105.952940	44.233340	75	49	12
505408	4560	-105.947561	44.223903	76	49	13
505388	4600	-105.941506	44.218333	76	49	13
505011	4632	-105.938200	44.214992	76	49	13
505361	4540	-105.937731	44.211050	76	49	24
523439	4489	-105.925246	44.203714	75	49	19
505328	4570	-105.916887	44.196966	75	49	30
505320	4510	-105.911758	44.193644	75	49	29
505309	4425	-105.907019	44.189717	75	49	29
505300	4460	-105.903950	44.185014	75	49	29
505291	4480	-105.896681	44.182851	75	49	32
505261	4420	-105.892403	44.172386	75	49	33
505233	4540	-105.887775	44.162521	75	48	4
526076	4480	-105.891878	44.158342	75	48	5
505205	4572	-105.877665	44.148334	75	48	9
521293	4458	-105.877990	44.140830	75	48	16

Well information for cross section C-C'

API No.	Elevation	Longitude	Latitude	Range	Township	Section
1920419	4731	-106.0144	43.935237	76	46	29
1920387	4665	-106.0129	43.941966	76	46	20
524205	4662	-106.0054	43.94352	76	46	21
542459	4576	-105.9962	43.95518	76	46	16
549543	4534	-105.9917	43.96583	76	46	16
525728	4505	-105.9865	43.97689	76	46	10
526718	4585	-105.982	43.988087	76	46	3
523764	4636	-105.9612	43.99541	76	46	2
536596	4771	-105.9466	44.005435	76	47	36
557680	4879	-105.9373	44.01323	76	47	25
557706	4761	-105.9227	44.01715	75	47	30
530566	4702	-105.9097	44.01966	75	47	29
539802	4743	-105.9	44.02949	75	47	20
523270	4641	-105.8925	44.043005	75	47	17
552885	4591	-105.8771	44.05056	75	47	16
526485	4647	-105.8728	44.06099	75	47	9
555740	4862	-105.8519	44.07669	75	47	3
555732	4787	-105.8371	44.08	75	47	2
538794	4706	-105.8268	44.087489	75	48	36
538127	4677	-105.8195	44.092971	75	48	36
538806	4707	-105.812	44.098575	75	48	36
536070	4752	-105.8074	44.102267	74	48	30
536047	4806	-105.8028	44.105953	74	48	30
536053	4768	-105.7978	44.109573	74	48	30
536055	4780	-105.793	44.113125	74	48	30
547703	4942	-105.7522	44.12806	74	48	21
547698	4949	-105.7472	44.13111	74	48	15
547711	4902	-105.7408	44.13527	74	48	15
547700	4967	-105.7372	44.13833	74	48	15
547691	5046	-105.7269	44.14556	74	48	11
547692	5061	-105.7213	44.14913	74	48	11
522445	4982	-105.7116	44.149759	74	48	11
542767	4976	-105.707	44.15275	74	48	12
542768	4938	-105.7019	44.15691	74	48	12
545513	4865	-105.6972	44.16053	74	48	1
545511	4866	-105.6917	44.16385	74	48	1
544653	4904	-105.6858	44.16731	73	48	6
544652	4971	-105.6803	44.17056	73	48	6
540588	4919	-105.6743	44.177481	73	49	31
540344	4850	-105.6693	44.181185	73	49	32
540339	4892	-105.6693	44.188495	73	49	29
540387	4856	-105.6643	44.192186	73	49	29
540384	4833	-105.6592	44.19566	73	49	29
540383	4859	-105.6543	44.199607	73	49	29
540380	4821	-105.6491	44.203304	73	49	21
541867	4865	-105.6435	44.206885	73	49	21
541441	4832	-105.639	44.210587	73	49	21
534897	4873	-105.634	44.217882	73	49	16
543270	4774	-105.6337	44.228748	73	49	16
526440	4765	-105.6184	44.243655	73	49	10
540908	4696	-105.6083	44.254791	73	49	2
523467	4732	-105.6084	44.265885	73	50	35
525425	4800	-105.5923	44.280028	73	50	26
525255	4771	-105.5828	44.284678	73	50	25
525859	4700	-105.5747	44.293408	73	50	24
522597	4634	-105.5569	44.295874	72	50	19
523060	4567	-105.5165	44.300153	72	50	21
522584	4584	-105.5117	44.303908	72	50	21

PLATES

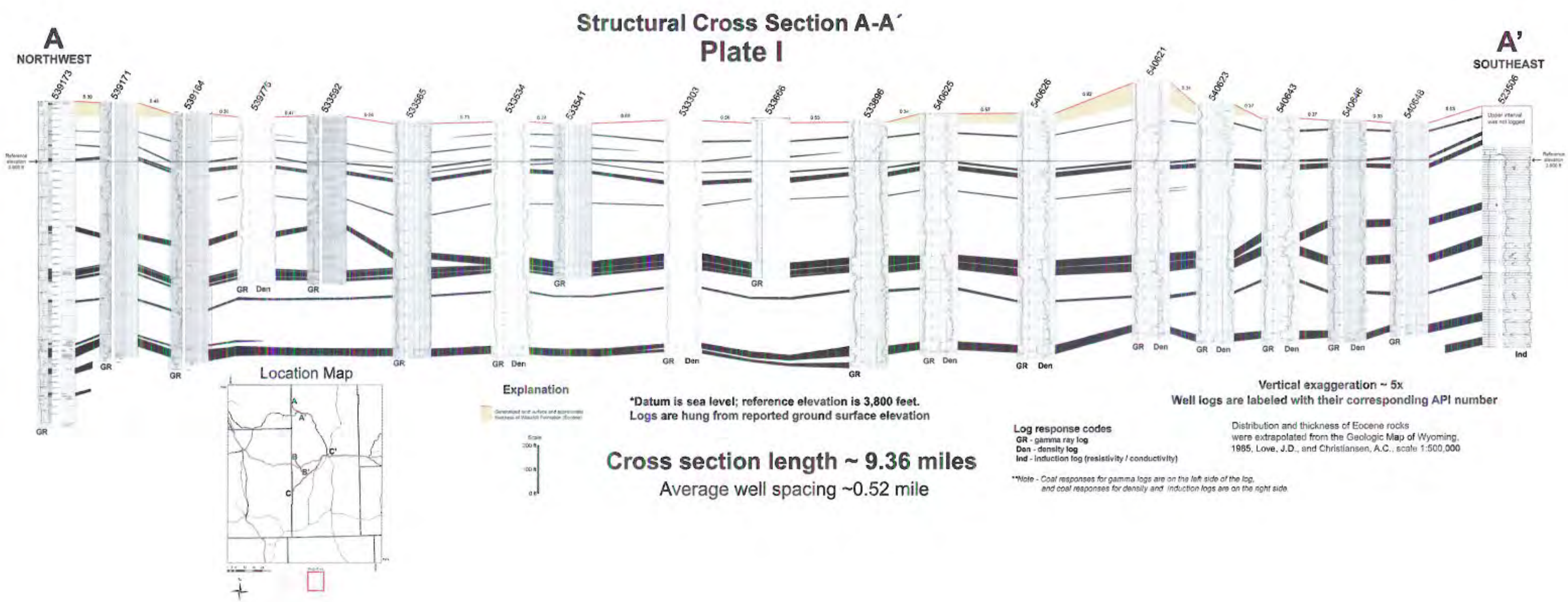


Plate I. Cross section A-A´.

(Full-size plates available on CD-ROM, located in pocket on back inside cover; full-size hardcopies can be ordered from WSGS.)

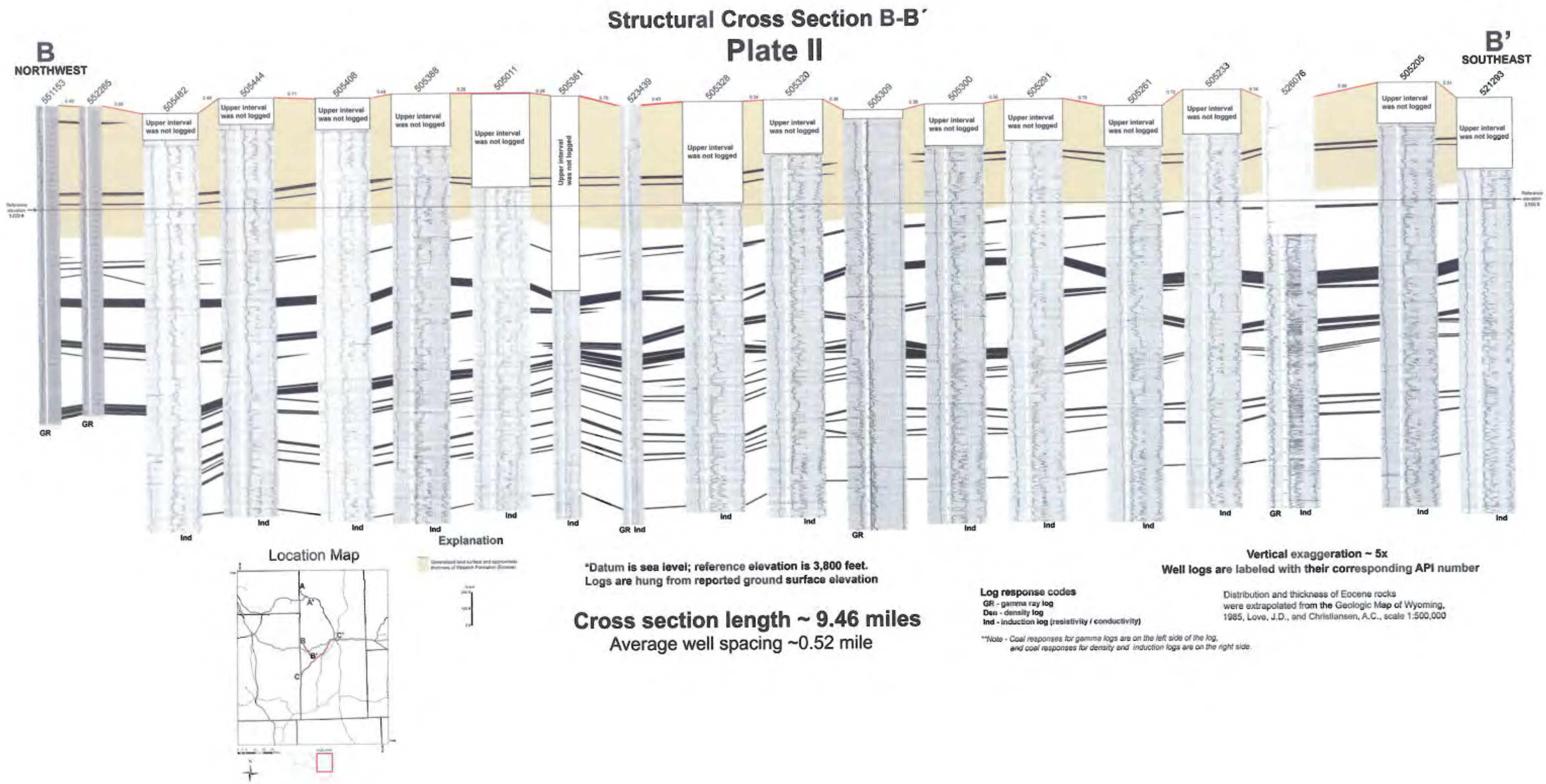


Plate II. Cross section B-B´.

(Full-size plates available on CD-ROM, located in pocket on back inside cover; full-size hardcopies can be ordered from WSGS.)

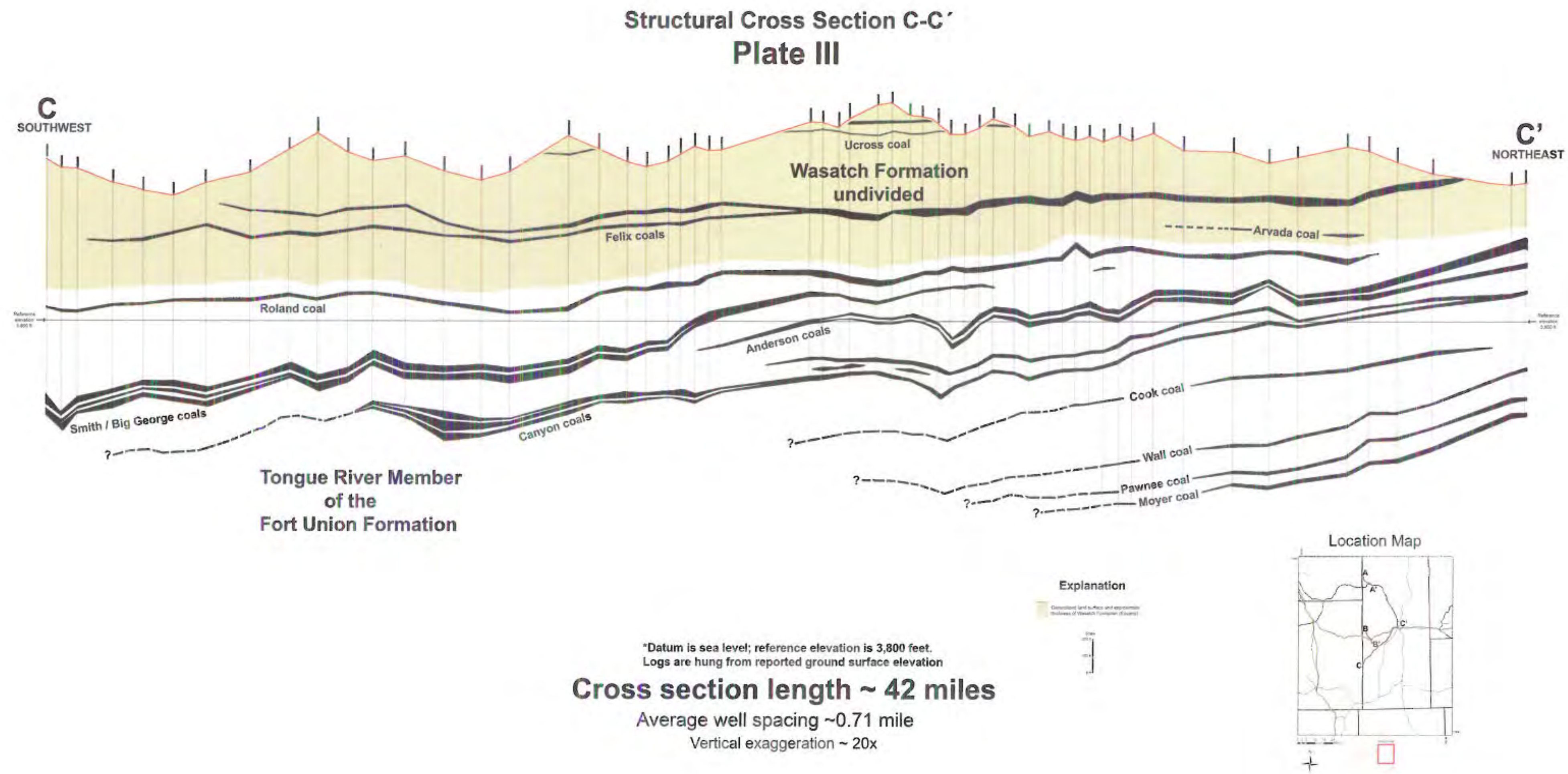


Plate III. Cross section C-C´.
(Full-size plates available on CD-ROM, located in pocket on back inside cover; full-size hardcopies can be ordered from WSGS.)

WSGS

www.wsgs.uwyo.edu

Mission Statement

The Wyoming State Geological Survey (WSGS) mission is to promote the beneficial and environmentally sound use of Wyoming's vast geologic, mineral, and energy resources while helping protect the public from geologic hazards. By providing accurate information and expanding knowledge through the application of geologic principles, the WSGS contributes to economic growth and improvement in the quality of life for Wyoming's residents.

9 781884 589539