To the University of Wyoming:

The members of the Committee approve the Thesis of Nick R. Jones presented on November 18, 2009.

Randi S. Martinsen, Chairperson

Mark E. Ritchie, External Department Member

James C. McClurg

APPROVED:

Arthur W. Snoke, Department Head, Department of Geology and Geophysics.

B. Oliver Walter, College Dean

Jones, Nick, R, A 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., Department of Geology and Geophysics, December, 2009.

Tertiary coal deposits in Wyoming's Powder River Basin contain the most abundant, thick, low-sulfur, low-ash, minable coal reserves in the U.S. Several of these coal deposits exceed 100 feet in thickness, and so have been of great interest to geologists. 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 bed 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 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 influences on differential development of accommodation within the basin, and 3) the coalification process − not compaction. The result of this study is a 2D structural reconstruction model showing the structural development of accommodation; alternating periods of clastic and organic deposition; and the development of stacked coal beds and parting geometry formation. Three plates, A−A', B−B', and C−C' illustrate the unique subsurface geometry of the coal deposits in the Powder River Basin. A structural reconstruction analysis was performed using cross section A−A', this analysis is the basis for the new model. There are four considerations implicit in this model: 1) the top of each coal represents a chronostratigraphic surface; 2) development of accommodation is syndepositional 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.

A PARADIGM IN THE GENESIS OF THICK COAL DEPOSITS AND THEIR UNIQUE ANGULAR RELATIONSHIPS: A RESULT OF DIFFERENTIAL DEVELOPMENT OF ACCOMODATION IN THE POWDER RIVER BASIN, WYOMING

By
Nick R. Jones

A thesis submitted to the Department of Geology and Geophysics
of the University of Wyoming in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
in
GEOLOGY

Laramie, Wyoming
December 2009

Acknowledgments

I would like to thank the members of my thesis committee, especially my advisor Randi Martinsen, for support, encouragement, and guidance throughout the project. I would also like to thank my colleagues Richard Jones and Wayne Sutherland at the Wyoming State Geological Survey for their thoughtful geological discussions; Dave Copeland for his time editing and reviewing the preliminary drafts; and to James Rodgers for his assistance with the illustrations.

I would also like to thank the members of the USGS coal resource team, James Luppens, Lee Osmonson, Dave Scott, Jon Haacke, and Tim Rohrbacher for our insightful discussions. I would like to thank Chris Carroll of the Colorado State Geological Survey for his review and comments on the final draft of this thesis. I would like to also thank Ed Heffern of the Wyoming Bureau of Land Management, for sharing his knowledge and for assisting me in locating reference materials.

I am very thankful and deeply indebted to Dr. James C. McClurg for sharing his enthusiasm and his intimate knowledge of wetland systems and coal, for our insightful discussions about depositional systems at outcrop and in the numerous swamps that we visited, and for his efforts reviewing and discussing the drafts that became this thesis.

I would also like to thank the late Robert M. Lyman, my former supervisor and mentor at the Wyoming State Geological Survey, for his support and encouragement early in my career.

Finally, I would very much like to thank my wife Vandy for her love, support, and patience that she always shares. And to my folks, Rod and Chloe, thanks for all the love, support, and encouragement you have shown me.

Table of contents (pages ii-vi)

List of Figures

List of Tables

List of Plates

List of Appendices

Introduction

The coal bearing Tongue River Member constitutes the uppermost member of the early Tertiary (Paleocene) Fort Union Formation in the Wyoming Powder River Basin. It is composed of fluvial, lacustrine, and mire deposits (mire is the generic term for wetlands: swamps, marshes, bogs, etc.) 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 (MSHA, 2009). This coal is produced from the Tongue River Member where the coal lies within 500 feet of the land surface.

These coal deposits also contain abundant coalbed methane (CBM) resources. At 65 cubic feet of CBM per ton of in-place coal, the CBM resource in the Wyoming Powder River Basin (PRB) is estimated to be approximately 37 trillion cubic feet (DeBruin, 2009 pers. comm). In 2008, approximately 535 billion cubic feet of CBM and more than 500 million barrels of water were collectively produced (WOGCC, 2009) from 24 unique coal deposits in 10 coal zones that occur in the Tongue River Member in Wyoming (Jones, 2008).

Since 1988, nearly 24,000 CBM 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 as part of a basin-wide study related to produced CBM water. This work was conducted by the Wyoming State Geological Survey (WSGS) as part of a larger basin-wide hydrologic and geologic study. Data for the coal model was interpreted, correlated, and modeled by the author and WSGS staff (Jones, 2008).

Purpose and scope

During the last forty years, the Tertiary coal beds in the basin have been the subject of many geologic investigations relating to their origin, stratigraphic distribution, and structural geometry. Information collected during these investigations 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. Thesis research for this study was conducted between 2007 and 2009 and included field work, well log analysis, and correlation. Intervals of subbituminous coal containing combinations of high-ash layers, bone coal (coal containing less than 50 percent carbon), rooted zones, and partings composed of clastic material were used together with concepts of sequence stratigraphy to identify regional subaerial paleo-surfaces within thick coals.

Location

The research area for this study is the Wyoming portion of the Powder River Basin in Campbell County. Three cross sections (Appendix A; Plates I, II, and III) were constructed within this county on the basis of the resolution, distribution, density, and depth of available well logs (fig. 1.1). Cross section A–A′, in northwest Campbell County, is approximately 9.3 miles long and trends SE from T56N, R76W, sec. 34 to T55N, R75W, sec. 27 (Appendix A, Plate I). Cross section B–B′, in west-central Campbell County, is approximately ten miles long and trends SSE from T49N, R76W, sec. 2 to T48N, R75W, sec. 16 (Appendix A, Plate II). A third generalized cross section, C–C′, was constructed across southern Campbell County. It is approximately 40 miles long and trends NNE from T46N, R76W, sec. 29 to T50N, R72W, sec. 21 (Appendix A, Plate III).

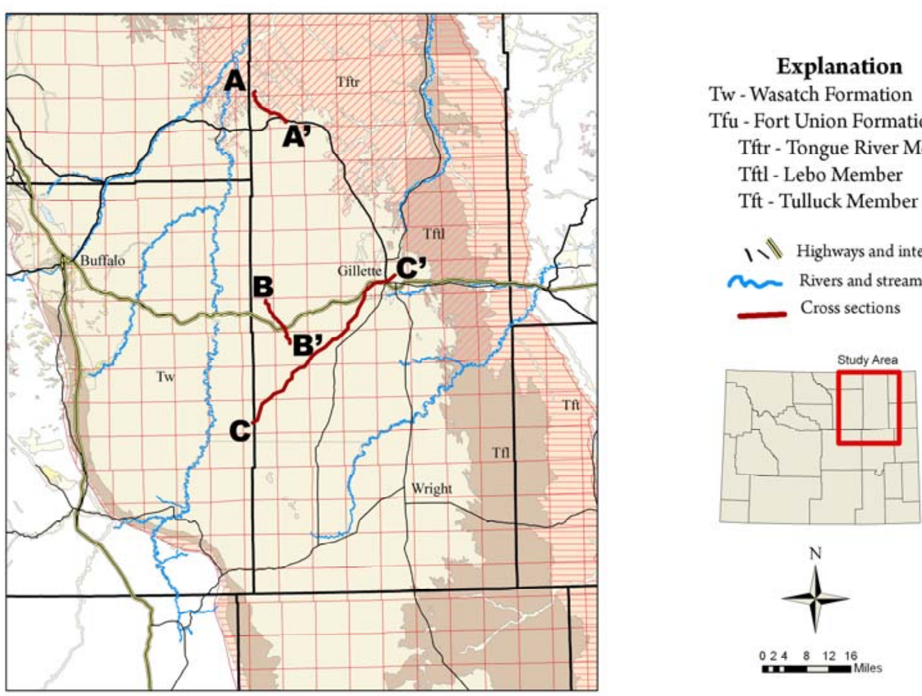

Figure 1.1 ─ Location map and study area showing locations of cross sections

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 workers. The earliest comprehensive field studies on Tongue River coal deposits began in 1907 by U.S. Geologic Survey geologists (Taff, 1909). Since the earliest studies, the question that puzzled geologists was the processes by which the thick deposits formed. Not only are these deposits thick (more than 100 feet); they split into several different coal sequences which further split into individual coal beds. The geometry of the splitting also puzzled field investigators. The thickness of the clastic material (the parting) between a split coal deposit may increase longitudinally from less than an inch to more than 100 feet and pinch out in less than two miles; furthermore, the upper coal may ramp up in a convex fashion above the parting where the lower coal remains parallel to the structural dip of the Tongue River Member (fig 1.2).

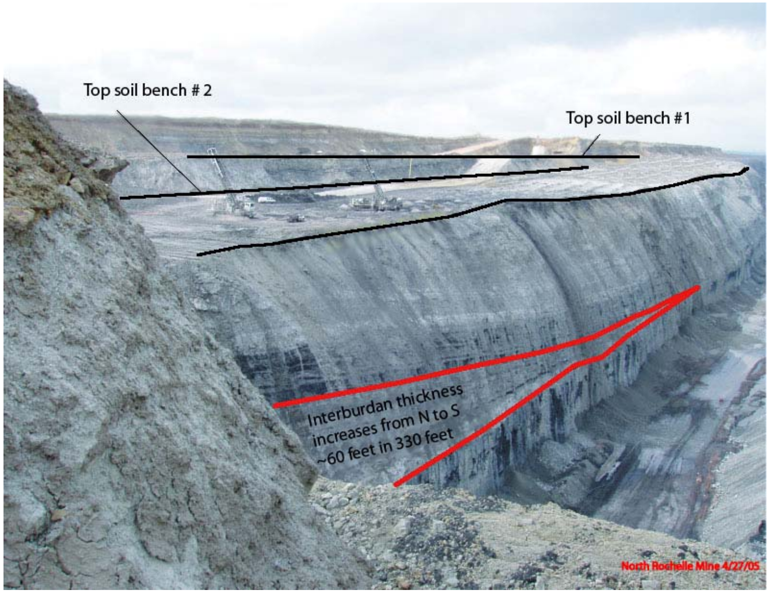

Figure 1.2 ─ Photo showing major split (highlighted in red) and development of parting between Wyodak coals, photo by Timothy J. Rohrbacher, USGS, circa 1990.

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 (fig 1.3a).

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

At other locations in the basin where the geometry of the parting is wedge shaped, the thickness of one or both of the interrelated (stratigraphically adjacent) coals "pinches out" (thins to zero) at some distance from the split, (fig 1.3b) and (fig 1.3c). These partings and bed geometries are currently considered to be the result of alternating wetland facies and fluvial-lacustrine facies (Flores 1981, 1986; Pocknall and Flores, 1987; Ayres and Kaiser, 1984; 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.

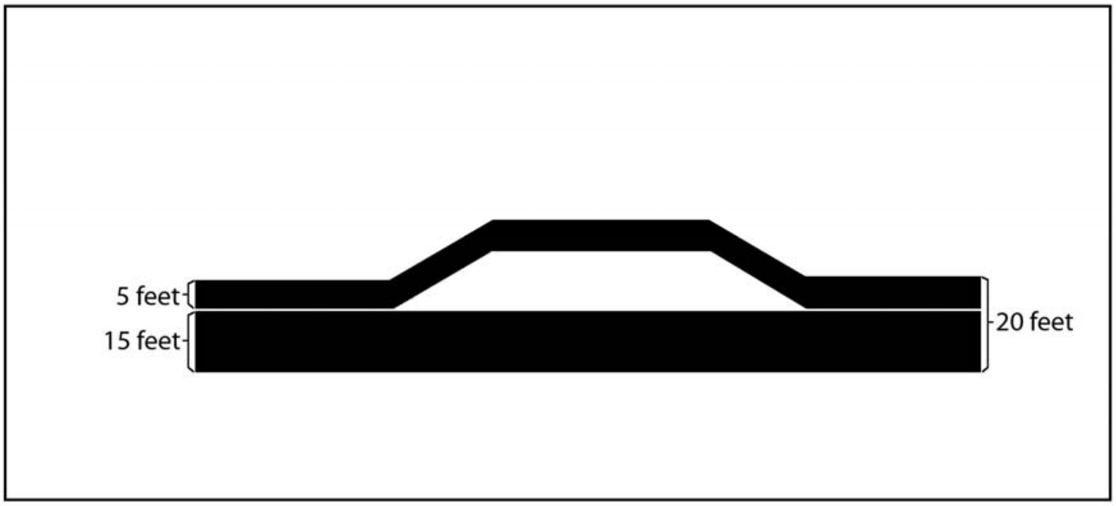

Figure 1.3a. Continuity of coal bed thickness across a lenticular shaped parting

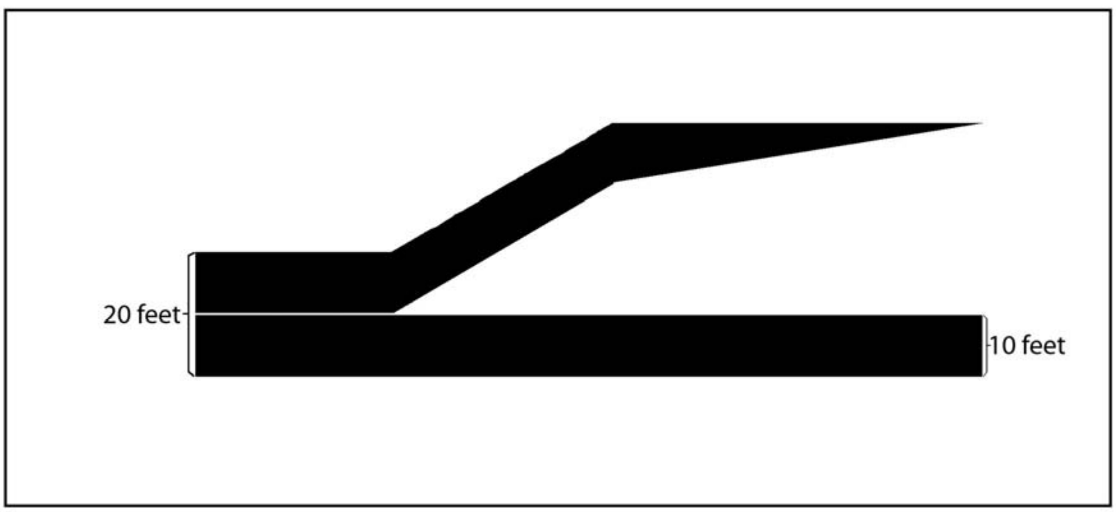

Figure 1.3b. Coal bed pinch-out at some distance from the wedge shaped split

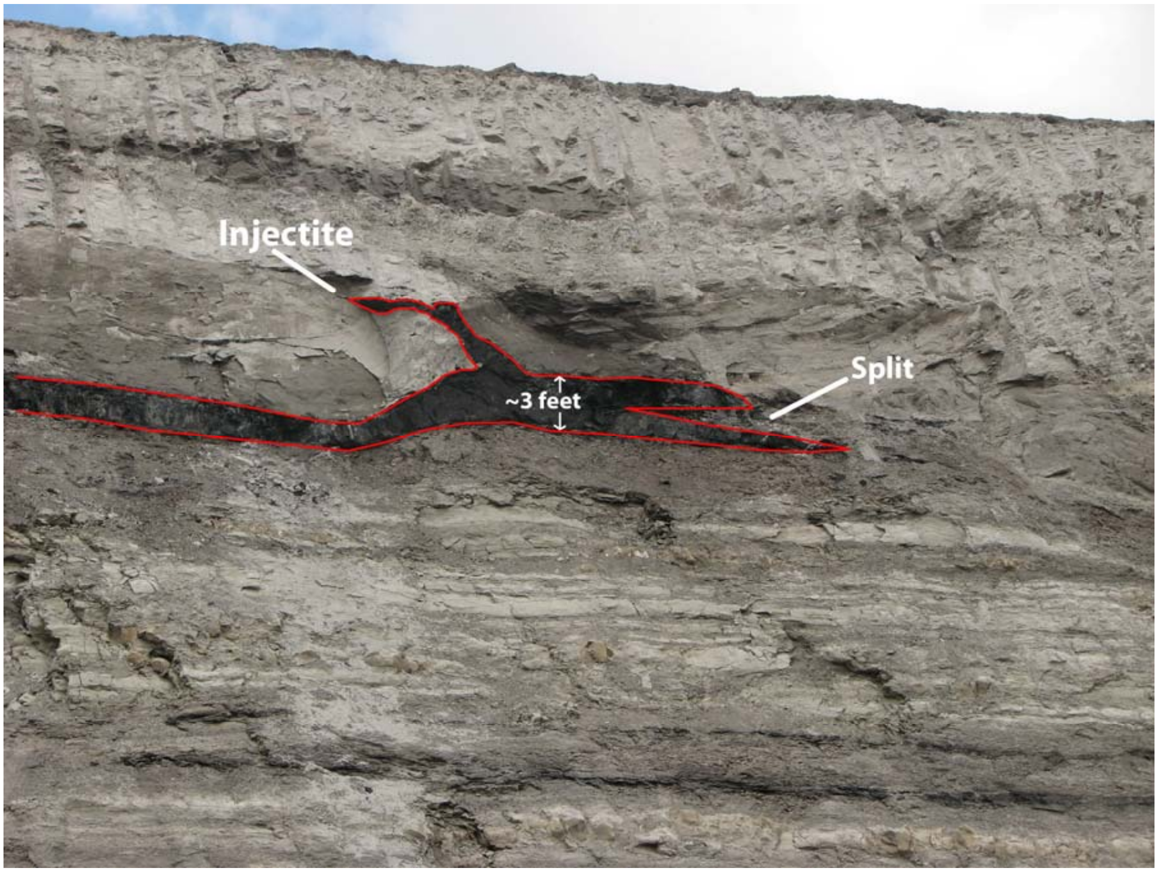

Figure 1.3c ─ Photo showing termination of coal bed and splitting resulting from transitional facies sequence. The injectite is a result of soft sediment deformation caused by loading of the precursor to coal, a hydrophilic gel called "gytta." Gytta is further discussed in the coalification section of this thesis p. 34-39, photo by Nick R. Jones, 2009.

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 (fig 1.4) (Jones, 2007−2009). Where the thickness of a parting goes to zero, the overlying and underlying coals merge (figs 1.4 and 1.5).

Figure 1.4 ─ Photo shows distinct stratigraphic horizons at the top and base of coals and increasing thickness of the clastic material between coal beds –"the interburden or parting material." For reference, the dip of the lower coal is parallel to the structural dip of the Fort Union Formation, photo by Nick R. Jones, 2009.

The contact between them continues into the combined coal. However, tracing this surface beyond the merge point of the two coals is very difficult, and requires detailed field observation, core analysis, and access to exposed faces of coal in coal mine highwalls.

This very subtle and often difficult-to-recognize layer is an oxidized coal interval that ranges in thickness from a 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 (Pzero through P12, figure

1.5) are heterogeneous and consist of claystone; gypsum; weathered coal; bone coal (a hard, coaly material that contains less than 50 percent carbon by volume); rooted zones; and high concentrations of the coal maceral fusain (ash created from burning peat), a charcoal that is produced when coal burns (Moore, 1994; Jones, 2007−2009, 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 Pzero and P1 figure 1.5).

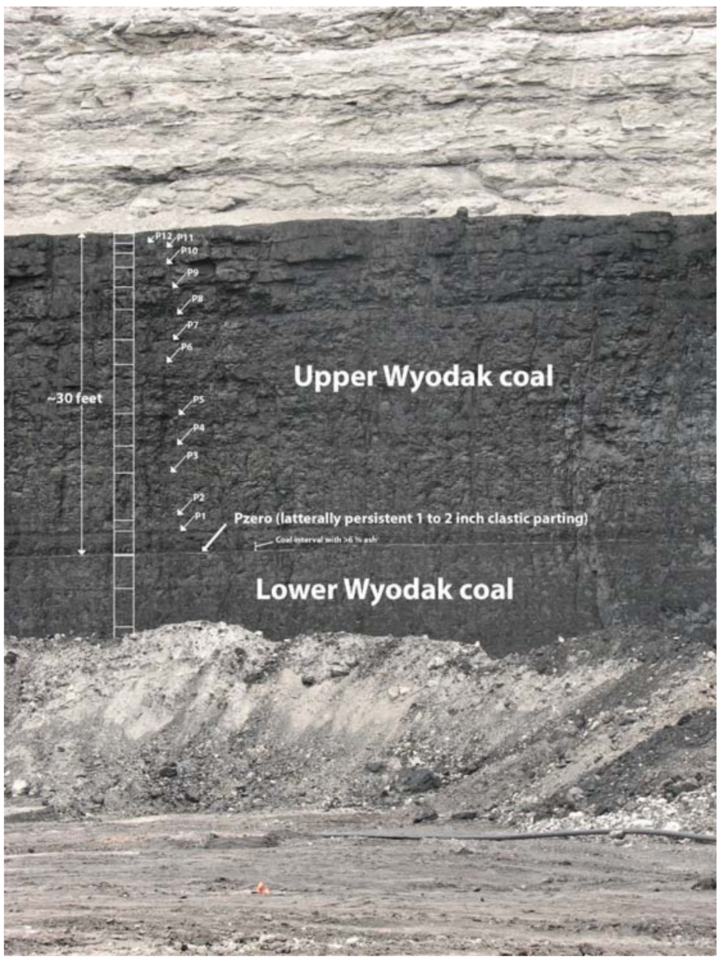

Figure 1.5 ─ Photo shows distinct stratigraphic horizons within and between the two major Wyodak coals where the parting material between them is minimal, photo by Nick R. Jones, 2009.

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 unique 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 relationship between stratigraphically adjacent coal deposits develop?

Structural Setting

The Powder River Basin is an elongate, north-south, asymmetric synclinal trough that formed during compartmentalization of the Cretaceous foreland east of the 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.

Initial compartmentalization of the Cretaceous foreland began approximately 100 million years ago and is attributed to the formation and eastward migration of intrabasinal highs and lows in response to eastward tectonic propagation from the Overthrust Belt in the west (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 Powder River Basin occurred between 75 and 80 million years ago during the transition between the Sevier and Laramide orogenies (Beck et al., 1988; Tikoff, 2001). The most significant development of the basin occurred 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 Big Horn 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 expression of these zones are called lineaments (fig. 1.6). Following this unroofing sequence, the Precambrian basement of the Big Horn and Black Hills blocks were exposed, because of the more competent nature of these rocks − uplift outpaced erosion, resulting in significant relief from the top of the rising blocks to the surface of the basin (Whipkey et al., 1991).

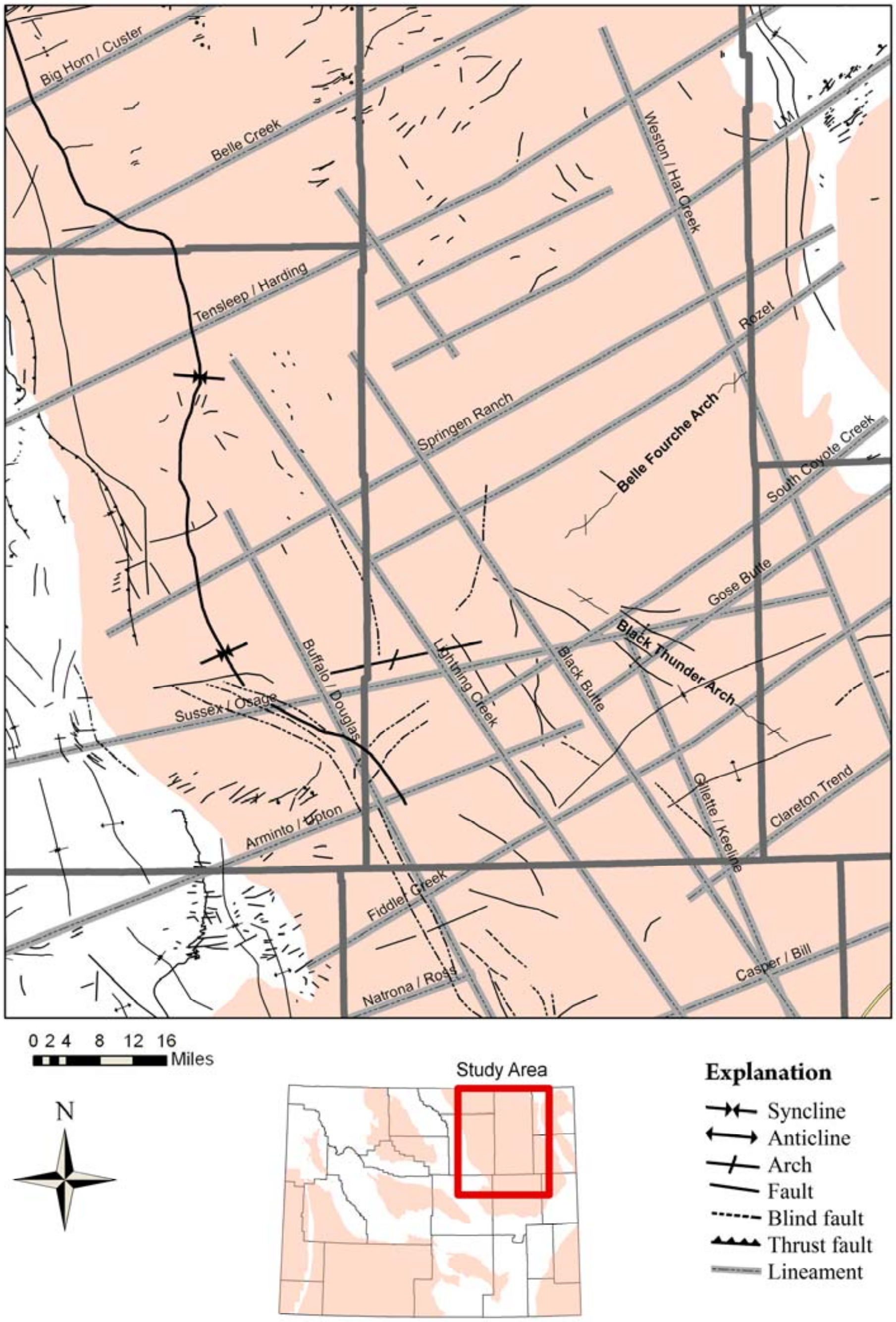

Figure 1.6 ─ Generalized structure map of the Powder Basin denoting subsurface structures, blind faults, and lineaments. (Denson et al., 1978; Marrs and Raines, 1984; Martinsen, 2003).

Stratigraphic Setting

The Tongue River Member was deposited during a brief (4-million-year) period between 63 and 59 million years ago (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). Ayres and Kaiser (1984) characterized the stratigraphic facies 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 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 Tongue River Member was informally divided into seven coal zones on the basis of distinct stratigraphic intervals containing coal sequences identifiable in well data. The coals zones include 1) Roland, 2) Wyodak Rider, 3) Upper Wyodak, 4) Lower Wyodak, 5) Cook, 6) Wall, and 7) Basal Tongue River Coal Zones (Jones, 2008) (Appendix A, Table 1).

Structural versus depositional influences on accommodation

The current consensus is that throughout the Paleocene, the rate of accommodation (the available space for sediments to accumulate) development and the rate of basin fill were in equilibrium, so that erosion of sediments kept pace with uplift. During this time, the Powder River Basin 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 because of 1) regional subsidence at a rate of 0.5 feet per thousand years (Ayers and Kaiser, 1984); 2) differential compaction of underlying sediments in response to loading; and 3) auto-compaction of peat based on compaction ratios between 3:1 (e.g., 3 feet of peat compacting to form 1 foot of coal) and 10:1(Flores 1981, 1986; Flores and Moore 1984; Pocknall and Flores, 1987; Moore and Shearer, 1993; Ayres and Kaiser, 1984; Kent, 1986).

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 a combination of changes in base level, aggrading river systems, and compaction of sediments in response to loading. Sedimentation kept pace with the available accommodation, causing it 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 thesis included field work and the study of present day subtropical wetland environments along the east coast of the U.S. from the Carolina's south to Georgia and Florida; as well as wetlands in 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, the Atchafalaya Basin and Pointe Lake in southern Louisiana. Throughout this field work I met with and learned a great deal from ecologists, botanists, and naturalists about subtropical wetland environments and developed a detailed understanding of these systems.

Wetlands that were studied during this field work share many similarities to the paleo-wetlands of the early Tertiary in the Powder River Basin (McClurg, pers comm.). These environments occur in areas with a subtropical climate, they are at or near sea-level, have very little to no topography, variations in daily temperature are minimal, and precipitation exceeds 50 inches per year.

Notable wetland characteristics that influence the nature of organic accumulation include the level of the water table, water chemistry, the ecological heterogeneity (the diversity of ecosystems in wetland environments), flow velocity, and seasonal fluctuations in temperature. Three characteristics that stand out the most include 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 is parallel to the surface of the water table. Organic detritus shed onto the floor of a wetland in subaerial conditions rapidly succumbs to nearly complete oxidation and decay. The residence time for this material under these conditions is short lived and the available nutrients are recycled back into the mega flora. If this material accumulates in anoxic, subaqueous conditions; oxidation and decay is restricted and available nutrients in the material are consumed by anaerobes. Under these conditions the residence time for the material is long-lived and nutrient cycling is restricted, this results in a thickening accumulation of an organic rich hydrogel relative to available accommodation (the space available for sediments to be deposited).

Water chemistry, specifically pH and dissolved oxygen are also important factors that affect 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 suppressed, the rate of microbial 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 swamps.” 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. This is an important process in terms of ash content of a coal deposit (ash in coal is the inorganic non-combustible material) because, it inhibits the intrusion and mixing of clastic material with the accumulating organics immediately behind the turbid water – black water interface (McClurg, pers comm.) (fig 1.7).

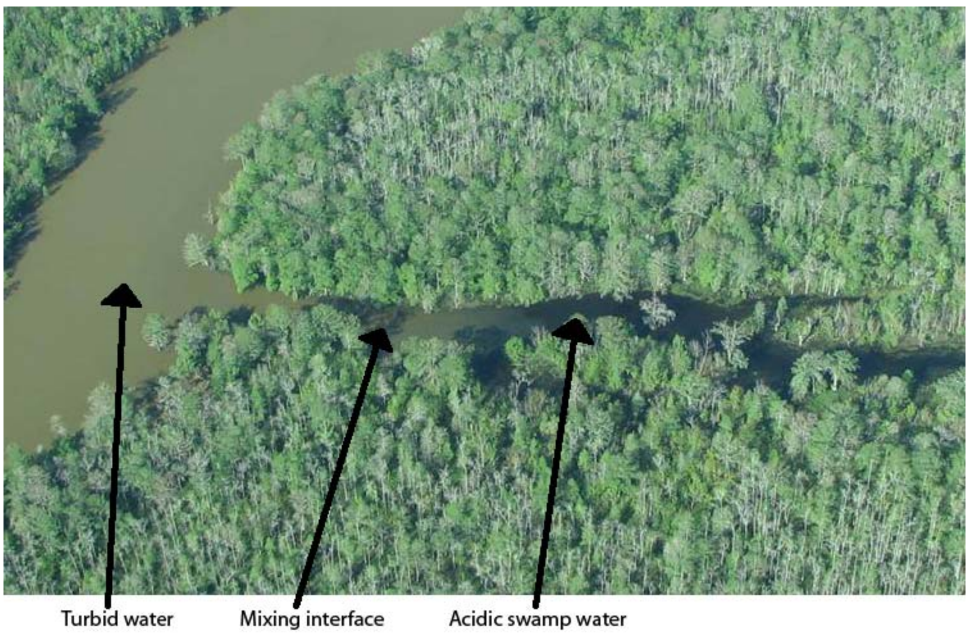

Figure 1.7 — Aerial photo showing the mixing interface and zone of flocculation between swamp waters and turbid waters in the Atchafalaya Basin. This physical buffering process prevents clastic material from mixing with organic material and results in low-ash coal deposits, photo by N.R. Jones, 2007.

The various interrelated ecosystems within wetlands include flooded meadows, flooded prairies, shallow bodies of open water, and densely vegetated flooded forests (figures 1.8 and 1.9). Due to changes in the level of the water table these environments 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 1.8 ─ Photos showing the ecological heterogeneity of swamp environments, **A.** Densely vegetated region within the Corkscrew Swamp, Florida; **B**. Flooded forest in Pointe Lake, Louisiana; **C.** Flooded forest in the Big Cypress swamp, Florida; **D.** Flooded meadow in the Okefenokee Swamp, Georgia; and **E.** Flooded meadow in front of a flooded forest also in the Okefenokee Swamp, Georgia, photos by N.R. Jones, 2007.

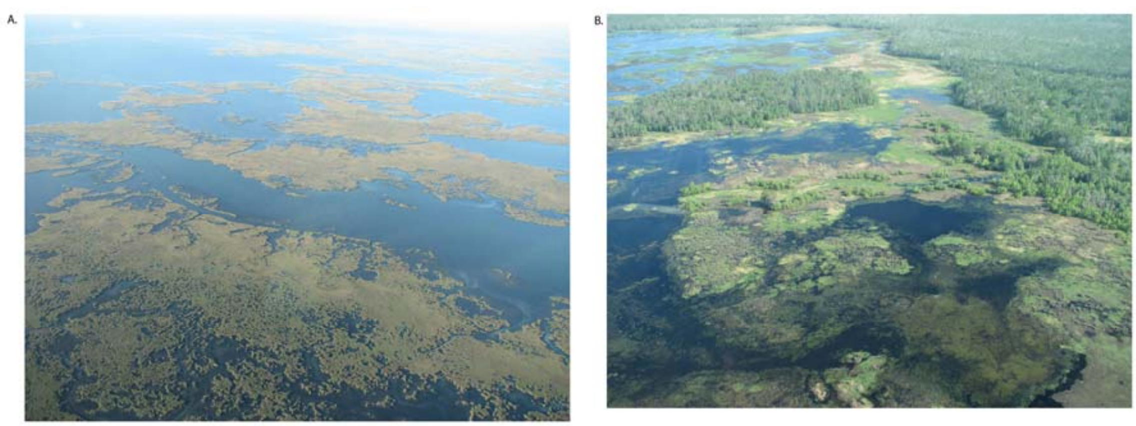

Figure 1.9 ─ Aerial photos showing the ecological diversity of marsh and marsh / swamp environments, **A.** Coastal marshes along the lower Mississippi River Delta; and **B.** Boundary between the upper and lower delta plains of the Mississippi River Delta. Note− variations in the level of the water table can shift the locations of adjacent wetland environments, photos by N.R. Jones, 2007.

Previous Work

There are four notable contemporary models of how very thick deposits of low-ash coal formed in the Tongue River Member of the Fort Union Formation in Wyoming's Powder River Basin. 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 ground water (Ayers and Kaiser, 1984); 3) The "teeterboard" hypothesis (Kent, 1986), and 4) Basin-wide wetlands and shallow lacustrine systems (McClurg, 1998).

Factors in these models are 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 (fig 2.1a) and a lower meandering fluvial facies (fig 2.1b). 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.

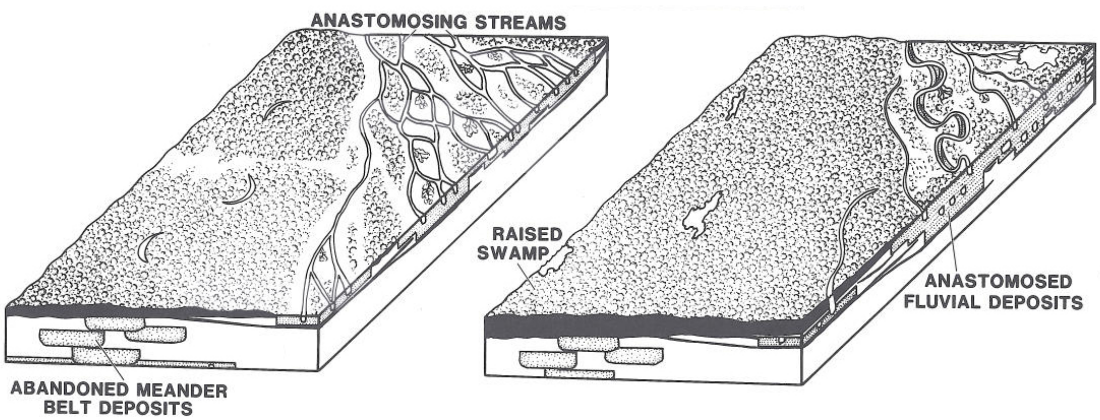

Figure 2.1a ─ Block diagrams illustrating anastomosing streams and raised swamps, from Flores, 1986.

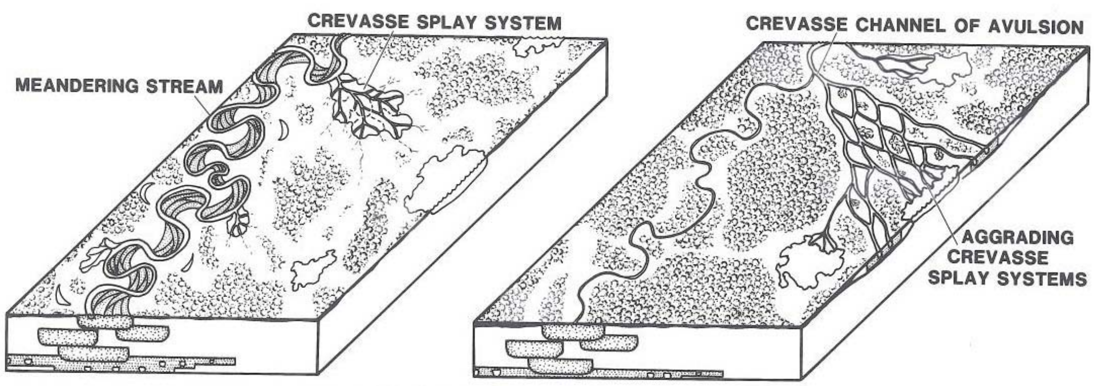

Figure 2.1b ─ Block diagrams illustrating meandering streams, crevasse splays, and channel avulsion, from Flores, 1986.

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 deposited 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 in parts of Indonesia today 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 Powder River Basin 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 (fig. 2.2).

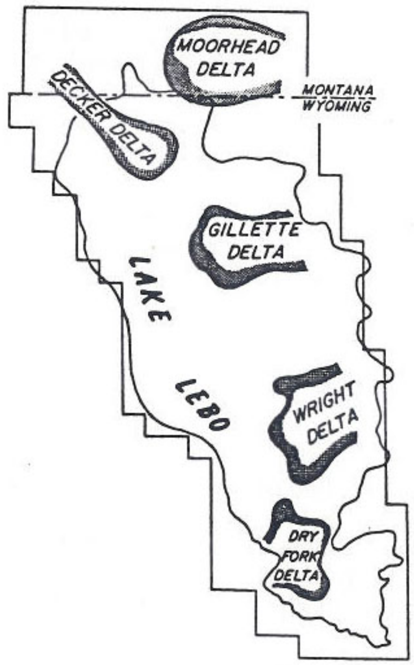

Figure 2.2 ─ Paleo-reconstruction of mid to late Paleocene lacustrine-interdeltaic systems in the Powder River Basin, from Ayres and Kaiser, 1984.

These sediments came from the east as elongate river deltas transporting mixed bed-load sediments from the ancestral Black Hills; from the southwest in 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 (fig. 2.2).

Basin subsidence commenced following deposition of the lower Tullock Member of the Fort Union 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 estimated to have been approximately 0.5 feet per 1,000 years, a rate that is typical of Laramide basins in Wyoming during the Paleocene. This rate is considered typical because each of the Laramide basins in Wyoming contains similar thicknesses of Fort Union and Fort Union-equivalent sediments.

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

The model of Ayers and Kaiser is based on the relationship between the framework elements (deltas and inter-deltaic 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 low ash content.

Studies on rates of modern peat accumulation suggest a mean peat accumulation rate in the Powder River Basin 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 Powder River Basin were not deposited in a fluvial dominated system, as proposed by Flores (1981,1986) (Ayers, 1986; Ayers and Kaiser, 1984).

The "teeterboard" hypothesis

Kent (1986) suggests that the Laramide Orogeny − specifically, subsidence along the western Powder River Basin 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 Powder River Basin − 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 (1998) concluded that the anomalously thick, low-ash, low-sulfur coal deposits in the Powder River Basin 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 described by McClurg is the Okefenokee Swamp in southeastern Georgia (fig 2.3).

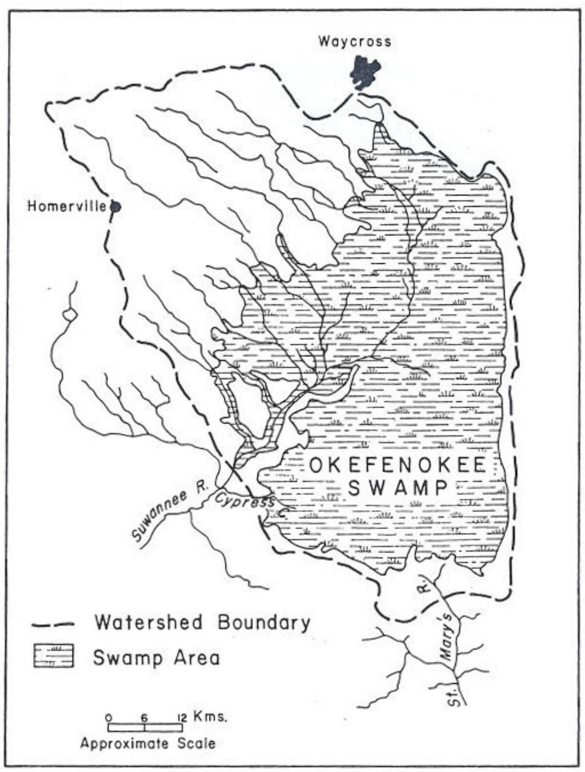

Figure 2.3 — Illustration of a small scale modern depositional analogue, the Okefenokee Swamp, for Paleocene depositional environments in Powder River Basin, from Rykiel, 1984.

The process by which thick coal beds 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. *(Swamp size as a function of a fluctuating water table accounts for splits in coal deposits).*

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 settles out of suspension. *(Large swamps and flocculation of clay result in low-ash coals).* Deposition of the clay results from different ionic charges at the interface between turbid river water and the black-water of a swamp: the negatively charged clay particles immediately flocculate and settle out of suspension where they enter the positively charged swamp-water environment, thus restricting sedimentation to the margin of the swamp. Swamp water is high in tannic and humic acids. These acids are produced in the swamp during the natural biogenic decay of organic material, a process that lowers pH and stains the water in a swamp a dark brown tea-color – hence the term black-water. 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.

Discussion

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

There is disagreement between the models of Flores et al., Ayres and Kaiser, and McClurg, as each model suggests a different type of wetland facies. Flores et al. suggest fluvial systems and raised mires based on the modern analogue of wetlands in parts of Indonesia. Ayres 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 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 (McClurg, pers. comm).

The basin-wide wetlands and shallow lacustrine systems model of McClurg is the only model 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 Ayres and Kaiser suggests discharge of groundwater from beneath the wetland system, a process that prevents clastic material from entering the wetland.

Apart from any specific wetland facies and processes that result in low-ash coal, Kent's "teeterboard-hypothesis" is the only model that addresses the interplay between uplift and subsidence that may have occurred in the developing basin. The raised mires model (Flores et al.), lacustrine-interdeltaic model (Ayres and Kaiser) see the development of accommodation solely as a function of basin subsidence; the basin-wide wetland model (McClurg) is the only model 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. However, none of the models consider differential development of accommodation in localized areas in the Powder River Basin 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 coal-bed splits likely result from overbank deposits where wetlands are associated with fluvial systems along a facies interface. However, McClurg's model, basin-wide wetlands and shallow lacustrine systems, 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 and is used to divide sedimentary basin fill into genetic packages that are 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 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 Powder River Basin of southeastern Montana (equivalent to the Wyodak coal in the eastern Powder River Basin 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 coalbed is actually composed of several stacked mire sequences.

The paradigm underlying Moore's conclusion is that thick coal deposits in the Powder River Basin 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 (fig 3.1).

Furthermore, evidence for paleosols including fusain layers (discrete horizons of oxidized coal), rooted zones, and evaporite deposits within and between coal deposits − indicate 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. And 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.

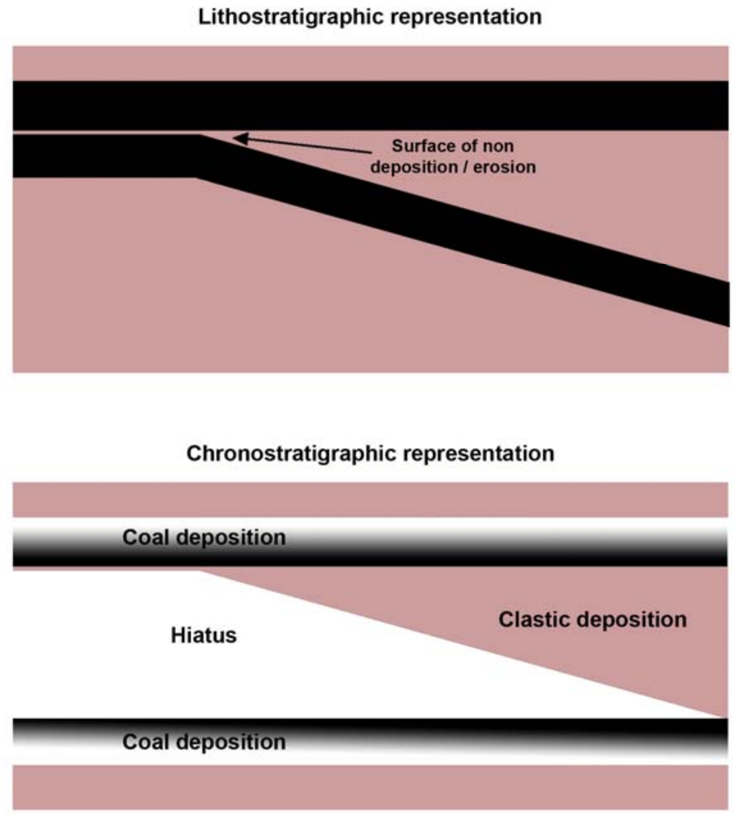

Figure 3.1 — Lithostratigraphic and chronostratigraphic representations illustrating major splits between thick coal deposits.

Structural influences

The Powder River Basin 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 Powder River Basin is one of eight intermontane basins bounded by Laramide uplifts within the Wyoming portion of the Rocky Mountain foreland province (fig 4.1). 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 expression of these basement fracture systems appear as linear, structurally related features termed lineaments (Hoppin, 1974).

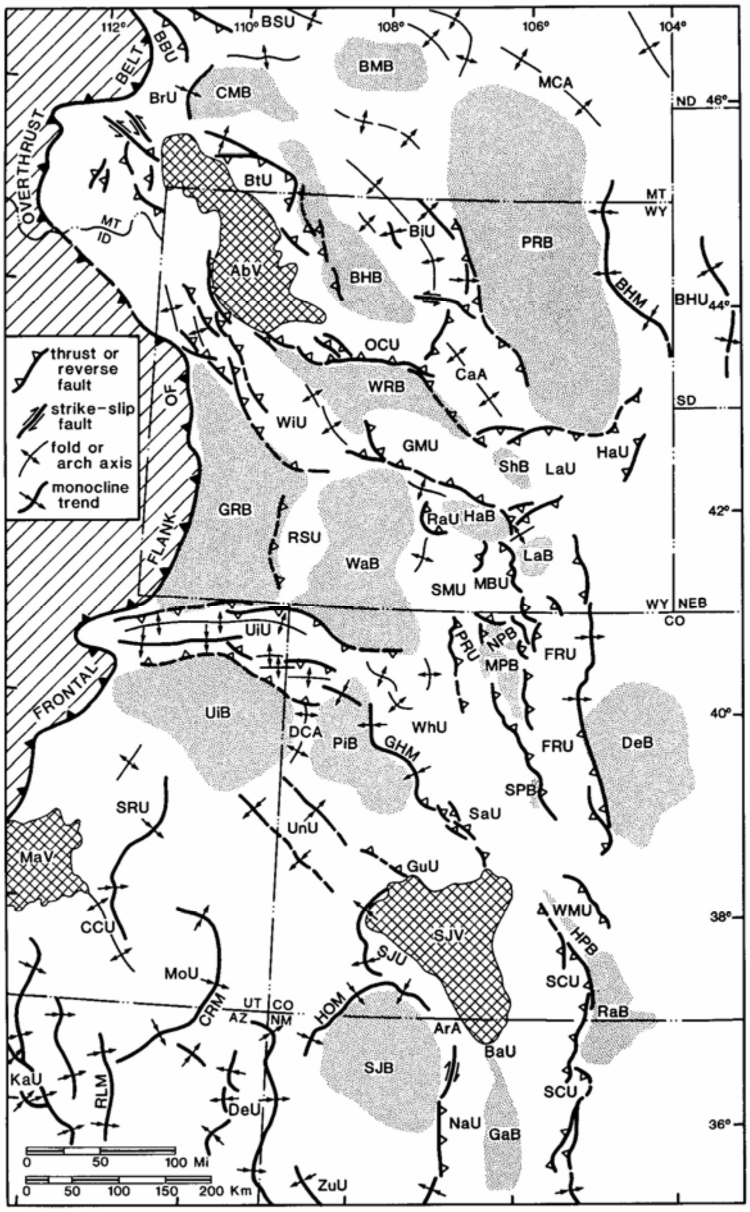

Figure 4.1 — Map showing continental basins and regional structure in the central Rocky Mountians that developed as a result of the Laramide Orogeny, from Dickinson et al., 1988. Sedimentary basins (stippled): Key for Wyoming basins -PRB, Powder River Basin; BHB, Big Horn Basin; WRB, Wind River Basin; ShB, Shirley Basin; HaB, Hanna Basin; LaB, Laramie Basin; GRB, Green River Basin; WaB, Washakie Basin, Abv, Absaroka Volcanics.

Timing of Laramide deformation and basin development

Prior to deposition of latest Cretaceous and early Tertiary continental deposits, the region that is now the Powder River Basin was in the central part of the greater Cretaceous foreland basin system. 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 (fig 4.2). By earliest Tertiary (Paleocene) time, only a remnant of the Cretaceous 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) (fig 4.3).

Figure 4.2 ─ (left) Illustration showing extent of Cretaceous Interior Seaway, from Cobban and McKinney, USGS. Figure 4.3 ─ (right) Illustration showing remaining extent of Cretaceous – Tertiary Cannonball Sea (Jones, 2009).

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

Deposition of early Tertiary sediments in the Powder River Basin 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 the development of the Casper Arch, a topographic high southwest of the Powder River Basin, 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 Formation (above the coal-bearing interval) and in the conglomeratic members in the overlying lower Wasatch Formation (Eocene) indicate that Paleozoic and Precambrian material was exposed in the core of the uplift 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, pers. comm.). Paleocurrent evidence suggests that as the basin developed, the basin axis migrated approximately 45 miles westward between Tongue River time and Wasatch time (Seeland, 1992; 1993).

Significant angular relationships exist between and within Eocene, late-Paleocene, and mid-Paleocene coals in the central and southern Powder River Basin (fig 4.4). This angular relationship can be seen in the north pit at the North Antelope Rochelle coal mine in southern Campbell County (fig 4.5). This thesis proposes that angular relationships represent the variable accommodation that developed as a result of basement block faulting.

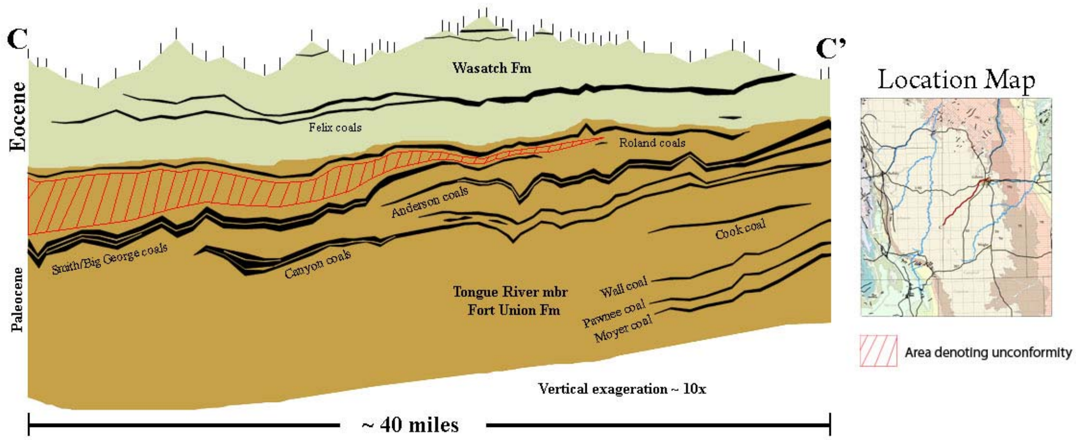

Figure 4.4 ─ Location map and cross section showing angular relationship between the Roland coal zone (Roland of Baker and Roland of Taff coal beds) and the lower Wyodak Rider coal zone (Smith Rider and Smith/Big George coal beds) (Jones, 2007-2009).

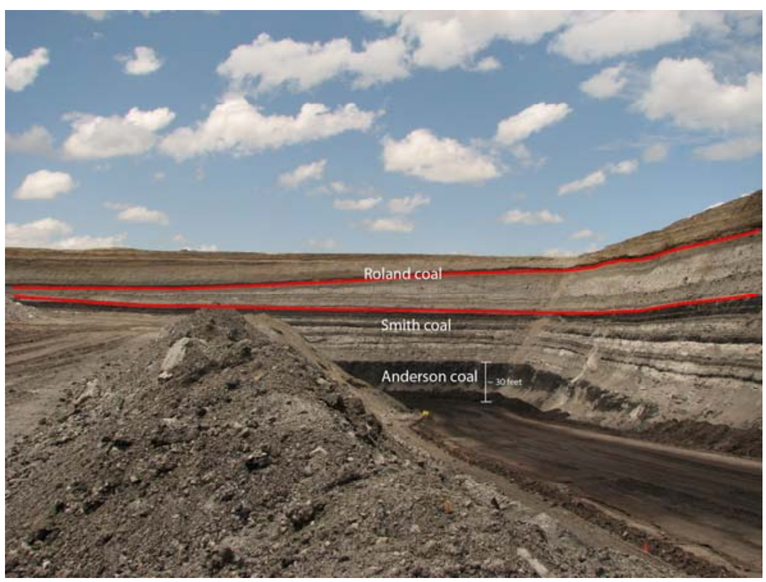

Figure 4.5 ─ Highwall at the North Antelope Rochelle Coal Mine showing the angular relationship between the Roland coal zone (Roland of Baker and Roland of Taff coal beds) and the underlying Wyodak Rider coal zone (Smith Rider and Smith/Big George coal beds). Photo by Nick R. Jones, 2009.

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 million years ago and are attributed to the formation and migration of intrabasinal highs that propogated 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) (Tikoff and Maxson, 2001; Beck et al., 1988). 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 deposits in Paleocene sequences 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 Moencrief 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 the Wind River Mountains. The axes of these mountain ranges 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 Powder River Basin 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 Powder River Basin, rectilinear features (lineaments: a linear topographic feature of regional extent that is believed to reflect crustal structure (Hobbs, 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 (Hoppin, 1974). In the Powder River Basin there are two distinct sets of lineaments, a set trending northeast and another set trending northwest (Marrs and Raines, 1984).

Differential uplift related to basement block faulting within the Powder River Basin 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, north-east trending structure, the Belle Fourche Arch, which separates the Little Powder River and Belle Fourche River drainages (Slack, 1981).

The influences of lineaments on sediment distribution

Understanding the paleotectonic role of lineaments and their geometry can be helpful 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 reversed (Martinsen, 2003a,b).

Periodic movement of basement blocks below the Powder River Basin 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,b). The syntectonic effects of local deformation associated with lineaments during the late Cretaceous may also have persisted throughout the Tertiary. Recurrent episodes of displacement along basement block boundaries was 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 Powder River Basin 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 evidence of these structural lineaments (Shurr 1982). Paleotectonic control of channel deposits in the Lower Cretaceous Muddy Sandstone was controlled by the development and reactivation of basement-involved structural lineaments in the Powder River Basin (Slack, 1981). The distribution of sands in the Upper Cretaceous Teapot and Shannon sandstones are also attributed to lineaments (Martinsen, 2003) (fig 4.6). Martinsen (2003a,b) has documented how differential accommodation associated with basement blocks influenced the deposition and preservation of Cretaceous shales in the Powder River Basin and resulted in the formation of several scales of depositional (erosional) remnants.

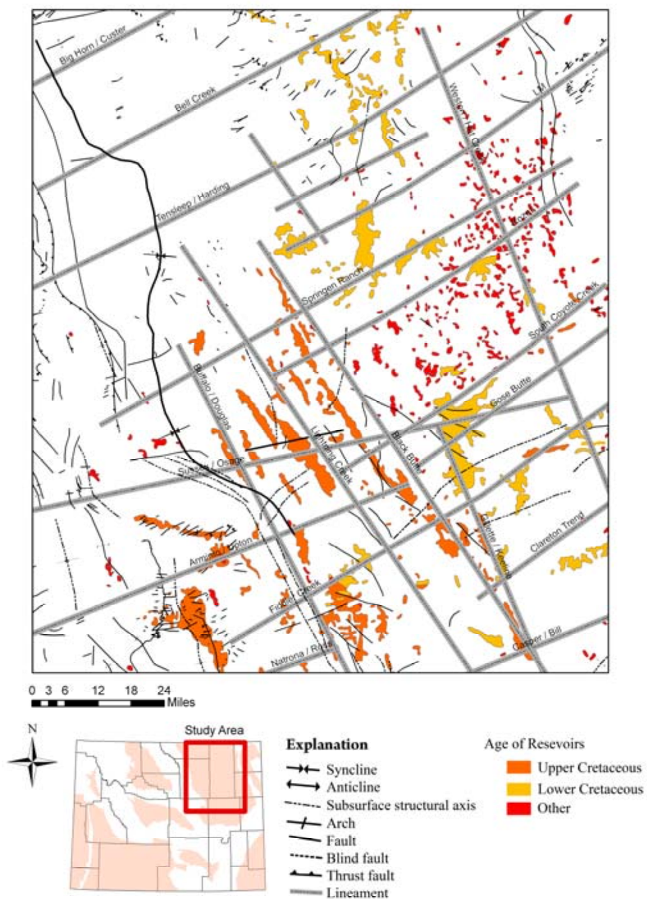

Figure 4.6 — Map of oil and gas fields and distribution of lineaments (Slack, 1981; Marrs and Raines, 1985, Martinsen and Marrs, 1985; Martinsen, 2003; DeBruin, 2007).

Differential development of accommodation in the Powder River Basin during Tongue River time in the Paleocene was coincident with the Laramide Orogeny. More specifically, this author believes that the accommodation where thick coal deposits formed can be attributed to the recurrent movement of basement blocks. Isopach maps of selected coal deposits that occur in the Tongue River Member of the Fort Union Formation (Jones, 2007, 2008) were compared with the distribution of lineaments in the Powder River Basin (fig 4.7 through 4.12). 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.

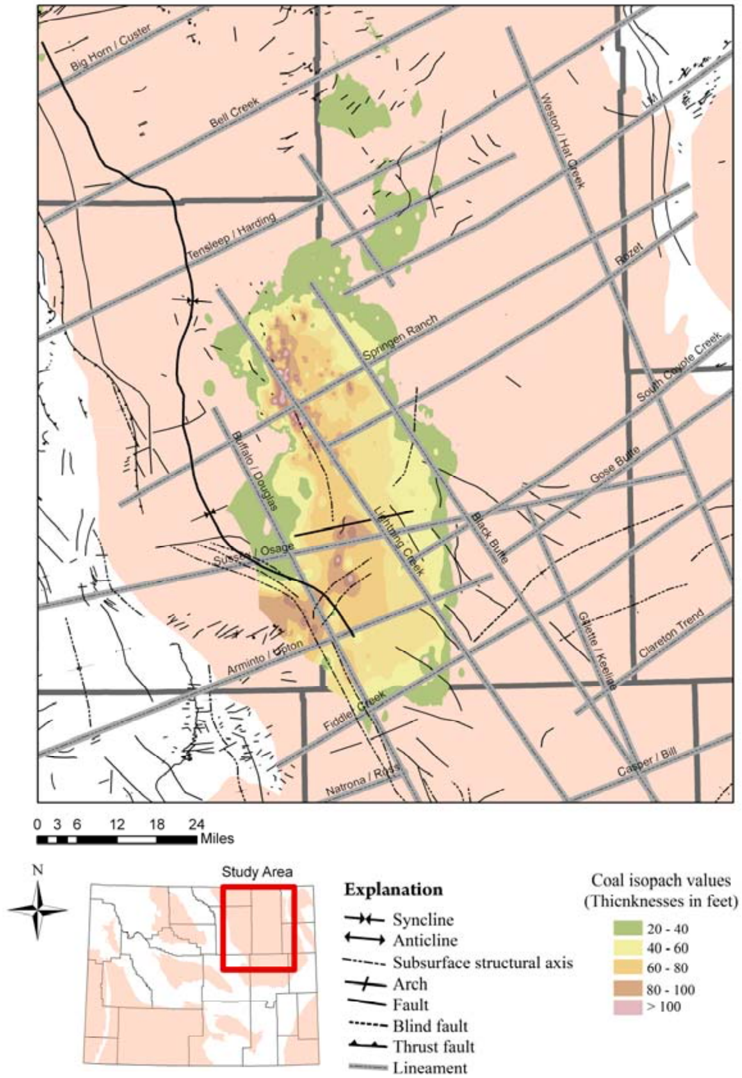

Figure 4.7 ─ Isopach map of the upper Smith / Big George coal deposit in the Wyodak Rider coal zone (Jones, 2007 – 2009) shown against basin structure (Slack, 1981; Marrs and Raines, 1985, Martinsen and Marrs, 1985; Martinsen, 2003; DeBruin, 2007). Thickness distribution of this coal deposit is controlled 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.

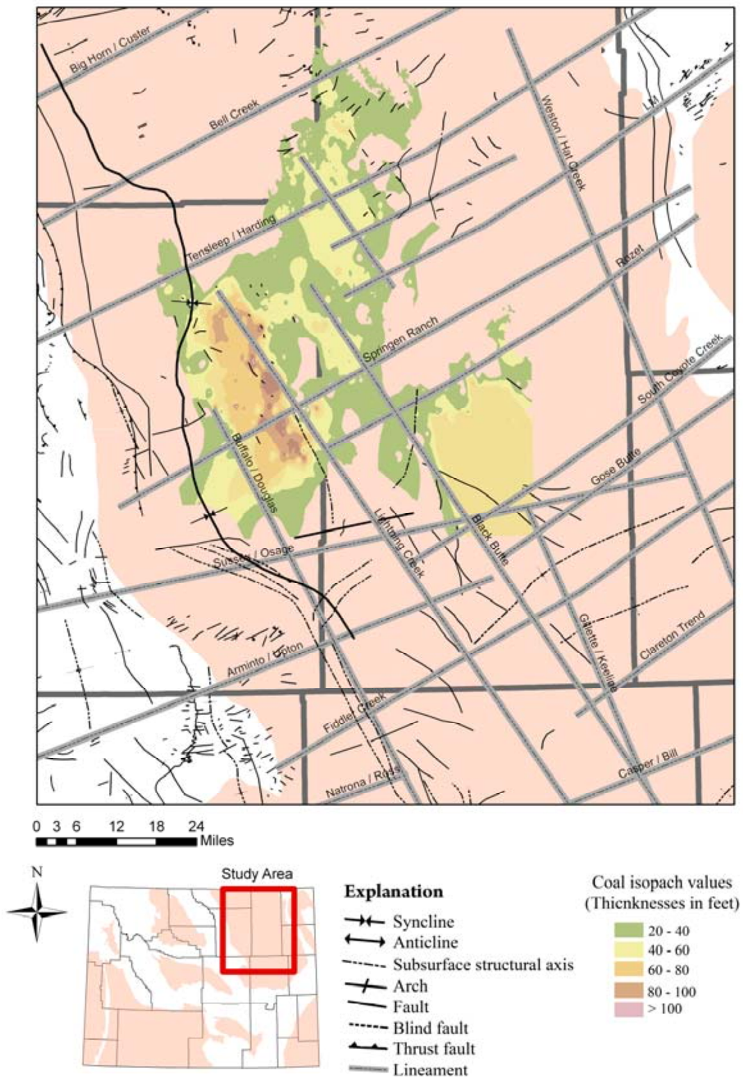

Figure 4.8 ─ Isopach map of the lower Smith / Big George coal deposit in the Wyodak Rider coal zone (Jones, 2007 – 2009) shown against basin structure (Slack, 1981; Marrs and Raines, 1985, Martinsen and Marrs, 1985; Martinsen, 2003; DeBruin, 2007). Thickness distribution of this coal deposit is controlled 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.

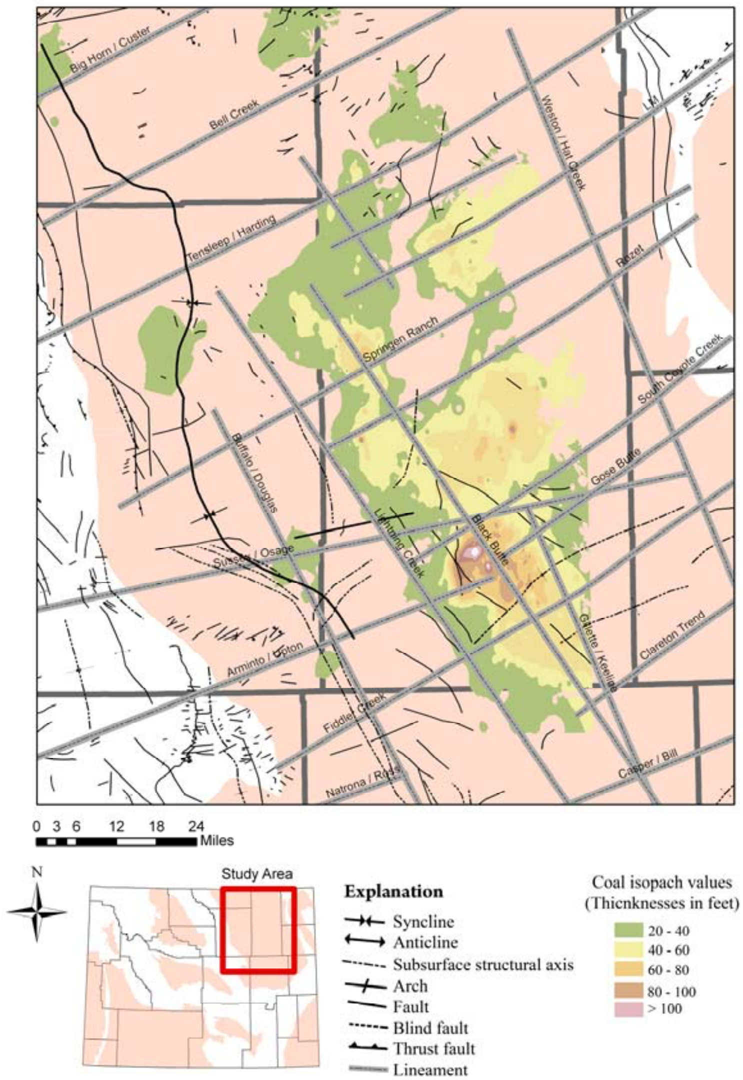

Figure 4.9 — Isopach map of the Anderson coal deposit in the Upper Wyodak coal zone (Jones, 2007 – 2009) shown against basin structure (Slack, 1981; Marrs and Raines, 1985, Martinsen and Marrs, 1985; Martinsen, 2003; DeBruin, 2007). Thickness distribution of this coal deposit is controlled by the northwest 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.

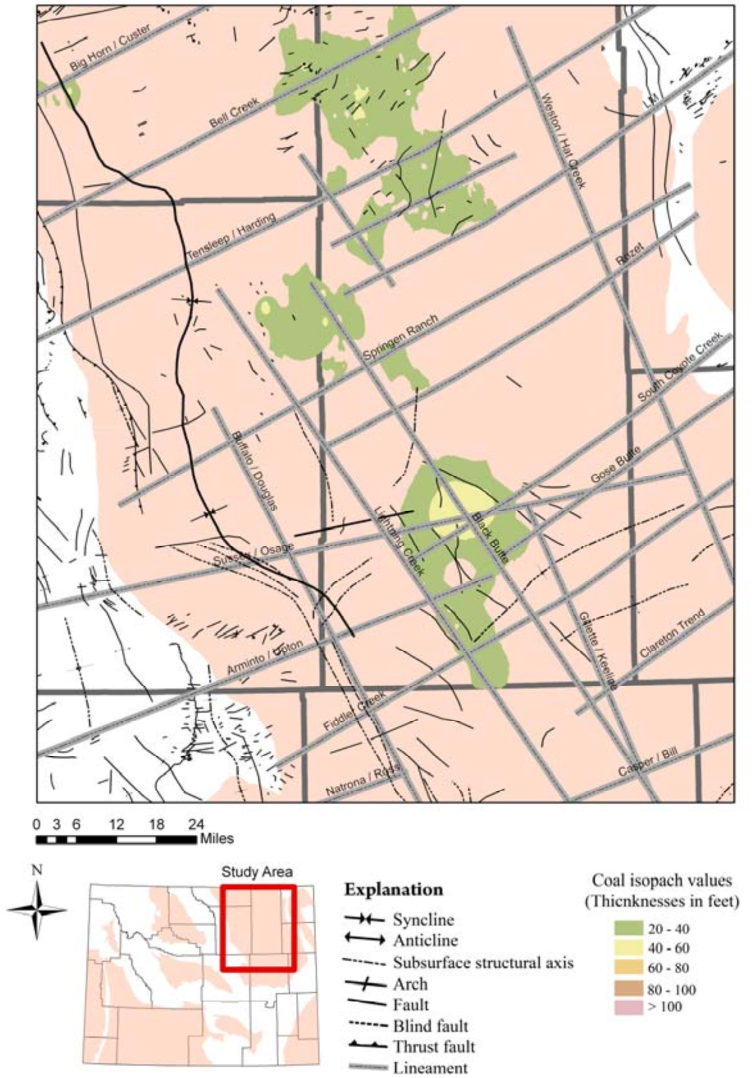

Figure 4.10 ─ Isopach map of the Canyon coal deposit in the Lower Wyodak coal zone (Jones, 2007 – 2009) shown against basin structure (Slack, 1981; Marrs and Raines, 1985, Martinsen and Marrs, 1985; Martinsen, 2003; DeBruin, 2007). Thickness distribution of this coal deposit is controlled by the northwest 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.

.

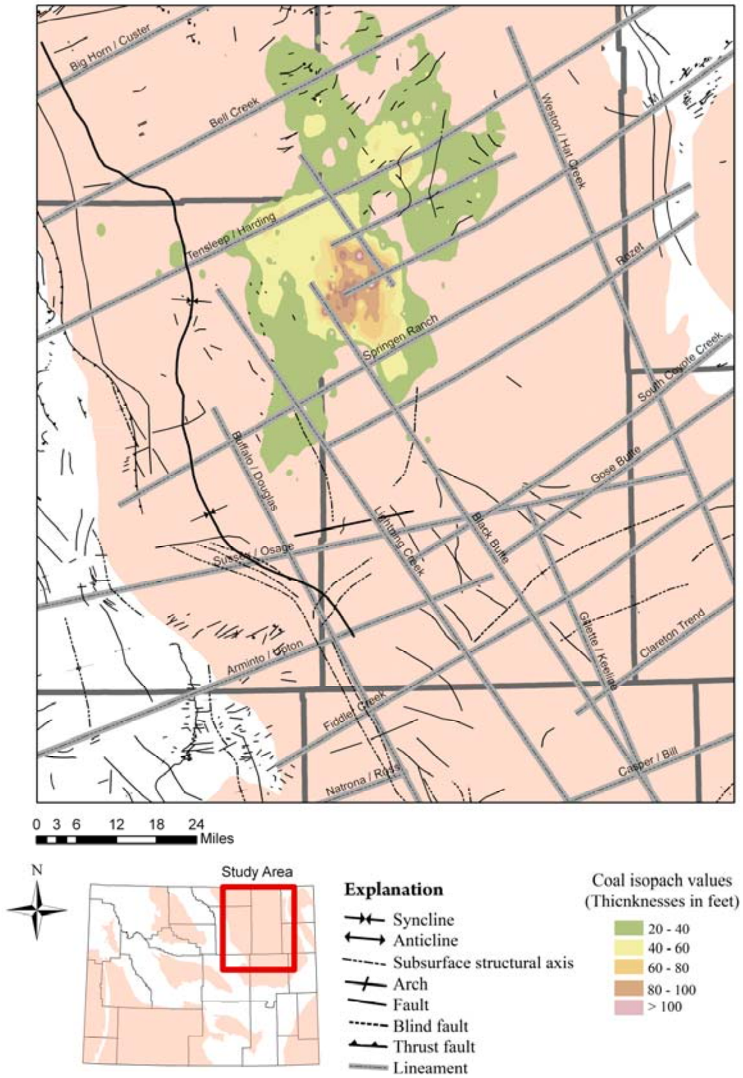

Figure 4.11 ─ Isopach map of the Cook coal deposit in the Cook coal zone (Jones, 2007 – 2009) shown against basin structure (Slack, 1981; Marrs and Raines, 1985, Martinsen and Marrs, 1985; Martinsen, 2003; DeBruin, 2007). Thickness distribution of this coal deposit is controlled by the northwest trending Lightning Creek, Black Butte, and Gillette / Keeline; and by the northeast trending Rozet, Springen Ranch, Tensleep Harding, and Bell Creek lineaments.

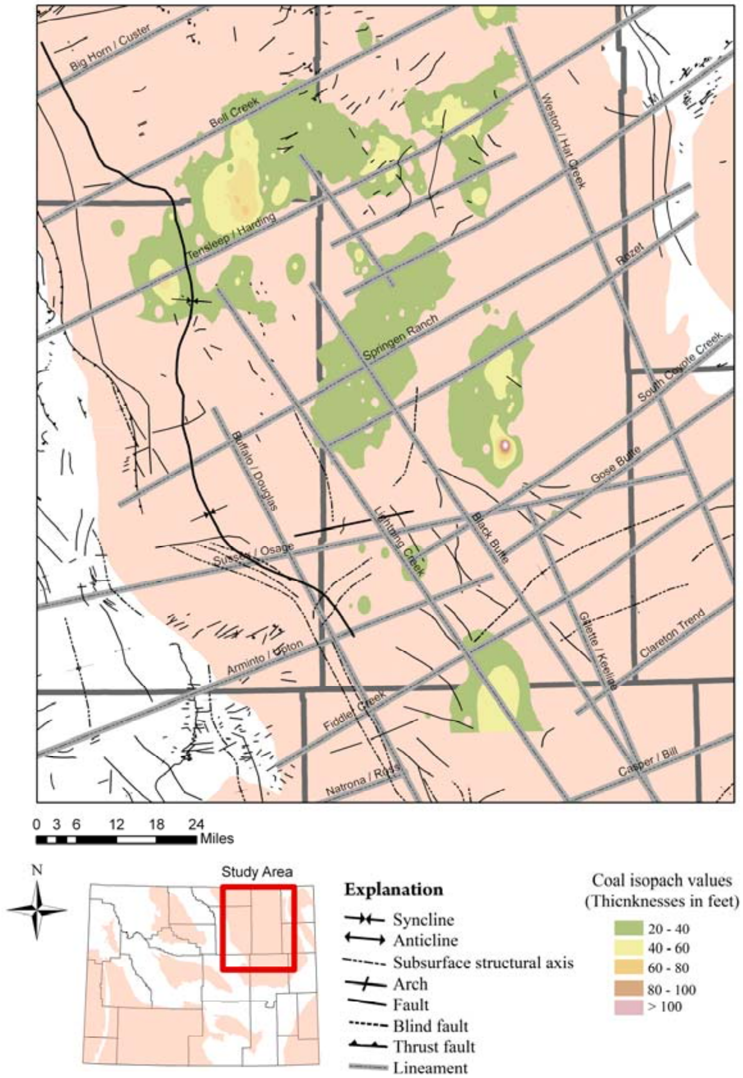

Figure 4.12 ─ Isopach map of the Wall coal deposit in the Wall coal zone (Jones, 2007 – 2009) shown against basin structure (Slack, 1981; Marrs and Raines, 1985, Martinsen and Marrs, 1985; Martinsen, 2003; DeBruin, 2007). Thickness distribution of this coal deposit is controlled by the northwest trending Lightning Creek and Black Butte; and by the northeast trending Fiddler Creek, South Coyote Creek, Rozet, Springen Ranch, Tensleep / Harding, and Bell Creek lineaments.

An isopach map showing the summed coal thicknesses of the selected Tongue River coals (fig 4.13) clearly identifies the key northeast trending lineaments that controlled coal distribution are the Gose Butte, Arminto / Upton, Rozet, Springen Ranch, Tensleep / Harding and Bell Creek; and key north-northwest trending lineaments that controlled coal distribution are the Buffalo / Douglas, Lightning Creek, Black Butte, and Gillette / Keeline.

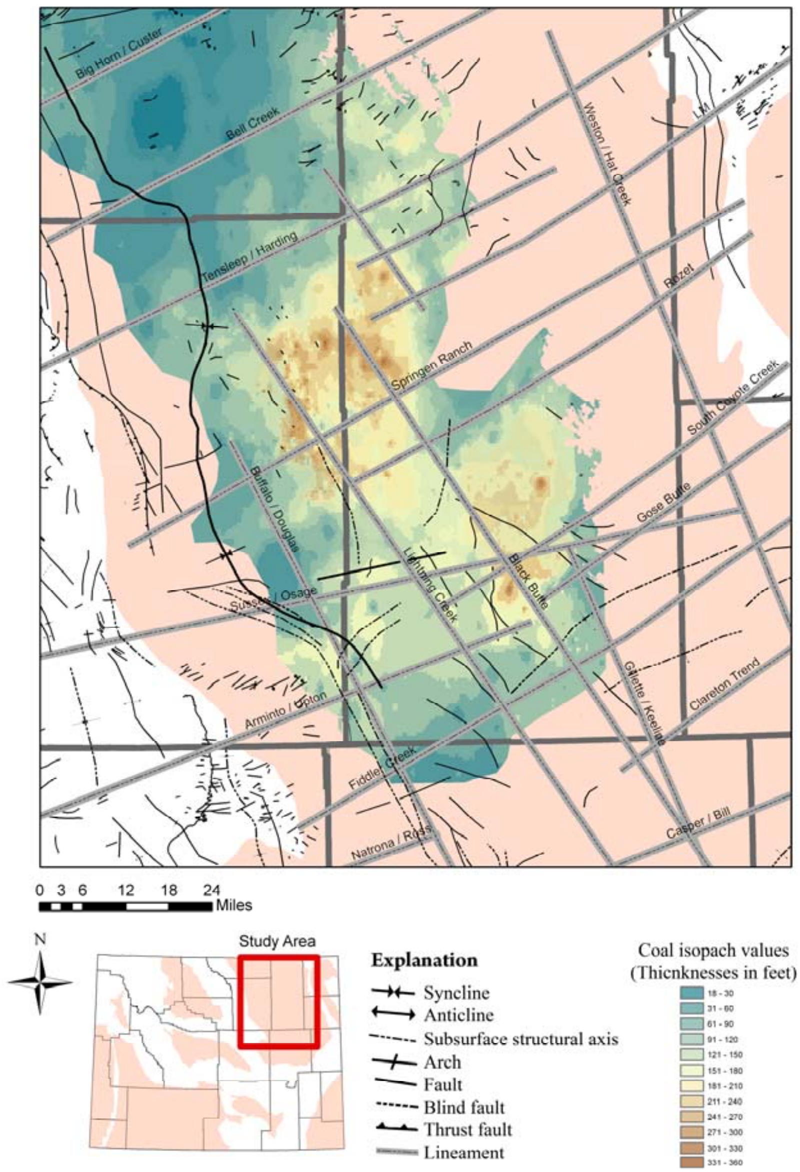

Figure 4.13 ─ Isopach map representing summed coal thicknesses (Upper Smith / Big George, lower Smith / Big George, Anderson, Canyon, Cook, and Wall coals) (Jones 2007 – 2009) and thickness distribution coincident with distribution of lineaments (Slack, 1981; Marrs and Raines, 1985, Martinsen and Marrs, 1985; Martinsen, 2003). Note: the extent of summed coal thickness is restricted to extent of the the Smith / Big George boundary.

Recurrent movement along lineaments 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 − bacterial reduction of peat is a subaqueous process that is very sensitive to surface hydrologic changes. Subtle changes in surface topography resulting from structural movement of basement blocks disrupt this process, by causing the water table to change, shifting fluvial systems, and affecting 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 all assume that tremendous amounts of accommodation are necessary to allow for great thicknesses of peat to accumulate. Thus, these models are based on the concept of peat-to-coal compaction ratios wherein a given amount of peat is compressed to form a given thickness of coal. Granted, these models explain various mechanisms for the development of accommodation; but, they do not take into account the actual process of coalification.

Coalification Process

Peat consists of partially decayed plant matter that accumulates on the bottom of a mire (mire is the generic term for a wetland). Coalification is the slow alteration of that plant matter into coal, and it proceeds in two phases. In the first phase, biogenesis, plant matter is biogenically changed into serial forms of peat, culminating in a dark colored hydrogel (complex hydrophilic gel) termed “gytta” (fig 5.1, and see note on gytta page 66). The second phase is thermogenesis: 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, pers. comm; 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 (Wilfrid, 1954; Tatsch, 1980).

Figure 5.1 ─ Exhumed, organic-rich hydrogel, “gytta” − quarter for scale. This material is the product of biogenic decay and alteration of floral litter, “peat”, which develops below the water table in wetlands. Photo by Professor James McClurg, circa 1985.

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, pers comm.). Well-preserved coalified woody plant material such as coalified tree limbs found in coal deposits and in clastic sediments show no evidence of compaction (fig 5.2). 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 support this include 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 that made those tracks were walking on the exposed surface of the gytta, not on the surface of the peat (fig 5.3).

Figure 5.2 ─ Photo of well preserved, coalified tree limb in a clastic matrix illustrates that 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 was found in the southern pit of the North Antelope / Rochelle coal mine. Photo by Nick R. Jones, 2009.

Figure 5.3 ─ 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 4" x 8". Photo by Micheal Vanden Berg, Utah Geologic Survey, 2004.

Biogenesis

The vertical succession of accumulated peat (the peat column) comprises a sequence of three zones that represent successive levels of aerobic and anaerobic bacterial decay. From top to bottom, these are the fibric zone (identifiable plant fragments, and dense root systems), the humic zone (few identifiable plant fragments), and the sapropelic zone (dominantly microscopic plant fragments) (fig 5.4). The end result of biogenic processes through these zones is the dark-brown to black hydrogel, gytta (Thiessen, 1925; Francis, 1954; McClurg, pers. comm.; Jones, 2007 −2009; Jones et al., 2009).

The uppermost few inches of the peat column contain abundant free oxygen that supports aerobic bacteria; below it, little to no free oxygen is available, having been consumed by the aerobic bacteria, allowing for anaerobic bacteria to take over. Closure of pore space occurs in the uppermost few inches and decay occurs 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, termed the attritus (another term that describes gytta). The attritus generally begins to develop within a foot of the surface; the ratio of the attritus to plant fragments increases with depth in the peat column (Thiessen, 1925). It is the gytta that is preserved and buried, not the peat.

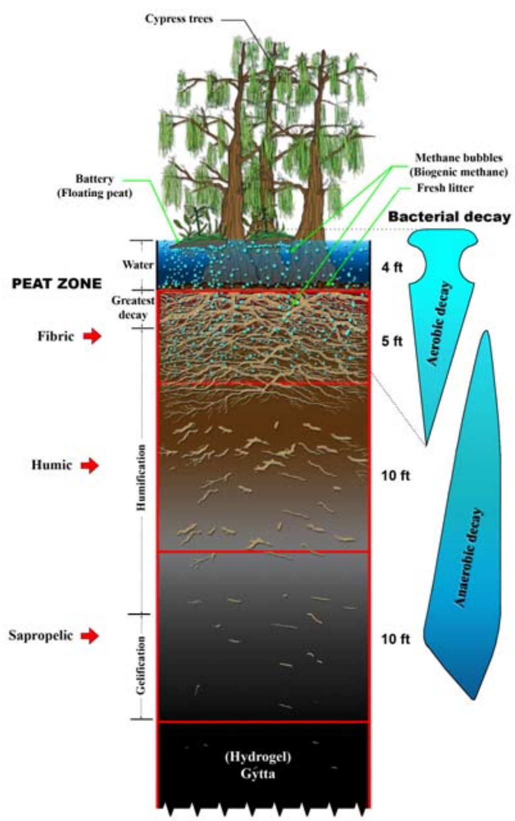

Figure 5.4 ─ Columnar representation of a peat column, numbers along right side of column represent generalized interval thickness, modified from illustration by James Rodgers in Jones et al., 2009.

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), and tannic and humic acids. As the biogenic decay of the peat progresses, the concentration of the tannic and humic acid increases, depressing the pH level of the surface water to as low as 3 to 2.5. Elevated concentrations of tannic and humic acid stain the stagnant water in mires brown (tea-colored) to black ("black-water" swamp). 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, 1916; Tatsch, 1980) − the "water exists in form not like the water in a wet sponge but rather like that in jelly" (Odell and Hood, 1916). 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 other volatile material, 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); endogenic (primary) cleats in young lignite develop (Francis, 1954).

Thermogenesis also releases gasses such as hydrogen, oxygen, nitrogen, and methane. Thermal maturation is a function of time and temperature. In order for gytta to be thermogenically converted to coal, subsurface temperatures must reach at least 212 degrees Fahrenheit (100° Celsius) for millions of years. These temperatures are generated by several geologic processes: the natural geothermal gradient of the earth (temperature increase with depth ~1° Fahrenheit per 60 feet), as maintained by the insulating effect of thick layers of sediment above the proto-coal; rarely by the emplacement of igneous rocks (intrusive and extrusive); and by naturally occurring fires in stratigraphically adjacent coal beds (Jones, 2008).

Methods

Three cross sections in Campbell County (Appendix A; Plates I, II, and III) were constructed on the basis of the resolution, distribution, density, and depth of available well logs (fig. 6.1). Cross section A–A′, in northwest Campbell County, is approximately 9.3 miles long and trends SE from T56N, R76W, sec. 34 to T55N, R75W, sec. 27 (Appendix A, Plate I). Cross section B–B′, in west-central Campbell County, is approximately ten miles long and trends SSE from T49N, R76W, sec. 2 to T48N, R75W, sec. 16 (Appendix A, Plate II). Cross section C–C′, crossing west-central Campbell

County, is approximately 40 miles long and trends NNE from T46N, R76W, sec. 29 to T50N, R72W, sec. 21 (Appendix A, Plate III).

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

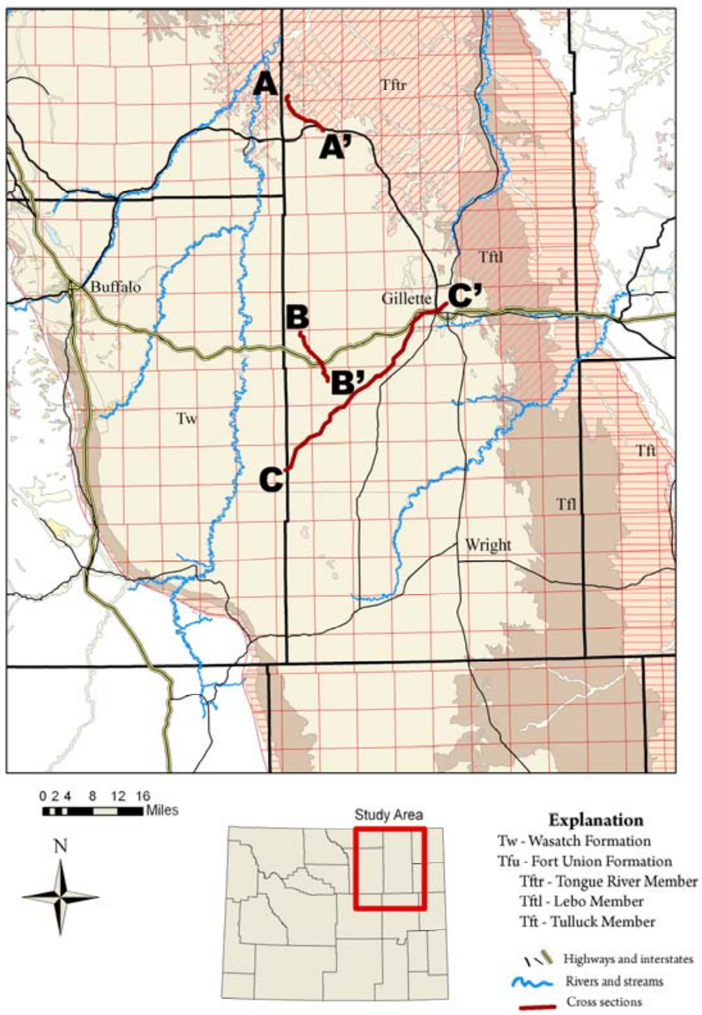

Figure 6.1 ─ Location map and study area showing locations of cross sections

Cross section A–A′ was selected for reconstruction analysis (a paleo-deformational reconstruction sequence) to illustrate the sequence of events that produce 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 (fig 6.2).

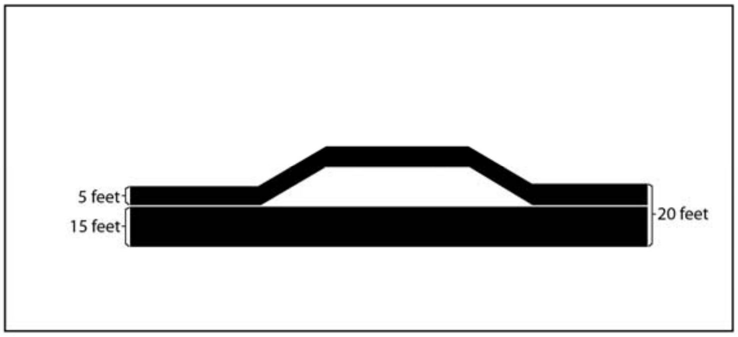

Figure 6.2 ─ Generalized cross sectional geometry of parting between two coals; the datum is sea level.

Data density and resolution

Coalbed methane development during the last decade in the Powder River Basin 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 CBM wells were drilled in Wyoming's Powder River Basin. Initial well spacing in the basin was 40 acres; in 2000 the spacing was increased to 80 acres. Coal beds 10 feet or thicker were targeted for coalbed 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; but in most cases, wells that are drilled close to each other are targeting coals at different geologic horizons. The result of the coalbed methane activity in the Powder River Basin is a very 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 − 2 inches per 100 feet), while coalbed methane well logs have a vertical resolution of 2 feet (paper scale − 5 inches per 100 feet) (fig 6.3). 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 coalbed methane wells, making it possible to accurately identify and map their extent in the subsurface.

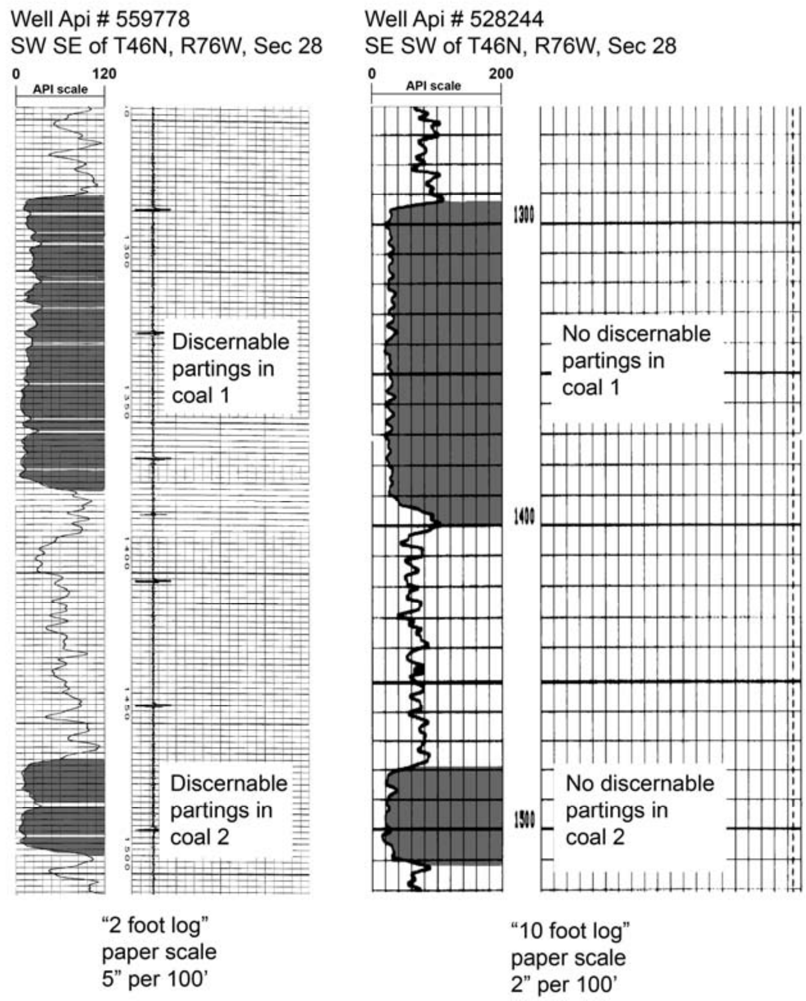

Figure 6.3 — A comparison of two gamma-ray well logs located ~0.2 miles apart showing the same stratigraphic interval. The log on the left is from a coalbed methane well and has higher, 5 inch per 100 feet resolution. The log on the right is from a conventional oil well with lower, 2 inch per 100 feet resolution. Notice the discernable high-ash/clastic partings detected by the gamma ray log on the coalbed methane 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,

Coal studies in the Powder River Basin that occurred prior to coalbed methane 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; a resolution not suited for identifying thin, laterally extensive partings. 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 bore-hole stability problems requiring surface casing set to below thick coal zones (Martinsen, pers. comm.).

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

Data collection and interpretation

Log data from conventional oil and gas and CBM wells in the Powder River Basin used in this study were collected via the internet from the WOGCC website. Selected geophysical logs were downloaded for each cross section. Wells were selected from the coal occurrence database developed by this author and Wyoming State Geological Survey (WSGS) staff. The coal occurrence database was developed as part of a basin-wide study on coal occurrence and distribution in the Powder River Basin (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 coalbed natural gas and conventional oil and gas wells. In addition to data generated by the WSGS, the database also includes coal occurrence data from Fort Union coal assessment team 1999; from Flores et al. 1999a; and from this author's cooperative work 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 were selected for correlation of coal beds in the Powder River Basin. The purposes for 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 (fig 6.4).

Interpretation of well logs involved viewing digital image files of geophysical logs using computers. Data was 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) low gamma-ray response (less than 20 gapi), 2) a low density response (less than 1.4 g/cc), 3) high resistivity response (greater than 50 ohms, m^2/ m), and 4) low conductivity response (less than 5 millimhos/m). Where coal geophysical signatures on a log were questionable, coal type responses on adjacent logs were used to verify interpretation.

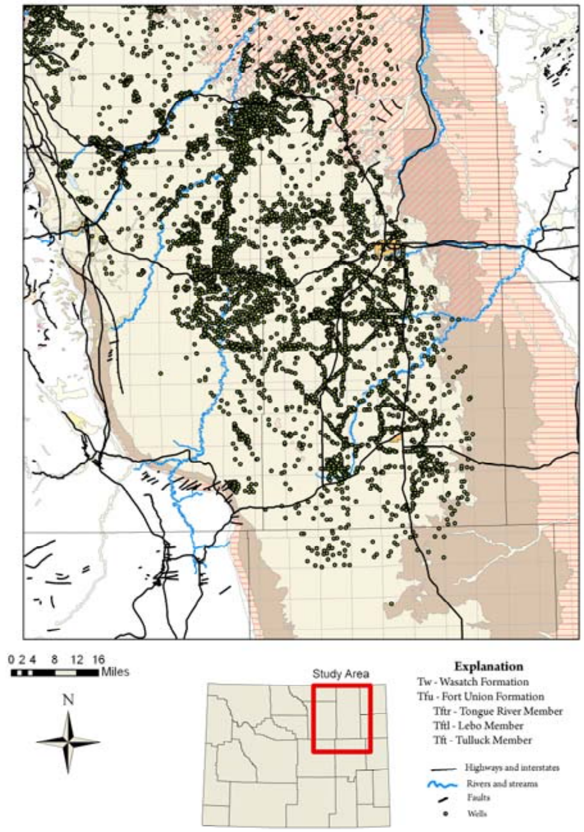

Figure 6.4 — Distribution of correlated geophysical well data used for the basin-wide coal study in the Powder River Basin, Jones, 2008.

Quality control of the data included verification of borehole location, elevation, and review of coal picks from well logs when 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-system-survey (PLSS) legal location that included township, range, section, and elevation. The legal PLSS location was checked against its plotted (Lat-Long) location using Arc GIS® software and geospatial data layers. The data layers include elevation grids and PLSS grids. Wells that plotted in the incorrect township, range, or section 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. This geological software package was used 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 (fig 6.5).

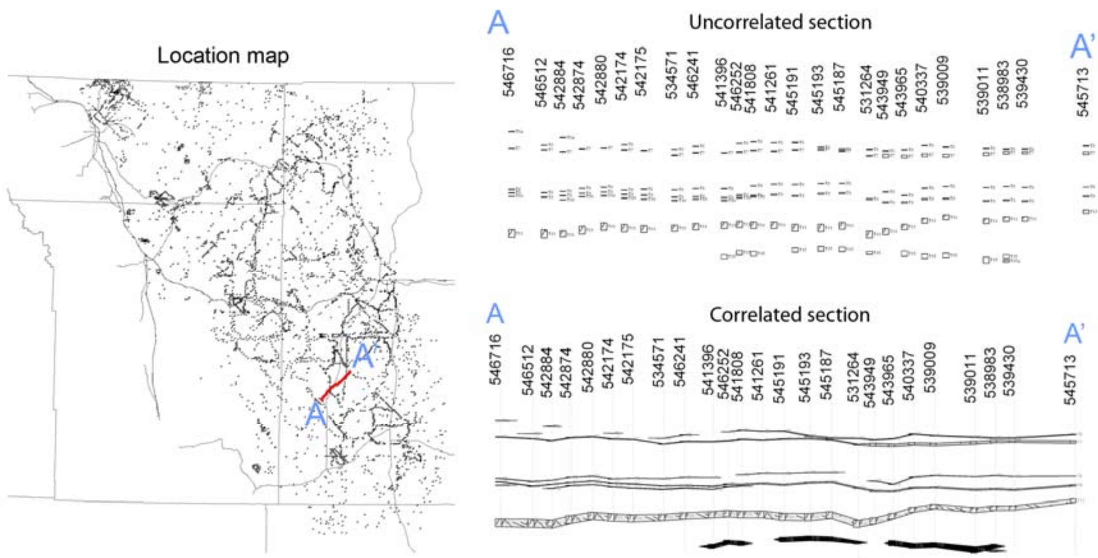

Figure 6.5 ─ (top right) Representative illustration showing uncorrelated coal picks from well logs; (bottom right) resulting interpretation of coal correlations in a final section, Jones, 2008.

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; this was done to insure consistency in the use of coding and for closure of correlations from area to area.

Important research for this project included field work focused on the study of outcrops and the study of modern depositional environments. This author visited and studied numerous coal bearing rocks exposed in outcrop in the Hanna Basin, Green River Basin, Wind River Basin, Big Horn Basin, Hams Fork area, and Powder River Basin. Field work included mine visits, discussions with mine geologists, sediment and coal sampling, photo-documentation, and paleoenvironment (depositional facies) reconstruction. Following these field trips, this author traveled to and studied modern subtropical wetland systems such as the Great Dismal Swamp, the Okefenokee Swamp, Great Cypress Swamp, the Florida Everglades, the Mississippi and Atchafalaya basins, and the Mississippi Delta. Field work in these wetlands included sediment and peat sampling, pH measurements of swamp waters, photo-documentation, and discussions with local wetland ecologists, colleagues, and the field instructor, Dr. James McClurg.

Reconstruction analysis

Cross section A−A' (Appendix 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 Wyoming State Geological Survey coal occurrence database for the Powder River Basin (Jones, 2008). Output from Rockworks © software was used to build representative cross section pairs for the reconstruction analysis (fig 7.1). Each cross section pair includes two cross sections with different datums and constructed from all of the well logs in the section. The cross section pairs were then exported as .jpeg image files. Each representative cross section pair was constructed by setting the datum in the software to the tops of pre-determined coals (the key bed); first to the top of the lowermost key bed, then to the top of the middle key bed. This process resulted in two representative cross sections that show the flat topography of the lowermost coal deposit during deposition and the amount of accommodation that developed post deformation. This process was then repeated for the middle key bed and the top key bed. For the top key bed the final datum used was the present-day land surface.

The image outputs of the representative cross section pairs were then opened in Adobe Photoshop CS3©, cropped, and copied into a single layout as individual layers in a single file. The pairs were placed in order from the bottom, the oldest key bed at the top of the layout (T1) and the youngest key bed at the bottom of the layout (T6). Red arrows were then placed along the bottom of each cross section pair to illustrate the relative motion of deformation that occurred, which accounted for the amount of accommodation available for clastic sediments to fill in. The result of the reconstruction analysis is a model that illustrates the sequence of syndepositional and syntectonic events in cross section that produce 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 (fig 7.1). 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 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.

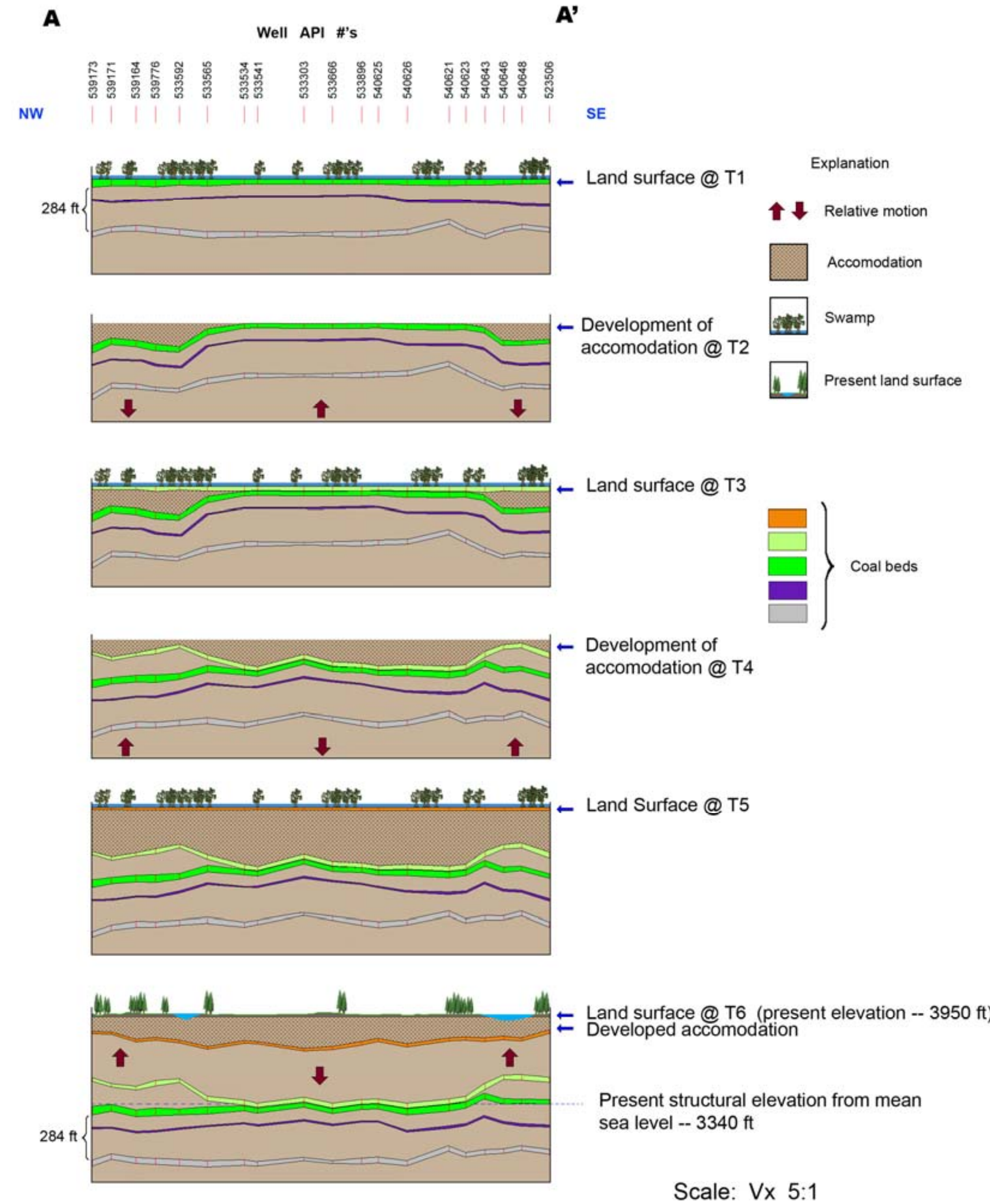

Figure 7.1 ─ Model showing the sequence of how differential development of accommodation resulted in the unique geometry of coal deposits and how they coalesce and split in the Tongue River Member of the Fort Union Formation, Powder River Basin. Illustration by James Rodgers.

Interpretation of results

Time one (T1) 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 include thin paleosols such as fusain layers (discrete horizons of oxidized coal), evaporate minerals (gypsum, anhydrite, etc.), variable 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 infill with packages of clastic sediment composed of lacustrine and fluvial deposits. Between T2 and T3, clastic sedimentation has filled in the available accommodation; the water table rises; and another wetland develops. On the outer edges the more recent accumulation of 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 result of 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.

The top and bottom of a parting in a coal deposit are surfaces that mark periods between different depositional facies, and the spacing of these chronostratigraphic surfaces (time lines) represent equal amounts of time (fig 7.2). These time lines are important because they indicate that thick coal deposits did <u>not</u> form from a singularly thick deposit of peat and that a thick coal deposit actually formed from numerous, stacked, thinner accumulations of gytta.

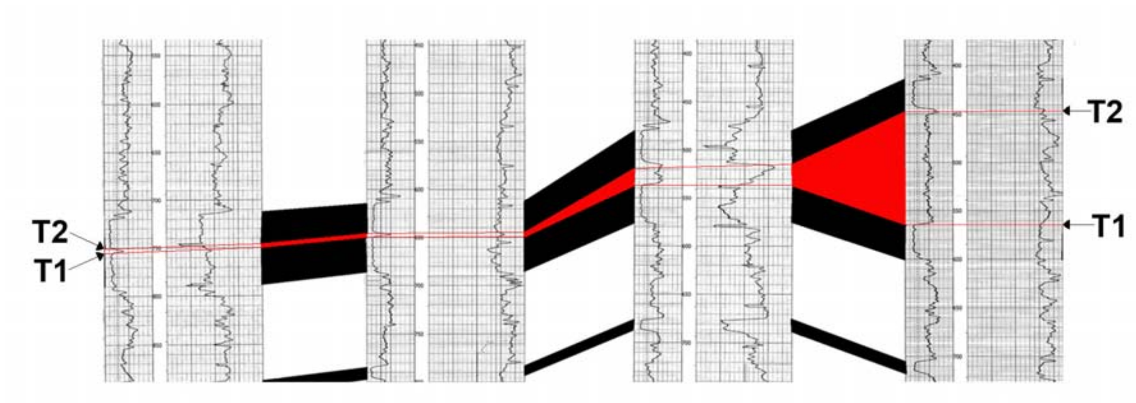

Figure 7.2 ─ Chronostratigraphic surfaces T1 (base of the parting) and T2 (top of the parting) between two distinct coals.

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 (fig 7.3). 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.

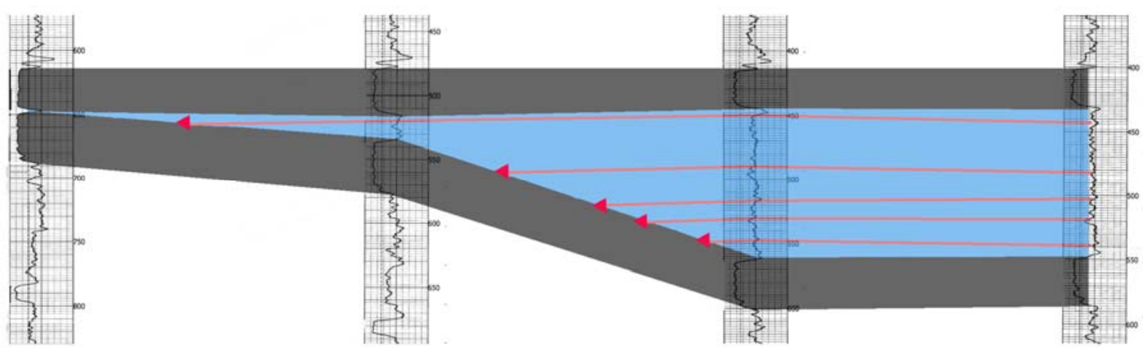

Figure 7.3 ─ Cross section showing onlap, datum is set to the top of the upper coal. Red arrows denote location and direction of onlap, Note – this figure was modified from figure 7.2. Log signatures are gamma ray responses.

Discussion

Wetlands are governed by the water table and therefore have little or no discernable surface topography. A swamp is basically a shallow lake with trees growing in it, and a marsh is a flooded grassland (McClurg, pers. comm. 2006; Jones, 2009, pers. comm.; Jones 2007−2009). A factor not addressed in the models of Flores and Ayers is localized deformation in the Powder River Basin, attributable, as discussed in this thesis, to tectonically active episodes in the Laramide Orogeny during the early Tertiary. Instead, they 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 basin and the Black Hills explains why peat developed where it did and how it was buried, but 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 preexisting 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 Powder River Basin created topographic highs and lows and was synchronous with the transition from a low-energy system of basin-wide black-water swamps to a higher-energy system of rivers, streams, and lakes (fig 8.1).

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. Coal-bed splitting under these circumstances can be attributed to growth faulting because of reactivation of basement faults, resulting in gentle downwarping of sections of accumulated organic material followed by deposition of non-organic material: after the low area fills up to the level not affected by downwarping, organic accumulation recommences (Thomas, 1992).

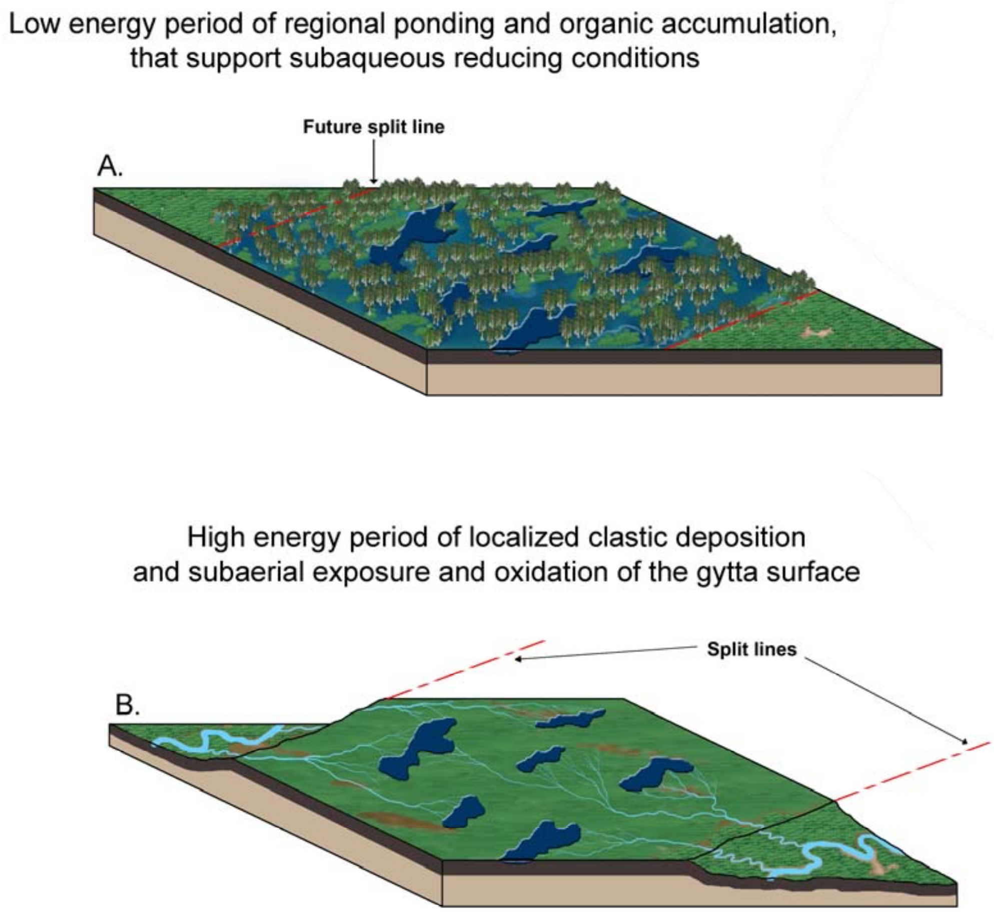

Figure 8.1 — Block diagrams showing generalized surface topography before (A.) and after (B.) development of differential accommodation due to fault reactivation of basement blocks. Illustration by James Rodgers.

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.

Conclusion

In conclusion, 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 attributed to intrabasinal tectonics. Parting geometry and angular relationships between coals laterally adjacent to thick sequences of stacked coal deposits resulted from intermittent, syndepositional, and recurrent movement along zones of weakness in basement rocks. Intermittent periods of dewatering, erosion, and oxidation of peat; subaerial exposure of gytta; and 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 further work

With the abundance of available subsurface bore-hole data that exists in the Powder River Basin, future work in the basin should 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 bed 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 coalbed methane wells between areas of the basin where subsurface coal bed geometry was likely influenced by fault reactivation of basement rocks; and 5) the interplay between large-scale and small-scale structural dynamics and their influence on subsurface basin structure and basin paleotopography.

Note on Gytta **−** *Gytta is a term of Swedish origin that describes the organic-rich layers of sediment (mud) that accumulate at the bottom of a lake, generally considered to be an organic- rich mud. Gytta sediments have low permeability. Gytta is also a term that is associated with the coal maceral gelinite.*

References

Ayres, 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, vol. 70, no. 11, p. 1651-1673.

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. 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., 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* Sedimentation and Tectonics: Wyoming Geological Association Guidebook, Forty-first Annual Field Conference, p. 151-166.

Brown, R.W., 1958, Fort Union Formation in the Powder River Basin, Wyoming: Wyoming Geological Association Guidebook, Thirteenth Annual Field Conference, p. 111-113.

Cobban, W.A., and McKinney, K.C., United States Geological Survey.

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: Geological Society of America, vol. 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, vol. 18, p. 332-406.

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

________, 2009, 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.

________, 1978b, Structure contour and isopach maps of the Wyodak – Anderson coal bed in the Reno Junction – Antelope Creek area, Campbell, Converse, Niobrara, and Weston 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, vol. 100, no. 7, p. 1023-1039.

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, vol. 75, no. 3, p.409-435.

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

Fenton, J.H.C., 1980, The rate of peat accumulation in Antarctic moss banks: Journal of Ecology, vol. 68, 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.

________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. 79-103.

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, R.W, and Jones, R.W., 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., 1999A, 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, two CD-ROMs.

Fort Union coal assessment team, 1999, 1999 resource assessment of selected Tertiarty coal beds and zones in the Northern Rocky Mountains and Great Plains Region: U.S. Geological Survey Professional Paper 1625–A, 2 CD-ROMs.

Francis, Wilfrid, 1954, Coal – Its formation and composition: London, Edward Arnold, 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.,1976, An outline of structural geology: New York, John Wiley and Sons, 571 p.

Hoppin, R.A, 1974, Lineaments − Their role in tectonics of central Rocky Mountains: American Association of Petroleum Geologists Bulletin, vol. 50., No. 11, p. 2260-2273.

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, vol. 109, 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, vol. 78, p. 633-647.

Jones, N.R., 2007, Coal correlation and coal zones in the Powder River Basin, Wyoming: Wyoming State Geological Survey Open-File-Report, Plates 07-3A through O7-3F.

_________2007−2009, Thesis research.

_________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., McClurg, J.C., and Quillinan, S., 2009, Wyoming Coal: Wyoming State Geological Survey Public Information Circular 44, 28 p.

Jones, R.W., 2009, Personal communication.

Kent, H.B., 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. 105-120.

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 72-220, 3 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: Wyoming State Geological Survey [Geological Survey of Wyoming] Memoir No. 5, p. 374-412.

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, vol. 68, no. 11, p.1718-1731.

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, vol. 87, no. 12, p.1869-1882.

Martinsen, R.S., 2003b, Depositional remnants, part 2: Examples from the Western Interior Cretaceous basin of North America: American Association of Petroleum Geologists Bulletin, vol. 87, no. 12, p.1883-1909.

________, 2008, 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, 11 p.

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

________2006-2009, Personal communication.

Merewether, E.A., 1983, The Frontier Formation and mid-Cretaceous orogeny in the foreland of southwestern Wyoming: The Mountain Geologist, vol. 20, 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, vol. 70, no. 4, p.453-455.

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. 83, 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: Wyoming Geological Survey, Memoir No. 5, p. 874-896.

MSHA, 2009, Mine Safety and Health Administration website: http://msha.gov

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

Odell, W.W., and Hood, O.P., 1916 [1926], Possibilities for the commercial utilization of peat: U.S. Bureau of Mines Bulletin 253, p. 8.

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, vol. 2, no. 2, p. 133-145.

Prescott, M.W., 1970, Hilight field, Campbell County, Wyoming, in Enyert, R.L., ed., Symposium on Wyoming sandstones: their economic importance – past, present, and future: Wyoming Geological Association 22nd Annual Field Conference guidebook, p. 89-103.

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, vol. 23, 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., Andrejiko, M.H., and Best, G.R., eds., The Okefenokee Swamp, Wetland Surveys.

Seeland, David, 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.

________1993, Origin of thick lower Tertiary coal beds in the Powder River Basin, Wyoming and Montana – Some paleogeographic constraints: U.S. Geological Survey Bulliten 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, vol. 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: 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, vol. 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: Wyoming 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: Sudbury, Mass., Edward Arnold, 590 p.

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

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

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

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.

WOGCC, 2004-2009, Wyoming Oil and Gas Conservation Commission website: http://wogcc.state.wy.us

Appendix:

Table 1. Coal zones and coal bed nomenclature, Powder River Basin, Wy.

Formation	Order	Maximum Thickness	Average Thickness	Number of Wells	Code	Coal bed name	Coal zone	Acres	Million Tons
WASATCH	1	40	22	41	t3	Ulm	Upper Wasatch	87,684	4,125
	2	54	11	164	t4	Buffalo Cameron } Lake DeSmet		468,400	12,416
	3	147	11	251	t5	Murray } Lake DeSmet		766,503	13,123
	4	212	18	377	t5a	Ucross } Lake DeSmet		814,184	19,736
	5	25	4	431	t6a	Felix Rider	Felix	1,412,514	13,269
	6	47	7	631	t6	Upper Felix		1,531,376	18,992
	7	77	13	1517	t7	Felix		2,103,350	40,391
	8	75	14	431	t7b	Arvada	Lower Wasatch	904,397	21,899
	9	45	7	485	t8a	Unnamed		162,702	4,352
FORT UNION	10	39	6	1185	t8	Upper Roland	Roland	402,998	11,121
	11	93	10	2849	t9	Roland of Baker		1,208,048	37,110
	12	58	13	1615	t10	Roland of Taff		1,127,022	37,087
	13	107	17	525	t11a	Smith Rider	Wyodak Rider	668,384	26,400
	14	216	38	2311	t11	Smith / Big George		1,791,288	147,573
	15	100	18	603	t12	Lower Smith		1,703,440	37,848
	16	52	13	382	t14	Anderson Rider	Upper Wyodak	1,032,257	29,952
	17	208	47	2856	t15	Anderson		3,789,227	225,800
	18	167	21	1015	t15a	Lower Anderson		2,998,382	97,312
	19	38	10	270	t16r	Canyon Rider	Lower Wyodak	335,146	9,114
	20	205	25	1131	t16	Canyon		1,689,675	79,848
	21	145	22	903	t17	Cook	Cook	1,788,301	76,430
	22	38	9	172	t18	Lower Cook		638,128	16,420
	23	139	19	996	t19	Wall	Wall	1,862,080	73,112
	24	58	11	494	t20	Lower Wall		3,177,455	54,701
	25	50	11	586	t21	Pawnee		1,097,580	30,996
	26	45	13	374	t22	Moyer	Basal Tongue River	1,250,938	39,498

Table 1 ─ Coal stratigraphy of Tertiary rocks in the Powder River Basin (modified from Jones, 2008). Order indicates stratigraphic order of coal beds from youngest to oldest; Number of wells represents the total number of wells wherein a coal bed was identified; Code indicates an arbitrary alpha-numeric naming scheme developed and used during correlation; Coal zone refers to a distinct stratigraphic horizon that contains packages of interrelated coal beds; Acres indicates the modeled subsurface extent of a coal bed; Million Tons indicates the modeled value of in-place coal resources for each coal bed. Summed coal resources in this table are approximately 1.1 trillion tons.

Table 2.

Well information for cross section A-A'

Name	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

Table 3.

Well information for cross section B-B'

Name	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

Table 4.

Well information for cross section C-C'

Name	Elevation	Longitude	Latitude	Range	Township	Section
1920419	4731	-106.014	43.93524	76	46	29
1920387	4665	-106.013	43.94197	76	46	20
524205	4662	-106.005	43.94352	76	46	21
542459	4576	-105.996	43.95518	76	46	16
549543	4534	-105.992	43.96583	76	46	16
525728	4505	-105.986	43.97689	76	46	10
526718	4585	-105.982	43.98809	76	46	3
523764	4636	-105.961	43.99541	76	46	2
536596	4771	-105.947	44.00544	76	47	36
557680	4879	-105.937	44.01323	76	47	25
557706	4761	-105.923	44.01715	75	47	30
530566	4702	-105.91	44.01966	75	47	29
539802	4743	-105.9	44.02949	75	47	20
523270	4641	-105.893	44.04301	75	47	17
552885	4591	-105.877	44.05056	75	47	16
526485	4647	-105.873	44.06099	75	47	9
555740	4862	-105.852	44.07669	75	47	3
555732	4787	-105.837	44.08	75	47	2
538794	4706	-105.827	44.08749	75	48	36
538127	4677	-105.82	44.09297	75	48	36
538806	4707	-105.812	44.09858	75	48	36
536070	4752	-105.807	44.10227	74	48	30
536047	4806	-105.803	44.10595	74	48	30
536053	4768	-105.798	44.10957	74	48	30
536055	4780	-105.793	44.11313	74	48	30
547703	4942	-105.752	44.12806	74	48	21
547698	4949	-105.747	44.13111	74	48	15
547711	4902	-105.741	44.13527	74	48	15
547700	4967	-105.737	44.13833	74	48	15
547691	5046	-105.727	44.14556	74	48	11
547692	5061	-105.721	44.14913	74	48	11
522445	4982	-105.712	44.14976	74	48	11
542767	4976	-105.707	44.15275	74	48	12
542768	4938	-105.702	44.15691	74	48	12
545513	4865	-105.697	44.16053	74	48	1
545511	4866	-105.692	44.16385	74	48	1
544653	4904	-105.686	44.16731	73	48	6
544652	4971	-105.68	44.17056	73	48	6
540588	4919	-105.674	44.17748	73	49	31
540344	4850	-105.669	44.18119	73	49	32
540339	4892	-105.669	44.1885	73	49	29

Table 4 continued.

Well information for cross section C-C' cont.

Name	Elevation	Longitude	Latitude	Range	Township	Section
540387	4856	-105.664	44.19219	73	49	29
540384	4833	-105.659	44.19566	73	49	29
540383	4859	-105.654	44.19961	73	49	29
540380	4821	-105.649	44.2033	73	49	21
541867	4865	-105.644	44.20689	73	49	21
541441	4832	-105.639	44.21059	73	49	21
534897	4873	-105.634	44.21788	73	49	16
543270	4774	-105.634	44.22875	73	49	16
526440	4765	-105.618	44.24366	73	49	10
540908	4696	-105.608	44.25479	73	49	2
523467	4732	-105.608	44.26589	73	50	35
525425	4800	-105.592	44.28003	73	50	26
525255	4771	-105.583	44.28468	73	50	25
525859	4700	-105.575	44.29341	73	50	24
522597	4634	-105.557	44.29587	72	50	19
523060	4567	-105.516	44.30015	72	50	21
522584	4584	-105.512	44.30391	72	50	21