Geology and Resource Appraisal of the Felix Coal Deposits Powder River Basin, Wyoming: A Research Project with the People's Republic of China

U.S. GEOLOGICAL SURVEY BULLETIN 1818

Work done in cooperation with the
Geological Bureau, Ministry of
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Geology and Resource Appraisal of the Felix Coal Deposit, Powder River Basin, Wyoming: A Research Project with the People's Republic of China

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People's Republic of China

Work done in cooperation with the
Geological Bureau, Ministry of
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By B. H. Kent, J. N. Weaver, S. B. Roberts, Tian Ming, Liu Shu, *and* Mao Bangzhuo

Abstract

An Earth Sciences Protocol between the United States and the People's Republic of China includes a "Project 6" for coal basin exploration and analysis. Project 6 representatives share concepts, approaches, and exploration techniques used in selected main basins in the United States and China, and participate in joint endeavors to solve representative common problems. The Powder River basin in Wyoming and Montana and the Ordos basin in the Shaanxi Province of China were selected for an initial round of study. The problem involving geology and resource appraisal of Felix coal was designed as a short-term Project 6 activity.

The Felix coal bed in Eocene age rocks crops out on the eastern flank of the Powder River basin in northeastern Wyoming, where the outcrop trace of the Felix encompasses an area of 2,500 mi^2. Within the encompassed area of subsurface Felix coal, individual beds merge to form single beds of combined coal, and the thickest single bed of combined Felix coal forms an elongate north-south, central core which splits both to the east and to the west. To facilitate area resource assessment at a 1:100,000 scale, "deposit" was defined as the principal resource unit of Felix coal. Individual Felix coal beds were combined wherever rock intervals between them are thinner than the coals, and the combinations were included in a Felix coal deposit. The deposit contains a total of 32 billion tons of subbituminous coal, and the central core of combined coal comprises 4.6 billion tons of that total.

The Felix coal deposit is also a regional geologic feature. During early Eocene time, basin subsidence and eastern uplifts interacted to establish and prolong optimal environments and conditions for (Felix) coal deposition and maintain a dynamic balance between subsidence and peat accumulation. The nature of such interactions is best described by a "teeter-board" analogy: if an area is subsiding while an opposing area is uplifted, an intervening fulcrum area is in dynamic equilibrium.

The pivotal effects of western subsidence (basin) and eastern uplifts (Black Hills) produced linear fulcrum areas in dynamic equilibrium, elongate north-south across the west-tilted paleoslopes that formed the eastern flank of the developing basin. During a quiescent period of early Eocene time, when subsidence and uplift were subdued and sediment infill was minimal, fulcrum areas became centers for (Felix) peat to accumulate. The fulcrum areas were shifted west by eastern uplifts and east by western subsidence. The areal pattern of Felix coal occurrence indicates that several fulcrum-area migrations occurred in response to interactions of subsidence and uplift over the prolonged period of Felix coal deposition, and that the overall migratory shift was westward, ahead of the succeeding episode of clastic influx that buried the peat beds.

The Powder River basin evolved as a product of Laramide structural movements (subsidence and uplift) during Paleocene and Eocene time. Some of the largest coal deposits in the world occur in Paleocene and Eocene rocks on the eastern flank of the basin, where the Felix is relatively small compared to underlying deposits such as the Wyodak coal in upper Paleocene rocks. The areal pattern of Wyodak coal is similar to that of the Felix, and the Wyodak coal deposit also models the teeter-board/fulcrum area concept. The Laramide orogeny was at peak activity during late Paleocene through early Eocene time, when thick coal deposits such as the Wyodak and the Felix evolved as products of basin evolution.

Background

An Earth Sciences Protocol between the United States and the People's Republic of China (PRC) includes Project 6 for coal basin exploration and analysis. Project 6 objectives are for scientists from the United States and China to study mutual problems in exploration and analysis, to observe concepts, approaches, and exploration techniques used in selected main basins in the United States and China, to participate in joint endeavors to solve representative common problems, and to utilize computerized data systems for coal resource assessment.

The Powder River basin in Wyoming and Montana and the Ordos basin in the Shaanxi Province of China were selected for an initial round of study (fig. 1).

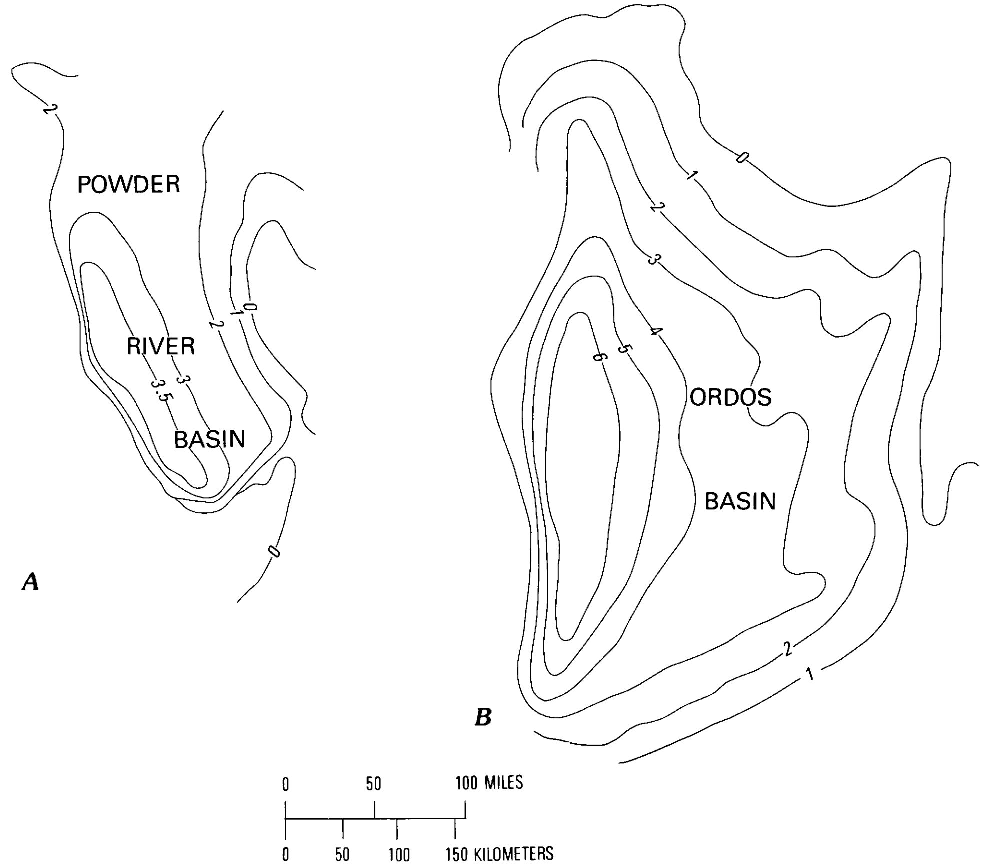

Figure 1. Tectonic maps showing the structural similarity of the Powder River basin in western U.S. (A) and the Ordos basin in North China (B). Contoured depths are below sea level (-0-) to Precambrian basement rocks. Contour interval, 1 kilometer. Sources of data, Tectonic map of North America (King, 1969), and Tectonic map of China and Mongolia (Terman, 1974).

Project 6 representatives from China spent three months (mid-September to mid-December 1982) working and touring in the United States under sponsorship of the U.S. Geological Survey (USGS). PRC representatives included the following scientists (surnames underlined):

Mr. Tian Ming, Technical Manager, Chief Geologist, Coal Field Geology Corporation of Shaanxi Province (Project 6 co-chief for China and leader of the group);

Mr. Liu Shu, Deputy Chief Geologist, Coal Field Geology Corporation of Shaanxi Province;

Mr. Mao Bangzhuo, Staff Geologist, Geological Bureau, Ministry of Coal Industry;

Mr. Gou Jingwei, Geophysicist (seismic), First Geophysical Exploration Team of Ministry of Coal Industry; and

Mr. Han Changlin, Geophysicist (bore hole), Coal Field Geology Corporation of Jiangxi Province.

Mr. Tian and Mr. Liu are in charge of coal exploration in the Ordos basin.

USGS geologists assigned to Project 6 defined a representative coal problem in the Powder River basin and organized a short-term research project that provided the PRC scientists with an opportunity to observe and practice U.S. exploration methods used to obtain a satisfactory solution.

The problem selected was regional geologic study and computerized area resource assessment, at a 1:100,000 scale, of the Felix coal bed in Eocene rocks on the eastern flank of the Powder River basin, northeastern Wyoming. Some results of cooperative Project 6 work on this problem are summarized in this jointly prepared report.

INTRODUCTION

The 1982 schedule of Project 6 activities allotted six weeks for cooperative work on the Felix coal problem; the main objective was to demonstrate a chronologic sequence of exploration methods that would provide the basic data and information needed for a satisfactory solution. Necessary literature research on previous studies of the Felix coal bed, data compilations, and computerized resource assessment operations were done later by USGS geologists assigned to Project 6 work.

Photogeologic methods were demonstrated using 1:25,000 scale vertical aerial color photos in a PG-2 precision photogrammetric plotter to review and establish correlations, areal connections, and areal extent of Felix coal outcrops. *Geophysical log interpretation methods* were used to obtain data on subsurface Felix coal from geophysical logs of drill holes within the 2,500 mi^2 area encompassed by the outcrop trace. *Subsurface mapping* *methods* were used to determine the areal pattern of Felix coal occurrence and to reconstruct the stratigraphic framework of Felix coal. *Field investigation methods* were used to correlate and extend the Felix coal bed through critical areas, and *coal exploratory drilling* was done to demonstrate drilling and logging techniques and to obtain stratigraphic data and cores of Felix coal for analysis.

The areal pattern of Felix coal occurrence was mapped on a subarea basis (fig. 2) to emphasize that at a regional scale, closely associated beds of Felix coal merge to form single beds of combined coal, and the thickest single bed of combined coal forms the elongate north-south, central core (subarea X) of a Felix coal deposit. For area resource assessment at a 1:100,000 scale, "deposit" was defined as the resource unit to be assessed; this resource unit of Felix coal was constructed following established guidelines which include 1) closely associated coal beds are combined (as one resource unit) where partings between them are thinner than the coals; and 2) parts of an individual coal bed are assessed separately (as separate resource units) where constituent rock units are thicker than the coal. This process of "streamlining" Felix coal occurrences to construct a Felix coal deposit as a resource unit made the deposit transitional from east to west (fig. 3B).

The Felix coal deposit was recognized as a regional geologic feature (fig. 3A). The geometry of the deposit strongly indicated that Felix coal deposition in early Eocene time was subject to active paleoenvironmental control and that the mechanics of coal deposition were controlled in some consistent, evolutionary way. These observations became topics for regional geologic study.

The Powder River basin and surrounding uplifts (fig. 4) were formed by Laramide structural movements during Paleocene and Eocene time. These structural movements (subsidence and uplift) must have been involved in any form of active paleoenvironmental control on Felix coal deposition. A review of the mechanics of coal deposition indicated that, for thick coal deposits to form, a dynamic balance must be maintained between subsidence and peat accumulation. The nature of active paleoenvironmental control involving tectonic subsidence and uplift was examined and described in context with a "teeter board" concept based on the assumption that if an area is subsiding while an opposing area is uplifted, a fulcrum area in between is in dynamic equilibrium. Fulcrum areas on the eastern flank of the Powder River basin were described as loci for Felix coal deposition in early Eocene time.

Some of the largest coal deposits in the world are in Paleocene and Eocene rocks on the eastern flank of the Powder River basin in northeastern Wyoming. Actually, the Felix coal deposit is relatively small compared to some of the underlying coal deposits of late Paleocene age. During late Paleocene and Eocene time, the Laramide orogeny was at peak activity, and subsidence and uplift interacted to establish and prolong optimal environments and conditions necessary for thick coal deposition on the eastern flank of the Powder River basin. In essence, the Felix and other thick coal deposits on the eastern flank evolved as products of basin evolution.

PREVIOUS STUDIES OF THE FELIX COAL BED

The Felix coal bed is virtually a landmark on the eastern flank of the Powder River basin. Studies of the Felix involve many of the coal fields that were established by USGS geologists from 1909 to 1957, including the Powder River, Barber, Gillette, Pumpkin Buttes, and Spotted Horse (fig. 5). Representative vertical sequences of coal beds in the Spotted Horse and Gillette coal fields are shown on figure 6.

Some aspects of a basin-wide correlation problem involving a Roland coal bed several hundred feet below the Felix (fig. 6) relate directly to the geology of Felix coal. These aspects are reviewed separately as "the Roland correlation problem." Additional coal fields involved in that problem include the Sheridan and Little Powder River (fig. 5).

Powder River Coal Field

Stone and Lupton (1910) established the Powder River coal field. The Felix coal bed, a thick bed of coal prominently exposed near the head of Wildhorse Creek in T. 51 N., R. 74 W., was named after the nearby Felix station, on the Burlington railroad. A mine was opened on the coal bed near Felix in the late 1890's; small mines were subsequently opened near Echeta and Croton.

East of the Powder River, the Felix coal bed was found to be more than 10 ft thick. It was traced easily by the reddish clinker of baked roof rock produced wherever the coal bed had been burned at the outcrop. West of the Powder River, the Felix coal bed was found to be 5 ft thick along Crazy Woman Creek. In T. 52 N., R. 78 W., the bed passes below drainage.

Barber Coal Field

Wegemann (1913) established the Barber coal field, south and west of the Powder River coal field. In the Barber coal field, Wegemann (1913, p. 277–278) found a coal bed 4 ft thick at or near the level of the Powder River flood plain in T. 51 N., R. 77 W., which he "rather doubtfully" correlated with the Felix as mapped by Stone and Lupton (1910) along the Powder River to the north; Wegemann traced that coal bed south along the east side

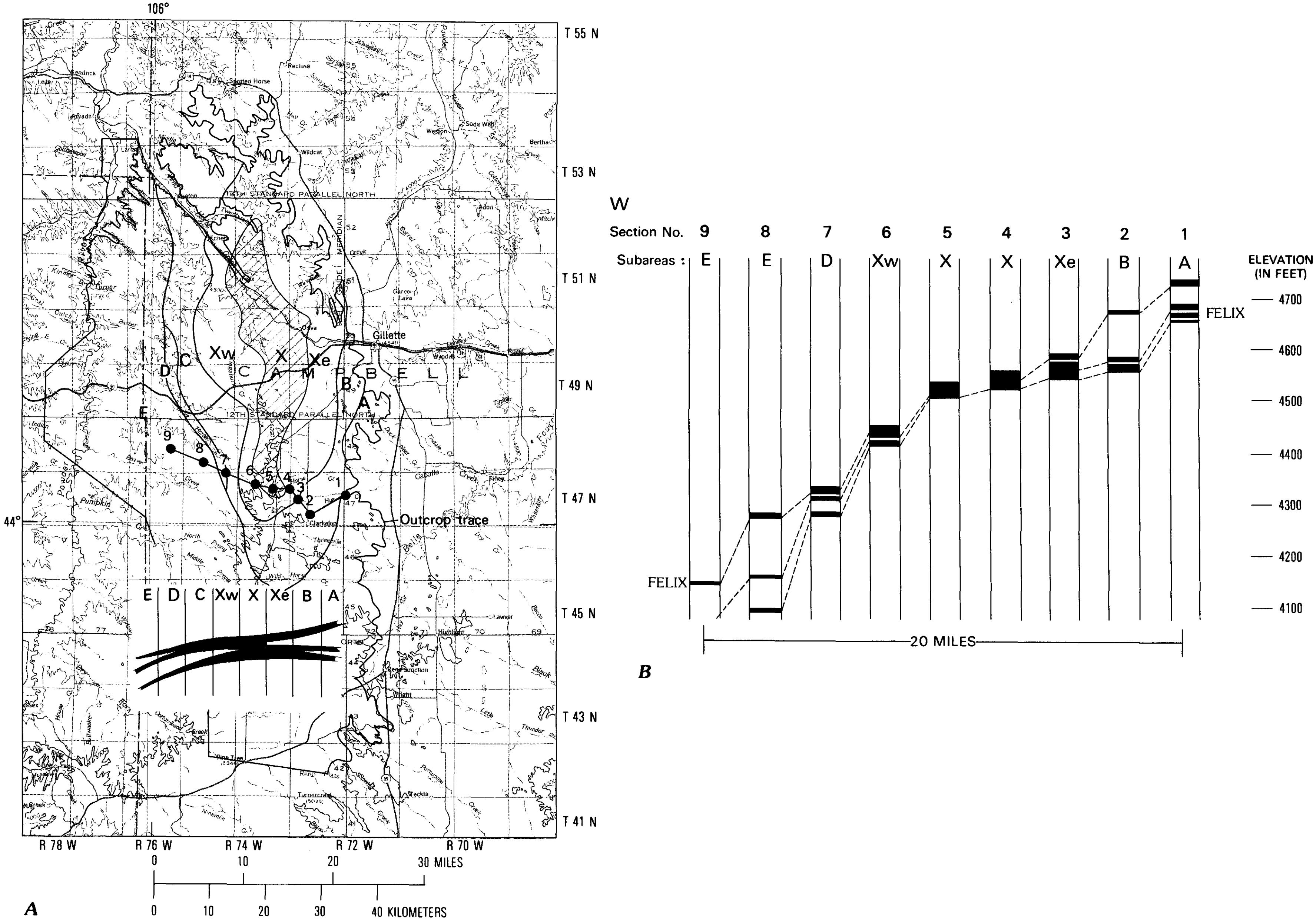

Figure 2. Map (A) and profile (B) of the Felix coal deposit, showing subareas of Felix coal occurrence on the eastern flank of the Powder River basin, northeastern Wyoming. Subarea X is the central core of the deposit.

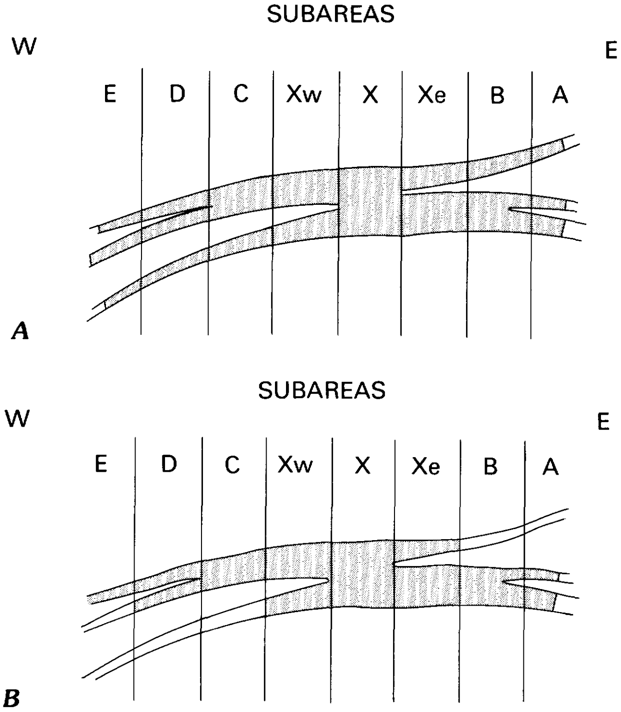

Figure 3. Diagrammatic east-west profiles of the Felix coal deposit as a regional geologic feature (A), and as a resource unit (B).

of the Powder River valley, through Tps. 51 and 50 N., R. 77 W.

Gillette Coal Field

Dobbin and Barnett (1928) established the Gillette coal field. They described the eastern and western parts of the Gillette coal; their report includes a chapter on the northwestern part of the coal field described separately by W. T. Thom, Jr. The northwestern part includes a Minturn District; the old town of Minturn is now Wyodak.

The northwestern part of the Gillette coal field is within the eastern part of the Powder River coal field. Stone and Lupton (1910) traced a Felix coal bed exposed northeast of Oriva to its easternmost exposure in the town of Gillette. Thom (1928) noted that the Felix coal bed crops out extensively in the hills west and south of Gillette; he correlated the Felix to the south with Dobbin and Barnett's bed B in the western part of the Gillette coal field (fig. 6).

Dobbin and Barnett (1928) mapped bed B in Tps. 43 through 47 N., R. 72 W. The bed is more than 10 ft thick but burned extensively along the outcrop, producing the familiar brick-red clinker of baked roof rock. Bed B was found to be 8 ft thick in T. 42 N., R. 73 W.; only 4 ft thick in R. 41 N., R. 73 W.; and represented only by carbonaceous shale in T. 41 N., R. 73 W. Dobbin and Barnett (1928, p. 15) concluded that, next to a bed D, bed B "is the most valuable coal bed in the Gillette field and is correlated with the Felix bed of the Gillette area." (Bed D, about 400 ft below the Felix, was correlated with the Roland coal bed in the Powder River coal field; the contact between the Fort Union Formation and the overlying Wasatch Formation was placed at the top of bed D.)

Pumpkin Buttes Coal Field

Wegemann and others (1928) established the Pumpkin Buttes coal field. They mapped a bed E in T. 45 N., R. 73 W., where it connects east to bed B (the Felix) of Dobbin and Barnett (1928) in the western part of the Gillette coal field. On that basis, bed E is equivalent to the Felix.

In the Pumpkin Buttes coal field, Wegemann and others found bed E (the Felix) to be 18 ft thick in the western part of T. 45 N., R. 72 W.; 15 ft thick in T. 45 N., R. 73 W.; and only 3 ft thick in T. 44 N., R. 73 W. Wegemann and others (1928, p. 14) noted that a bed E (about 3 ft thick) is exposed along Pumpkin Creek in T. 46 N., R. 76 W. where it passes below the level of Pumpkin Creek in sec. 9 of the township. The bed reappears 3 miles downstream; it can be traced just above stream level to the Powder River in T. 47 N., R. 77 W., about 15 miles south of the Barber coal field.

Spotted Horse Coal Field

Olive (1957) established the Spotted Horse coal field. He found the Felix coal bed of Stone and Lupton (1910) to be 15 ft thick and easy to trace through the southern part of the Spotted Horse coal field because the coal bed had been burned extensively along the outcrop, producing the conspicuous red clinker.

The Roland Correlation Problem

Taff (1909, p. 129–130) established a Tongue River coal group in the northwestern part of the Sheridan coal field, where the group is 800 ft thick and consists of shale, sandstone, and seven minable coal beds. The Roland of Taff (1909) is the uppermost coal bed of the group; a Smith coal bed is 125 ft below the Roland.

In the Powder River coal field, the Arvada coal bed of Stone and Lupton (1910) is exposed in T. 54 N., R. 77 W. (fig. 5), where the Arvada is about 350 ft below the Felix (fig. 6). A coal bed 125–225 ft below the Arvada,

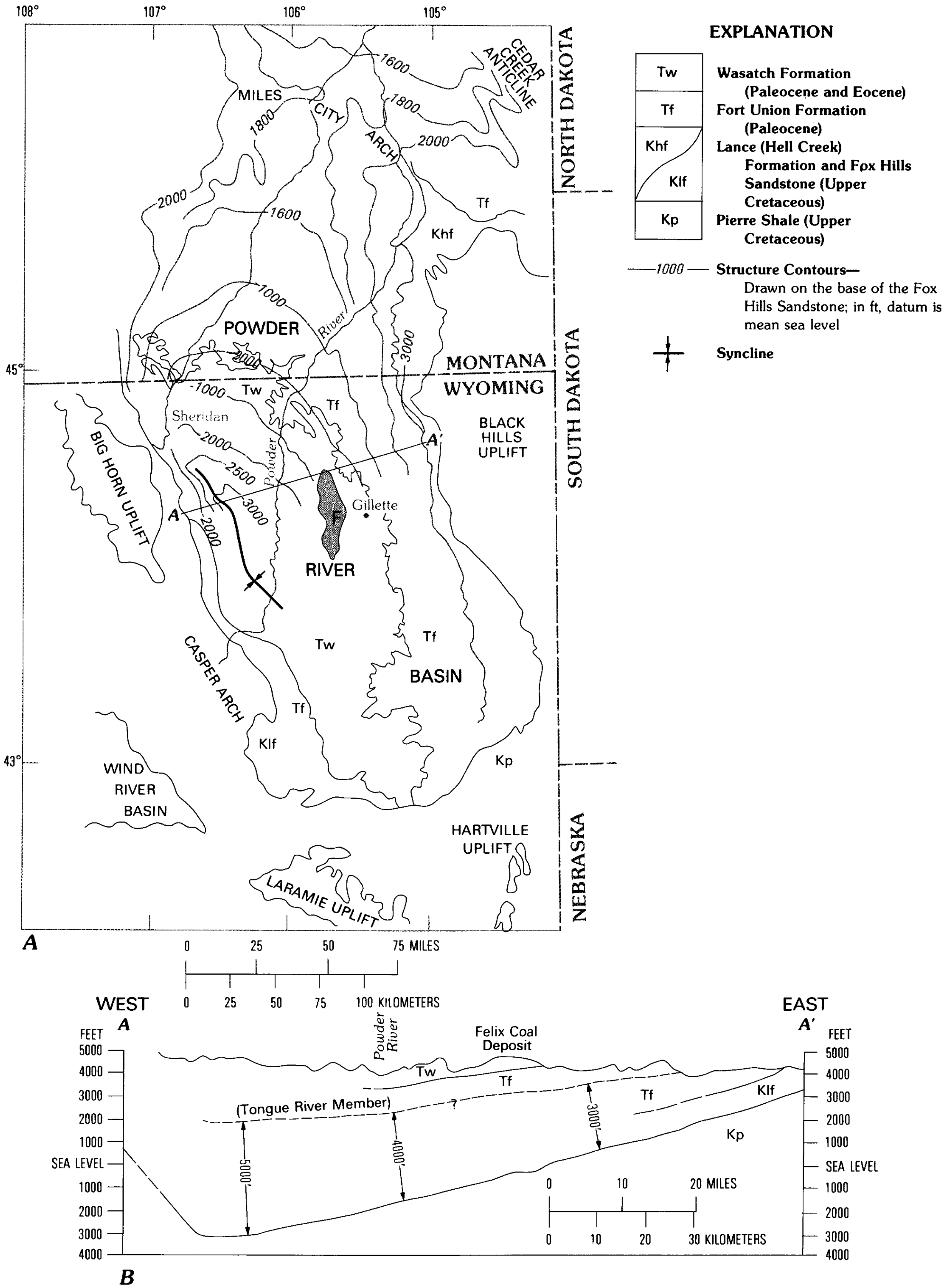

Figure 4. Geologic setting of the Felix coal deposit on the eastern flank of the Powder River basin, northeastern Wyoming. A, geologic map of the Powder River basin and surrounding uplifts, Wyoming and Montana. B, east-west profile of the Powder River basin as formed by rocks of the Fox Hills Sandstone and Lance Formation (Klf), the Fort Union Formation (Tf), and the Wasatch Formation (Tw) containing the Felix coal deposit. On the geologic map, the shaded area (F) is the central core (subarea X) of the Felix coal deposit. (See fig. 2).

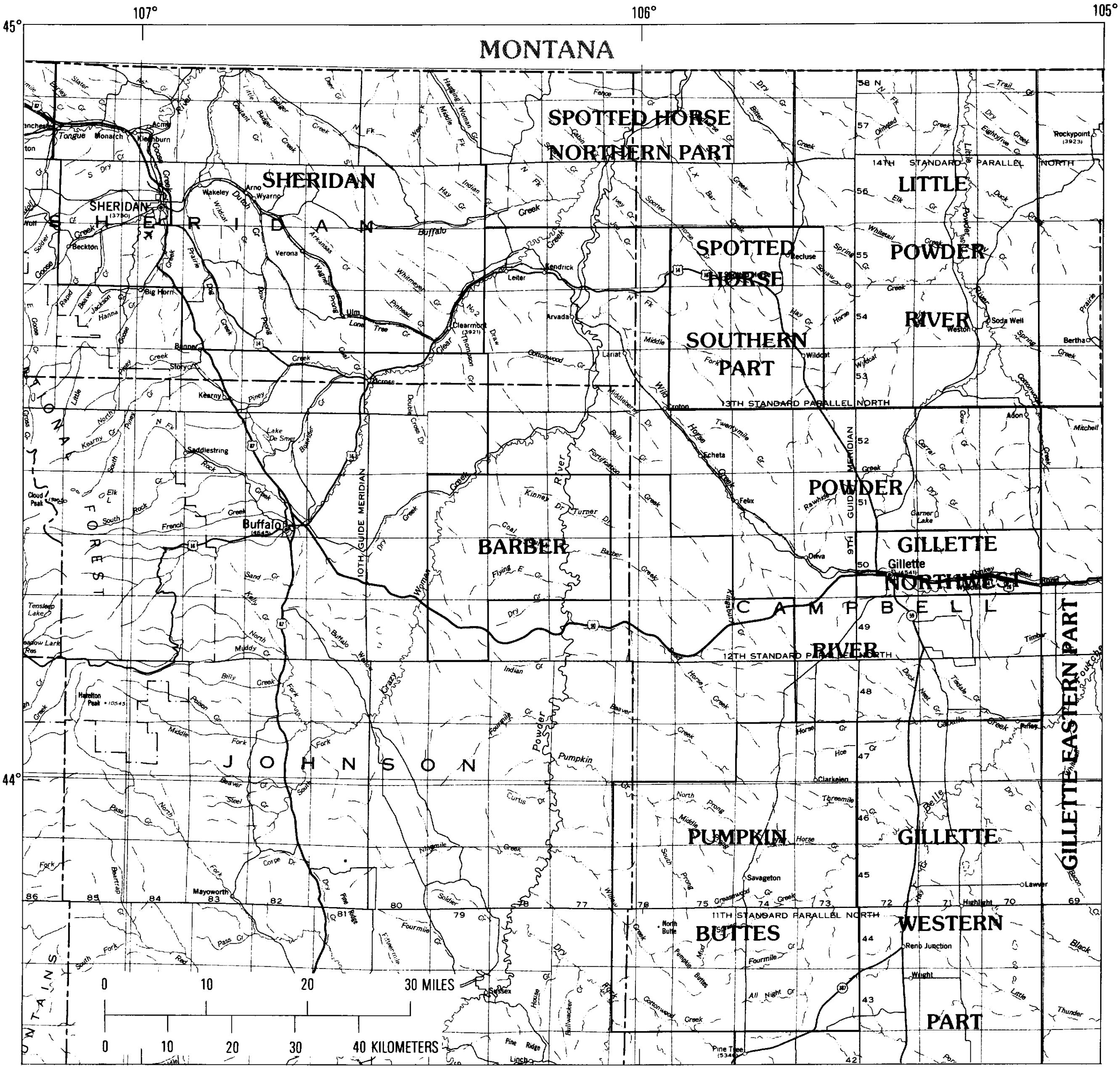

Figure 5. Index map of coal fields in the Powder River basin, northeastern Wyoming.

exposed in T. 55 N., Rs. 76 and 77 W., was correlated with one exposed in Tps. 57 and 58 N., R. 79 W. in the Sheridan coal field, which Taff (1909, p. 142) thought was "in about the position of the Roland coal."

In the eastern part of the Powder River coal field, Stone and Lupton (1910, p. 118) noted that the Tongue River coal group of Taff (1909) "outcrops between Minturn and Gillette in a north-south belt, but it is so tilted and burned that its thickness cannot be measured." Under a heading of "Other Coal Beds" (which were neither named nor correlated), Stone and Lupton (1910, p. 129) reported that a 25-ft-thick coal bed was exposed in the northern part of T. 52 N., R. 72 W. at the west edge of the broad, irregular belt of clinker; some other coal beds thought to be the source of the burning were found at a few places in T. 51 N., R. 72 W. and in T. 49 N., R. 71 W. near Minturn (Wyodak).

Davis (1912) established the Little Powder River coal field. In the eastern half of Tps. 53 and 54 N., R. 73 W., and in the southern part of T. 53 N., R. 72 W., Davis (1912) mapped a bed A 130 ft above a bed C, and a bed E 170 ft below bed C (fig. 6). The bed C exposed in the southern part of T. 53 N., R. 72 W. connected south to the 25-ft-thick coal bed noted by Stone and Lupton (1910). Davis (1912, p. 428) summarized regional coal-bed correlations as follows:

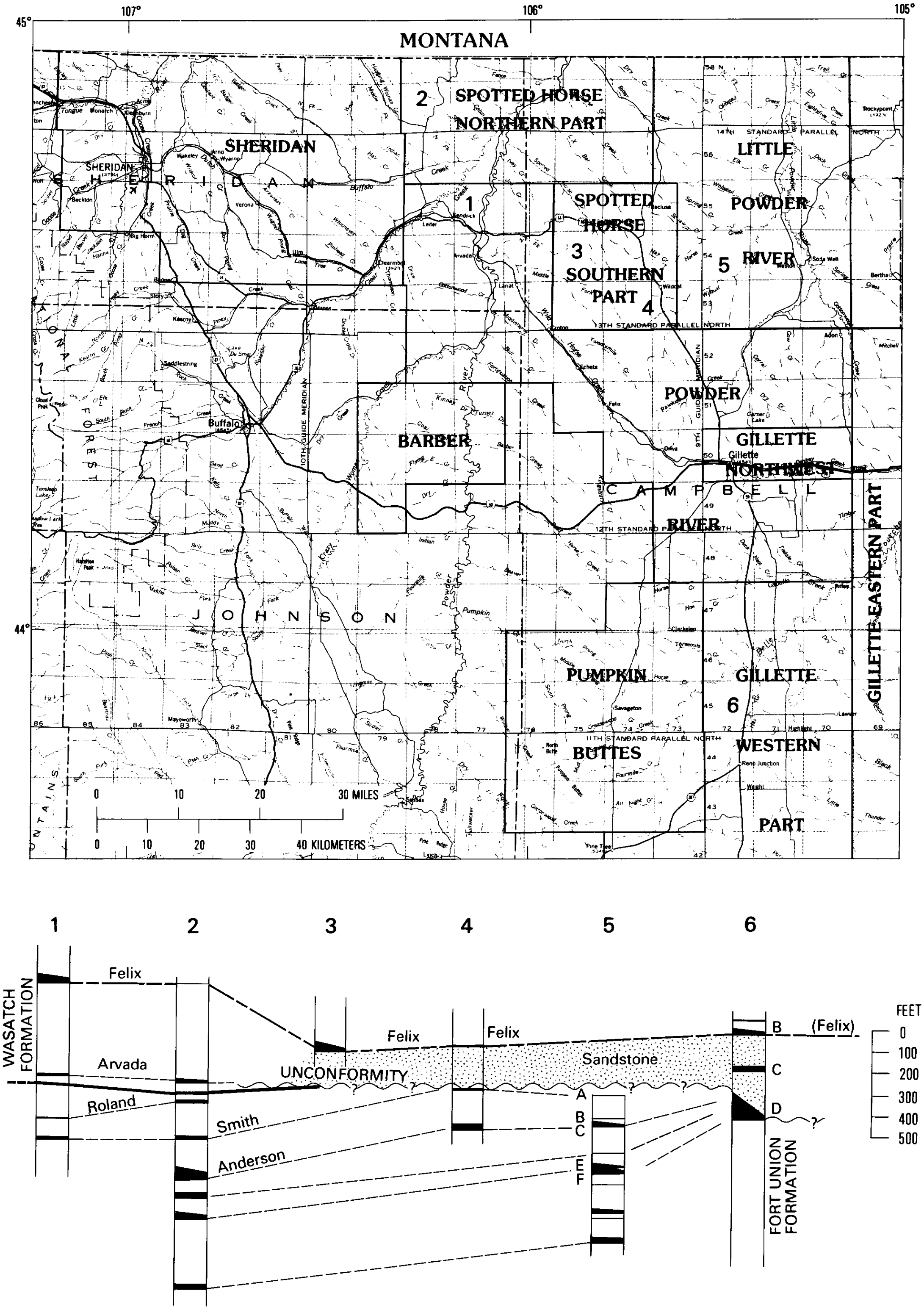

Figure 6. Correlation diagram of vertical sequences of coal beds in the (1) Powder River, (2) Spotted Horse (northern part), (3) and (4) Spotted Horse (southern part), (5) Little Powder River, and (6) Gillette (western part) coal fields, Powder River basin, northeastern Wyoming. Sources of data and coal-bed nomenclature: (1) Stone and Lupton, 1910; (2), (3), and (4) Olive, 1957; (5) Davis, 1912; and (6) Dobbin and Barnett, 1928.

"Bed C is undoubtably the one correlated by Stone and Lupton (1910) with the Roland bed described by Taff (1909). This bed and the zone of red rocks produced by its burning are most valuable aids in correlating the other coal beds in this field. Bed A is probably the Arvada bed of Stone and Lupton and bed E may possibly be the Smith bed of Taff."

Thom and Dobbin (1924) introduced the name, Tongue River Member of the Fort Union Formation in a report on the stratigraphy of Cretaceous-Eocene transition beds in eastern Montana and the Dakotas. The Tongue River Member was named for exposures along the Tongue River near the Sheridan coal field of Taff (1909). The Tongue River Member was virtually the same as the Tongue River coal group of Taff (1909)—except that Thom and Dobbin (1924, p. 495) placed the top of the member *beneath* the Roland coal bed of the Sheridan field.

In their report on the Gillette coal field, however, Dobbin and Barnett (1928) and Thom (1928) placed a Roland coal bed at the top of the Tongue River Member of the Fort Union Formation, and they designated the top of the member as the base of the Wasatch Formation. Thom (1928, p. 57) summarized Roland correlations as follows:

"From the work of Stone and Lupton (1910) and of Davis (1912) and from work done by Dobbin and Barnett in preparing this report, it is evident that the Roland coal bed of the Sheridan field is the principal coal bed (bed D) of the Minturn district and of the Gillette field as a whole."

Olive (1957) mapped the Arvada, Roland, Smith, and Anderson coal beds in the northern part of the Spotted Horse coal field (fig. 6). However, the Arvada and Roland coal beds were mapped only in the western half of the northern part of the Spotted Horse coal field; neither the Arvada nor the Roland extended into the southern part of the Spotted Horse coal field. Although Olive (1957) accepted the Roland coal bed of Taff (1909) as the uppermost unit of a Tongue River Member, he also (1957, p. 13) recognized that:

"Inasmuch as the Roland bed is not continuous in the Spotted Horse field and its top cannot be used as a convenient mappable horizon, the top of the member was mapped at the top of a persistent, highly fossiliferous unit of shale, sandstone, and limestone which occurs 5–65 feet above the Roland bed."

In the southern part of the Spotted Horse coal field, Olive (1957) mapped an Anderson coal bed stratigraphically 200 ft below the Smith coal bed in the western half of T. 54 N., R. 73 W. The Anderson coal bed connected east to bed C (the Roland) of Davis (1912) in the eastern half of that township (fig. 6). Olive (1957, p. 13) proposed the following solution for the Roland correlation problem:

"In the Gillette coal field Dobbin and Barnett (1928) placed the upper boundary of the Tongue River member at the top of the "D" coal bed, which they believed to be the Roland bed. The D bed of the Gillette coal field is correlated in this report with the Anderson coal bed of the Spotted Horse field and is about 350 feet stratigraphically below the fossiliferous unit used to mark the top of the Tongue River member. Tongue River rocks above the D Coal bed probably have been removed by pre-Wasatch erosion in the Gillette coal field."

Olive's solution revealed a sequence of geologic events which he (1957, p. 13–14) described as follows:

"Eastward and southeastward of the NW¼ sec. 12, T. 55 N., R. 75 W., strata of the Tongue River member above the Smith coal bed wedge out and the Wasatch Formation overlies the Smith coal bed. East of the Powder River-Little Powder River divide, the interval between the Smith coal bed of Tongue River age and the Felix coal bed of Wasatch age is occupied by 160 feet of cross-bedded, coarse-grained sandstone. In places to the west the interval between these two beds is occupied by 670 feet of interbedded sandstone, shale, and coal—225 feet belonging to the Tongue River member and 445 feet to the Wasatch formation (see plate 3). This relationship suggests that the southern part of the mapped area was uplifted slightly at the close of the Paleocene, with a resulting change from deposition to nondeposition or erosion."

The correlation diagram for vertical sequences of coal beds in coal fields on the eastern flank of the Powder River basin (fig. 6) illustrates the following sequence of geologic events: 1) coal-bearing rocks of the Tongue River Member of the Fort Union Formation were uplifted and tilted westward during late Paleocene time; 2) they were truncated by erosion at the close of the Paleocene; 3) the eroded Paleocene rocks were reworked, transported westward, and redeposited as Paleocene and Eocene rocks of the lower part of the Wasatch Formation; 4) uplifts of source areas to the east stimulated influx of clastics which spread westward over the erosion surface during early Eocene time; and 5) Felix coal was deposited across that sandstone platform.

EXPLORATION METHODS

The main objective of cooperative Project 6 work on the Felix coal problem was to demonstrate and practice exploration methods of obtaining the basic data and information needed for a satisfactory solution. In accordance with overall Project 6 objectives, the scientists from China participated in all phases of the work involved, and exploration methods were examined in the process of applying them. Methods used included photogeology, geophysical log interpretation, subsurface mapping, field investigations, and coal exploratory drilling.

Photogeology

Photogeology is an exploration method used extensively in Powder River basin coal studies; it involves detecting, interpreting, measuring and mapping geologic features shown on overlapping vertical aerial color photographs. In practice, 1:25,000 scale color photos are used in a PG–2 precision photogrammetric plotting instrument (fig. 7), and geologic features are detected, interpreted, measured, and mapped in one operation. Most of the

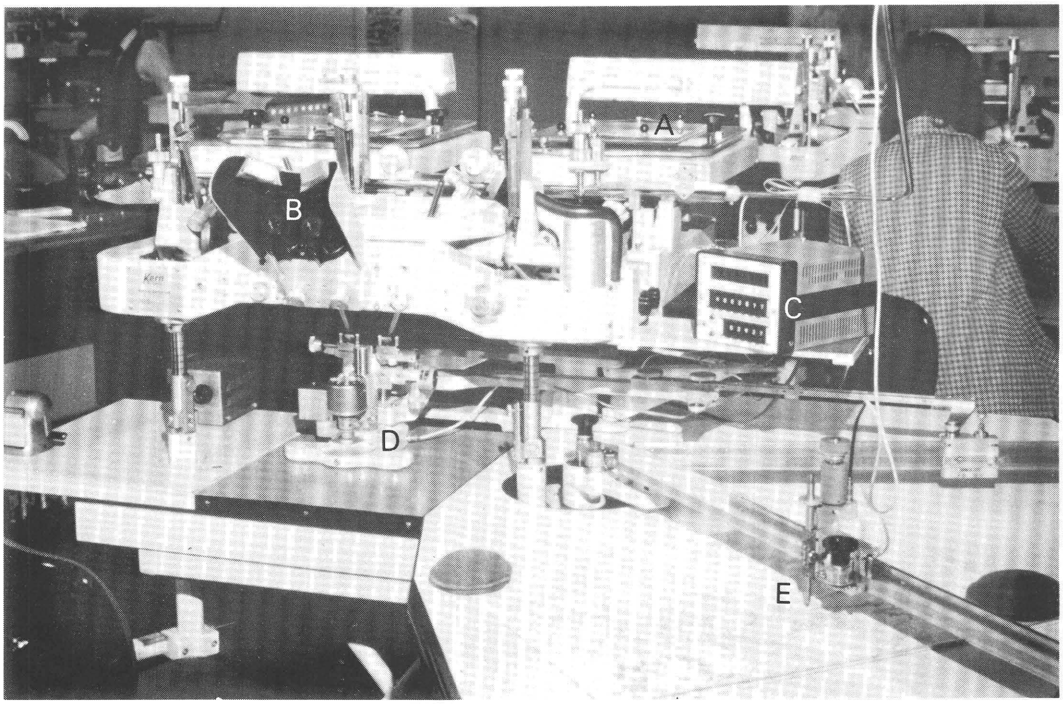

Figure 7. A Kern PG–2 precision photogrammetric plotting instrument for geologic use by U.S. Geological Survey geologists, Denver, Colo. Photo and description from Molnia (1983).

region shown on figure 5 had been mapped photogeologically at 1:24,000 scale on 7½-minute topographic quadrangle bases.

Clinker is the most obvious surficial geologic feature of the Powder River basin. Wherever a coal bed has been burned at the outcrop or beneath shallow cover, the roof rocks have been baked to reddish clinker, and they have slumped or collapsed down to the level of the base of the unburned coal; usually, the downthrow of slumped clinker is equal to the original thickness of the coal. Clinker stands out vividly on natural-color photos, and the contact between reddish clinker and underlying unbaked, light pastel-colored rocks is easy to detect and follow.

Dobbin and Barnett (1928, p. 48) summarized interpretive and mapping aspects of clinker, in observing that the position of unburned coal "was pretty accurately determined by mapping the contact of baked and unbaked rock." Locally, however, side-hill exposures of clinker may have slumped below the level of the unburned coal; and at places where closely associated coal beds have been burned, clinker associated with one coal bed may have merged with clinker associated with another. If the original coal bed was very thick, and if shallow cover is extensive, the vast piles of clinker that formed can be overwhelming to a field geologist charged with sorting out the chaos. Slumped clinker along the outcrop trace of a principal coal bed such as the Felix can also be overwhelming. A geologist working at a 1:1 scale in the field is too close to such problems to resolve them. Photogeology at a 1:25,000 scale provides a much better perspective.

The color photo/PG-2 combination has been particularly effective for tracing and correlating principal coal beds across Powder River basin coal fields and from one field to another. However, that combination had not yet been used to map the outcrop trace of the Felix coal bed through some places in the western part of the Gillette coal field (fig. 5). Project 6 geologists from the People's Republic of China participated in using the color photo/PG-2 combination to map the Felix through those places.

Parts of the Barber coal field, the area south along the Powder River, and the northwestern part of the Pumpkin Buttes coal field contain coal beds which are too thin to be traced or detected on the 1:25,000 scale color air photos. We planned to investigate these areas in the field, to see if they contained any coal beds stratigraphically equivalent to the Felix.

The outcrop trace of the Felix coal bed (fig. 2) was compiled from published geologic and photogeologic maps and Project 6 photogeologic work. The outcrop trace encompasses an area of 2,500 mi^2.

Geophysical Log Interpretation

USGS coal geologists have frequent opportunities to interpret geophysical logs in the course of Powder River basin coal studies, because geophysical logs of drill

DESCRIPTION

A) Glass plates to hold aerial photographs
B) Operator's binocular viewer
C) Digital readout device for elevation of floating mark
D) Operator's controls
E) Plotting table with basemap and automatically positioned pen

Geologists operate the photogrammetric plotter to produce geologic and coal bed maps directly from vertical aerial photographs. The Kern PG-2 plotter can accomodate either paper prints or film transparencies; these are inserted into the machine at "A". When the various settings on the machine are adjusted, the user sees (through "B") a brightly-lit, three-dimensional image containing a tiny bright spot (floating mark). Three magnifications can be selected with which to view the stereoscopic image.

During the setting of each stereopair, the plotter is calibrated (from a topographic map or other elevation control) so that it displays (at "C") the precise elevation, in feet above sea level, of the floating mark within the stereoscopic model. The location of the floating mark is controlled by the operator, using the controls at "D". The operator can move the floating mark so that it appears to "climb" up or down a hillside or to remain stationary on a given horizon or feature.

Attached to the body of the plotter is a pantograph arm with pen ("E"); the arm travels over an oriented basemap so that the location of the pen on the map represents the location of the floating dot within the stereomodel. As the geologist looks through the viewer ("B") and moves the floating mark along a certain feature in the stereomodel, the pen automatically records the path of the floating mark, at the correct elevation, onto the basemap. Thus the geologist compiles an accurate map while he views the stereoscopic image.

Stereoscopic vision is required to operate the photogrammetric plotter. The techniques of calibrating for elevation control and orienting the photographs and the basemap are not difficult to learn, and improve with practice.
(Use of manufacturer's name in this paper is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey).

holes are the main source of data on subsurface coal. In China, however, geophysical log interpretation is the prerogative of geophysicists. Therefore, it was necessary for Project 6 geologists to first review some of the basics involved.

Although "formation" is the basic unit of measurement in geophysical log interpretation, the technology of borehole geophysical logging does not provide for determining rock types directly from the logs; thus, formations are nothing more than containers for fluids and gases. Formations do contain different amounts of fluids and gases which, for example, introduce different degrees of resistivity to electric current. Such differences are recorded as different formation units on a resistivity log, but such responses have little to do with any lithic matrices of the formations involved. In effect, all types of dry rock have high resistivity to electric current.

On a type of geophysical log known as a resistivity log, formations having the highest resistivity are usually interpreted as coal. However, water-bearing sandstone units are also highly resistive, as are limestone units. On a quantitative basis, it is difficult to compare resistivities recorded on the log of one drill hole with those recorded on the log of another, because resistivity responses are controlled by log-sensitivity settings and by the logging tool used.

A gamma-ray (natural gamma) log records the natural radioactivity inherent to all rocks. Powder River basin coal geologists prefer this type of geophysical log for coal interpretation because the subbituminous coals of the Powder River basin have extremely low radioactivity; gamma-ray log deflections opposite coal beds are sharp and pronounced, and rock partings in a coal bed usually are easy to detect because the partings have relatively high radioactivity. Low radioactivity is an acquired characteristic of Powder River Basin coal, and uraniferous coal may exist in the basin, but we found gamma-ray log interpretations for Felix coal to be very reliable.

A bulk density log records the bulk densities of formations, and this type of geophysical log generally is a direct and reliable indicator of coal because extremely low density (or specific gravity) is a distinctive property of coal which serves to separate coal from other types of rock. However, the log records a composite response to the densities of coal (as a substance), impurities in the coal, fluids and gases, rock partings, and whatever else the formation may contain; thus, quantitative responses are often misleading.

We found the validity of coal interpretations made from geophysical logs to be reinforced by the number of different types of logs available for the same drill hole. For example, if a resistivity log, a gamma-ray log, and a bulk density log were available for the same drill hole, a formation that has very high resistivity is probably coal; if the same formation also has very low radioactivity, we could be almost positive that it is coal; and if the same formation also has very low density, we could guarantee tonnage. Coal interpretations were also reinforced if coal was known to occur at the stratigraphic horizon of the formation in question.

For the Project 6 study, data on subsurface Felix coal were derived from geophysical logs of 300 drill holes within the 2,500 mi^2 area encompassed by the outcrop trace. The logged drill holes included oil and gas test holes and coal exploratory holes drilled over the past 20 years.

Geophysical logs of oil and gas wells are measured from Kelly Bushing (KB) elevations, which are 8–16 ft above surface elevations depending on the heights of the drilling platforms. It was necessary to subtract measured (or indicated) depths to formations from the KB elevation, to obtain the correct elevations of those features.

In contrast, geophysical logs of coal exploratory holes are measured from surface elevations of the drill holes. It was necessary to subtract measured (or indicated) depths to formations from the surface elevation, to obtain the correct elevations of those features.

Subsurface Mapping

The exploration method of mapping subsurface coal in the Powder River basin involves reconstructing the stratigraphic framework of coal by lines of sections prepared from logs of drill holes and contouring data-point (drill hole) sources of coal data. The sections commonly are prepared in strip log form. As a Project 6 activity, a strip log was prepared from the geophysical logs for each of the 300 drill holes involved. The strip-log format used (fig. 8) illustrates relations between measured depths and KB, GL, and coal bed elevations above sea level, as obtained from a gamma-ray log of an oil and gas well.

The strip-log method of reconstructing the stratigraphic framework of coal is very versatile. Any number of strip logs can be arranged along any orientation line, and the lines of sections can be set to either sea-level or coal-bed datum. We preferred to use sea-level datum. The process of placing coal beds "where they are" emphasized structure and eliminated distortions caused by miscorrelations.

The line of sections shown on figure 2 is an east-west profile of a Felix coal zone. Parts of the Felix coal drop about 500 ft over the 20-mile distance from section 1 to section 9, indicating a west dip of 25 ft/mi. The profile shows how closely associated beds of Felix coal merge to form single beds of combined coal, and the thickest single bed of combined coal forms the elongate north-south, central core of a Felix coal deposit. This pattern of coal occurrence is deceptively symmetrical: the central core of Felix coal splits both to the east and to the west, but the core splits eastward to a thin upper bench and a thick lower bench and westward to a thick upper bench and a thin lower bench.

A subarea system (fig. 2) was introduced to subdivide the areal pattern of Felix coal occurrence for purposes of area resource assessment. All of the Felix coal occurrences located at data points (drill holes) were classified according to the subarea system, and the areal pattern of Felix coal occurrence was contoured on that basis.

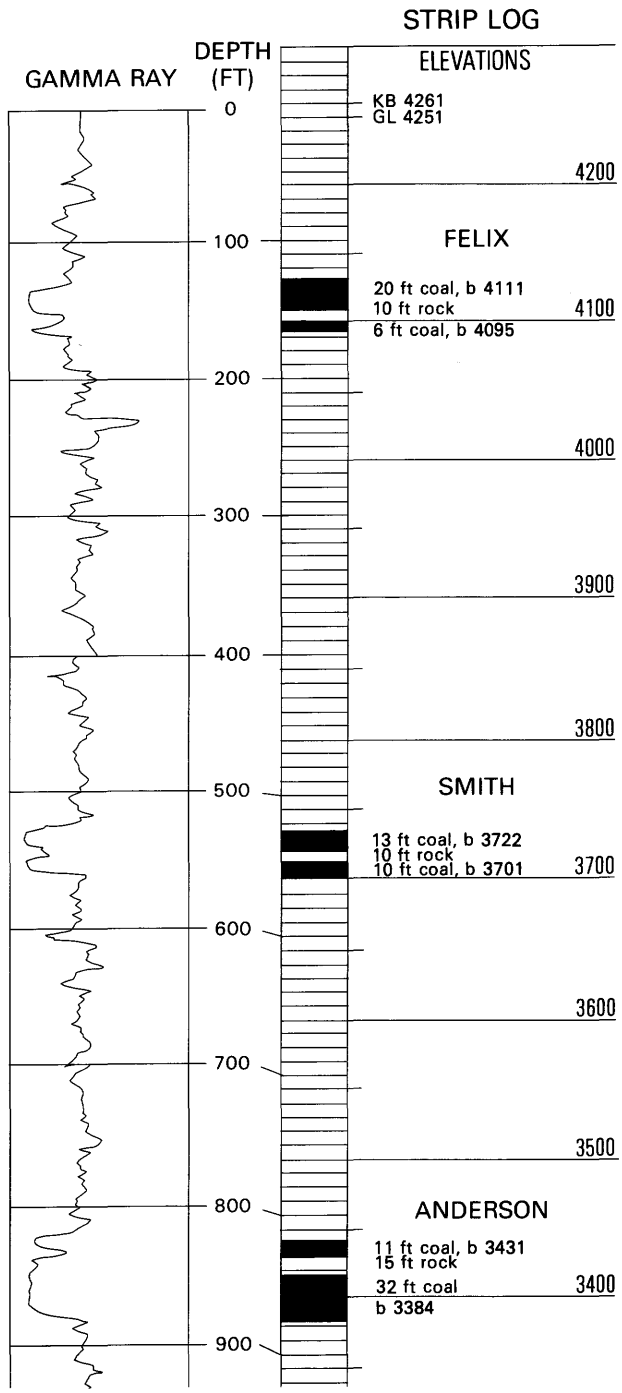

Figure 8. Example of strip-log format used in preparing strip logs from geophysical logs. The example is a strip log prepared from a gamma-ray log of an oil and gas well. KB, Kelly Bushing; GL, ground level; b, base of coal bed. Elevations are in feet above sea level.

Field Investigations

Previous field work established the Felix coal bed in T. 52 N., R. 77 W., and previous photogeologic mapping traced the Felix coal bed of Stone and Lupton (1910) to a level of 3,900 ft near the Powder River (fig. 9). The upper Felix coal bed in section no. 9 (fig. 2), at a level of 4,150 ft, is about 8 mi east of the Powder River;

if the west dip of 25 ft/mi continued, the upper Felix coal bed would project westward to a 3,950 ft level at the Powder River. According to Wegemann and others (1928, p. 14), a bed E (equivalent to the Felix) is exposed at a level of about 4,450 ft along Pumpkin Creek in T. 76 N., R. 76 W. (fig. 9); the bed was reported to pass below the level of Pumpkin Creek in sec. 9 of that township and to reappear 3 mi downstream. Those trends of Felix coal focussed on the area along the Powder River in Tps. 48 through 52 N., R. 77 W. (fig. 9). We investigated that area in the field.

We found the Felix coal bed of Stone and Lupton (1910) to be at least 5 ft thick in T. 52 N., R. 77 W., where it had been burned extensively; a 6-ft-thick Felix coal bed is exposed at locality A at a level of 3,900 ft (fig. 9). We traced that bed south, to a level of 3,800 ft at locality B. The Felix coal bed splits at that point, and lower parts of the Felix pass below the level of the Powder River floodplain; however, an upper Felix coal bed, about 3 ft thick, was traced south to a level of 3,880 ft at locality C, and to a level of 3,980 ft at locality D. The upper Felix coal bed splits near locality D.

An upper Felix coal bed, 4 ft thick, reappeared at a level of 4,020 ft at locality E, about 8 mi south of locality D. We traced the coal bed south to a level of 4,030 ft at locality F, where the bed is split as follows: 2 ft coal/6 ft rock/5 ft coal.

A coal bed 4 ft thick is exposed at a level of 4,440 ft at locality G, along Pumpkin Creek in the northwestern part of the Pumpkin Buttes coal field. We identified that coal bed as an upper Felix. Although we did not trace the upper Felix all the way down Pumpkin Creek to the Powder River, we determined its stratigraphic position to be within 50 ft of Pumpkin Creek levels along that route.

Coal Exploratory Drilling

As an exploration method, coal exploratory drilling is used extensively in Powder River basin coal studies, and USGS drilling programs are conducted in direct support of project work. As a Project 6 activity, a coal exploratory hole was drilled at a site we selected, to demonstrate USGS drilling techniques, to illustrate how coal exploratory drilling supplements coal investigations, and to obtain stratigraphic information and cores of Felix coal for analysis.

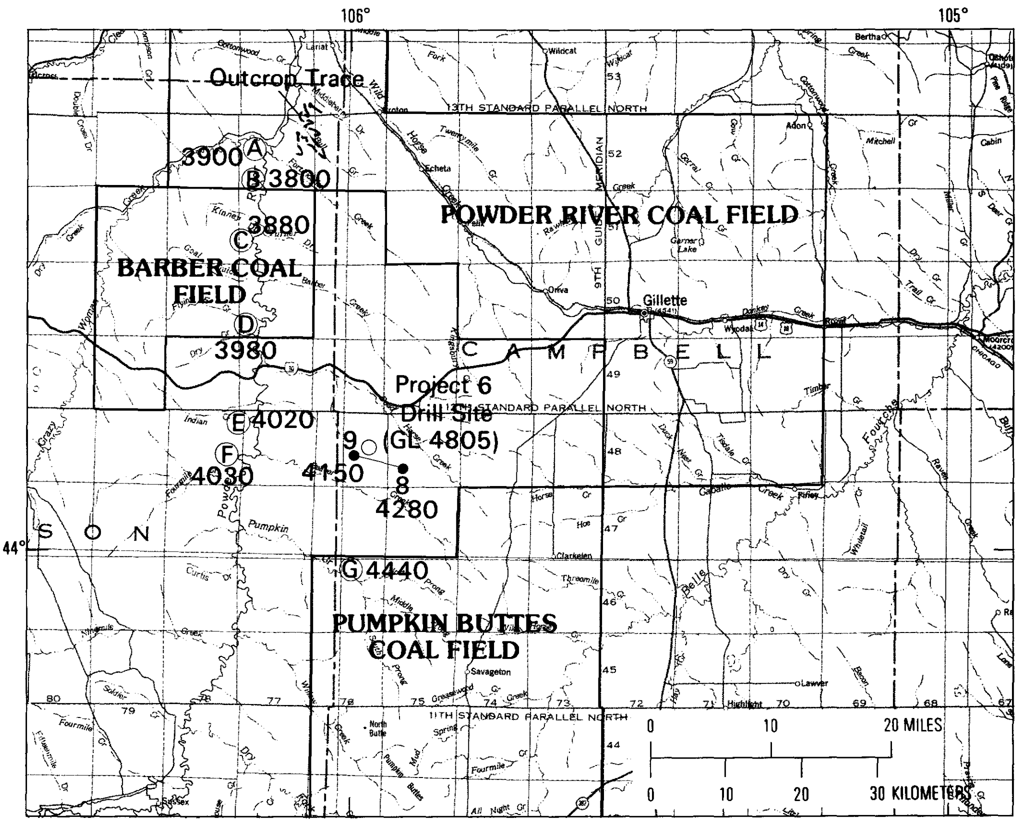

Figure 9. Index map of the Powder River basin, northeastern Wyoming, showing localities that were investigated in the field. Elevations, in feet, at localities A through G are on the base of the Felix coal bed. The Project 6 drill site is shown in T. 48 N., R. 76 W. Localities 8 and 9 are drill holes, for which sections 8 and 9 were prepared. (See fig. 2).

The drill site selected is at a ground level (GL) elevation of 4,805 ft, in T. 48 N., R. 76 W. (fig. 9). Our primary reasons for selecting that site were to verify the position of an upper Felix coal bed and to obtain stratigraphic information on Wasatch coal-bearing rocks above the Felix. We expected to encounter the Felix at a level of about 4,200 ft.

The Twin-hole Drilling Technique

Coal exploratory drilling at the site selected was done using a twin-hole drilling technique (Hobbs, 1979). The technique combines rotary drilling and core drilling; it is used whenever drilling assignments in the Powder River basin call for recovery of coal core. Tertiary rocks of the Powder River basin comprise soft shale, mudstone, coal, and poorly consolidated sandstone; they are easily penetrated by rotary drilling, and drilling rates of 200 ft/hr are not uncommon. In contrast, core drilling is always laborious and time-comsuming.

In the twin-hole drilling technique, a pilot hole is rotary drilled to the total depth desired, and intervals to be cored are determined from geophysical logs of the pilot hole. The drill rig is moved about 30 ft. A twin hole is rotary drilled to the first interval to be cored. The drill rig is tooled for core drilling, and the desired core is recovered. The rig is tooled to resume rotary drilling to the next interval to be cored, and the core drilling process is repeated.

Results

A pilot hole started at a surface elevation of 4,805 ft was drilled to a depth of 715 ft. Mr. Liu served as geologist-on-site to describe the cuttings. His original lithologic log, prepared in Chinese, and a translation prepared by Mr. Mao, are presented in appendixes A-1 and A-2.

The geophysical logs of the pilot hole (fig. 10) indicated that the top of a 9-ft-thick coal bed was reached at a depth of 51 ft, and the top of a 6-ft-thick coal bed was reached at 592 ft; the strip log shows that the base of the 9-ft-thick coal bed (Truman) is at a level of 4,745 ft, and the base of the 6-ft-thick coal bed (upper Felix) is at 4,207 ft.

The drilling rig was moved about 30 ft in preparation for rotary drilling a twin hole to the first core-point level. A core of upper Felix coal was recovered.

COMPUTERIZED AREA RESOURCE ASSESSMENT OF FELIX COAL

Ideally, computerized area resource assessments of Powder River basin coal are made systematically on a bed-by-bed basis; the area-unit for assessment is the 7½-minute (1:24,000 scale) topographic quadrangle, individual coal beds are designated as resource units, and the resources they contain are assessed at a 1:24,000 scale. Established procedures define resource units according to guidelines as follows: (1) closely associated coal beds are combined (as one resource unit) where partings between them are thinner than the coals, and (2) parts of an individual coal bed are assessed separately (as separate resource units) where constituent rock partings are thicker than the coal. The design of a resource unit is intended to emphasize its economic and mining potential.

At a regional (1:100,000) scale, however, individual beds of Powder River basin coal merge and split in all parts of the basin and most of the resources are contained in principal coal beds which merge locally to form thick deposits of combined coal. This characteristic areal pattern of coal occurrences is difficult to assess on a bed-by-bed, resource-unit basis. Whenever computerized area resource assessments of Powder River basin coal have been made at a 1:100,000 scale, it has usually been necessary to incorporate some type of subarea system to account for the many resource units involved. A diagrammatic sketch of the Canyon coal deposit (fig. 11) provides an example of subareas and resource units involved in assessing Canyon coal at a 1:100,000 scale.

As initially designed, the short-term research project for cooperative work with scientists from the People's Republic of China included area resource assessment of the Felix coal bed at a 1:100,000 scale. However, the (previously unknown) areal pattern of Felix coal occurrence in the subsurface (fig. 2) was an initial product of that cooperative work; a subarea system was introduced as soon as the areal pattern of Felix coal occurrence began to develop, and plans for assessing Felix coal were adjusted accordingly.

The Felix Coal Deposit

The areal pattern of Felix coal occurrence (fig. 2) typifies the regional mode of Powder River basin coal occurrence: closely associated coal beds merge to form single beds of combined coal, and the thickest single bed of combined coal forms a central core. In contrast with the pattern of Canyon coal occurrence (fig. 11) however, the Felix pattern involves various combinations of upper, middle, and lower Felix coal beds; the central core of Felix coal *is* the Felix coal bed, and all of the coal beds involved are splits from that central core.

The technical problem of dividing Felix coal for assessment purposes was resolved by (a) defining "deposit" as the resource unit to be assessed, and (b) utilizing the guidelines for grouping or separating coal beds to construct a Felix coal deposit (fig. 3B). The central

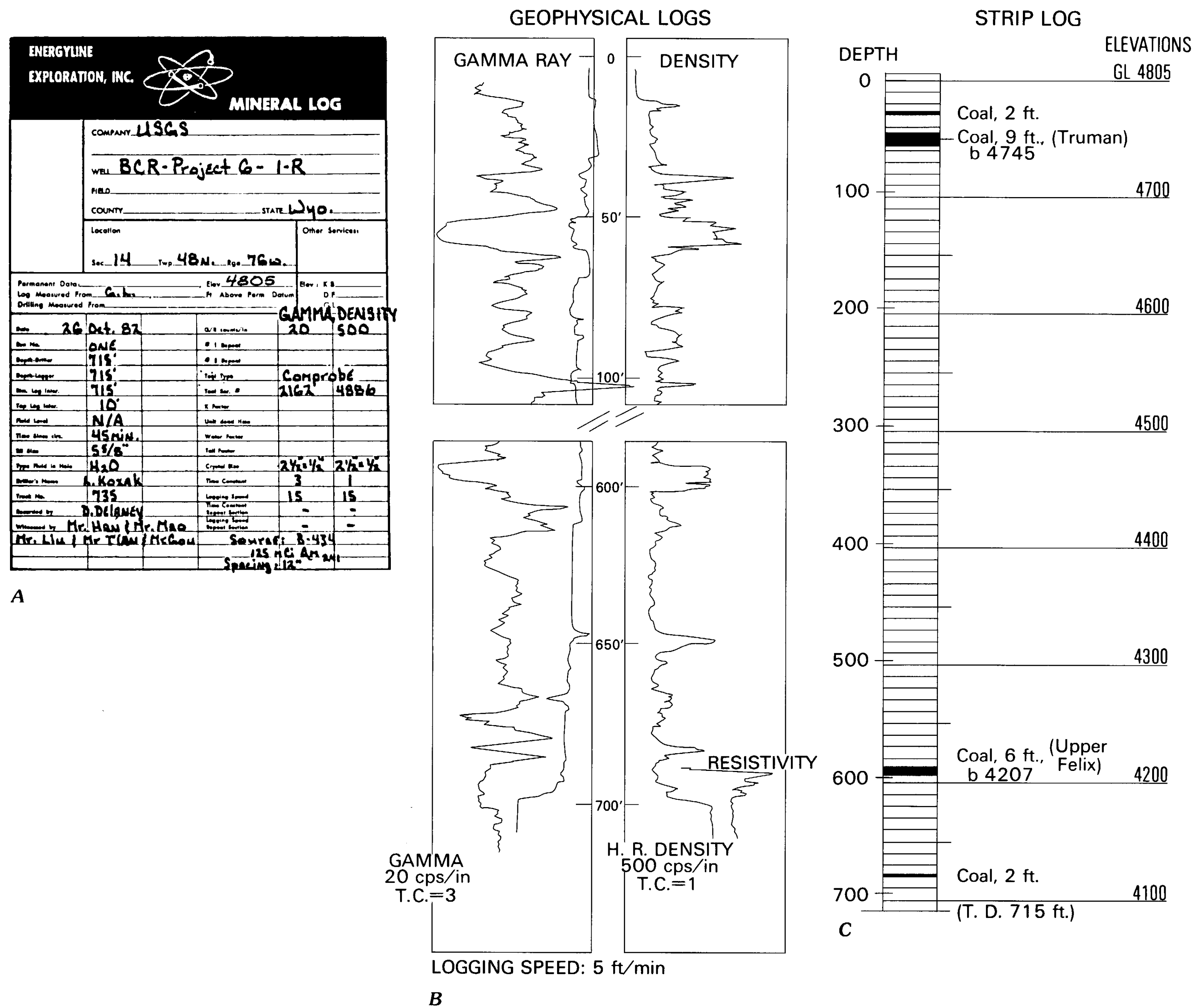

Figure 10. Geophysical logs and strip log of coal beds in the pilot hole at the Project 6 drill site (fig. 9). A, header data; B, geophysical logs; C, strip log.

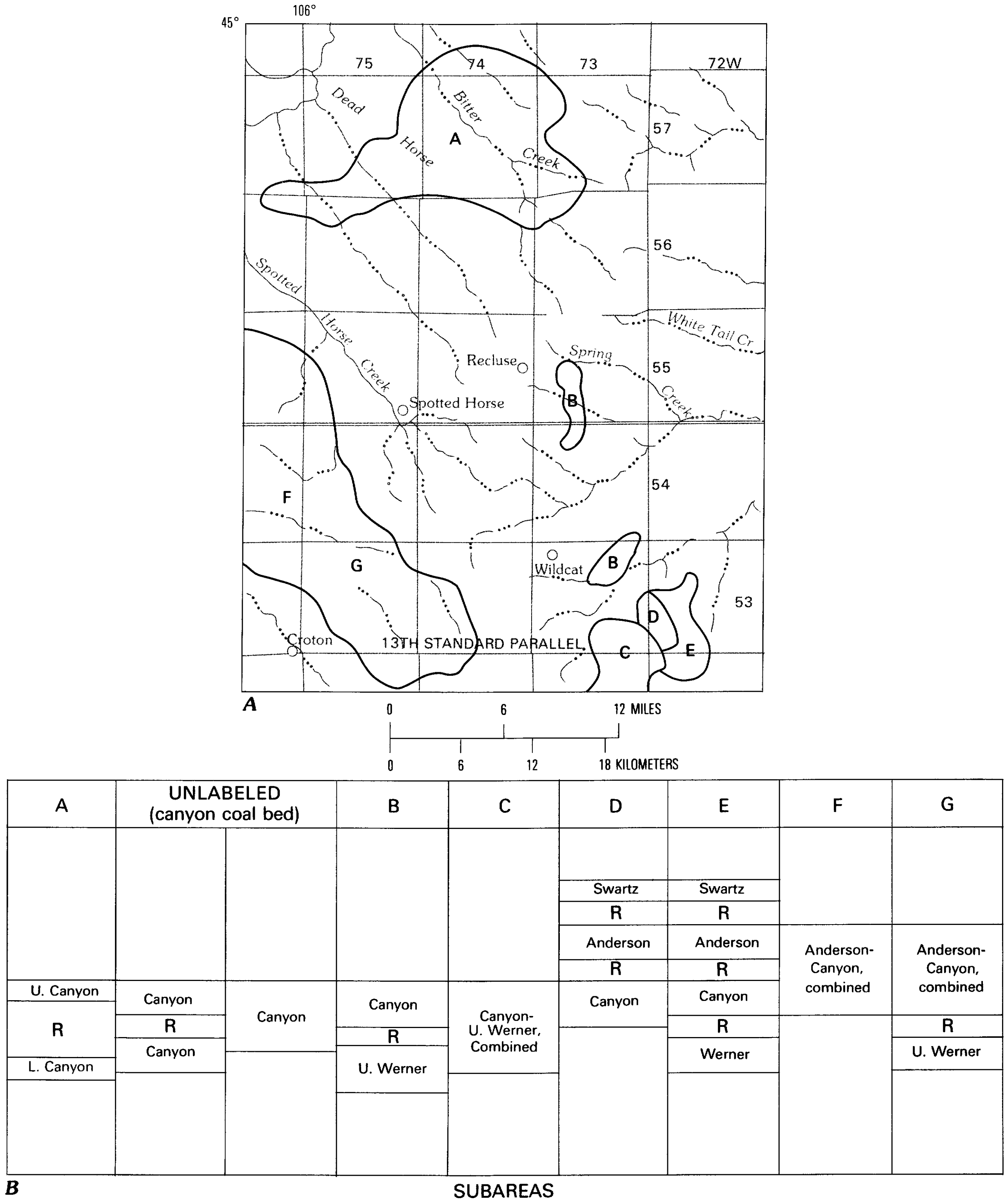

Figure 11. Map (A) and diagram (B) of subareas of the Canyon coal deposit in rocks of late Paleocene age underlying the Felix coal deposit on the eastern flank of the Powder River basin, northeastern Wyoming. Coal beds in subarea E merge to the south to form the central core of the Wyodak coal deposit. (See fig. 13).

body of Felix coal forms the core of the deposit. West of the central body, the thick upper bed of combined coal is included in the deposit, but the lower bed is excluded; and at the west margin of the profile (fig. 3B), the upper bed is included but middle and lower beds are excluded. East of the central body, the thick lower bed of combined coal is included whereas the upper bed is excluded. This process of "streamlining" the resource unit made it transitional from east to west.

As constructed, the Felix coal deposit contained nearly all of the resources of Felix coal, and the geology of the Felix coal bed was not compromised by that process. For area resource assessment at a 1:100,000 scale, the transitional aspect of the Felix coal deposit as a resource unit (fig. 3B) made it possible for computer graphics and resource calculations to be generated collectively for the entire area underlain by Felix coal, rather than separately for each of the subareas involved. Resources contained in the lower, middle, and upper Felix coal beds that were excluded from the Felix coal deposit were to be assessed separately as separate, unique resource units. Such assessments were not included as a Project 6 activity.

Computer Graphics and Resource Calculations

Computer graphics and resource calculations for the Felix coal deposit (fig. 3A) were prepared by the National Coal Resources Data System (NCRDS) of the U.S. Geological Survey. Graphic Analysis of Resources using Numeric Evaluation Techniques (GARNET) software, developed by NCRDS, was used to generate the graphics and resource estimates presented in appendix B and appendix C. (Analytical data from core samples of Felix coal are summarized in appendix D.)

The data base comprised Felix coal data derived from geophysical logs of the 300 drill holes that were distributed throughout the 2,500 mi^2 area underlain by Felix coal. Each drill hole represented a data point. In accordance with procedures for computerized area resource assessment, the component items that were digitized for entry into NCRDS included map locations of the drill holes (data points), a unique identification of each data point, the outcrop trace of the Felix coal bed, a "limit of estimation" line connecting the outcrop trace along the Powder River to the Felix outcrop trace in T. 42 N., R. 73 W., the outline of subarea X, and 200- and 500-ft contours of overburden thickness on the Felix coal deposit. Resources of Felix coal are concentrated in subarea X (fig. 2). Resources contained in that part of the resource unit were calculated separately to emphasize economic and mining potential.

GEOLOGY OF THE FELIX COAL DEPOSIT

As initially planned, the geology of the Felix coal bed was to be reviewed and studied briefly as a short-term Project 6 activity. However, new dimensions were added to that work when the Felix coal deposit was recognized as a regional geologic feature, when the geometry of the deposit indicated that some form of active paleoenvironmental control influenced (Felix) coal deposition in early Eocene time, and when it seemed evident that the mechanics of coal deposition were controlled in a consistent, evolutionary way.

The brief geologic review presented in this report covers the evolution of the Powder River basin, the mechanics of coal deposition, and the evolution of thick coal deposits in upper Paleocene and Eocene rocks on the eastern flank of the basin. A "teeter-board" concept is introduced to describe how interacting subsidence (basin) and uplift (Black Hills) controlled coal deposition.

Evolution of the Powder River Basin

The Powder River basin in northeastern Wyoming is surrounded by the Bighorn uplift, the Casper arch, and the Laramie, Hartville, and Black Hills uplifts (fig. 4). These structural features were formed by Laramide structural movements (subsidence and uplift) during Paleocene and Eocene time. Stratigraphic units deposited in the Powder River basin include the Lance Formation of Late Cretaceous age, the Tullock, Lebo, and Tongue River Members of the Fort Union Formation of Paleocene age, and the Wasatch Formation of Paleocene and Eocene age that contains the Felix coal deposit.

McGrew (1971) concluded that the Bighorn Mountains and the Black Hills were in evidence by the beginning of the Tertiary, following deposition of nonmarine rocks (Lance Formation). According to Curry (1971) however, the first clear evidence of Laramide deformation in the Powder River basin is marked by deposition of nonmarine rocks (Tullock Member) during the early Paleocene; and prominent subsidence along the axis of the basin did not begin until later deposition of mudstone (Lebo Member). Through late Paleocene time, strong subsidence continued along the axis of the basin (fig. 4), and the influx of sandstone was the first evidence of adjacent mountains being uplifted and eroded; the mountains continued to be uplifted and eroded during the Eocene, when they were eroded to their Precambrian core (Curry, 1971).

Shapiro (1971) thought the Black Hills uplift was completed during late Paleocene and early Eocene time. Robinson and others (1964, p. 116) agreed that "The major structural deformation and uplift of the Black Hills began in early Tertiary time—or possibly latest Cretaceous time—and ended before deposition of the Oligocene White River Formation." The igneous plugs and domes in the northern part of the Black Hills that were intruded at a time of uplift before deposition of White River sediments have been cited as supporting evidence of dominantly vertical forces forming the main structural features of the Black Hills (Robinson and others, 1964, p. 116).

Late Paleocene Structural Movements

As described by Olive (1957, p. 13–14) and quoted in a previous section of this report, the coal-bearing rocks of late Paleocene age on the eastern flank of the Powder River basin were uplifted, tilted westward, and truncated by erosion prior to the advent of an Eocene influx of sand which formed a platform for Felix coal deposition. A schematic profile of upper Fort Union and Wasatch coal-bearing rocks from the Gillette area west to the Powder River (fig. 12) illustrates those geologic events. The events were activated by Black Hills uplifts to the east.

The profile of coal-bearing rocks of Tongue River age near Gillette (fig. 13B) shows how closely associated coal beds merge eastward to form the world-famous Wyodak coal bed (a.k.a. Roland, Roland-Smith, Anderson, Anderson-Canyon); the Wyodak is strip-mined extensively along a north-south trend just east of Gillette. Actually, the Wyodak is the central core of a huge Paleocene coal deposit. In the Wildcat area north of Gillette (fig. 13), the Wyodak forms the central core of the Canyon coal deposit (subarea E, fig. 11). The areal pattern of Wyodak coal occurrence is similar to that of Felix coal occurrence, except that eastern parts of the Wyodak were removed by pre-Wasatch erosion and beveling in the Gillette area.

Eocene Structural Movements

Following erosion and beveling of Tongue River

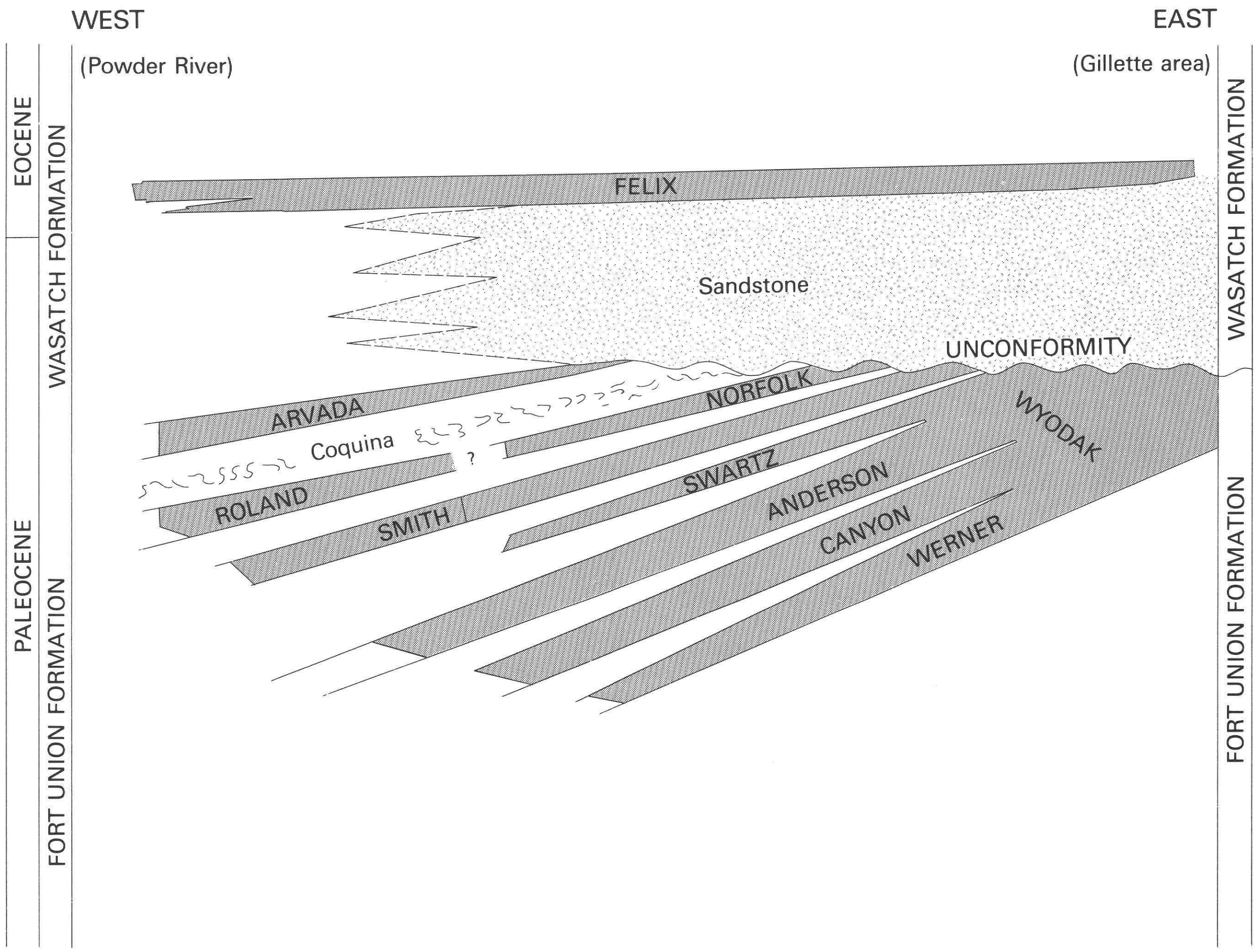

Figure 12. Schematic east-west profile from the Gillette area to the Powder River, illustrating stratigraphic relations of Fort Union and Wasatch coal-bearing rocks. Shaded areas are coals. Coal-bed nomenclature is that of Kent and others (1980). Not to scale.

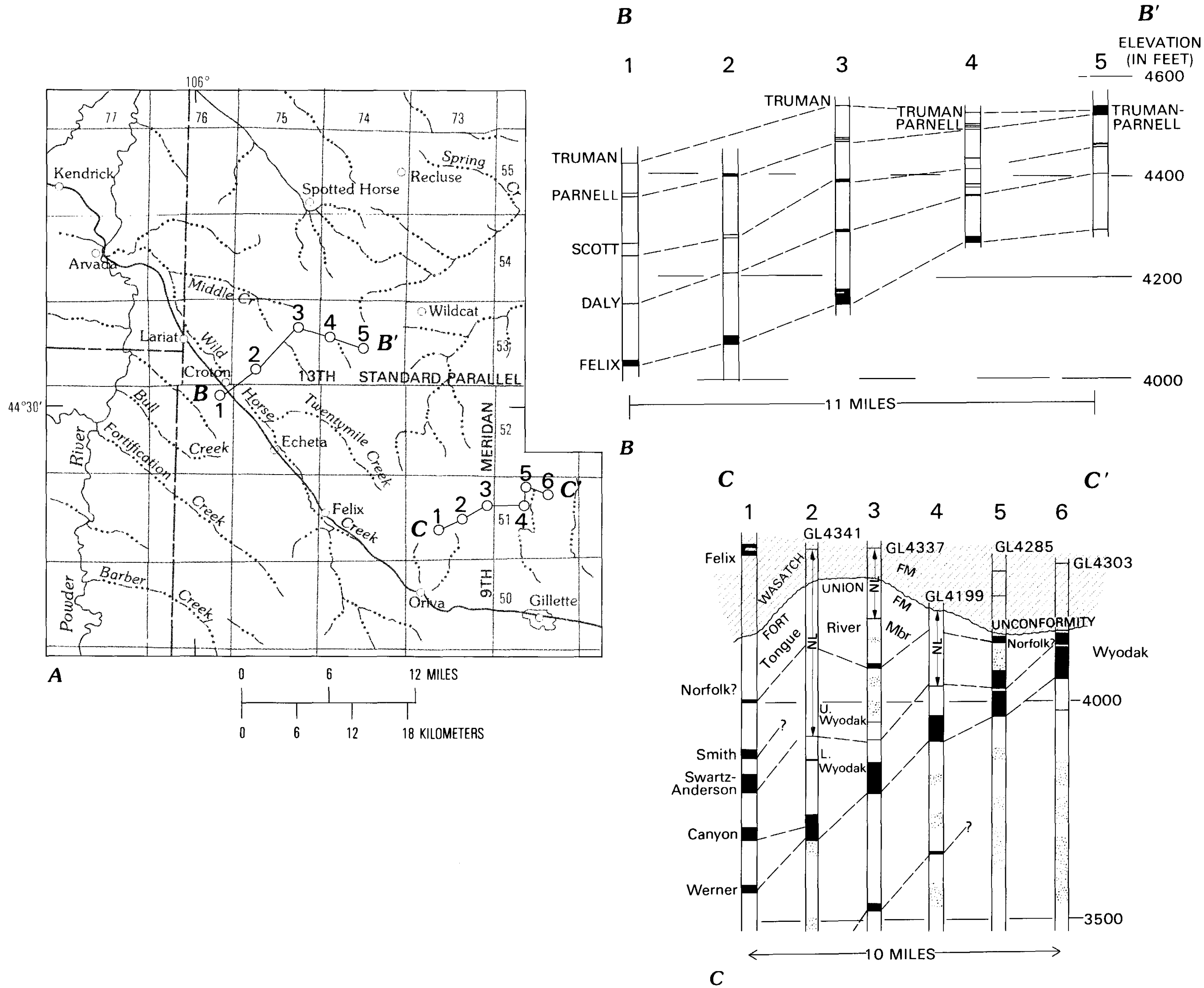

Figure 13. Index map (A) showing locations of representative east-west profiles of Tongue River and Wasatch rocks near Gillette, Wyoming. B, profile of the Wasatch coal sequence and the Truman-Parnell coal deposit; C, profile of Tongue River rocks containing the Wyodak coal deposit. Elevations in feet above sea level; GL, ground level; NL, not logged. Sources of data, (B) Kent and others (1980); (C) Kent and others (1977).

rocks, Black Hills uplifts to the east stimulated an enormous influx of sand that spread westward over the erosion surface (fig. 12). Environments and conditions favoring coal deposition were reestablished, and Felix coal was deposited across that sandstone platform. Then uplifts stimulated another influx of clastics which arrested Felix coal deposition and covered the Felix peat beds.

A representative profile of the Wasatch sequence of coals and clastics (fig. 13C) illustrates the interplay between tectonics, sedimentation, and coal deposition that took place during Eocene time. The sequence is tilted westward, and the degree of tilt decreases both upward and westward through the sequence; the coal beds converge eastward; and Black Hills uplifts continued on past the Eocene time of Truman-Parnell coal deposition. The areal pattern of Truman-Parnell coal occurrence is similar to that of Felix coal occurrence, except that eastern parts of the Truman-Parnell have been removed by erosion in Holocene time.

Mechanics of Thick Coal Deposition

Coal originates from accumulation and partial decomposition of organic materials in a subaqueous environment, controlled and restricted by water levels, water depths, and subsidence. The thickness a peat bed attains is determined by (a) a settling coefficient, (b) the degree of balance maintained between incremental subsidence and incremental peat accumulation, and (c) the duration those processes were operative before some event upset either the depositional environment or the balance.

Accumulation involves settling, and as organic materials settle and decompose, the lower parts of the developing peat bed become more dense and compacted than upper parts. The scope of that peat-forming process has been expressed by a "settling coefficient" of 5:1 (Raistrick and Marshall, 1939, p. 53–54; Stutzer and Noe, 1940, p. 175–178). The coefficient implies, for example, that a cumulative thickness of 50 ft of water-saturated organic materials settled, accumulated, decomposed, and compacted to form a peat bed 10 ft thick; however, the coefficient would be influenced by the nature of the organic materials involved.

The incremental, upward-building process of accumulating organic materials to form peat beds generally takes place below water levels, and such systems may not be more than 10 ft thick at any given time. Thus, depositional environments might accommodate accumulations of peat beds 10 ft thick or so in a static way, but accumulation must be balanced by subsidence for much thicker peat to form. However, peat accumulation could continue indefinitely for as long as that balance is maintained, and the cumulative amount of incremental, balancing subsidence involved should be about the same as the thickness of the peat bed at the time of burial.

A peat bed continues to compact from the time of burial to some present stage of coalification, and the scope of the compactional process can be expressed by a "compaction coefficient" based on water loss; for example, the bed moisture content of peat has been estimated as 75 percent and that of "subbituminous B" coal 25 percent (Teichmuller and Teichmuller, 1978, p. 169), expressing a compaction coefficient of 3:1. The ratio varies inversely with the specific moisture content of the coal involved. Compaction ratios are not appreciably affected by a 75–90 percent range of peat-moisture content, but they vary dramatically with the moisture content of coal; for example, if the moisture content of the peat was 75 percent, and a bituminous coal has a moisture content of 5 percent, the compaction coefficient is 15:1.

A compaction coefficient of 3:1 is a specific expression of the thickness change of a peat bed to a correlative bed of subbituminous coal; the coefficient relates coal thickness back to peat thickness at the time of burial, and the cumulative amount of subsidence involved (or required) during peat accumulation should be about equal to peat thickness attained to that time. The Felix and the Wyodak deposits of subbituminous coal have a moisture content of about 25 percent, and they are as much as 30 and 100 ft thick, respectively. If the moisture content of the peat was 75 percent, the compaction coefficient (3:1) indicates a Felix peat bed was as much as 90 ft thick at the time of burial, and a Wyodak peat bed was as much as 300 ft thick. Cumulative amounts of subsidence involved during Felix and Wyodak coal deposition would be 90 and 300 ft, respectively.

Subsidence and flooding may kill forests and vegetation (thereby activating the peat-forming process), new growth on organic debris may be killed in the same way, and an episode of pronounced subsidence may cause sediments to be deposited over those peat beds. Or uplift of the source area may cause an influx of clastics over a subsiding coal swamp, thereby arresting peat accumulation and burying the peat beds; continuing subsidence would increase depths of burial. A new cycle of peat accumulation may develop on the clastics. In that manner vertical sequences of coal and clastics develop.

The Powder River basin was subsiding before, during, and after thick coal deposition on the eastern flank, and rates of subsidence probably increased progressively westward toward the basin axis where drainage base levels developed; conversely, rates of uplift probably increased eastward toward uplifted (Black Hills) source areas (fig. 2). Swamp development and coal deposition across west-tilted paleoslopes may have been limited westward by flooding and eastward by high ground, but eastern uplift would have caused those systems to shift westward, and western subsidence would have shifted them east. Several eastern and western migrations could be involved during a prolonged period of thick coal deposition.

Although the migratory response of coal deposition to subsidence and uplift is reminiscent of strandline response to transgression and regression, coal is not a clastic and is rarely reworked and redeposited as such; rather, coal is formed in situ from buried peat at some later time. The migration was by environments favorable to peat accumulation, either to maintain or to re-establish optimum conditions.

Evolution of Thick Coal Deposits

Basin subsidence and Black Hills uplifts were active during late Paleocene and Eocene time when thick coal deposits were formed on the eastern flank of the Powder River basin. These Laramide structural movements must have interacted in some way to establish and prolong the optimal environment conditions necessary for thick coal deposition. A "teeter-board" concept is introduced here to explain how those interactions may have worked. The concept is based on a simple assumption: if a western area is subsiding while an eastern area is uplifted, a fulcrum area in between is in dynamic equilibrium. Such fulcrum areas were pivots for basin subsidence and Black Hills uplifts during early Tertiary time.

The pivotal effects of western subsidence (basin) and eastern uplifts (Black Hills) produced linear fulcrum areas in dynamic equilibrium, elongate north-south across the west-tilted paleoslopes that formed the eastern flank of the developing basin. During quiescent periods, when subsidence and uplift were subdued and sediment infill was minimal, the linear fulcrum areas became centers for peat accumulation. Fulcrum areas (where optimal environments and conditions for thick peat accumulation were maintained) were shifted west by eastern uplifts and east by western subsidence. Several such fulcrum-area migrations occurred in response to interactions of subsidence and uplift over a prolonged period. The overall migratory shift was westward, ahead of a succeeding episode of clastic influx that would bury the peat beds.

The Felix and the Wyodak coal deposits are models for the teeter-board/fulcrum area concept. Subarea X of the Felix coal deposit (fig. 2) forms an elongate north-south, central core comprising the thickest single bed of combined Felix coal. Subarea X may have been the loci for linear fulcrum areas where optimal environments and conditions prevailed during the prolonged period of Felix coal deposition in Eocene time. This central core of the Felix coal deposit splits eastward to a thin upper bench and a thick lower bench, and westward to a thick upper bench and a thin lower bench, suggesting that (a) fulcrum areas migrated east and west during the course of coal deposition and (b) the overall migratory shift was westward. Similarly, the central core of the Wyodak coal deposit is the thickest single bed of combined Wyodak coal (fig. 13A); the Wyodak core is thought to represent the loci for elongate north-south, fulcrum areas where optimal environments and conditions prevailed during the prolonged period of Wyodak coal deposition in late Paleocene time. In the Gillette area, eastward splits from the central core were removed by pre-Wasatch erosion.

CONCLUSIONS

This Project 6 work on the geology and resource appraisal of Felix coal deposits on the eastern flank of the Powder River basin in northeastern Wyoming satisfied Project 6 objectives by (a) outlining the geologic setting for Felix coal deposition, (b) examining and using some exploration methods used in the United States to map the areal pattern and extent of Felix coal, (c) utilizing a computerized data base for a 1:100,000 scale area assessment of resources contained in a Felix coal deposit, and (d) developing some new concepts and approaches to coal basin exploration and analysis.

The Powder River basin was tectonically active in early Eocene time when basin subsidence and eastern uplifts (Black Hills) interacted to establish and prolong optimal environments and conditions for Felix coal deposition. The nature of this allocyclic control is illustrated by a "teeter-board" concept based on a simple assumption: if a western area is subsiding while an eastern area is uplifted, a fulcrum area in between is in dynamic equilibrium. The pivotal effects of western subsidence (basin) and eastern uplifts produced linear fulcrum areas elongate north-south across the west-tilted paleoslopes that formed the eastern flank of the developing basin.

At a regional (1:100,000) scale, closely associated beds of Felix coal merge to form single beds of combined coal, and the thickest single bed of combined coal forms the elongate north-south, central core of a Felix coal deposit. The central core represents the loci of fulcrum areas where environments and conditions were optimal for thick peat to accumulate. Such linear fulcrum areas were shifted west by eastern uplifts and east by basin subsidence, during the prolonged period of Felix coal deposition. Thus, the Felix coal deposit evolved as a product of basin evolution.

The Powder River basin and the Ordos basin of North China are structurally similar, and the Ordos basin also was tectonically active when coal-bearing rocks were deposited along its eastern flank. The teeter-board/fulcrum area concept may guide continuing exploration for Ordos basin coal.

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APPENDIXES A–D

Table A-1. Lithologic log, in Chinese.

1982.10.26. 晴天.多云.

34号:
34口高程,

[illegible]:

0~5 英尺: 浅褐灰色.粉砂质泥岩.粗砂岩.以风化岩块等黄褐色.中见细砂岩岩块,可能为细砂岩层.
5~10": 浅黄灰色泥岩.内部见砂岩岩块.
10~15": 灰色泥岩.
15~20": 浅黄色细粒砂岩~细粒砂质泥岩.
20~25": 浅灰色砂质泥岩.
25~30": 灰色砂质泥岩.
30~35": 灰色泥岩.
35~40": 煤层.底部可能为黄灰色泥岩薄层.
40~45": 浅灰色砂质泥岩.
45~50": 灰~深灰色泥岩.
50~55": 灰~深灰色泥岩.炭质泥岩.煤层.
55~60": 煤层.
60~65": 浅白灰色细砂岩.
65~70": 浅灰色砂质泥岩.
70~75": 浅灰色粗粒砂岩.
75~80": 灰色砂质泥岩.
80~85": 灰色砂质泥岩.
85~90": 浅灰色粗粒砂岩.
90~95": 浅黄灰色砂质泥岩.
95~100": 浅黄灰色砂质泥岩.深灰色含[illegible]泥岩.
100~105": 黑灰色炭质页岩.薄煤.
105~110": 灰色泥岩.
110~115": 灰色泥岩.顶部为细砂岩.

115~120 英尺: 浅白灰色细砂岩.
120~125": 仝上.
125~130": 仝上.
130~135": 仝上.
135~140": 浅白灰色粗粒砂岩~细砂岩.
140~145": 浅灰色粗粒砂岩.
145~150": 灰色细~中粒砂岩,含云母片.
150~155": 灰色泥岩.炭质泥岩.夹薄煤线.
155~160": 灰色含砂质泥岩.
160~165": 灰色泥岩.炭质泥岩.
165~170": 灰~深灰色炭质泥岩.上部为灰色砂质泥岩.
170~175": 浅黄灰色砂质泥岩.
175~180": 灰色泥岩~砂质泥岩.
180~185": 灰色泥岩.深灰色含炭泥岩.
185~190": 浅灰色砂质泥岩.
190~195": 浅灰黄色砂质泥岩.粗砂岩.
195~200": 灰色泥岩.
200~205": 灰色泥岩.夹砂质泥岩薄层.
205~210": 浅白灰色砂岩.细粒.
210~215": 仝上.
215~220": 仝上.
220~225": 仝上.
225~230": 灰~浅灰色砂质泥岩.夹[illegible]粗砂岩~细砂岩薄层.
230~235": 浅灰色细砂岩.底部含中粒砂岩.
235~240": 灰色砂质泥岩~泥岩.
240~245": 灰色泥岩.
245~250": 灰色泥岩~浅深灰色泥岩.
250~255": 浅黄灰色细砂岩.

[illegible]~260 英尺: [illegible]色细砂岩.[illegible].
260~265": 仝上.
265~270": 仝上.
270~275": 浅灰色细砂岩.上部[illegible]泥岩.
275~280": 浅白灰色~浅灰色细砂岩.[illegible]中粒砂岩.
280~285": 仝上.
285~290": 灰色泥岩.深灰色含炭泥岩.[illegible].
290~295": 浅灰色泥岩~砂质泥岩.
295~300": 浅白灰色细砂岩.
300~305": 仝上.
305~310": 深灰色泥岩.炭质泥岩.夹薄煤线.
310~315": 浅灰色泥岩.上部为浅灰色砂岩.细粒.
315~320": 浅白灰色细砂岩.
320~325": 仝上.
325~330": 仝上.
330~335": 浅灰色砂质泥岩.
335~340": 浅灰色砂质泥岩.深灰色泥岩.
340~345": 浅黄灰色泥岩.粗砂岩([illegible]).
345~350": 浅黄灰色粗砂岩.砂质泥岩.
350~355": 浅黄灰色砂质泥岩夹粗砂岩薄层.
355~360": 浅白灰色细砂岩.
360~365": 仝上.
365~370": 仝上.中夹砂质泥岩薄层.
370~375": [illegible]砂岩(如355段为仝一层).
375~380": 仝上.
380~385": 仝上.
385~390": 仝上.
390~395": [illegible].

395~400 英尺: 浅灰色砂质泥岩.
400~405": 灰色泥岩.
405~410": 灰色泥岩~砂质泥岩.
410~415": 仝上.
415~420": 灰色泥岩.
420~425": 浅灰色砂质泥岩.
425~430": 仝上.
430~435": 浅灰~深灰色泥岩.
435~440": 仝上.
440~445": 灰色泥岩夹砂质泥岩.
445~450": 灰色泥岩.
450~455": 仝上.
455~460": 仝上.
460~465": 灰色砂质泥岩.泥岩.
465~470": 仝上.
470~475": 灰色泥岩.
475~480": 仝上.
480~485": 灰色砂质泥岩与泥岩.
485~490": 灰色泥岩.
490~495": 灰色泥岩.
495~500": 仝上.
500~505": 仝上.
505~510": 仝上.
510~515": 灰色砂质泥岩夹泥岩层.
515~520": 灰色泥岩.
520~525": 灰色泥岩.深灰色含炭泥岩薄层.
525~530": 灰色泥岩夹砂质泥岩薄层.
530~535": 灰色泥岩.
535~540": 仝上.

Table A-1. Lithologic log, in Chinese—Continued.

540～545呎：灰～浅灰色泥岩、砂质泥岩。
545～550〃：浅棕灰色泥岩，中含半炭化植物碎片。
550～555〃：仝上。
555～560〃：灰色泥岩。
560～565〃：灰色砂质泥岩或泥岩互层。
565～570〃：灰～浅灰色泥岩
570～575〃：灰色砂质泥岩或泥岩互层。
575～580〃：灰色泥岩。
580～585〃：仝上。
585～590〃：灰色泥岩。
590～595〃：灰色泥岩。
595～600〃：深灰色炭质泥岩、炭化层(小部)
600～605〃：炭化层。
605～610〃：炭化层，下部为灰色泥岩层(含黄色泥岩结块)。
610～615〃：灰色泥岩(含少量炭化植物碎屑)。
615～620〃：灰色泥岩。
620～625〃：灰色砂质泥岩、泥岩层。
625～630〃：灰色砂质泥岩。
630～635〃：浅褐灰色砂质泥岩
635～640〃：浅棕灰色泥岩。
640～645〃：浅棕灰色泥岩，下部为浅灰～黑灰色泥岩、炭质泥岩、煤屑碎片。
645～650〃：灰色泥岩、黑灰色炭质泥岩或薄炭化层。
650～655〃：灰色泥岩。
655～660〃：仝上。(岩粉过细，不清)。
660～665〃：浅棕灰色砂质泥岩、泥岩。
665～670〃：仝上
670～675〃：灰色泥岩、炭质泥岩、煤粒。
675～680〃：灰色泥岩。
680～685呎：深灰色～浅棕灰色砂质泥岩。
685～690〃：浅棕灰色砂质泥岩－泥岩、灰色泥岩。
690～695〃：灰色泥岩含黑炭质泥岩(?)。
695～700〃：灰色泥岩、下部为浅棕灰色砂质泥岩～细粒砂岩。
700～705〃：浅棕灰色细粒砂岩、砂质泥岩。
705～710〃：浅棕灰色泥岩、砂质泥岩与灰色～浅灰色泥岩互层。

Table A-2. Lithologic log of cuttings from the pilot hole drilled for Project 6 coal exploratory drilling.
[Originally prepared by Mr. Liu (see table A-1). Translation by Mr. Mao, geologist, People's Republic of China.]

Project: Research Project with People's Republic of China

Hole No.: BCR 82-1 Geologist: Mr. Liu

Type log.: Cuttings Log Elev.: 4805 ft Total depth: 715 ft

Location: SE 1/4 SE 1/4 Sec.: 14 T.: 48 N. R.: 76 W.

Nearest town: Gillette County: Campbell State: Wyo. Quad.: Morgan Draw

Drilled by: U.S. Geological Survey

Drillers (s): Larry Kozak, Rob Mathews, Mike Dahlin

Drill: GD-17W Date start: 10/26/82 Complete: 10/26/82

Non-core intervals and size hole: 0-715 ft; 5 1/8 inch

Cored intervals and size: N/A

Remarks: Spud and set surface casing 10/25/82

Log

From (ft)	To (ft)	Description
0	5	Light-brownish sandy shale; siltstone; weathering color yellowish brown
5	10	Light-greenish-gray shale with sandy shale parting
10	15	Gray shale
15	20	Light-brown shaly siltstone or silty shale
20	25	Dark-gray silty shale
25	30	Gray sandy shale
30	35	Gray shale
35	40	Coaly shale and coal with carbonaceous shale on top and bottom of interval
40	45	Light-gray sandy shale
45	50	Gray to dark-gray shale
50	55	Gray to dark-gray shale, carbonaceous shale, and coal
55	60	Coal
60	65	Grayish-white fine-grained sandstone
65	70	Light-gray sandy shale
70	75	Light-gray coarse siltstone
75	85	Gray sandy shale
85	90	Dark-gray coarse siltstone
90	95	Light-greenish-gray sandy shale
95	100	Light-greenish-gray sandy shale and dark-gray carbonaceous shale
100	105	Carbonaceous shale and coal
105	110	Gray shale
110	115	Gray shale; upper part of interval fine-grained sandstone
115	135	Light-whitish-gray very fine grained sandstone
135	145	Light-whitish-gray coarse siltstone to fine-grained sandstone
145	150	Gray fine- to medium-grained sandstone; mica fragments
150	155	Gray shale, carbonaceous shale, and very thin coal
155	160	Gray sandy shale
160	165	Gray shale and carbonaceous shale
165	170	Gray to dark-gray carbonaceous shale with greenish-gray sandy shale in upper part of interval
170	175	Light-greenish-gray sandy shale
175	180	Gray shale to sandy shale
180	185	Gray shale and dark-gray carbonaceous shale
185	190	Light-gray sandy shale
190	195	Light-grayish-green sandy shale and siltstone
195	200	Gray shale
200	205	Gray shale with some sandy shale
205	225	Light-whitish-gray fine-grained sandstone
225	230	Light-gray sandy shale interbedded with calcium siltstone to fine-grained sandstone
230	235	Light-gray fine-grained sandstone; lower part medium-grained sandstone
235	240	Gray-sandy shale to gray shale
240	245	Gray shale
245	250	Gray shale, darker than above
250	255	Light-greenish-gray fine-grained sandstone
255	270	Light-gray fine-grained sandstone; interbedded thin shale
270	275	Light-gray fine-grained sandstone; upper part thin shale
275	285	Light-whitish-gray to light-gray fine-grained sandstone, some medium-grained quartzite with sand
285	290	Gray shale; dark-gray carbonaceous shale; upper part thin shale
290	295	Light-gray shale to sandy shale
295	305	Light-whitish-gray fine-grained sandstone
305	310	Dark-gray shale, carbonaceous shale, and thin coal
310	315	Light-gray shale with light-whitish-gray fine-grained sandstone in upper part
315	330	Light-whitish-gray fine-grained sandstone
330	335	Light-gray sandy shale
335	340	Light-gray sandy shale and light-greenish-gray shale
340	345	Light-greenish-gray shale and siltstone (predominant)
345	350	Light-greenish-gray siltstone and sandy shale
350	355	Light-greenish-gray sandy shale; interbedded with thin siltstone
355	365	Light-whitish-gray fine-grained sandstone
365	370	Light-whitish-gray fine-grained sandstone; interbedded with thin sandy shale
370	390	Light-whitish-gray fine-grained sandstone
390	395	Gray sandy shale (drillers start H_2O injection)
395	400	Light-gray sandy shale (poor sample)
400	405	Gray shale
405	415	Gray shale to sandy shale
415	420	Gray shale
420	430	Light-gray sandy shale
430	440	Light-gray to dark-gray shale
440	445	Gray shale; interbedded with sandy shale
445	460	Gray shale
460	470	Gray sandy shale and shale
470	480	Gray shale
480	485	Gray sandy shale and shale
485	510	Gray shale
510	515	Gray sandy shale
515	520	Gray shale
520	525	Dark-gray shale; contains thin carbonaceous shale
525	530	Gray shale with thin-bedded sandy shale
530	540	Gray shale
540	545	Light-gray and gray shale; sandy shale
545	555	Light-greenish-gray shale with carbonaceous streaks
555	560	Gray shale
560	565	Gray sandy shale; shale
565	570	Gray and dark-gray shale
570	575	Gray sandy shale with interbedded thin shale
575	595	Gray shale
595	600	Gray shale, carbonaceous shale, and coal (Felix)
600	605	Coal
605	610	Coal; bottom of interval gray shale
610	615	Gray shale; coal cuttings present
615	620	Gray shale
620	625	Gray sandy shale and shale
625	630	Gray sandy shale
630	635	Light-brown sandy shale
635	640	Light-greenish-gray shale
640	645	Light-greenish-gray shale; lower part of interval dark-gray-shale and carbonaceous shale with coaly streaks
645	650	Gray shale; dark-gray carbonaceous shale with coaly streaks
650	655	Gray shale
655	660	Gray shale (poor sample)
660	670	Light-greenish-gray sandy shale and shale
670	675	Gray shale; contains thin, coaly-carbonaceous shale
675	680	Gray shale
680	685	Greenish-gray to light-greenish-gray sandy shale
685	690	Light-greenish-gray sandy shale; gray shale
690	695	Gray shale; contains carbonaceous shale
695	700	Gray shale; lower part of interval light-greenish-gray sandy shale to fine siltstone
700	705	Light-greenish-gray fine silstone; sandy shale
705	715	Light-greenish-gray shale, sandy shale, and dark-gray shale

total depth at 715 ft, 2:30 PM, 10/26/82

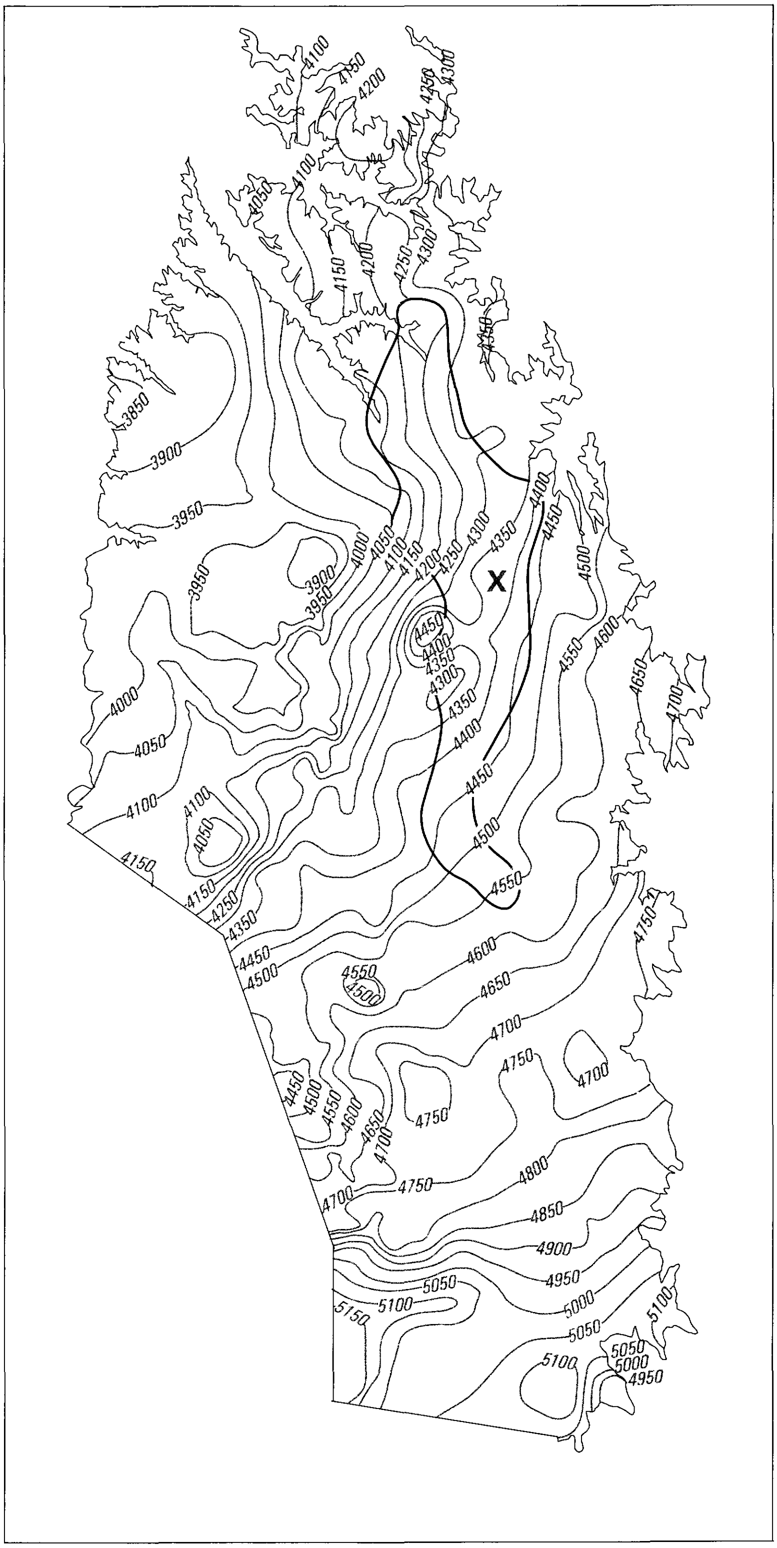


Figure B-1. Computer-generated structure contour map of the top of the Felix coal deposit in the Wasatch Formation. Elevations, in feet, above sea level. Contour interval, 50 ft. The outlined area is subarea X. (See figure 2.)

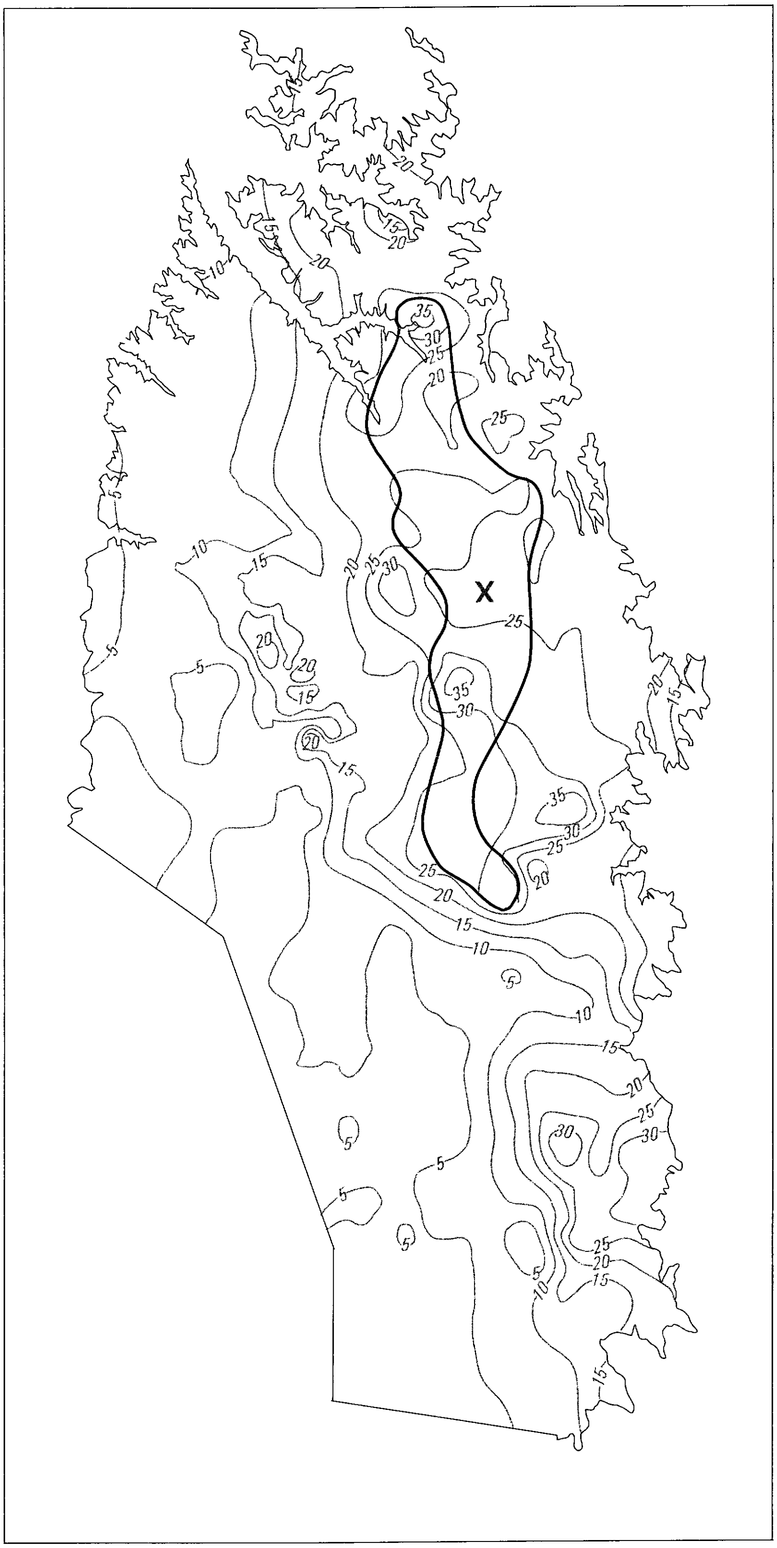


Figure B-2. Computer-generated thickness map of the Felix coal deposit in the Wasatch Formation. Contour interval, 5 ft. The outlined area is subarea X. (See figure 2.)

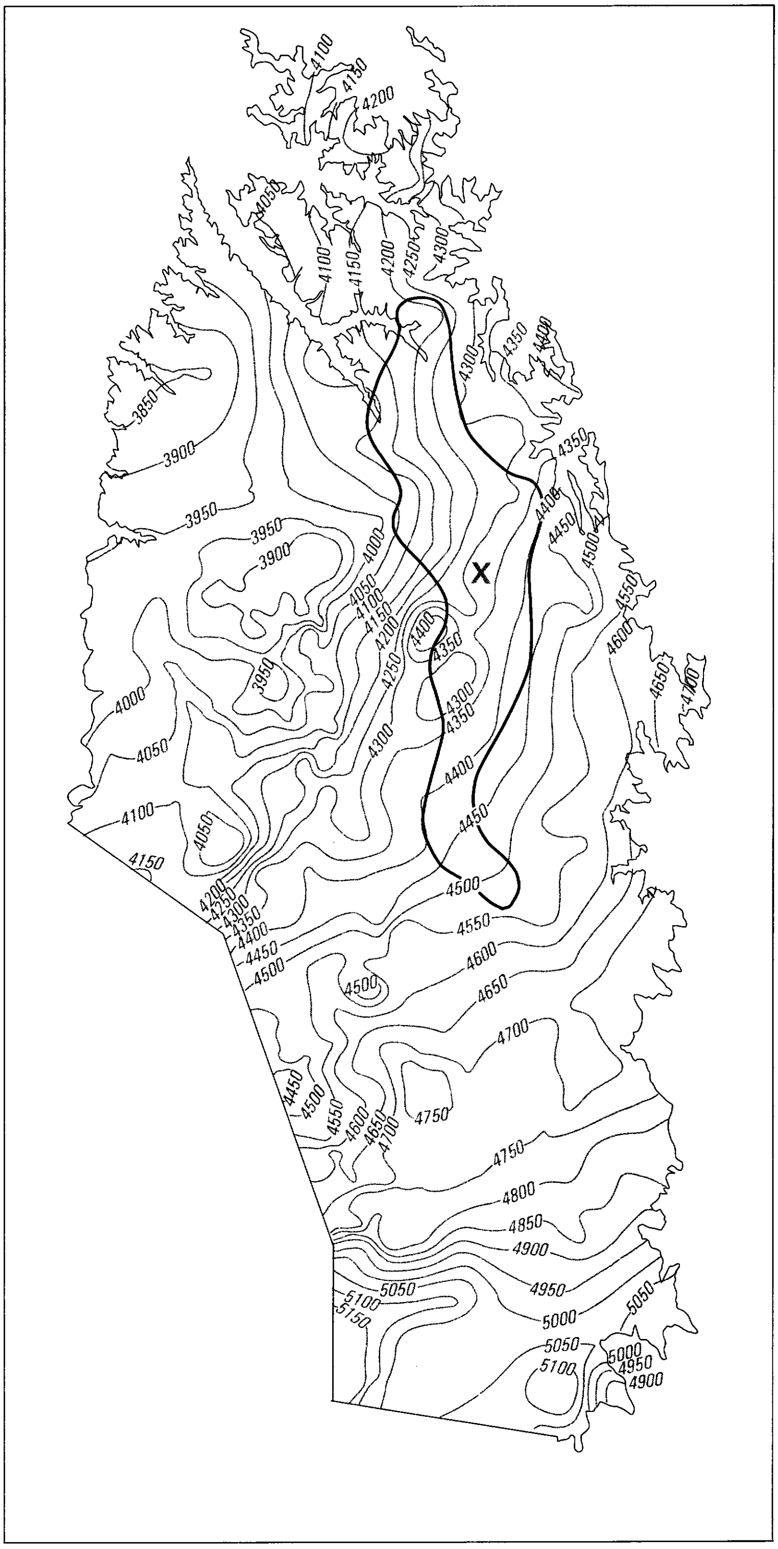
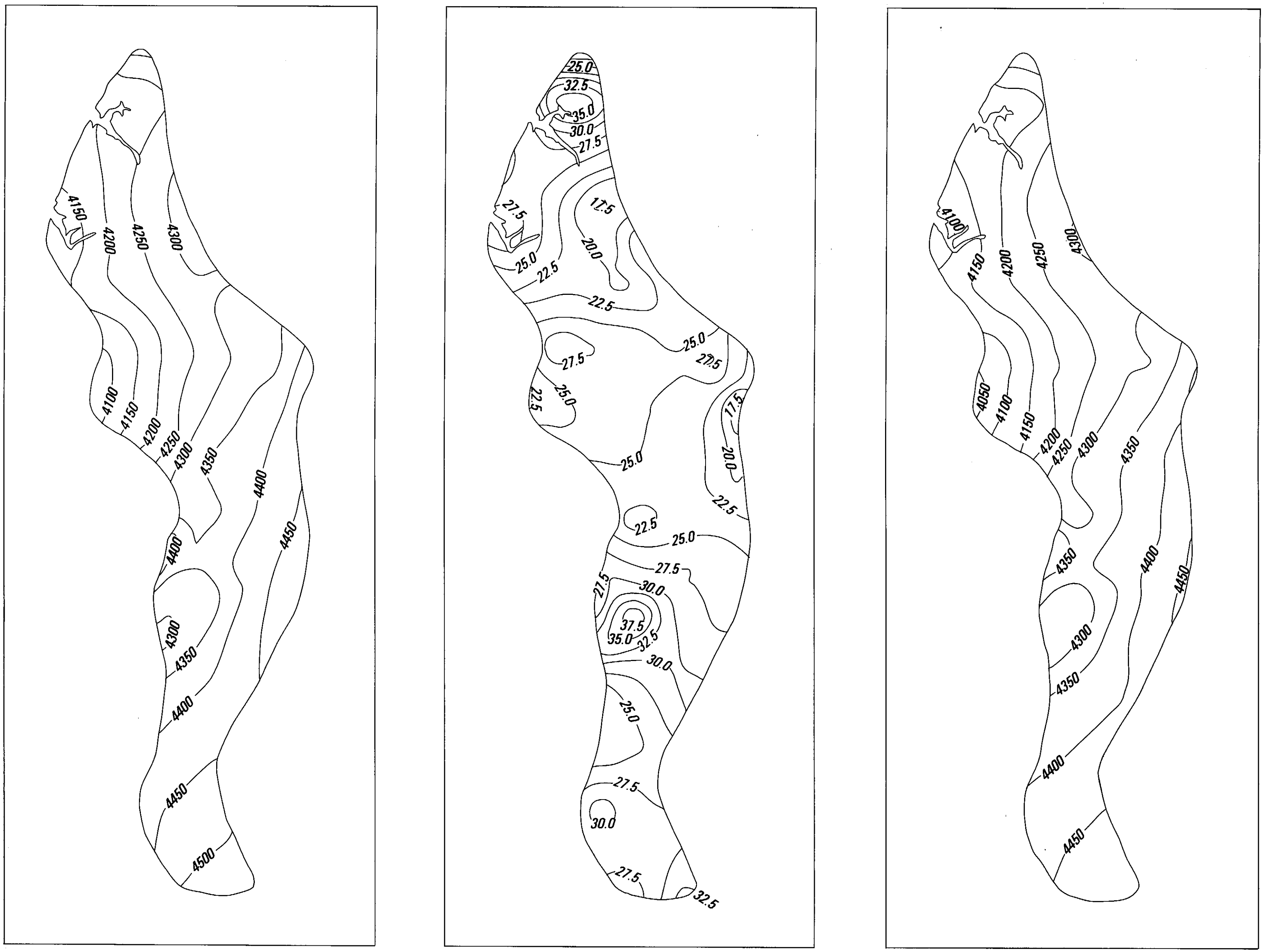


Figure B–3. Computer-generated structure contour map of the base of the Felix coal deposit in the Wasatch Formation. Elevations, in feet, above sea level. Contour interval, 50 ft. The outlined area is subarea X. (See figure 2.)



A B C

Figure B-4. Computer-generated structure contour and thickness maps of Felix coal in subarea X, Felix coal deposit in the Wasatch Formation. (See figure 2.) Elevations, in feet, above sea level; thickness, in feet. *A*, Structure contour map of the top of subarea X; contour interval, 50 ft; *B*, Thickness map of Felix coal in subarea X; contour interval, 2.5 ft; *C*, Structure contour map of the base of subarea X; contour interval, 50 ft.

Table C-1. Estimated coal resources contained in the Felix coal deposit, Wasatch Formation, Powder River Basin, Johnson and Campbell Counties, Wyoming, as of January 1, 1984.

[In millions of short tons (1 short ton, 0.9072 metric tons); 1,770 short tons/acre-foot (1.30 tons/m^3) used in all calculations. Resource terms are defined according to Geological Survey Circular 891 (1983). Thicknesses are in feet (1 foot, 0.305 meter)]

Combined Federal/State/Private

Overburden category	Average thickness	Acres	Tons
0-200	16.3	395,000	11,400
200-500	13.7	653,000	15,800
500-1,000	17.5	99,200	3,070
Totals	15.8	1,150,000	32,200

Table C-2. Estimated coal resources of the Felix coal deposit contained in subarea X, Powder River Basin, Campbell County, Wyoming, as of January 1, 1984.

[In millions of short tons (1 short ton, 0.9072 metric tons); 1,770 short tons/acre-foot (1.30 tons/m^3) used in all calculations. Resource terms are defined according to Geological Survey Circular 891 (1983). Thicknesses are in feet (1 foot, 0.305 meter)]

	Federal Coal			State Coal			Private Coal			Deposit Total		
Overburden category	Average thickness	Acres	Tons	Average thickness	Acres	Tons	Average thickness	Acres	Tons	Average thickness	Acres	Tons
0-200	24.5	21,000	911	26.7	2,010	95	21.7	669	26	24.6	23,700	1,030
200-500	25.7	62,300	2,830	22.3	5,000	197	24.1	1,290	55	25.4	68,600	3,080
500-1,000	28.0	10,600	525	29.6	448	23	25.6	79	4	28.1	11,200	559
Totals	25.7	93,900	4,270	23.9	7,460	316	23.4	2,040	84	25.5	103,000	4,650

Table D-1. Analytical data from core samples of Felix coal in a cored hole drilled for Project 6 coal exploratory drilling in T. 48 N., R. 76 W., Powder River Basin, northeastern Wyoming.

[In percent, except Btu/lb, ash-fusion temperature, Apparent Specific Gravity (ASG), Free Swelling Index (FSI), and Hardgrove Grindability Index (HGI). Forms of analysis: 1, as received; 2, moisture free; 3, moisture and ash free. All analyses by Geochemical Testing, Somerset, Pennsylvania.]

		Proximate analysis					Ultimate analysis					Forms of sulfur			Ash-fusion temperature (°F)					
Hole No.	Form of analysis	Moisture[1]	Ash	Volatile matter	Fixed carbon	Btu/lb[2]	Hydrogen	Carbon	Nitrogen	Oxygen	Sulfur	Sulfate	Sulfide	Organic	Initial deformation	Softening	Fluid	ASG	FSI	HGI
BCR 6-1c	1	21.28	10.25	31.12	37.35	8814	5.91	51.26	0.92	30.60	1.06	0.01	0.15	0.90	2130	2240	2290	1.32	0.0	60
	2	---	13.01	39.53	47.46	11196	4.48	65.12	1.17	14.87	1.35	0.02	0.19	1.14						
	3	---	---	45.44	54.56	12871	5.15	74.86	1.35	17.09	1.55	0.02	0.22	1.31						

1. Equilibrium moisture, 22.86 percent.
2. Calorific value, 9715 Btu/lb, calculated on a moist, mineral-matter-free basis; apparent ASTM rank, subbituminous B.

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