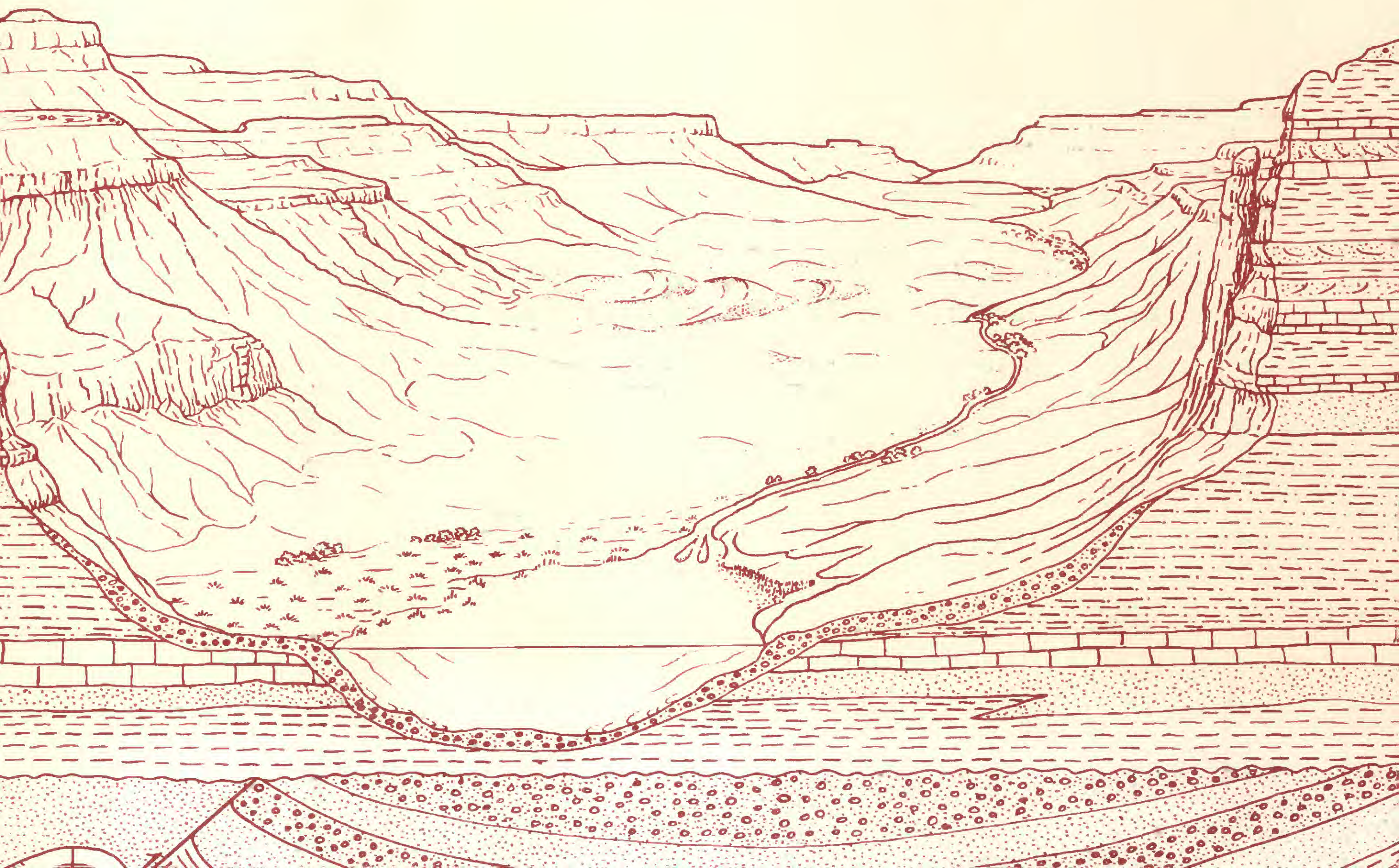
Origin of Thick Lower Tertiary Coal Beds in the Powder River Basin, Wyoming and Montana—Some Paleogeographic Constraints

U.S. GEOLOGICAL SURVEY BULLETIN 1917–Q



AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that may be listed in various U.S. Geological Survey catalogs **(see back inside cover)** but not listed in the most recent annual "Price and Availability List" may no longer be available.

Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices listed below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Earthquakes & Volcanoes, Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Map Distribution
Box 25286, MS 306, Federal Center
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, DC 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U. S. Geological Survey, Map Distribution
Box 25286, Bldg. 810, Federal Center
Denver, CO 80225

Residents of Alaska may order maps from

U.S. Geological Survey, Earth Science Information Center
101 Twelfth Ave., Box 12
Fairbanks, AK 99701

OVER THE COUNTER

Books and Maps

Books and maps of the U.S. Geological Survey are available over the counter at the following U.S. Geological Survey offices, all of which are authorized agents of the Superintendent of Documents.

- **ANCHORAGE, Alaska**–Rm. 101, 4230 University Dr.
- **LAKEWOOD, Colorado**–Federal Center, Bldg. 810
- **MENLO PARK, California**–Bldg. 3, Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**–USGS National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**–Federal Bldg., Rm. 8105, 125 South State St.
- **SPOKANE, Washington**–U.S. Post Office Bldg., Rm. 135, West 904 Riverside Ave.
- **WASHINGTON, D.C.**–Main Interior Bldg., Rm. 2650, 18th and C Sts., NW.

Maps Only

Maps may be purchased over the counter at the following U.S. Geological Survey offices:

- **FAIRBANKS, Alaska**–New Federal Bldg, 101 Twelfth Ave.
- **ROLLA, Missouri**–1400 Independence Rd.
- **STENNIS SPACE CENTER, Mississippi**–Bldg. 3101

Chapter Q

Origin of Thick Lower Tertiary Coal Beds in the Powder River Basin, Wyoming and Montana—Some Paleogeographic Constraints

By DAVID SEELAND

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1917

EVOLUTION OF SEDIMENTARY BASINS—POWDER RIVER BASIN

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1993

For sale by
USGS Map Distribution
Box 25286, Building 810
Denver Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Seeland, David A.
Origin of thick lower Tertiary coal beds in the Powder River Basin, Wyoming and Montana—Some paleogeographic constraints / by David Seeland.
p. cm.—(U.S. Geological Survey bulletin ; 1917–Q)(Evolution of sedimentary basins— Powder River Basin ; ch. Q)
Includes bibliographical references.
Supt. of Docs. no.: I 19.3:B1917–Q
1. Geology, Stratigraphic—Paleocene. 2. Geology, Stratigraphic—Eocene. 3. Coal—Geology—Powder River Basin (Wyo. and Mont.) I. Title. II. Series. III. Series: Evolution of sedimentary basins—Powder River Basin ; ch. Q.
QE75.B9 no. 1917–Q
[QE692]
557.3 s—dc20
[553.2'4'09787] 92–47110
CIP

CONTENTS

FIGURES

Origin of Thick Lower Tertiary Coal Beds in the Powder River Basin, Wyoming and Montana—Some Paleogeographic Constraints

By David Seeland

Abstract

The Powder River Basin contains extensive deposits of thick low-ash coal, primarily in fluvial rocks of late Paleocene (upper part of the Tongue River Member of the Fort Union Formation) and late Paleocene and early Eocene (lower part of the Wasatch Formation) age. The coals are as much as 75 m thick and collectively contain more than 80 percent of Wyoming's coal resources.

Despite similar early Tertiary climate and biomass production, nearby Laramide basins contain very little coal. The abundance of coal in the Powder River Basin, relative to the climatically and tectonically similar Bighorn and Wind River Basins, may be a consequence of a major extrabasinal water source (the Wind River Basin) that brought about conditions favoring peat accumulation and, more importantly, preservation by insuring water-saturated anoxic conditions in major swamps that were parallel with trunk streams in the basin.

The thick low-ash coals of the basin formed from peat deposited in swamps rarely invaded by floodwaters. Two mechanisms of formation have been postulated for swamps that are almost free of floodborne sediment. The first is a topographically high (raised or ombrogenous) swamp fed only by rainwater, and the second is a low-lying swamp in which humic acids flocculate clay at the swamp margins during flooding.

Many recent investigators have favored ombrogenous swamps to explain the thick low-ash coal beds of the basin; however, the lack of thick coal beds in equivalent lower Tertiary rocks of the adjacent Wind River and Bighorn Basins suggests that this model is inadequate. The thick coal beds of the Powder River Basin were developed from peat formed in, or in part transported into, low-lying swamps adjacent to the basin-axis trunk streams after development of basinal drainage in post-early Paleocene time.

Other models for the origin of the thick coal beds relate the coal beds to peat deposition associated with lacustrine environments, either transported allochthonous peat deposited in shallow swampy lakes or peat deposited in the interdeltaic areas on the margins of a basin-scale lake. Both models require centripetal drainage; however, paleocurrent studies of lower Tertiary sandstones in the basin suggest that basin-axis streams exited the basin to the north and northeast. Most of the thick coals of the basin are adjacent to basin-axis streams, and the origin of the thick coals must be related to a paleogeographic reconstruction that incorporates a basin-axis fluvial system.

Subsidence is necessary for both accumulation and preservation of peat, and the thickest coal beds of the basin indicate the position of greatest subsidence. Paleocurrent studies of the Paleocene and lower Eocene rocks indicate that, despite high biomass production during the early Paleocene, major peat accumulation did not occur until after drainage integration in post-early Paleocene time.

In the late Paleocene, peat deposits that became the Wyodak and Big George coal beds in the upper part of the Tongue River Member accumulated in dip-oriented swamps that were parallel with major north-flowing basin-axis trunk streams of the central basin. A paleocurrent study of the Tongue River Member shows that basin-axis streams flowed north-northwest through the geographic center of the basin and joined an east-flowing stream at the Montana-Wyoming State line. Coal beds also formed from peat deposits that formed in dip-oriented swamps along this east-flowing trunk stream.

A paleocurrent study of the upper Paleocene and lower Eocene Wasatch Formation shows that the basin axis had migrated westward to the westernmost part of the basin near the Bighorn uplift by Wasatch time. Coal beds of the Wasatch Formation are also concentrated in the western basin. The thickest of these coal beds, the 75-m-thick Lake DeSmet coal bed, is parallel with and adjacent to the basin-axis trunk stream of early Wasatch Eocene time.

INTRODUCTION

In the Powder River Basin of Wyoming and Montana coal beds are present throughout the sequence of rocks formed from fluvial sediments deposited after the eastward retreat of the Cretaceous Western Interior seaway but are thickest and most abundant in uppermost Paleocene and lower Eocene strata (fig. 1). The coal beds of this sequence can be separated into thin beds, less than 2.1 m thick, and thick beds, more than 2.1 m thick (Ethridge and others, 1981). These two groups of coal beds have different origins (Ethridge and others, 1981).

The thin, high-ash (more than 15 percent) coal beds of the Powder River Basin were formed from peat that accumulated in small swamps that were often invaded by floodwaters ("low-lying swamps" of McCabe, 1984). The origin of the thick, low- to moderate-ash coal beds (averaging 6.3 percent) (Glass, 1980) of the basin is controversial, however, because these coal beds require long-term stability for formation, not a typical attribute of continental fluvial depositional systems. The Wyodak coal bed in the Tongue River is as thick as 36 m. A 7:1 compaction ratio for the Wyodak (White, 1986) indicates that the Wyodak was formed from more than 250 m of peat. Based on a mean peat accumulation rate of 1.72 m/1,000 years for 26 modern swamps (Ayers and Kaiser, 1984), the Wyodak swamp may have persisted for as long as 145,000 years.

Thick coal beds are commonly thought to be autochthonous, formed from plant debris accumulated at or near its growth site, but one of the thick Paleocene coal beds of the basin has been postulated to be allochthonous (Chao and others, 1984), consisting of plant debris transported a substantial distance to the site of accumulation. Autochthonous coals form in low-lying swamps such as the Okefenokee of the southeastern United States (Cohen,

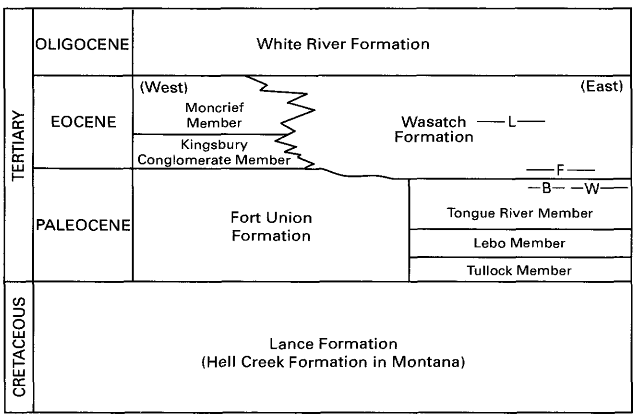


Figure 1. Late Cretaceous through early Tertiary nomenclature for the Powder River Basin, Wyoming and Montana. Selected coal beds are also shown: W, Wyodak; B, Big George; F, Felix; L, Lake DeSmet.

1974) or in raised (ombrogenous) swamps nourished by rainfall such as those of Sarawak and Brunei (Anderson, 1964).

McClurg (1988) proposed a basin-scale lacustrine swamp as the peat-forming environment of the thick coals of the Powder River Basin. The Great Dismal and Okefenokee Swamps of the southeastern United States were identified as recent partial analogs, though they lack the subsidence necessary to form thick peat deposits.

Another theory for the origin of thick coals in the Powder River Basin is that of Kent (1987) and Kent and others (1986, 1988) and involves allocyclic structural control of sedimentation and peat deposition based on a north-south structural fulcrum area of equilibrium between uplift and subsidence, thought to be the most favorable area for the development of thick peat in low-lying swamps. Obernyer (1978, 1980) related the thickness and linear development of the very thick Lake DeSmet coal bed to fault control of subsidence. Ayers and Kaiser (1984) and Ayers (1986) suggested that the thick upper Paleocene coals of the Powder River Basin are of interdeltaic origin and formed from peats deposited in elongate lake-margin swamps developed between deltas that were part of a centripetal drainage system feeding a large lake.

The most common model suggested recently for the origin of the thick low-ash coals of the Powder River Basin is that of raised ground-water-fed or raised rain-fed (ombrogenous) swamps. Recent examples of ombrogenous raised swamps were described by Gore (1963). Raised swamps lie topographically above sediment-laden floodwaters, and the resultant peat is thus a possible precursor of a low-ash coal. The raised ground-water-fed swamp model was first proposed for the thick coals of the Powder River Basin by Jackson (1979; see also Ethridge and others, 1981). Jackson (1979) and Ethridge and others (1981) proposed that ground-water discharge into the swamps facilitated development of coal. The ground water was thought to be nutrient rich, as compared to rainwater, and as such supported a diverse flora for which Ethridge and others (1981) found paleobotanic and petrographic evidence. The flora of rain-fed raised swamps becomes stunted and of reduced diversity as the substrate evolves from mineral rich to mineral poor. Ethridge and others (1981) showed that the ground-water table was substantially below the ground surface; thus capillary action was required to saturate the swamp in order to prevent oxidation and peat destruction. McCabe (1984) pointed out, however, that Romanov (1968) showed that capillary action in peat only allows 30–40 cm movement of water upward from the ground-water table; abundant rainfall would therefore be necessary for the development of floodproof raised swamps.

The raised-swamp ground-water-fed model, proposed by Jackson (1979), as illustrated in Ethridge and others (1981), shows thick peat (the Lake DeSmet coal bed?)

accumulating adjacent to basin-margin alluvial fans and west of a basin-axis trunk stream forming synchronously with thick peat (the Wyodak coal bed?) accumulating east of a basin-axis trunk stream. Ethridge and others (p. 196) were the first to point out that the thick coals are "in a belt or belts peripheral to the major north-south trunk streams" but did not recognize that changes in the position of the basin axis and its associated trunk stream occurred in latest Paleocene time.

Flores (1981, p. 188, 189) mentioned "dome-shaped peat deposits" and "topographically high" swamp floors to avoid "massive inundations" by sediment-laden floodwaters. He postulated that swamp water originates from capillary ground water or by perching of the water table. Perching implies a rainfed swamp, but Flores (1981) did not state this. Warwick (1985), Pocknall (1986), and Pocknall and Flores (1987) proposed a similar raised-swamp model for the lower Eocene Felix coal bed but suggested that the swamps were fed by rainfall, better fitting an upward vegetative progression from woody to herbaceous.

Satchell and Davies (1984) did not support the raised-swamp hypothesis for one of the economically important thick coals of the Powder River Basin. They interpreted their pollen-analysis study of the 36-m-thick Wyodak coal near Gillette as showing that a *Glyptostrobus* swamp forest grew in almost permanent standing water. Clearing by periodic fires allowed *Sphagnum*-heath bogs to form; these bogs produced minor amounts of attrital peat. Inorganic sediments were mostly excluded from the low-lying swamp by the forest density, which slowed and diffused water flow. Near Gillette, coal beds as much as 10 m thick are defined by thin carbonaceous shale partings (Satchell and Davies, 1984).

In a reinterpretation of the palynologic data discussed by Satchell and Davies (1984), Satchell (1985, p. 11) suggested that the *Glyptostrobus* forests "formed raised swamps in a warm climate with high, nonseasonal rainfall." Satchell (p. 11) dismissed present-day low-lying taxiodaceous swamp forests as relict and came to the above conclusion because "sedimentology supports a raised-peat model for these thick Powder River Basin coal beds." The raised-swamp model was proposed because thick, clean peats are not accumulating in present-day low-lying swamps (McCabe, 1984). Two other ways, however, were also described for forming low-ash coals within clastic sequences: first, flocculation of clay by acid swamp waters and, second, peat deposition not temporally synchronous with local clastic deposition.

During the late Paleocene an optimum temperature-precipitation combination resulted in a maximum of vegetative biomass production (Nichols and others, 1988). Low rates of decay produced by anoxia in water-saturated conditions are necessary, however, if accumulation of organic material is to outstrip degradation (Schopf, 1973). Peat accumulations at high latitudes emphasize the relative importance of low rates of decay as compared to rates of accumulation.

Oxidation will destroy a peat swamp that is not kept water saturated and then buried soon after its formation. Aggradation of adjacent fluvial systems must keep up with peat formation if thick peats are to be buried soon after formation. Subsidence is necessary to allow aggradation, and as a result unusually thick coals are found in basins characterized by rapid subsidence (Teichmuller and Teichmuller, 1982). The geographic position of the thickest coals in the Powder River Basin may indicate the position of greatest subsidence, most likely the axial part of the basin at the time of deposition of the precursor peats of those coal beds.

The depositional framework of the basin, with its associated major stream axes, paleoslopes, and paleostream directions, allows evaluation of each of the hypotheses for the origin of thick coal outlined above. The origin and regional paleogeographic settings of the thick coals of the Powder River Basin are discussed using four typical thick coals as examples: the Wyodak and Big George coal beds in the upper part of the upper Paleocene Tongue River Member of the Fort Union Formation and the Lake DeSmet and Felix coal beds in the lower Eocene Wasatch Formation.

SELECTED COAL BEDS OF THE TONGUE RIVER MEMBER OF THE FORT UNION FORMATION— BIG GEORGE AND WYODAK COAL BEDS

The Big George and Wyodak coal beds are approximately age equivalent (figs. 1, 3) and are in the uppermost part of the Tongue River Member of the Fort Union Formation in the central Powder River Basin (fig. 2). They are as much as 61 and 31 m thick, respectively. The Wyodak crops out in the Gillette area and has been mined for many years. The Big George is a recently discovered, 100-trillion-kilogram, areally extensive (2,500 km^2), subsurface coal deposit (Pierce and others, 1982). A diagrammatic east-west cross section (fig. 3)(F.W. Pierce, written commun., 1985) shows coals merging and splitting to form the Wyodak and Big George deposits. Prior to the discovery of Big George the basin contained 80 percent of Wyoming's identified coal resources as of 1980 (Glass, 1980). The discovery of the Big George coal bed in 1981 doubled the coal resources of the Powder River Basin.

Models for the origin of either or both the Wyodak and Big George coal deposits have been proposed by Ayers and Kaiser (1984), Chao and others (1984), Ethridge and others (1981), Flores (1986), Jackson (1979), Kent and others (1986), Kent (1987), McClurg (1988), and Warwick and Stanton (1986). Budai and Cummings (1987) modeled

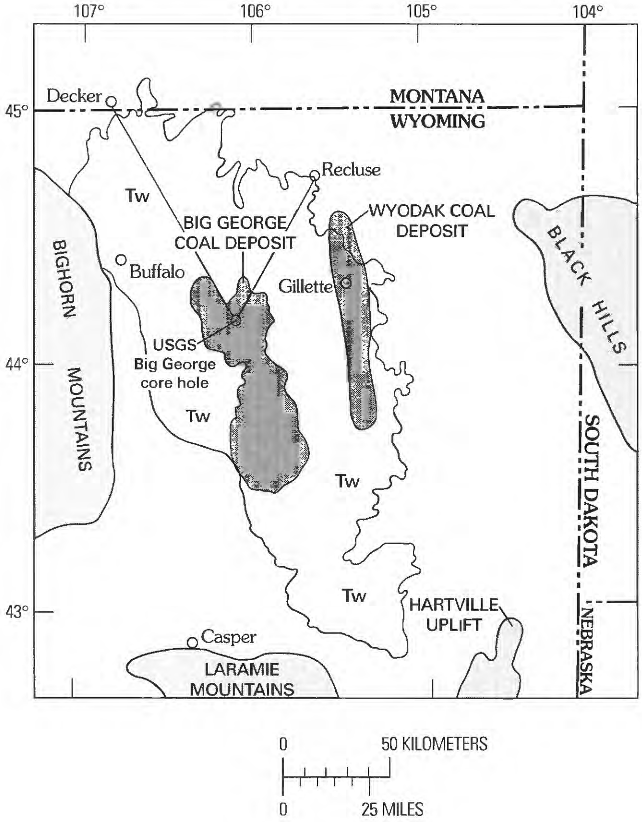


Figure 2. Upper Paleocene coal deposits in the Powder River Basin of Wyoming and Montana. Tw indicates Wasatch Formation. Line of section for figure 3 is shown (Decker to Big George coal deposit to Recluse).

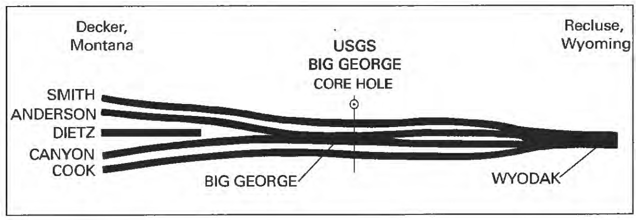


Figure 3. Schematic cross section showing correlation of upper Paleocene coal beds in the upper part of the Tongue River Member of Fort Union Formation from Decker, Montana, to Recluse, Wyoming, through the U.S. Geological Survey Big George core hole in the central part of the Powder River Basin. Line of section shown in figure 2. Modified from F.W. Pierce (U.S. Geological Survey, written commun., 1985).

the origin of the partially equivalent Anderson and Canyon coal beds to the south and east.

Kent and others (1986, 1988) and Kent (1984, 1987) applied the teeterboard hypothesis to the origin of Powder River Basin coal beds including the upper Paleocene Wyodak and Big George coal beds. According to this hypothesis linear north-south fulcrum areas developed on a westwardly inclined paleoslope in the central and eastern parts of the area of Tertiary outcrop during deposition of the Tongue River Member of the Fort Union and the Wasatch Formation as a result of subsidence to the west and uplift to the east. Kent and others (1986) reasoned that in the area just west of the fulcrum conditions were optimal for peat accumulation because subsidence and peat formation were in equilibrium.

A paleogeographic interpretation (fig. 4) based on a paleocurrent study (Seeland and others, 1988) of the upper Paleocene Tongue River Member of the Fort Union Formation demonstrates that stream directions are parallel with rather than perpendicular to the elongation of the Wyodak and Big George coal deposits (fig. 2), as required by Kent's teeterboard model. This parallelism between coal trends and fluvial trends was observed by Kaiser (1974) and Beaumont (1979), who noted that coals formed in swamps of fluvial systems commonly form stream-parallel belts lateral to major fluvial axes.

The paleocurrent results from the outcropping upper Paleocene rocks of the Powder River Basin, together with the distribution patterns of thick coal deposits, allow the construction of an inferred drainage pattern in which linear swamps are parallel with and adjacent to major drainages (Seeland and others, 1988). Figure 4 shows this paleogeographic interpretation together with the maximum coal-bed thickness map of Ayers and Kaiser (1984, fig. 8, p. 71) for the Tongue River Member. The two major areas of maximum coal thickness correspond to the Big George and Wyodak coal deposits (fig. 2) and indicate the major areas of peat accumulation. Interpretation of paleocurrent results and the locations of two of the largest (and partially coeval) coal deposits of the basin, the Big George and Wyodak, strongly suggests that the structural and drainage axes of the basin during late Paleocene time were between these two coal deposits.

The paleoslope in the northern basin was eastward during the late Paleocene, and a major west- to east-flowing trunk stream at about the latitude of the present-day Wyoming-Montana State line is inferred (Seeland and others, 1988). Coal-bed thickness trends, as indicated by a maximum coal thickness map (Ayers and Kaiser, 1984), that are parallel with this inferred trunk stream (fig. 4) suggest that there was a genetic relationship between major streams, swamp development, and, ultimately, coal formation throughout the basin.

The large, long-lived, mid- to late-Paleocene lake postulated by Ayers (1986) is not likely to have existed because results of a basinwide paleocurrent study of the Tongue River Member demonstrate that a basin-axis fluvial system existed during the late Paleocene (Seeland and others, 1988). The paleogeography of the late Paleocene (fig. 4) was substantially different than that of the early Eocene (fig. 5). The late Paleocene basin axis, as inferred from the paleocurrent study, and the major thick coals

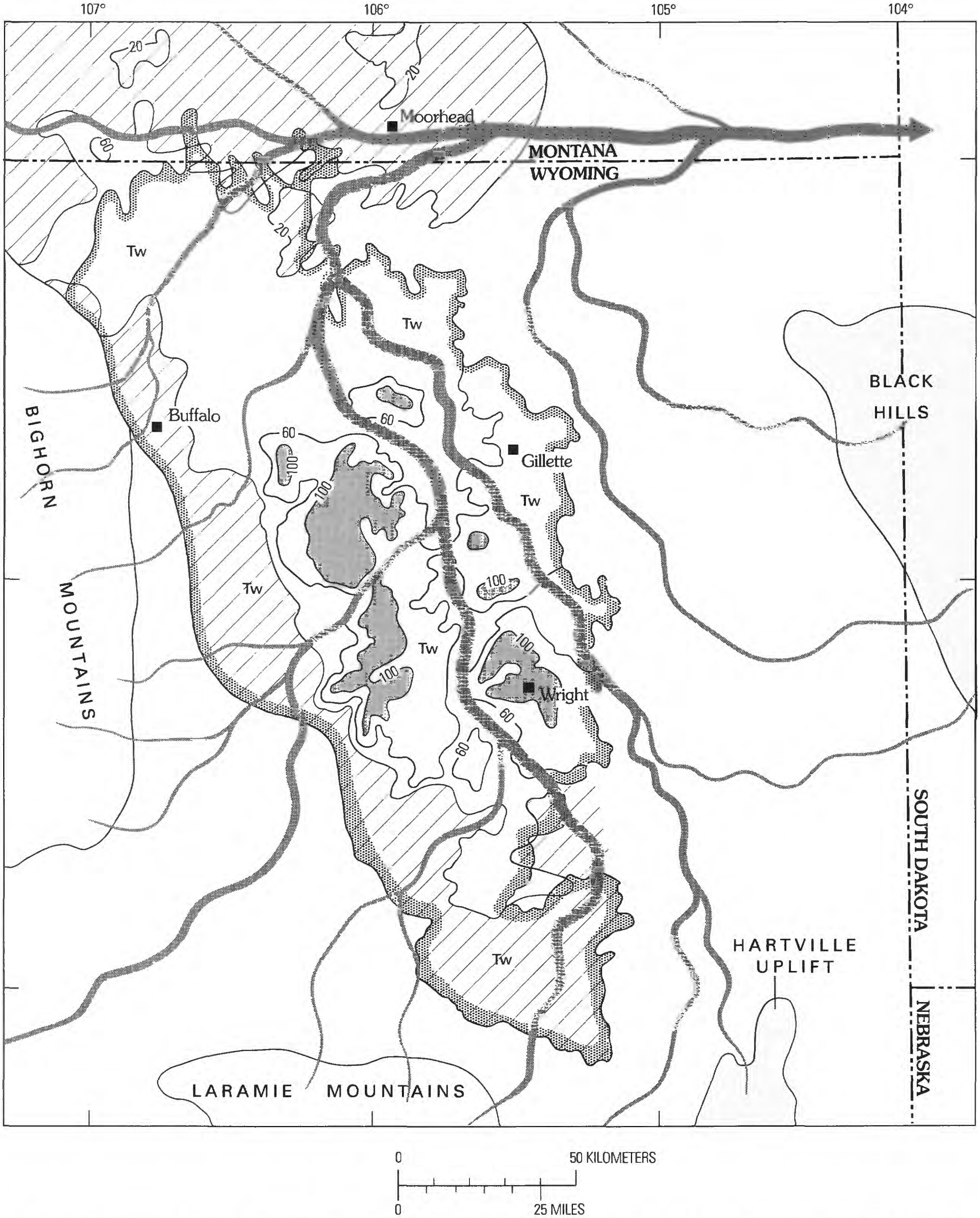


Figure 4. Paleogeography in the Powder River Basin of Wyoming and Montana during late Paleocene time based on paleocurrent measurements of outcropping sandstone beds of the Tongue River Member of the Fort Union Formation. From Seeland (1992); paleocurrent measurements from Seeland and others (1988); distribution of thick coal seams simplified from Ayers and Kaiser (1984). Contours show thickness of single thickest coal bed; contour interval 40 ft. Pattern indicates maximum coal bed thickness is less than 20 ft (5.2 m), and shading indicates maximum coal bed thickness is greater than 100 ft (32 m). Tw indicates Wasatch Formation.

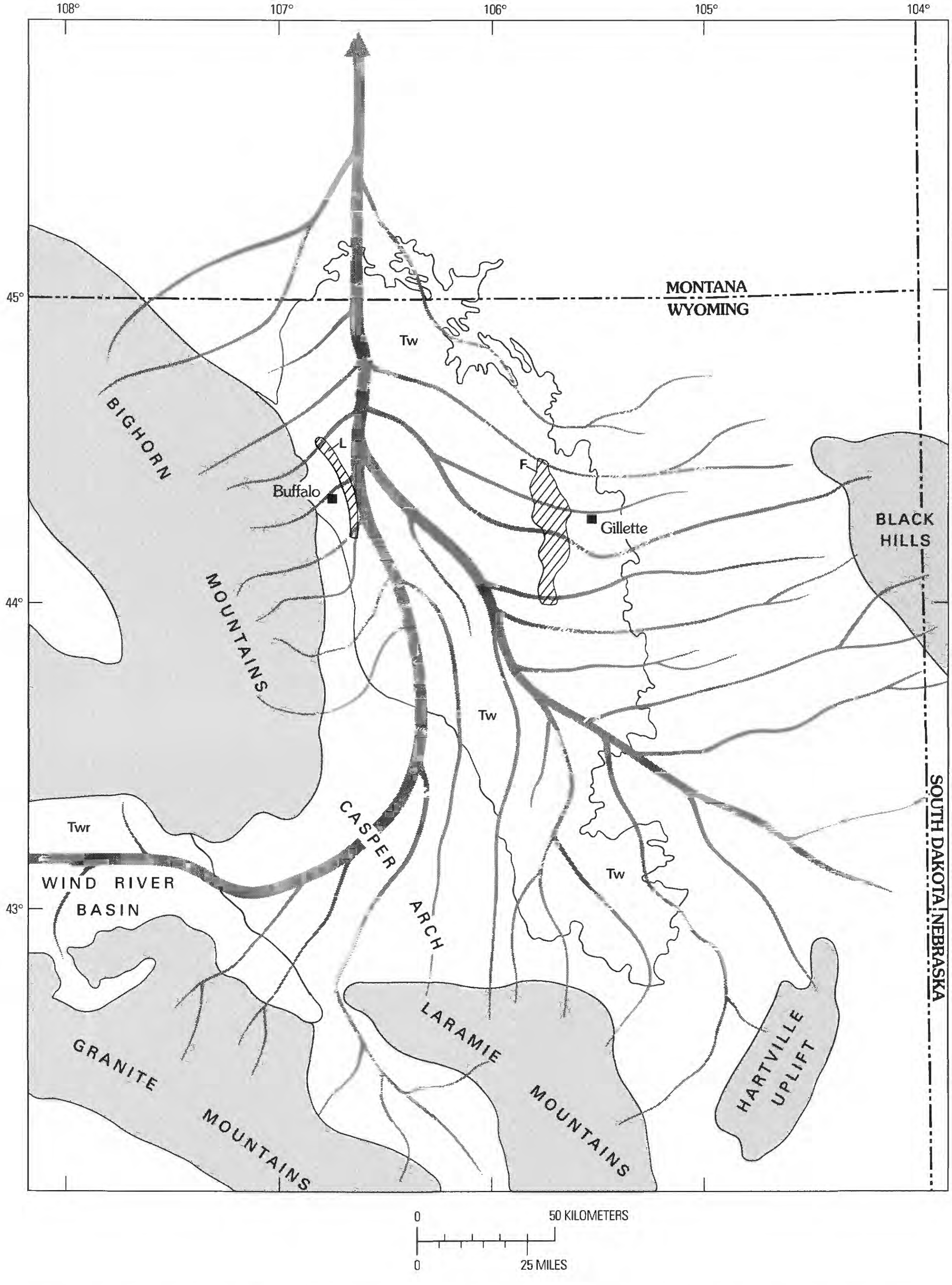


Figure 5. Interpretative paleogeographic stream map for latest Paleocene and early Eocene (Wasatch Formation) time for the Powder River Basin of Wyoming and Montana. Relative size of streams is proportional to line width. Location of central-core coal bodies of the Felix (F) and Lake DeSmet (L) coal deposits is also shown. Tw indicates Wasatch Formation, Twr lower Eocene Wind River Formation. From Seeland (1992).

were near the geographic axis of the basin rather than in the western basin as in Eocene time.

A model proposed by McClurg (1988) incorporates elements of both the Kent and Ayers models. It suggests long-lived shallow swampy lakes that shifted laterally in response to basin tilting and localized the peat-forming environment. In the case of both the McClurg and Ayers models, paleocurrent studies do not confirm the centripetal drainage necessitated by either deep or shallow large central lakes. Another difficulty with the lake models is maintaining hydrologic balance so that a lacustrine swamp could be maintained for periods as long as 100,000 years.

McClurg (1988) discussed the model of Jackson (1979), as also presented in Ethridge and others (1981), in which he proposed that ground water moves upward through a raised peat deposit providing water and nutrients to raised swamps. McClurg pointed out that water is unlikely to move upward through peat because as peat accumulates its basal part becomes gel-like and nonporous (Lewis Smith and Clymo, 1984).

Chao and others (1984) studied the petrographic characteristics of samples from a cored drill-hole in the thickest part (61 m) of the Big George coal bed. They concluded, on the basis of petrographic structures and textures, that the Big George coal is of allochthonous origin. They postulated that the source of the woody plant material was adjacent forested swamps to the south. Most degradation of the plant material probably occurred in the source swamps.

If the Big George coal bed formed from allochthonous peat, then its elongate north-northwest orientation (fig. 2) could be a direct indication of paleostream-flow direction (Ghosh, 1987). It does parallel probable stream directions in this part of the basin (Seeland and others, 1988), but coal swamps of autochthonous origin also form in dip-oriented belts parallel with streams. Stanton and others (1988) argued that the fragmental nonlaminated coal texture used by Chao and others (1984) to indicate allochthonous origin could also have originated by in situ mulching and degradation of plant parts. They also cited low ash content and radial "drainage indentations" indicated by the coal isopachs as indicative of autochthonous raised-swamp origin.

Allochthonous peats and coals are rare (McCabe, 1984). They are usually too rich in mineral matter (ash) to be economic (Teichmuller and Teichmuller, 1982).

The Felix and the Wyodak coals, said to be of raised-swamp origin (Warwick, 1985; Warwick and Stanton, 1986), have mean ash contents of 7.8 and 6.0 percent, respectively (Glass, 1980). These values are near the upper limit of, or above, ash values characteristic of raised swamps. Teichmuller and Teichmuller (1982) stated that raised swamps frequently have an ash content of less than 1 percent, and McCabe (1984) gave a range of 0.2–6.5 percent ash in raised-swamp peats. The Big George coal, a coal believed to be allochthonous by Chao and others (1984) and which therefore should have a high ash content, has an ash content of 3.6 percent based on 37 analyses, lower than any of the 12 Powder River Basin coals studied by Glass (1980).

Furthermore, ash-content variability was high in many of the coals: 5–22 percent ash with a mean of 7.8 percent in 15 Lake DeSmet coal samples (Glass, 1980) and 1.6–22 percent ash in the Big George coal bed (Chao and others, 1984). This high variability suggests the possibility of changing swamp types. Fires in the Okefenokee swamp of Georgia changed low-lying swamps to open water (Cohen, 1974) and could open a swamp to sediment-laden floodwaters by removal of the forest baffle or could allow the deposition of high-ash allochthonous peat to follow deposition of low-ash autochthonous peat, particularly near major streams. Fire is indicated by fusinite, which is variably abundant in six Powder River Basin coal beds (Rich, 1980).

McCabe (1984, p. 27) stated that "an interpretation that an entire seam of low or medium ash is allochthonous in nature must envisage a process which prevented clastic sediment from being transported and deposited with the organic material." If some or all of the low-ash Big George coal was formed from allochthonous peat, then flocculation of clay by humic acids on the swamp margins may be the required process. Staub and Cohen (1979) found that pH values are lower in freshwater swamps than in salt marshes and suggested that humic acids in freshwater swamps flocculate and cause deposition of clay at the swamp margin during flooding. This same process could keep the ash content of the nonmarginal parts of low-lying autochthonous swamps low.

Thin coals as much as about 2 m thick in the basal Lance Formation in the southern part of the Powder River Basin have an average ash content of 6.8 percent based on 10 analyses (Glass, 1980). Inferred precipitation during the Late Cretaceous was about half that in the late Paleocene and temperature was about 4°C higher (Nichols and others, 1988). Consequently, evapotranspiration was greater in the Maastrichtian than in the late Paleocene, and the much drier Maastrichtian climate was not likely to allow formation of ombrogenous swamps. Nevertheless, the ash content of the sampled coal beds, probably of nonombrogenous origin, was only 0.8 percent higher than that of the Wyodak, a coal bed thought by some to be of ombrogenous origin. As a result, the ash content of these coal beds either is unrelated to its mode of origin, or, more likely, the coal beds all were formed from peat deposited primarily in low-lying swamps. The rainfall in the latest Cretaceous was much less than the 3 m required for ombrogenous swamps (McCabe, 1984). The increase in rainfall from the latest Cretaceous into the late Paleocene probably only increased the rate of biomass production and did not change the dominant swamp type.

SELECTED COAL BEDS OF THE WASATCH FORMATION

Lake DeSmet Coal Bed

The thickest coal bed in the Wasatch Formation in the Powder River Basin is the Lake DeSmet coal bed (bed L, fig. 1). It is also the thickest coal bed in the United States (Glass, 1980) and the second thickest in the world (Obernyer, 1980). It is locally as thick as 75 m (Mapel, 1959; Obernyer, 1978). Wasatch coal beds are thicker, more numerous, and more widespread in the central and western parts of the Wasatch Formation than in the eastern Wasatch Formation (Lageson and Spearing, 1988), a relationship shown on a coal-bed fence diagram presented by Glass (1980).

The mode of occurrence of the Lake DeSmet coal in the Wasatch Formation is typical of lower Tertiary coals in the Powder River Basin; as described by Kent and others (1988), "closely associated coal beds merge to form single beds of combined coal, and the thickest single bed of combined coal forms a central core." The merging of coal beds and the relationship between the Lake DeSmet and adjacent basin-margin alluvial-fan conglomerates was illustrated by Obernyer (1980) (fig. 6). Obernyer stated that "the coals within the study area form marginal to the channels" but also suggested that the linearity and parallelism of the deposits relative to the mountain front may be due to control by a basin-margin fault.

The Lake DeSmet coal bed separates the alluvial fan environment and its easterly paleocurrent indicators from the alluvial channel environment and its north-northwesterly crossbedding (fig. 6). Three hundred and thirty paleo-current measurements in a study area near Buffalo, Wyoming (Obernyer, 1978), ar e in agreement with the paleodrainage pattern of Seeland (1976). These paleocurrent measurements (fig. 6) provide more local detail but confirm the basinwide data and interpretations of Seeland (1976, 1992) that place the Lake DeSmet coal just west of the Wind River of early Eocene time, a north-flowing basin-axis stream (fig. 5). The early Eocene basin axis as defined by the Wind River of early Eocene time should indicate a line of maximum subsidence and is a likely place to find the thickest early Eocene coal of the basin.

Obernyer (1978) attributed the Lake DeSmet coal to peat formed in a low-lying swamp. The moderately low ash content of the Lake DeSmet (7.6 percent; Glass, 1980) indicates little floodborne sediment even though the Lake DeSmet swamp was in a particularly floodprone area between the trunk stream of the basin and alluvial fans of a major mountain range.

Felix Coal Bed

The Felix coal deposit (bed F, fig. 1; fig. 7) has a maximum thickness of 8 m; it is near the base of the Wasatch Formation and lies in part on a 50-m-thick sandstone that unconformably overlies the Tongue River Member of the Fort Union Formation (fig. 1). Its north-south orientation (fig. 5) and the splitting of its central core to the east and west (fig. 7) are similar to the geometry of other thick Wasatch and Fort Union coals of the basin.

Early Eocene paleogeography (Seeland (1976, 1992) (fig. 2) indicates that the Felix coal bed is strike oriented, extending approximately north-south on a west-northwest-dipping paleoslope. The axial part of the coal bed lies about 70 km east of what was the north-flowing basin-axis master stream of the basin, the Wind River of early Eocene time (Seeland, 1976, 1978).

The paleogeographic interpretation of Warwick and Flores (1987) and Flores and Warwick (1984) is based in part on an average of one crossbed at each of 84 localities in the lower Wasatch Formation spanning an interval from about 30 m below to 40 m above the Felix coal. In their interpretation, based on their paleocurrent and sandstone isolith studies, the Felix coal swamp is immediately to the east of a north-flowing trunk stream, in direct contradiction to the paleogeography inferred from paleocurrent results in Seeland (1976, 1992) and Obernyer (1980) which suggest that the early Eocene axial drainage was 50 km farther to the west. Flores and Warwick (1984) showed east-flowing streams in a large area of the basin for which other paleocurrent evidence shows the streams flowing in an almost opposite northwesterly direction. The area of disagreement is 50 km wide and is between the Wind River of early Eocene time (Seeland, 1976, 1992) and the basin-axis trunk stream inferred by Warwick and Flores (1987).

Summary rose diagrams were used by Warwick and Flores (1987) to present crossbedding measurements. Assuming that the center of each rose-diagram segment was the mean of the measurements in that segment, vector means were calculated. Mean crossbed dip azimuths were 332° for the 30 m of Wasatch below the Felix and 3° for the 40 m above the Felix; the overall vector-mean azimuth was 348° for the entire stratigraphic interval in the study area of Warwick and Flores.

Seeland (1992) made 121 crossbed measurements at 10 localities in the area studied by Warwick and Flores (1987). The overall vector mean calculated from unweighted locality vector means is 299°. This result is supported by data from other field stations collected outside the study area of Warwick and Flores (1987). The results of Warwick and Flores and of Seeland differ by 53°, a substantial difference but much less than the almost 90° difference suggested by the two paleogeographic interpretations.

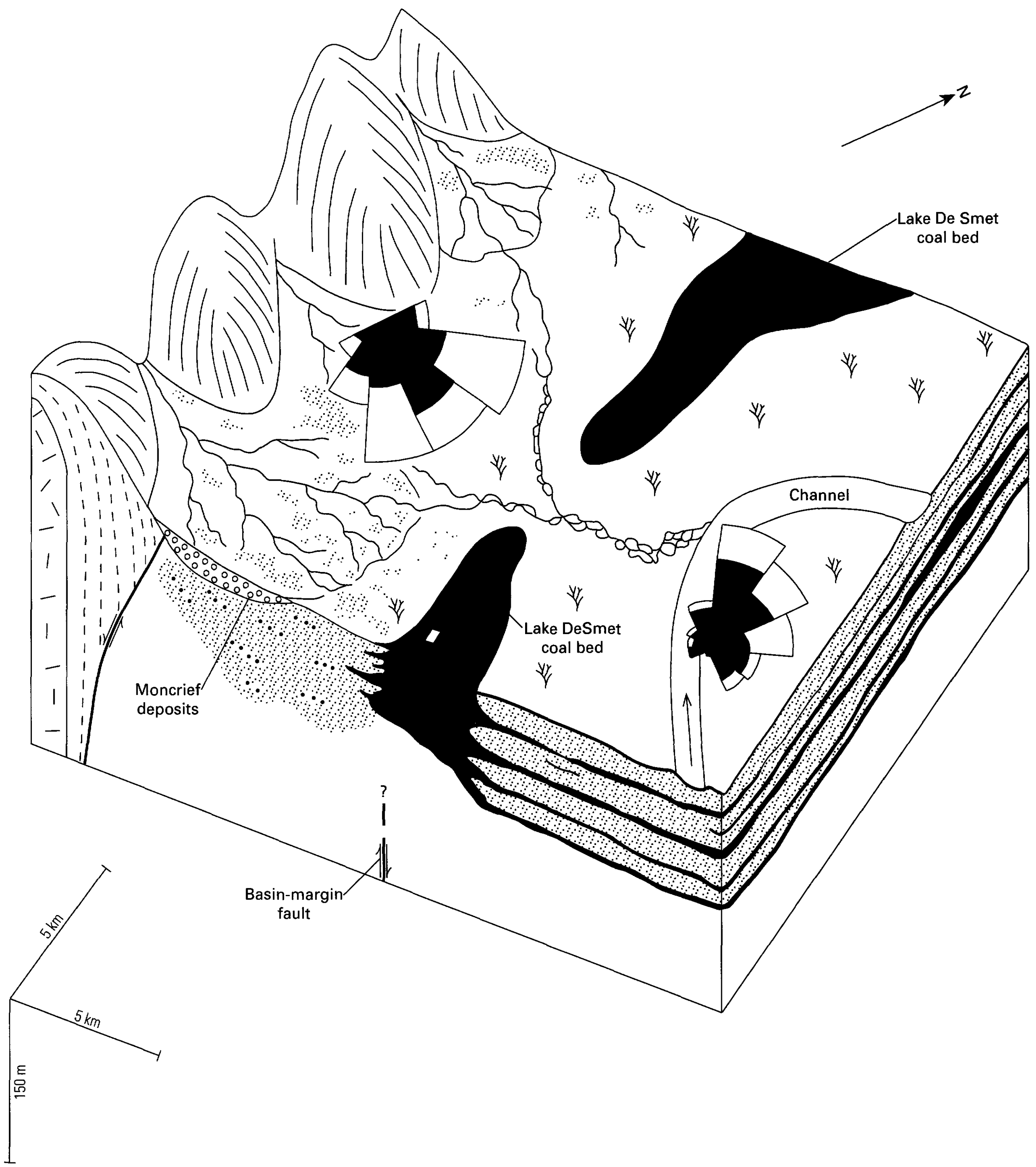


Figure 6. Block diagram illustrating merging of coal beds to form the Lake DeSmet coal bed and relationship between Lake DeSmet coal bed and adjacent basin-margin alluvial-fan conglomerates. Rose diagrams of transport directions east (200 measurements) and west (130 measurements) of the Lake DeSmet coal bed are also shown. Shaded area of the eastern rose diagram represents crossbedding of sandstones that are time equivalents of the upper third of the Lake DeSmet coal bed. Shaded area of the western rose diagram represents crossbedding in conglomerates. Parallelogram represents approximate location of town of Buffalo. Modified from Obernyer (1980, figs. 9, 13).

Sandstone isoliths in fluvial rocks may not provide reliable paleogeographic information, particularly if based on widely spaced data points and (or) thick intervals. In addition to the contradictory paleogeographic interpretations discussed above, similar contradictions or nonconcidence exist between sandstone trends and paleogeography based on paleocurrent studies in Tertiary fluvial rocks of the Powder River Basin. Sandstone percentages in 500-ft

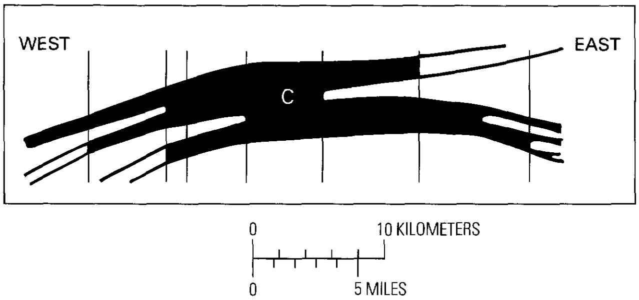


Figure 7. East-west profile of Felix coal deposit. C indicates central core of deposit. Modified from Kent (1988, fig. 2).

slices of the Wasatch (Bendix Field Engineering Corporation, Geology Division Staff, 1976) appear to be unrelated to the paleogeographic interpretation based on a paleocurrent study (Seeland, 1976, 1992). A "percentage major sands map (sands greater than 12 m thick)" (Ayers and Kaiser, 1984) shows many east-west trends in the Tongue River Member of the Fort Union Formation that are perpendicular to river flow directions as determined from the paleocurrent study of Seeland and others, (1988). In contrast, the trends of sandstone isoliths in the Wasatch Formation of the southern Powder River Basin based on closely spaced uranium exploration drill holes are parallel with paleocurrent flow directions (Santos, 1981).

If the Felix coal bed was formed from peat deposited in a raised swamp that was transverse to general stream flow in Wasatch time, then stream directions on the swamps downstream side could have been anomalous and may poorly reflect regional trends. Warwick and Flores (1987) did not locate their paleocurrent measurements, and this hypothesis cannot be tested.

The strike-parallel orientation of the Felix coal (fig. 3) and its precursor swamp could be explained by the teeterboard hypothesis of Kent and others (1986) and Kent (1987). This hypothesis, as previously discussed, requires the coal bed to be elongate perpendicular to the paleoslope (and paleostream directions). Although paleostream directions suggest that the teeterboard hypothesis does not apply to the origin of the Big George and Wyodak coals, it might be applied to the Felix because its "footprint" is transverse to Wasatch stream-flow directions in the central basin. A simpler explanation is that underlying upper Tongue River depositional patterns and differential compaction affected development of lower Wasatch sedimentation patterns.

If the interpretation of Warwick and Flores (1987) that the Felix is a dip-oriented coal is accepted, then, because of the stratigraphic position of the Felix coal bed near the base of Wasatch Formation, it might be possible to argue that the basin axis remained in the geographic center of the basin through Felix time in the earliest Eocene and then rapidly moved to the western basin. Paleocurrent data (Seeland 1976, 1992) do not, however, support this interpretation. In addition, the uplift of the Black Hills (and (or) basin subsidence) suggested by the low-angle unconformity between the Wasatch and Fort Union Formations (Kent and others, 1988) is also a likely cause of a pre-Felix westward movement of the basin axis.

SUMMARY AND CONCLUSIONS

The late Paleocene and early Eocene paleogeography of the Powder River Basin suggests that the thick coals in the basin formed from peat deposits in dip-elongate swamps near the basin-axis trunk streams. In late Paleocene time the trend of the basin axis was north through the central part of the basin; in latest Paleocene and early Eocene time the trend of the basin axis was also north but was in the westernmost part of the basin. Most major thick coals were formed adjacent to basin-axis trunk streams. Modes of origin involving peat from raised swamps, peat from low-lying swamps, and allochthonous accumulations of peat all have proponents and evidence. All these modes of origin depend on climatically controlled high rates of vegetative biomass production and low rates of decay produced by anoxic conditions in water-saturated peat.

Climate and subsidence rates were similar in the Powder River, Wind River, and Bighorn Basins, but no coals comparable to the thick coals of the Powder River Basin are known along the early Eocene basin-axis trunk streams (Seeland, 1985), or elsewhere, in either the Wind River Basin or the Bighorn Basin. The late Paleocene paleogeography of these basins is not well known but is not likely to have been radically different from early Eocene paleogeography. Little late Paleocene coal is in either basin. If a raised-swamp depositional environment and a high subsidence rate were all that was necessary to produce thick coal, then extensive thick coals of late Paleocene and early Eocene age should be found in the Wind River and Bighorn Basins, as well as in the Powder River Basin. Consequently, raised swamps, dependent on rainfall, were not necessary or sufficient to form thick coals, given the early Tertiary climatic and tectonic conditions of the Laramide basins, and it is more likely that autochthonous and possibly allochthonous organic materials deposited in low-lying swamps were the precursors of most of the extensive coal deposits of the Powder River Basin.

The Powder River Basin has more than 80 percent of the coal resources in Wyoming (Glass, 1980), and therefore other factors not related to climate or subsidence rate must be unique to the Powder River Basin. The most likely factor is regional paleogeography. Drainage from the Wind River Basin to the Powder River Basin throughout most of the early Tertiary greatly increased the volume of water flowing through the basin along the basin-axis trunk streams. Greater amounts of water favored accumulation and preservation of peat and the formation of thicker and more widespread coal deposits than in adjacent basins that were climatically and tectonically similar but lacked a major extrabasinal water source.

Pre-middle Paleocene coal is not abundant either in the basin or region. The paleogeographic evolution of the basin is directly related to the time of the formation of major peat deposits. Paleocurrent analysis and studies of outcrop lithology (Seeland, 1988) and lithofacies patterns (Ayers, 1986) of the lower Paleocene Tullock Member of the Fort Union Formation suggest that the basin had not yet begun to form in the early Paleocene. In spite of high biomass production in early Paleocene time (Nichols and others, 1988), basinal drainage was not yet integrated and biomass preservation was low. The Tullock contains abundant sandstone that originated either in uplifts far to the west or from reworked uppermost Cretaceous sandstone of the Lance or Hell Creek Formations.

In mid-Paleocene (Lebo) time uplift of the Black Hills and Bighorn Mountains formed a north-trending basinal trough, integrating the previously diffuse subparallel northeasterly drainages into a north-trending basin-axis drainage system. The first sediments produced by the Laramide uplift of these ranges were dominantly fine grained silt and mud derived from thick Mesozoic marine shale sequences. Lebo-age coals are rare because of the vast quantities of silt and mud that entered the basin at this time. Rare channel sandstones exhibit paleocurrent directions similar to those in the overlying Tongue River Member. As contributions of fine-grained sediment derived from the Mesozoic shales decreased during late Paleocene (Tongue River) time, extensive low-lying swamps developed parallel with the north-flowing basin-axis streams. The Wind River Basin to the west had a basin-axis stream (Seeland, 1978) that flowed across the Casper arch, a structural feature between the two basins, and substantially augmented the flow of the axial streams in the Powder River Basin creating conditions that favored development and preservation of thick peat deposits in dip-oriented low-lying swamps parallel with the basin-axis streams. Waltman Lake (Keefer, 1965) in the Wind River Basin may have interrupted this drainage during part of the late Paleocene but more likely had a continuous overflow outlet on its northeast (Casper arch) side.

As the north-south basin axis migrated westward from its late Paleocene position near the geographic axis of the basin near Gillette to its latest Paleocene and early Eocene position in the westernmost basin near Buffalo, so did the associated major low-lying swamps. Wasatch-age coal beds are thus more abundant and thicker in the western part of the basin. The Wind River Basin continued to drain eastward into axial streams of the Powder River Basin, continuing the uniquely favorable conditions that allowed extensive development of thick coal beds in early Tertiary fluvial rocks of the Powder River Basin.

REFERENCES CITED

Anderson, J.A.R., 1964, The structure and development of the peat swamps of Sarawak and Brunei: Journal of Tropical Geography, v. 18, p. 7–16.

Ayers, W.B., Jr., 1986, Lacustrine and fluvial-deltaic depositional systems, Fort Union Formation (Paleocene), Powder River Basin, Wyoming and Montana: American Association of Petroleum Geologists Bulletin, v. 70, no. 11, p. 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.A., and Flores, R.M., eds., Sedimentology of coal and coal-bearing sequences: International Association of Sedimentologists Special Publication 7, p. 61–84.

Beaumont, E.A., 1979, Depositional environments in Fort Union sediments (Tertiary, northwest Colorado) and their relation to coal: American Association of Petroleum Geologists Bulletin, v. 63, p. 194–217.

Bendix Field Engineering Corporation, Geology Division Staff, 1976, Uranium favorability of the Fort Union and Wasatch Formations, in the northern Powder River Basin, Wyoming and Montana: Grand Junction Operations, Report GJBX-58(76), 106 p. Available from Books and Open-File Reports Sales, U.S. Geological Survey, Federal Center, Box 25286, Denver, Colorado 80225.

Budai, C.M., and Cummings, M.L., 1987, A depositional model of the Antelope coal field, Powder River Basin, Wyoming: Journal of Sedimentary Petrology, v. 57, no. 1, p. 30–38.

Chao, E.C.T., Minkin, J.A., Back, J.M., and Pierce, F.W., 1984, Petrographic characteristics and depositional environment of the Paleocene 61-m-thick subtuminous Big George coal bed, Powder River Basin, Wyoming, *in* Houghton, R.L., and Clausen E.N., eds., 1984 Proceedings of the Symposium on the Geology of Rocky Mountain Coal: North Dakota Geological Society Special Publication 84–1, p. 41–60.

Cohen, A.D., 1974, Petrography and paleoecology of Holocene peats from the Okefenokee swamp-marsh complex of Georgia: Journal of Sedimentary Petrology, v. 44, p. 716–726.

Ethridge, F.G., Jackson, T.J., and Youngberg, A.D., 1981, Floodbasin sequence of a fine-grained meander belt subsystem—The coal-bearing Lower Wasatch and Upper Fort Union Formations, southern Powder River Basin, Wyoming, *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. 191–209.

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. 79–104.

Flores, R.M., and Warwick, P.D., 1984, Dynamics of coal deposition in intermontane alluvial paleoenvironments, Eocene Wasatch Formation, Powder River Basin, Wyoming, *in* Houghton, R.L., and Clausen, E.N., eds., 1984 Proceedings of the Symposium on the Geology of Rocky Mountain Coal: North Dakota Geological Society Special Publication 84–1, p. 184–199.

Ghosh, R., 1987, The variation in thickness and composition of coal seams and its use in interpretation of paleocurrents—A case study from the Raniganj coalfield, West Bengal, India: International Journal of Coal Geology, v. 9, no. 2, p. 209–220.

Glass, G.B., 1980, Coal resources of the Powder River coal basin, *in* Glass, G.B., ed., Guidebook to the coal geology of the Powder River coal basin, Wyoming: Geological Survey of Wyoming Public Information Circular 14, p. 97–131.

Gore, A.J.P. 1963, Introduction, *in* Gore, A.J.P., ed., Ecosystems of the World, 4A Mires—Swamp, bog, fen and moor: Amsterdam, Elsevier, p. 1–30.

Jackson, T.J., 1979, Origin of thick coals of the Powder River Basin, Wyoming: Unpublished report, University of Texas, Austin, Texas, 18 p.

Kaiser, W.R., 1974, Texas lignite—Near-surface and deep-basin resources: Bureau of Economic Geology, The University of Texas at Austin, Report of Investigations 79, 70 p.

Keefer, W.R., 1965, Stratigraphy and geologic history of the uppermost Cretaceous, Paleocene, and lower Eocene rocks in the Wind River Basin, Wyoming: U.S. Geological Survey Professional Paper 495–A, 77 p.

Kent, B.H., 1984, Evolution of thick coal deposits in the Powder River Basin, northeastern Wyoming: Geological Society of America, Abstracts with Programs, v. 16, no. 6, p. 558.

———1987, Evolution of thick coal deposits in the Powder River Basin, northeastern Wyoming: Geological Society of America Special Paper 210, p. 105–122.

Kent, B.H., Pierce, F.W., Molnia, C.L., and Johnson, E.A., 1986, Allocyclic controls on thick coal deposition in sedimentary basins—Some Powder River Basin examples [abs.], *in* Carter, L.M.H., ed., USGS Research on Mineral and Energy Resources: U.S. Geological Survey Circular 974, p. 31–32.

Kent, B.H., Weaver, J.N., Roberts, S.B., Ming, T., Shu, L., and Bangzhuo, M., 1988, Geology and resource appraisal of the Felix coal deposit, Powder River Basin, Wyoming—A research project with the Peoples Republic of China: U.S. Geological Survey Bulletin 1818, 32 p.

Lageson, D.R., and Spearing, D.R., 1988, Roadside geology of Wyoming: Missoula, Mountain Press Publishing Company, 274 p.

Lewis Smith, R.I., and Clymo, R.S., 1984, An extraordinary peat-forming community on the Falkland Islands: Nature, v. 309, p. 616–620.

Mapel, W.J., 1959, Geology and coal resources of the Buffalo–Lake DeSmet area, Johnson and Sheridan counties, Wyoming: U.S. Geological Survey Bulletin 1078, 146 p.

McCabe, P.J., 1984, Depositional environments of coal and coal-bearing strata, *in* Rahmani, R.A., and Flores, R.M., eds., Sedimentology of coal and coal-bearing sequences: International Association of Sedimentologists Special Publication 7, p. 13–42.

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

Nichols, D.J., Wolfe, J.A., and Pocknall, D.T., 1988, Latest Cretaceous and early Tertiary history of vegetation in the Powder River Basin, Montana and Wyoming, *in* Holden, G.S., ed., Geological Society of America field trip guidebook: Colorado School of Mines Professional Contributions 12, p. 205–210.

Obernyer, S.L., 1978, Basin margin depositional environments of the Wasatch Formation in the Buffalo–Lake DeSmet Area, Johnson County, Wyoming, *in* Hodgson, H.E., ed., Proceedings of the Second Symposium on the Geology of Rocky Mountain Coal—1977: Colorado Geological Survey Resource Series 4, p. 49–65.

———1980, The Lake DeSmet coal seam—The product of active basin-margin sedimentation and tectonics in the Lake DeSmet area, Johnson County, Wyoming, during Eocene Wasatch time, *in* Glass, G.B., ed., Guidebook to the coal geology of the Powder River Basin, Wyoming: Geological Survey of Wyoming Public Information Circular 14, p. 31–70.

Pierce, F.W., Kent, B.H., and Grundy, W.D., 1982, Geostatistical analysis of a 113-billion-ton coal deposit, central part of the Powder River Basin, northeastern Wyoming, *in* Gurgel, K.D., ed., Proceedings, 5th ROMOCO Symposium: Utah Geological and Mineralogical Survey Bulletin 118, p. 262–272.

Pocknall, D.T., 1986, Palynological data from the Fort Union and Wasatch Formations, Powder River Basin, Wyoming and Montana: U.S. Geological Survey Open-File Report 86–117, 58 p.

Pocknall, D.T., and Flores, R.M., 1987, Coal paleontology and sedimentology in the Tongue River Member, Fort Union Formation, Powder River Basin, Wyoming: Palaios, v. 2, p. 133–145.

Rich, F.J., 1980, Brief survey of chemical and petrographic characteristics of Powder River Basin coals, *in* Glass, G.B., ed., Guidebook to the coal geology of the Powder River coal basin, Wyoming: Geological Survey of Wyoming Public Information Circular 14, p. 133–158.

Romanov, V.V., 1968, Hydrophysics of bogs: Gimiz, Gidrometeorologischeskoe izdatel'stvo, Leningrad. Translated by Kaner, N., 1968, Israel Program for Scientific Translations Ltd.; U.S. Department of Commerce, Springfield, Virginia, 299 p.

Santos, E.S., 1981, Facies distribution in uranium host rocks of the southern Powder River Basin, Wyoming: U.S. Geological Survey Open-File Report 81–741 15 p.

Satchell, L.S., 1985, Climate and depositional environment of *Glyplostrobus* forest swamps that formed thick low-ash coals in the Paleocene Powder River Basin: Society of Organic Petrology Annual Meeting, 2nd, Abstracts and Programs, p. 11.

Satchell, L.S., and Davies, T.D., 1984, Reconstruction of vegetation and environments from palynology of Paleocene coals from Wyoming, U.S.A. [abs.]: International Palynological Conference, 6th, p. 146.

Schopf, J.M., 1973, Coal, climate and global tectonics, *in* Tarling, D.H., and Runcorn, S.K., eds., Implications of continental drift to the earth sciences, v. 1: London, Academic Press, p. 609–622.

Seeland, D.A., 1976, Relationships between early Tertiary sedimentation patterns and uranium mineralization in the Powder River Basin: Wyoming Geological Association 28th Annual Field Conference Guidebook, p. 221–230.

———1978, Sedimentology and stratigraphy of the lower Eocene Wind River Formation, central Wyoming: Wyoming Geological Association 30th Annual Field Conference Guidebook, p. 181–198.

———1985, Oligocene paleogeography of the northern Great Plains and adjacent mountains, *in* Flores, R.M. and Kaplan, S.S., eds. Cenozoic paleogeography of the west-central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Paleogeography Symposium, p. 187–205.

———1988, Laramide paleogeographic evolution of the eastern Powder River Basin, Wyoming and Montana: Wyoming Geological Association 39th Annual Field Conference Guidebook, p. 29–34.

———1992, Depositional systems of a synorogenic continental deposit—The late Paleocene and early Eocene Wasatch Formation of the Powder River Basin, northeast Wyoming: U.S. Geological Survey Bulletin 1917–H, 20 p.

Seeland, D.A., Flores, R.M., Johnson, E.A., and Pierce, F.W., 1988, Some paleogeographic inferences from paleocurrents of the Tongue River Member, Fort Union Formation, Powder River, Bull Mountains and southwestern Williston basins, Montana and Wyoming, *in* Holden, G.S., Geological Society of America field trip guidebook: Colorado School of Mines Professional Contributions 12, p. 191–193, 222–226.

Stanton, R.W., Moore, T.A., Warwick, P.D., Crowley, S.S., and Flores, R.M., 1988, Styles of organic facies development in selected coal beds of the Powder River Basin—A petrographic evaluation, *in* Holden, G.S., Geological Society of America field trip guidebook: Colorado School of Mines Professional Contributions 12, p. 195–204, 222–226.

Staub, J.R., and Cohen, A.D., 1979, The Snuggedy Swamp of South Carolina—A back barrier estuarine coal-forming environment: Journal of Sedimentary Petrology, v. 49, p. 133–144.

Teichmuller, M., and Teichmuller, R., 1982, The geological basis of coal formation, *in* Stach E., Mackowsky, M.T., Teichmuller, M., Taylor G.H., Chandra, D., and Teichmuller, R., eds., Stach's textbook of coal petrography (3rd ed.): Berlin, Gebruder Borntraeger, p. 5–86.

Warwick, P.D., 1985, Depositional environments and petrology of the Felix coal interval (Eocene), Powder River Basin, Wyoming: Lexington, University of Kentucky, Ph.D. dissertation, 333 p.

Warwick, P.D., and Flores, R.M., 1987, Evolution of fluvial styles in the Eocene Wasatch Formation, Powder River Basin Wyoming, *in* Ethridge, F.G., Flores, R.M., and Harvey, M.D., eds., Recent developments in fluvial sedimentology: Society of Economic Paleontologists and Mineralogists Special Publication 39, p. 303–310.

Warwick, P.D., and Stanton, R.W., 1986, Depositional controls on the geometry of the Wyodak-Anderson coal bed, northeastern Wyoming [abs.], *in* Carter, L.M.H., ed., The Second Annual McKelvey Forum on Mineral and Energy Resources: U.S. Geological Survey Circular 974, p. 71–72.

White, J.M., 1986, Compaction of the Wyodak coal, Powder River Basin, USA: International Journal of Coal Geology, v. 6, p. 139–148.

Published in the Central Region, Denver, Colorado
Manuscript approved for publication December 1, 1992
Graphics prepared by Norma J. Maes
Photocomposition by Marie F. Melone
Edited by Judith Stoeser

☆U.S. GOVERNMENT PRINTING OFFICE: 1993-774-049/66060

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations; as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that maybe cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales, they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases which show geology as interpreted from aerial photographs. The series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; the principal scale is 1:24,000, and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from USGS Map Distribution, Box 25286, Building 810, Denver Federal Center, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879-1961" may be purchased by mail and over the counter in paperback book form and as a set microfiche.

"Publications of the Geological Survey, 1962-1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971-1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only.

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" is available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 22092.

Note.–Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849