Chapter PF

FRAMEWORK GEOLOGY OF THE FORT UNION COAL IN THE POWDER RIVER BASIN

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STRUCTURAL SETTING

- The Powder River Basin (fig. PF-1) is in northeast Wyoming and southeast Montana.
- The Powder River Basin is an asymmetrical structural basin with the axis trending northwest and southeast close to the western margin of the basin, and covers an area of more than 22,000 square-miles.
- The beds dip on average 20-25 degrees to the east along the west-central margin of the basin and average 2-5 degrees to the west along the eastern margin.
- The Paleocene Fort Union Formation outcrops along the basin margin and is overlain by the Eocene Wasatch Formation in the central part of the basin. The Wasatch Formation contains numerous coal beds as much as 250 ft thick (Mapel, 1959).
- The Fort Union Formation is more than 6,000 ft thick in the deepest part of the basin, along the axis (Curry, 1971).

STRATIGRAPHIC SETTING

- The Fort Union Formation is divided into the Tullock Member in the lower part, Lebo Member (Wyoming part) or Lebo Shale Member (Montana part) in the middle part, and Tongue River Member in the upper part.
- The Tongue River Member contains the most and thickest coal deposits, and the Lebo or Lebo Shale Member contains the least number and thinnest coal beds.
- Coal beds in the Tongue River Member of the Fort Union Formation are more than 200 ft thick. The average coal beds are about 20-30 ft thick and increase in thickness toward the upper part of the member.

DEPOSITIONAL SETTING

- Depositional environments of the Fort Union Formation include fluvial systems (figs. PF-2 and PF-3) consisting of braided, meandering, and anastomosed streams in the basin center, and alluvial fans at the basin margin (Flores and Ethridge, 1985; Flores, 1986).
- Coal-forming peat accumulated in low-lying swamps (fig. PF-4) and raised or domed mires (fig. PF-5), in fluvial floodplains (fig. PF-6), abandoned fluvial channels, and interchannel environments (Flores, 1981; Warwick and Stanton, 1988).
- The thickest peat deposits accumulated in raised mires well above drainage level (fig. PF-7) and were sustained by rainfall in a tropical-subtropical climate with a mean annual temperature of 20°C (68°F) and a precipitation rate of 90.6 in/yr (>2,300 mm/yr) (Nichols and others, 1989). These coal deposits are pod to lenticular shaped (Warwick and Stanton, 1988).

COAL QUALITY

- Coal rank is mostly subbituminous with subordinate lignite (Stricker and others, 1998).
- Coal quality reflects low percentages of sulfur and ash. The minable Wyodak-Anderson coal zone contains very low sulfur and ash contents (Ellis and others, 1998)
- Concentrations of selected trace elements of environmental concern are low (Stricker and others, 1998).

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS OF ASSESSMENT UNITS

STRATIGRAPHY

- The Fort Union Formation in the Powder River Basin ranges in thickness from 2,300 to 6,000 ft (Curry, 1971). The thickest Fort Union Formation is found in the western part of the basin and the thinnest is in the eastern and southern parts.
- Biostratigraphic zonations (fig. PF-8) of the formation include zones P1–P6.
- The Fort Union Formation is composed primarily of conglomerate, sandstone, siltstone, and mudstone, and subordinately of limestone, carbonaceous shale, and coal (Flores, 1981). The sandstone in the Tullock Member ranges from 21 to 88 percent and averages 53 percent; in the Lebo Member it ranges from 6 to 93 percent and averages 31 percent, and the Tongue River Member ranges from 21 to 91 percent and averages 54 percent (Lewis and Hotchkiss, 1981).
- The coal beds and zones that were assessed include the Wyodak-Anderson and the laterally equivalent beds, and the Knobloch and Rosebud coal zones (fig. PF-9).
- The Wyodak-Anderson coal zone includes as many as 11 coal beds that are found in the upper part of the Tongue River Member of the Fort Union Formation.
- This coal zone contains various coal beds named, from bottom to top, Werner, Canyon, Dietz, Anderson, Lower and upper Wyodak, Wyodak, Big George, Sussex, School, Badger, Swartz, and Smith.
- The Knobloch and Rosebud coal zones are found in the lower part of the Tongue River Member of the Fort Union Formation.
- For this study of the Fort Union coal, 6,909 proprietary and nonproprietary drill holes were used. The stratigraphic information is interpreted by various sources from geophysical logs of coal, oil, and gas drill holes.

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DEPOSITIONAL ENVIRONMENTS

- Depositional environments of the Fort Union Formation consisted of northeastward-flowing fluvial systems comprised of braided, meandering, and anastomosed streams (Flores and Ethridge, 1985).
- These basin-axis, trunk-tributary, fluvial systems were fed by alluvial fans that drained surrounding ancestral uplifts.
- Thick, low-ash and low-sulfur coal beds of the Tongue River Member formed in raised swamps that developed in interfluvial environments and on abandoned stream deposits.
- Thin, high-ash and high-sulfur coal beds of the Tongue River Member were formed in low-lying swamps in interfluvial environments.

GEOLOGY OF THE TONGUE RIVER MEMBER (FORT UNION FORMATION) COAL BEDS

DISTRIBUTION

- The Tongue River Member coal beds are stratigraphically distributed in distinct coal zones.
- Regionally, the coal zones merge, split, and pinch-out laterally, forming a shingled or overlapping pattern; locally they display a zigzag pattern.
- The coal beds are primarily in the subsurface of Campbell and Converse Counties, Wyoming, and Big Horn and Powder River Counties, Montana.
- The coal beds of the Tongue River Member are exposed in outcrops along the margin of the Powder River Basin.

- Strippable coal beds are found in the south, east, and northwest flanks of the basin.
- Lateral and vertical distributions of the Wyodak–Anderson coal beds and zones are shown in a network of cross sections with cross ties (fig. PF-10). The term "rocks," which is used on the cross sections, indicates undifferentiated sandstone, siltstone, and mudstone. The cross sections do not necessarily use the same number of drill holes for stratigraphic control.

STRATIGRAPHIC FRAMEWORK

- The Tongue River Member coal beds are interbedded with mudstone, limestone, carbonaceous shale, siltstone, sandstone, and conglomerate.
- The Wyodak-Anderson coal zone is within an interval as much as 900 ft thick. This coal zone consists of as many as eleven coal beds including the Werner, Swartz, Smith, Sussex, Big George, Canyon or Monarch, Dietz, Anderson, Badger, and School (Wyoming part), which merge into a single bed more than 200 ft thick.
- The Knobloch and Rosebud-Robinson coal zones are within a 175-ft-thick interval. These coal zones consist of four beds, the Knobloch, Calvert, Nance, and Flowers-Goodale (Culbertson and Saperstone, 1987). Coal beds equivalent to this coal zone include the Sawyer, Lay Creek, and King according to Sholes and Daniel (1992). The Rosebud coal has been laterally correlated by Sholes and Daniel (1992) to the upper split bed of the Knobloch coal.
- Laterally, coal beds of these coal zones merge, split, and pinch out. The coal splits into two or more beds that gradually thin or pinch out or interfinger with other clastic rocks.
- The split coal beds are interbedded with limestone, mudstone, siltstone, and sandstone.

- Merged coal beds are interbedded with thin carbonaceous shale partings.
- Rocks above and below the Tongue River Member coal beds and zones consist of mudstone, siltstone, and sandstone. In outcrop investigations, sandstone greater than 5 ft thick was interpreted as a crevasse-splay deposit and sandstone greater than 5 ft thick was interpreted as a fluvial channel deposit (Flores, 1981; 1986). These criteria were used as a guide in interpreting genetic rock types in the subsurface.
- The sediments that formed these rocks were deposited in channels, overbank floodplains, floodplain lakes, and crevasse channel splays in a fluvial system drained by meandering, anastomosed, and braided streams.
- The peat that formed the coal beds was deposited in raised mires and low-lying swamps associated with distal floodplains, at margins of floodplain lakes, and on abandoned fluvial channels and crevasse-splay lacustrine deposits (Flores, 1981, Flores and Ethridge, 1985; Flores and Moore; 1994; Moore, 1994).

BASINWIDE WYODAK-ANDERSON COAL ZONE STRUCTURAL CROSS SECTIONS

WYODAK-ANDERSON COAL ZONE

STRUCTURAL CROSS SECTION A-A'

- Structural cross section A-A' (fig. PF-11) extends about 115 mi along the eastern side of the Powder River Basin; it shows the Wyodak-Anderson coal zone and associated rocks. At the north end of the cross section, the rocks dip to the west-southwest, and at the south end the rocks dip to the west-northwest. The cross section was drawn using data from 126 drill holes, which are not labeled on the cross section.

- The Wyodak-Anderson coal zone includes all coal beds from the Werner at the bottom to the Smith at the top in the northern part of the cross section. In the southern part of the cross section the coal zone includes all coal beds from the lower to upper Anderson.

- Throughout most of this cross section the Wyodak-Anderson coal zone consists of four merged coal beds that form a 115-ft-thick bed. Laterally this merged coal bed is continuous for 15-40 mi, and it exists as a series of lenticular bodies that accumulated in raised mires (figs. PF-12 and PF-13).

- These lenticular coal bodies of the Wyodak-Anderson coal zone are laterally split by, and pinch out into, sandstone (shown in yellow), which was deposited in fluvial channels (fig. PF-14), and mudstone (shown in green), which was deposited in overbank, floodplain, and floodplain-lake environments (fig. PF-15).

- The lenticular coal bodies in the northern half of the cross section are laterally discontinuous. They are split and re-split by fluvial deposits, displaying a zigzag pattern on the cross section. They merge to form bodies that vary from 3 to 12 mi in length. Re-splitting of coal bodies may be caused by sediments deposited in crevasse channels and splays.

- The rocks below the Wyodak-Anderson coal zone consist of a more than 1,000-ft-thick interval of interbedded fluvial channel sandstone and overbank, floodplain, and lacustrine mudstone. Thin to thick, lenticular coal bodies of the interval, as much as 50 ft thick, formed from peat deposited in raised mires and low-lying swamps.

- The rocks above the Wyodak-Anderson coal zone consist of an interval more than 800 ft-thick of interbedded fluvial channel sandstone and overbank-floodplain-lacustrine mudstone. The thin lenticular coal bodies in the interval formed from peat deposited in low-lying swamps (fig. PF-16).

- The rocks of the Wyodak-Anderson coal zone were deposited in peat swamps and mires drained by meandering, anastomosed, and braided streams (Flores, 1981; 1986).

WYODAK-ANDERSON COAL ZONE

STRUCTURAL CROSS SECTION B-B'

- Structural cross section B-B' (fig. PF-17) extends about 200 mi along the western side of the Powder River Basin; it shows the Wyodak-Anderson coal zone and associated rocks. At the north end of the cross section, the rocks dip to the east-southeast, and at the south the rocks dip east-northeast. The cross section was drawn using data from 91 drill holes, which are not labeled on the cross section.

- The Wyodak-Anderson coal zone in the northern part of the cross section includes all coal beds from the Canyon at the bottom to the Anderson at the top. In the southern part of the cross section the coal zone includes all coal beds from the School at the bottom to the Badger at the top. The Wyodak-Anderson coal zone is called the Big George and Sussex coal zones in the central part of the basin (see cross section).

- The Wyodak-Anderson coal zone consists of two merged coal beds that form a bed 202 ft thick (see the south-central part of the cross section). This merged coal bed is found as discontinuous, lenticular coal bodies that laterally vary in length from 31 to 40 mi. The coal-forming peat was deposited in raised swamps.

- The lenticular Wyodak-Anderson coal bodies are laterally split by, and pinch out into, sandstone (shown in yellow) that was deposited in fluvial channels and mudstone (shown in green) that was deposited in overbank, floodplain, and floodplain-lake environments.

- The lenticular coal bodies of the Wyodak-Anderson coal zone are overlapping, laterally offset, and shingled, as best displayed from the central to southern parts of the cross section (see Big George through School-Badger coal zones). This indicates a younger age from the central to the southern part of the coal zone.

- The age differentiation of the overlapped coal zones is indicated by pollen and spore biozones that range from P5 in the Big George coal zone to P6 in the School-Badger coal zone.

- The rocks below the Wyodak-Anderson coal zone consist of an interval more than 700 ft thick of interbedded fluvial-channel sandstone and overbank-floodplain-lacustrine mudstone. The thin to thick lenticular coal beds in this interval formed from peat deposited in low-lying swamps.

- The rocks above the Wyodak-Anderson coal zone consist of an interval more than 1,000 ft thick of interbedded fluvial-channel sandstone, and overbank-

floodplain-lacustrine mudstone. The thin lenticular coal beds in this interval formed from peat deposited in low-lying swamps.

- The rocks of the Wyodak-Anderson coal zone were deposited in peat swamps and mires drained by meandering, anastomosed, and braided streams.

WYODAK-ANDERSON COAL ZONE

STRUCTURAL CROSS SECTION C-C'

- Structural cross section C-C' (fig. PF-18) extends about 52 mi from west to east through the central part of the Powder River Basin; it shows the Wyodak-Anderson coal zone and associated rocks. At the east end of the cross section, the rocks dip to the west. The cross section was drawn using data from 58 drill holes, which are not labeled on the cross section.

- In the eastern part of the cross section, the Wyodak-Anderson coal zone, about 480-ft-thick, includes a merged coal bed more than 160 ft thick. This bed splits toward the west and east along a belt more than 8 mi wide, and pinches out toward the east.

- In the western part of the cross section, the Wyodak-Anderson coal zone, about 900 ft thick, includes a merged coal bed that is as much as 200 ft thick. This bed repeatedly splits and merges, forming a zigzag pattern along a belt 35 mi wide.

- The coal zone on the west is overlapped by the coal zone on the east, indicating that the latter zone is younger.

- The age differentiation of the overlapped coal zones is indicated by pollen and spore biozones that range from P5 on the west to P5-P6 on the east.

- The coal beds of the Wyodak-Anderson coal zone formed in raised mires that were laterally split by, and pinch out into, sandstone (shown in yellow) that was deposited in fluvial channels. The mudstone (shown in green) was deposited in overbank, floodplain, and floodplain-lake environments.

- The rocks below the Wyodak-Anderson coal zone consist of an interval more than 700 ft thick of interbedded fluvial-channel sandstone, and overbank, floodplain, and lacustrine mudstone. The thin to thick lenticular coal beds formed from peat deposited in low-lying swamps.

- The rocks above the Wyodak-Anderson coal zone consist of an interval more than 1,000 ft thick of interbedded fluvial-channel sandstone, and overbank, floodplain, and lacustrine mudstone. The thin lenticular coal beds formed from peat deposited in low-lying swamps.

- The rocks of the Wyodak-Anderson coal zone, and rocks above and below the coal zone, were deposited in peat-forming fluvial environments drained by meandering, anastomosed, and braided streams.

WYODAK-ANDERSON COAL ZONE

STRUCTURAL CROSS SECTION D-D'

- Structural cross section D-D' (fig. PF-19) extends about 64 miles from west to east through the south-central part of the Powder River Basin; it shows the Wyodak-Anderson coal zone and associated rocks. At the east end of the cross section, the rocks dip to the west. The cross section was drawn using data from 69 drill holes, which are not labeled on the cross section.

- In the eastern part of the cross section, the Wyodak-Anderson coal zone consists of a merged coal bed, about 150 ft thick, which splits toward the west and east along a belt 30 mi wide.

- In the western part of the cross section, the Wyodak-Anderson coal zone, about 800 ft thick, includes a merged coal bed, as much as 200 ft thick. This bed splits and merges westward and eastward along a belt 40 mi wide, forming a zigzag pattern.

- The coal zone on the west is overlapped by the coal zone on the east, exhibiting a shingled pattern and indicating that the latter coal zone is younger.

- The age differentiation of the overlapped coal zone is indicated by pollen and spore biozones P5 to the west and P5-P6 to the east.

- The coal beds of the Wyodak-Anderson coal zone, which formed in raised mires, are laterally split by, and pinch out into, sandstone (shown in yellow) that

was deposited in fluvial channels and mudstone (shown in green) that was deposited in overbank, floodplain, and floodplain-lake environments.

- The rocks below the Wyodak-Anderson coal zone consist of an interval 1,500 ft thick of interbedded fluvial-channel sandstone and overbank, floodplain, and lacustrine mudstone. The thin to thick lenticular coal beds formed from peat deposited in low-lying swamps.

- The rocks above the Wyodak-Anderson coal zone consist of an interval 1,500 ft thick of interbedded fluvial-channel sandstone, and overbank, floodplain, and lacustrine mudstone. The thin lenticular coal beds formed from peat deposited in low-lying swamps.

- The rocks of the Wyodak-Anderson coal zone, and rocks above and below the coal zone, were deposited in peat-forming fluvial environments drained by meandering, anastomosed, and braided streams.

WYODAK-ANDERSON COAL ZONE

STRUCTURAL CROSS SECTION E-E'

- Structural cross section E-E' (fig. PF-20) extends about 59 mi from west to east through the south-central part of the Powder River Basin; it shows the Wyodak-Anderson coal zone and associated rocks. At the east end of the cross section, the rocks dip to the west. The cross section was drawn using data from 32 drill holes, which are not labeled on the cross section.

- The Wyodak-Anderson coal zone, about 490 ft thick, includes a merged coal bed more than 100 ft thick that splits toward the west and east.

- The coal beds of the Wyodak-Anderson coal zone formed in raised mires; the coal zone is laterally split by, and pinches out into sandstone (shown in yellow) that was deposited in fluvial channels. The mudstone (shown in green) was deposited in overbank, floodplain, and floodplain-lake environments.

- The rocks below the Wyodak-Anderson coal zone consist of an interval more than 1,500 ft thick of interbedded fluvial-channel sandstone, and overbank, floodplain, and lacustrine mudstone. The thin to thick lenticular coal beds formed in low-lying swamps.

- The rocks above the Wyodak-Anderson coal zone consist of an interval more than 1,000 ft thick of interbedded fluvial-channel sandstone, and overbank, floodplain, and lacustrine mudstone. The thin lenticular coal beds formed in low-lying swamps.

- The rocks of the Wyodak-Anderson coal zone, and rocks above and below the coal zone, were deposited in peat-forming fluvial environments drained by meandering, anastomosed, and braided streams.

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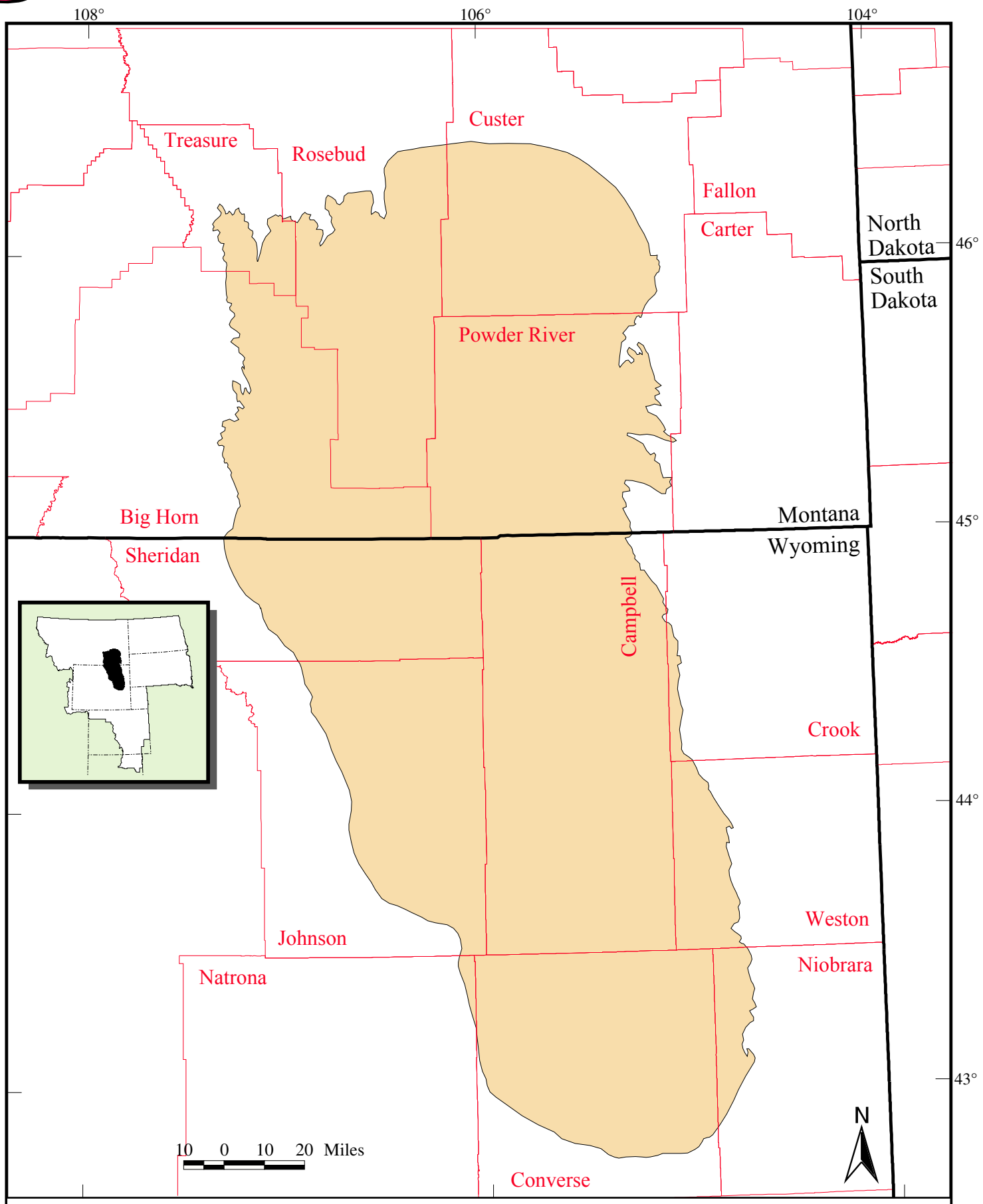

Figure PF-1. Location map showing the Powder River Basin.

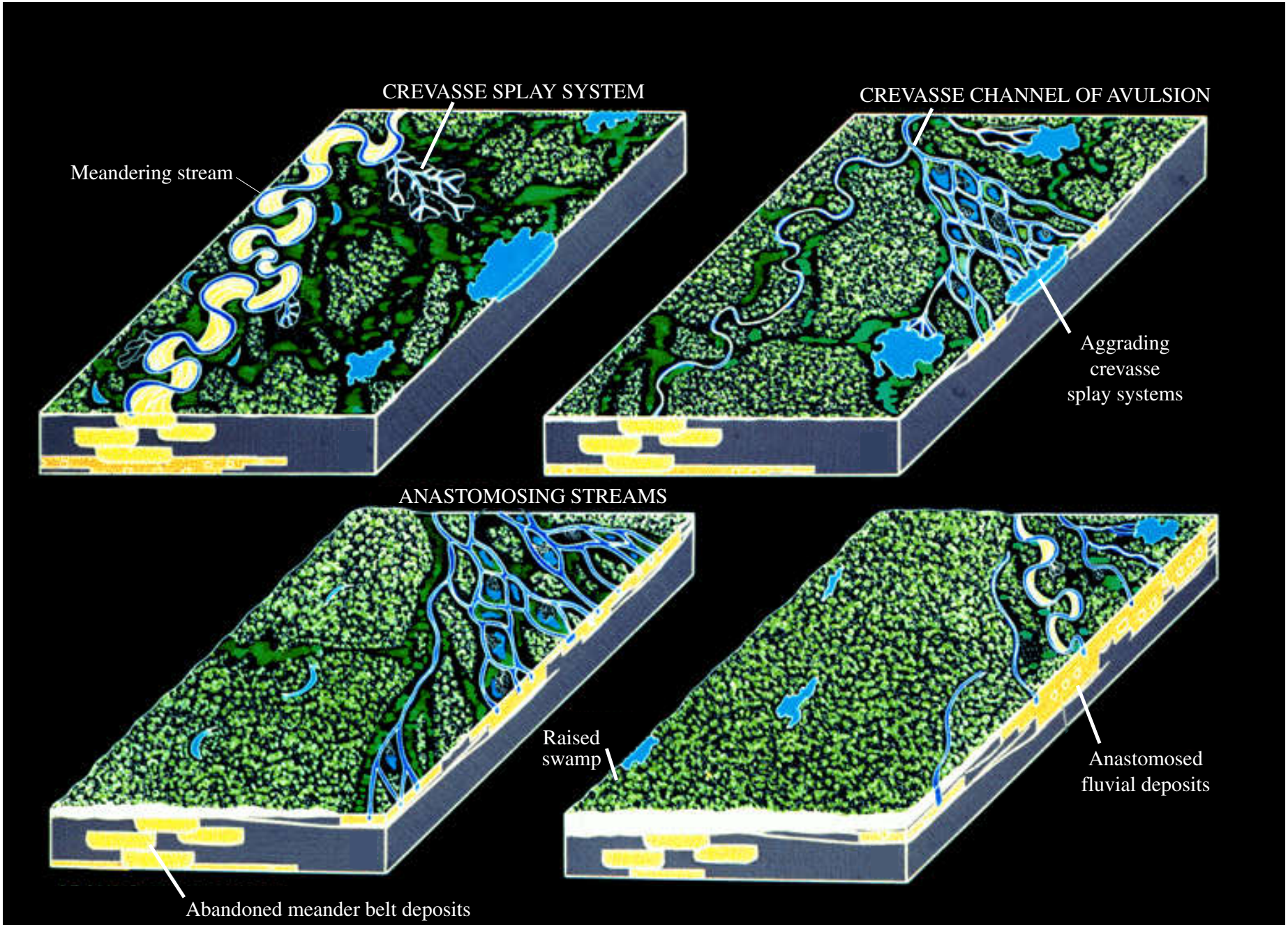

Figure PF-2. Depositional models of braided, meandering, and anastomosed streams in the Powder River Basin, adapted from Flores (1986).

Figure PF-3. Modern analog of a fluvial system consisting of braided, meandering, and anastomosed channels of the Susitna River in Alaska. Photograph by J.H. McGowen.

Figure PF-4. Modern analog of a peat-forming, low-lying swamps in the Atchafalaya River Basin in Louisiana. Photograph by R.M. Flores.

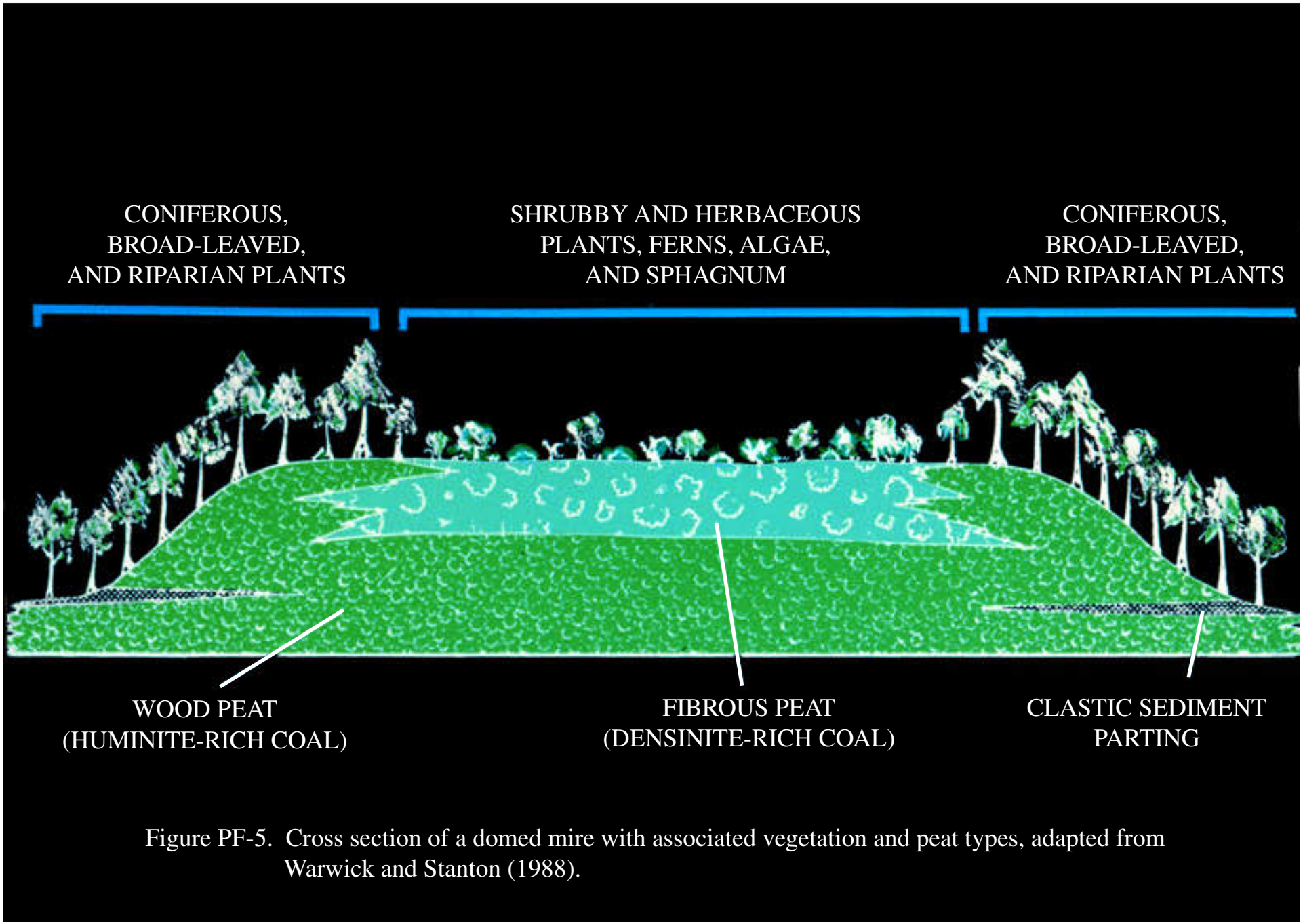

Figure PF-5. Cross section of a domed mire with associated vegetation and peat types, adapted from Warwick and Stanton (1988).

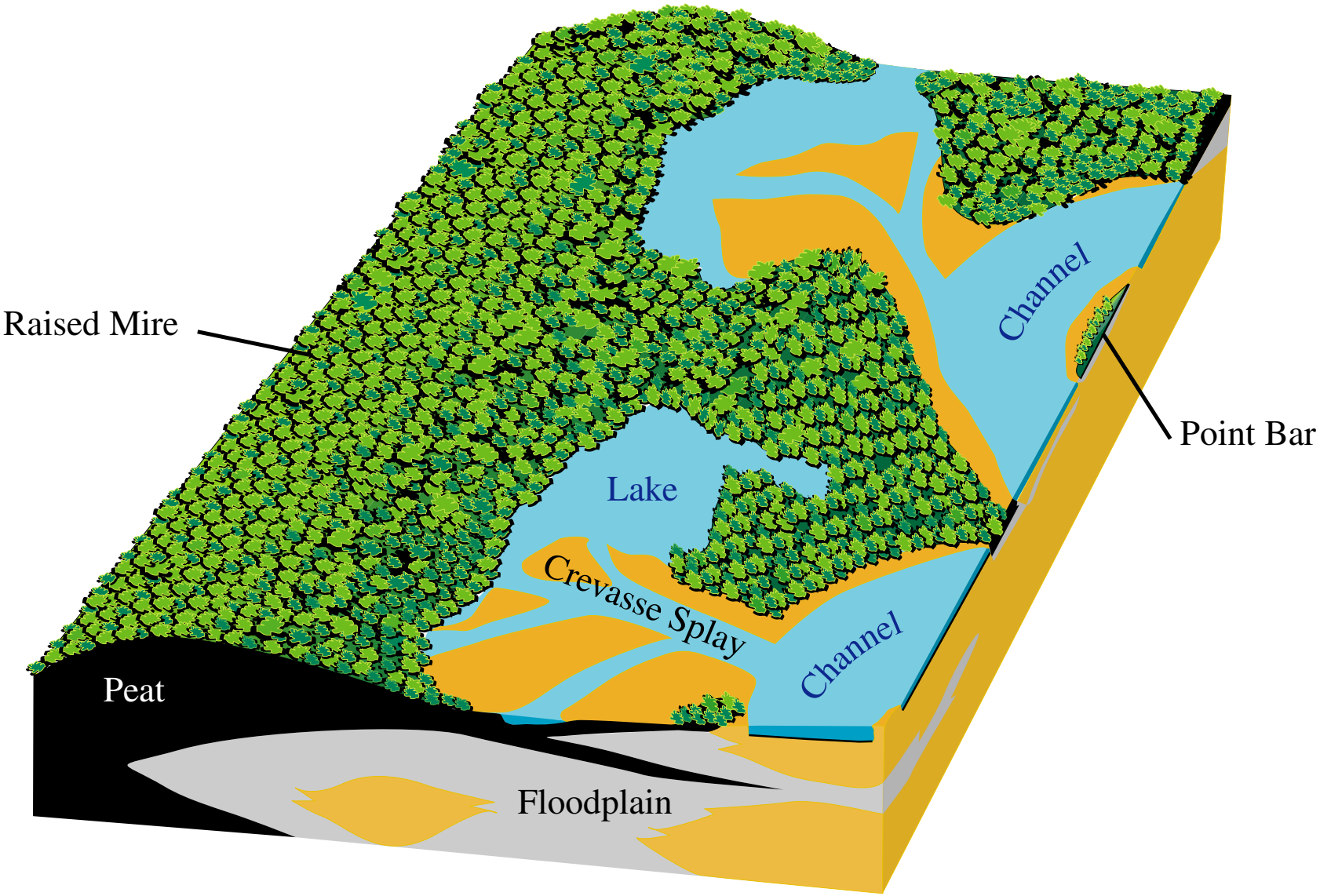

Figure PF-6. Depositional model of the Wyodak-Anderson coal zone and associated sediments in the Decker coalfield, Montana. Adapted from Moore (1986) and Flores and others (1989).

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Figure PS-7. Peat exposed along a drainage ditch cut near the margin of a raised bog in central Kalimantan, Borneo. Photograph by C. Blaine Cecil.

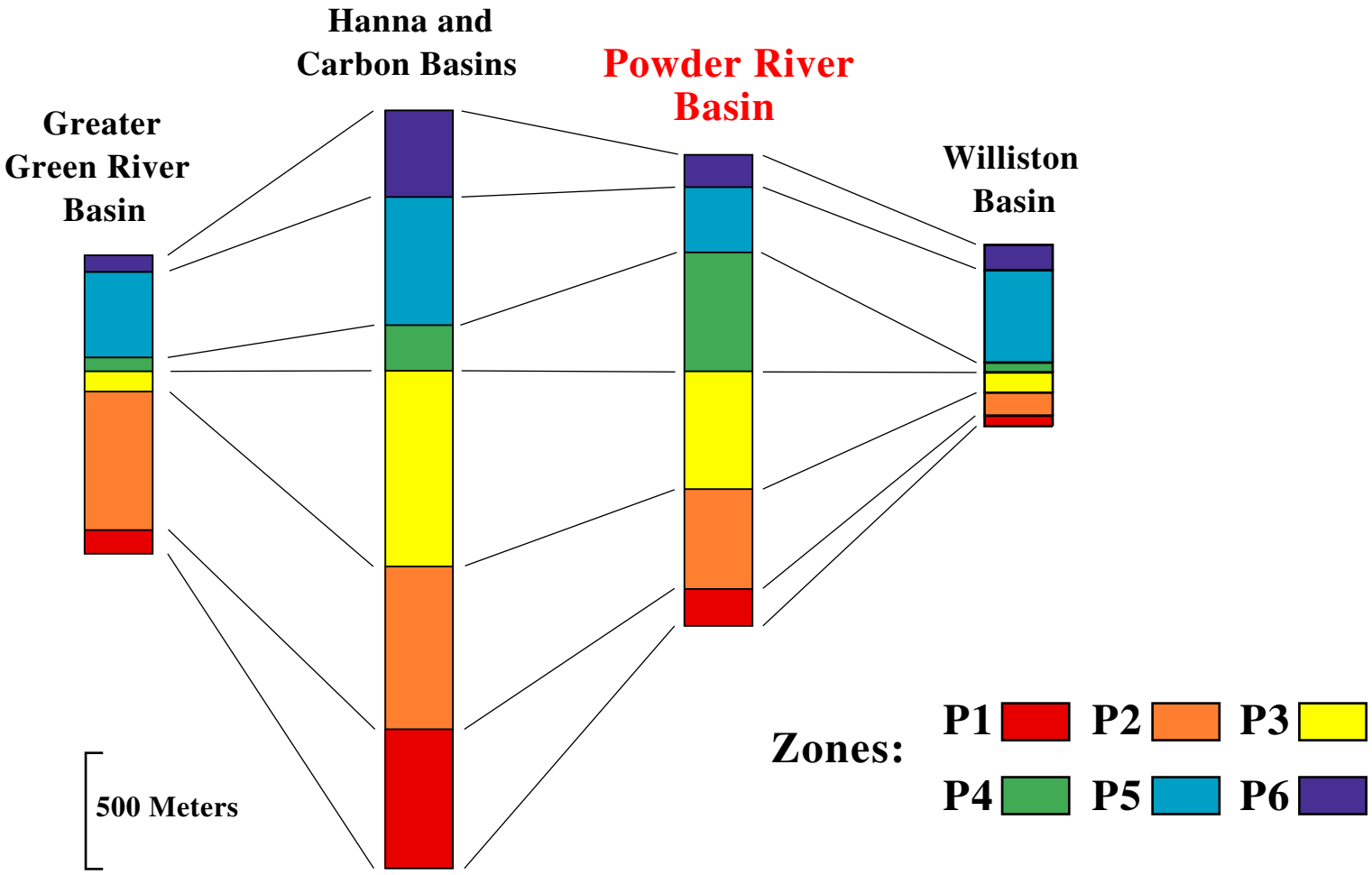
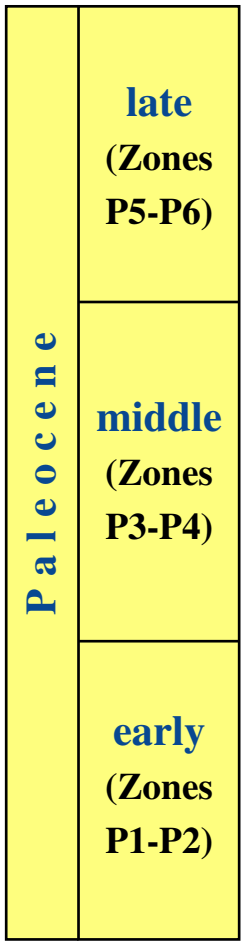


Figure PF-8. Composite correlation of Paleocene sections based on palynostratigraphy.



Wyodak-Anderson.....Powder River Basin

Beulah-Zap.....Williston Basin

Hanna Nos. 77-79, 81.....Hanna Basin

Hagel.....Williston Basin

Johnson-107.....Carbon Basin

Knobloch, Rosebud } .....Powder River Basin

Harmon, Hansen } .....Williston Basin

Deadman Seams 1-5....Greater Green River Basin

Ferris Nos. 23, 25, 31, 50, & 65 } .....Hanna Basin

Figure PF-9. Composite stratigraphic section for the assessment region showing the studied coal beds and zones with age relationships based on palynology. Assessment units in the Powder River Basin are highlighted in red.

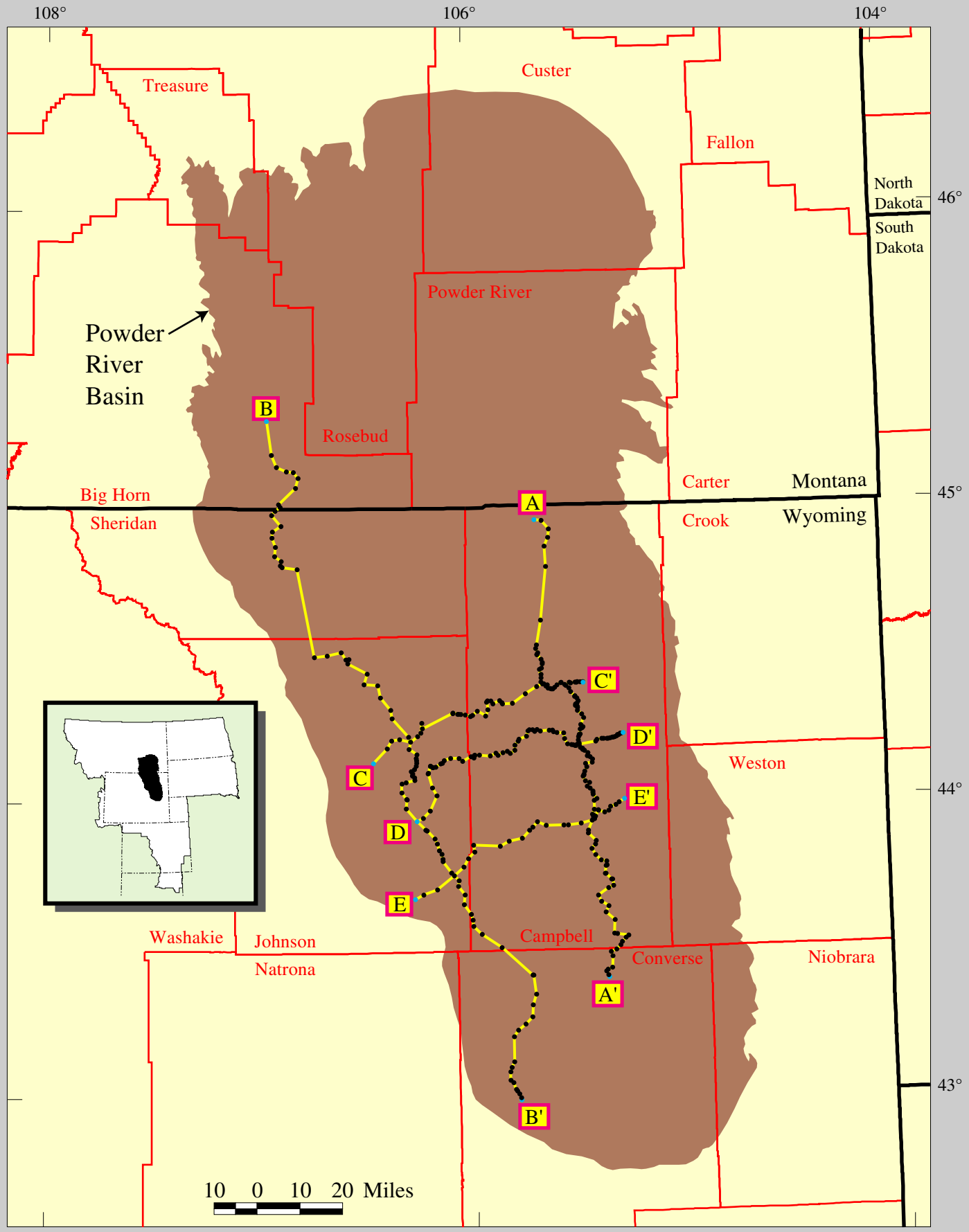


Figure PF-10. Map showing locations of Wyodak-Anderson coal zone cross sections.

A — A' Cross section with nonproprietary drill holes

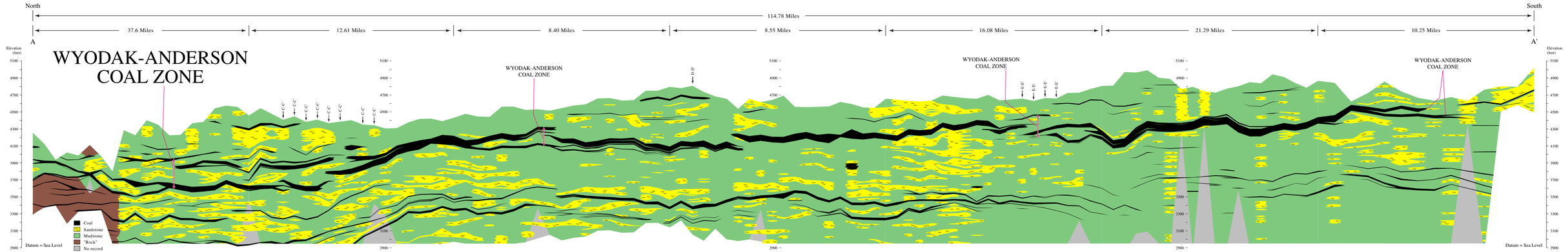


Figure PF-11. Wyodak-Anderson coal zone structural cross section A-A'.

Figure PF-12.Vegetation and logging railroad on top of a raised mire in Central Kalimantan, Borneo. Photograph by C. Blaine Cecil.

Figure PF-13. Domed mire along a drainage ditch that parallels an oil field road between the Siak and Kampar River/estuaries in Sumatra, Indonesia. Photograph by C. Blaine Cecil.

Figure PF-14. Meandering and anastomosed channels of the Beluga River in the Upper Cook Inlet, Alaska. Photograph by R.M. Flores.

Figure PF-15. Fluvial channels, overbank, lakes, floodplains, and low-lying swamps of the Saskatchewan River in the Saskatchewan Province, Canada. Photograph by N.D. Smith.

Figure PF-16. Abandoned crevasse channels, splays, and low-lying swamps of the Saskatchewan River in the Saskatchewan Province, Canada. Photograph by N.D. Smith.

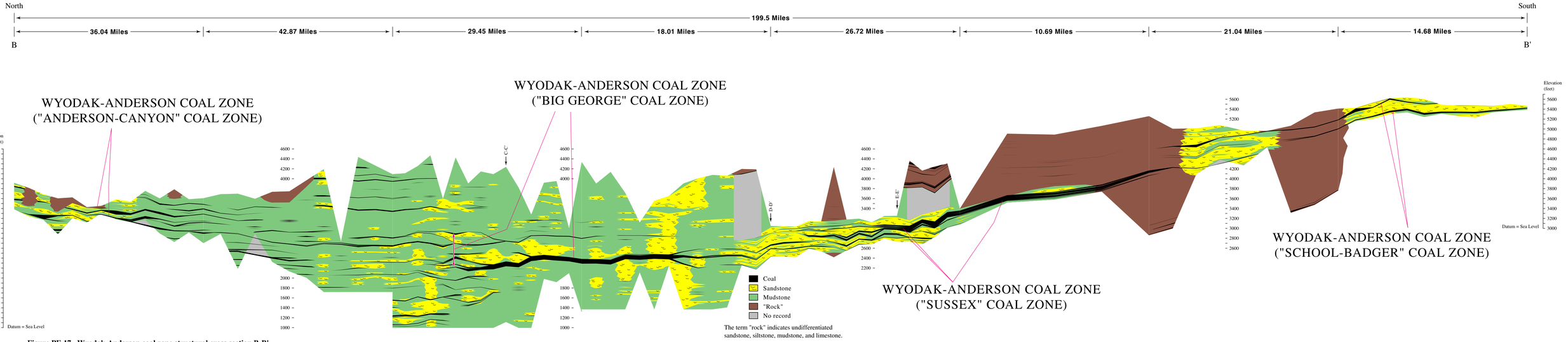
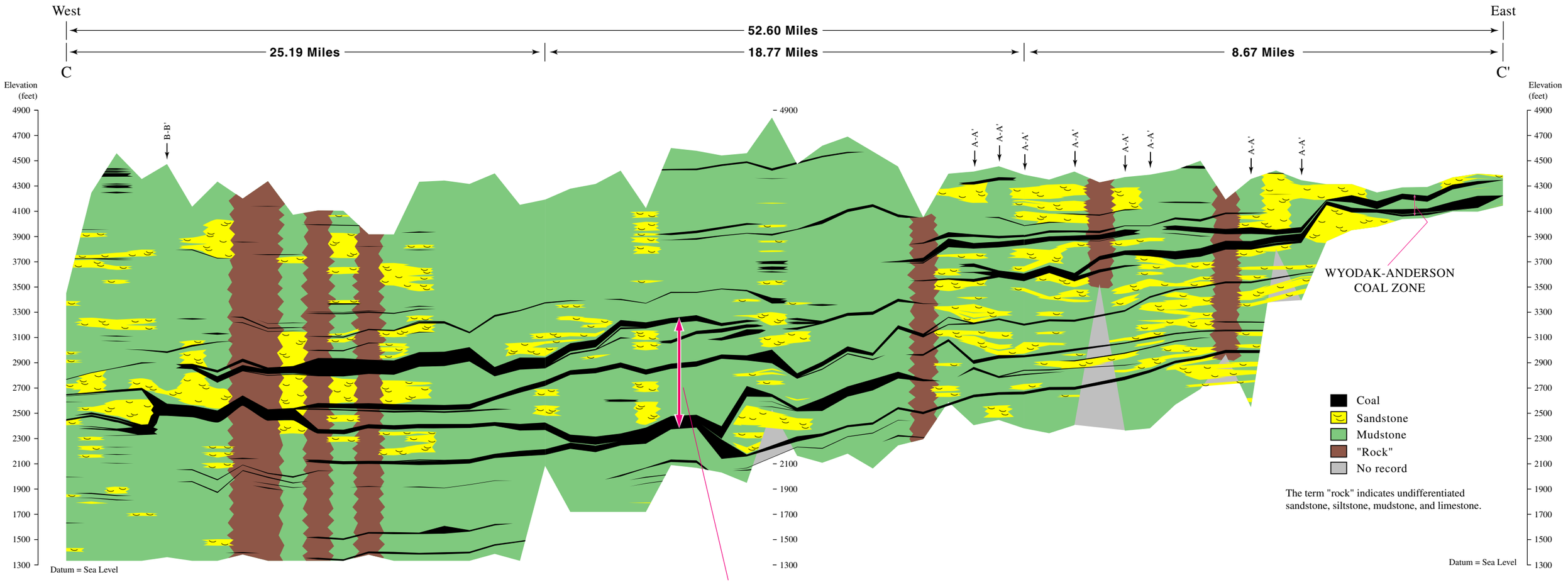


Figure PF-17. Wyodak-Anderson coal zone structural cross section B-B'.



Wyodak-Anderson coal zone

Figure PF-18. Wyodak-Anderson coal zone structural cross section C-C'.

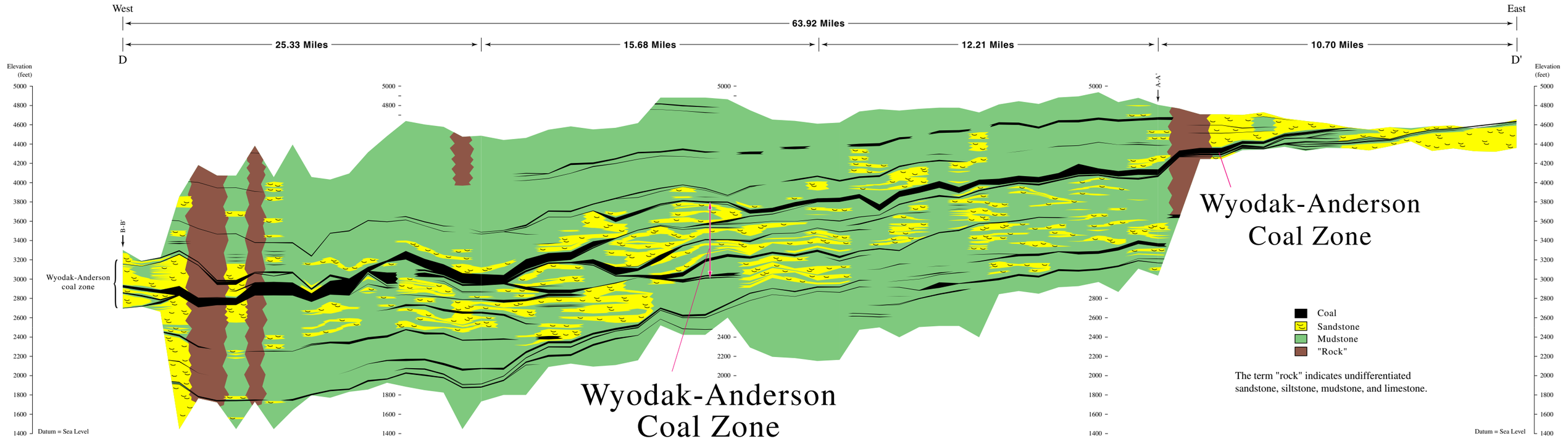


Figure PF-19. Wyodak-Anderson coal zone structural cross section D-D'.

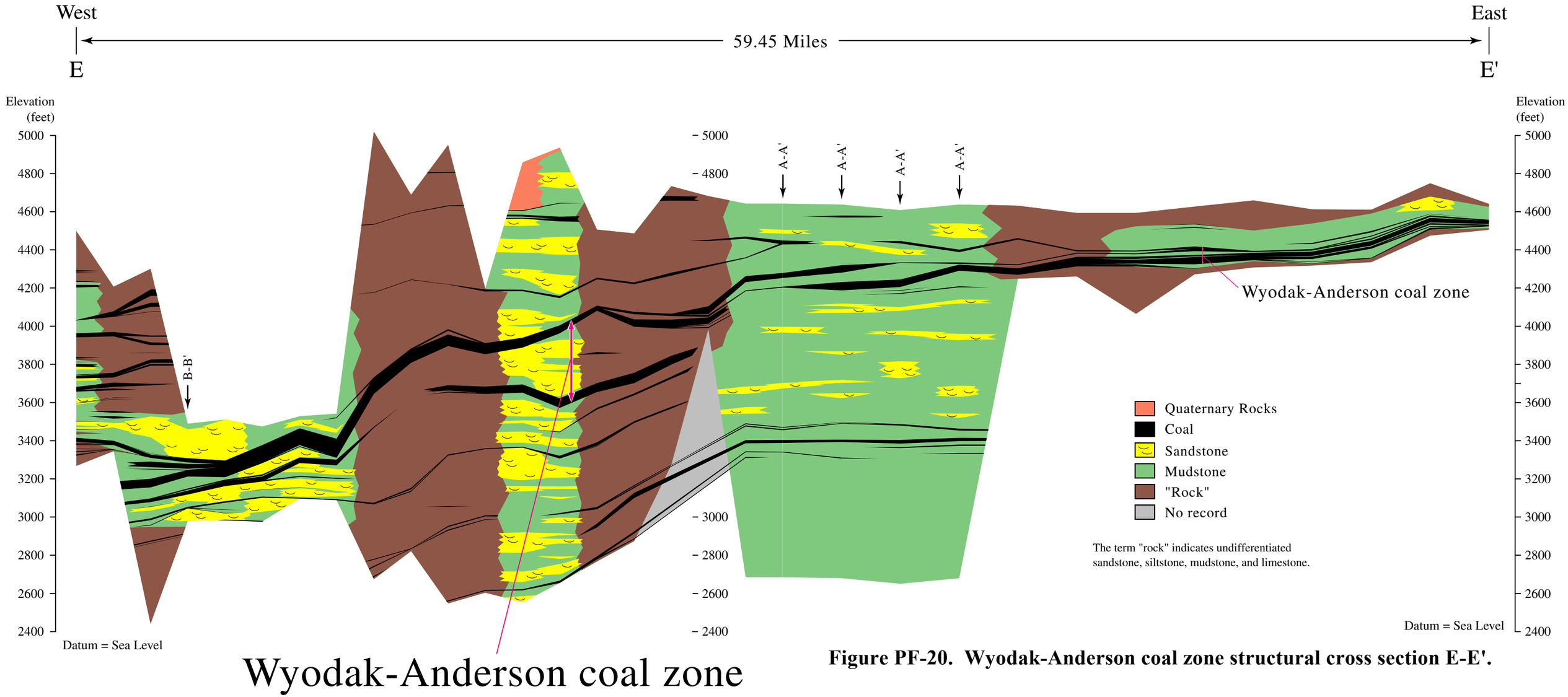


Figure PF-20. Wyodak-Anderson coal zone structural cross section E-E'.