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GEOLOGICAL SURVEY

SUMMARY OF THE GEOLOGY, MINERAL RESOURCES, LANDSCAPE GEOCHEMISTRY, AND ENGINEERING GEOLOGIC CHARACTERISTICS OF THE NORTHERN POWDER RIVER COAL REGION, MONTANA

PART A.--Geology and mineral resources
by W. J. Mapel and V. E. Swanson

PART B.--Landscape geochemistry
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PART C.--Engineering geologic characteristics
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SUMMARY OF THE GEOLOGY, MINERAL RESOURCES, AND ENGINEERING GEOLOGIC CHARACTERISTICS OF THE NORTHERN POWDER RIVER COAL REGION, MONTANA

PART A.--GEOLOGY AND MINERAL RESOURCES

by W. J. Mapel and V. E. Swanson

INTRODUCTION

The Powder River coal region is a large area of coal-bearing rocks which together with the laterally continuous Fort Union coal region to the northeast occupies substantial parts of Wyoming, Montana, and North and South Dakota (Trumbull, 1960) (fig. 1). This report describes a part of this region, called here the northern Powder River coal region. As defined for the purposes of this report the northern Powder River coal region includes about 20,000 square km in southeastern Montana, extending roughly from the Montana-Wyoming boundary northward to the Yellowstone River near Forsyth and Miles City, and from an irregular north-trending line 3-15 km east of the Little Bighorn and Bighorn Rivers eastward to about the Little Powder and Powder Rivers (fig. 2). The area includes most of Powder River County, and parts of Custer, Big Horn, Rosebud, and Treasure Counties, Montana.

The Northern Cheyenne and eastern part of the Crow Indian Reservations occupy about 4,600 square km in the western and central parts of the region.

This report summarizes the geology and mineral resources in the northern Powder River coal region, with special emphasis on the coal resources. The information is intended for use in assessing environmental impacts of coal mining in the area.

GEOGRAPHIC FEATURES

Rosebud Creek, the Tongue River, and the Powder River, all northward or northeastward flowing tributaries of the Yellowstone River, are the major drainageways in the northern Powder River coal region. The region is deeply and intricately dissected by these streams and their tributaries. The highest parts of the region reach elevations of nearly 1,340 m in the Wolf and Little Wolf Mountains in and near the Crow Indian Reservation in the western part of the region, in the Badger Hills along the Montana-Wyoming border, and on a few high peaks and buttes, including Garfield Peak, Cook Mountain, and King Mountain in the central part of the region. The lowest elevation is about 790 m along the Powder River south of Miles City.

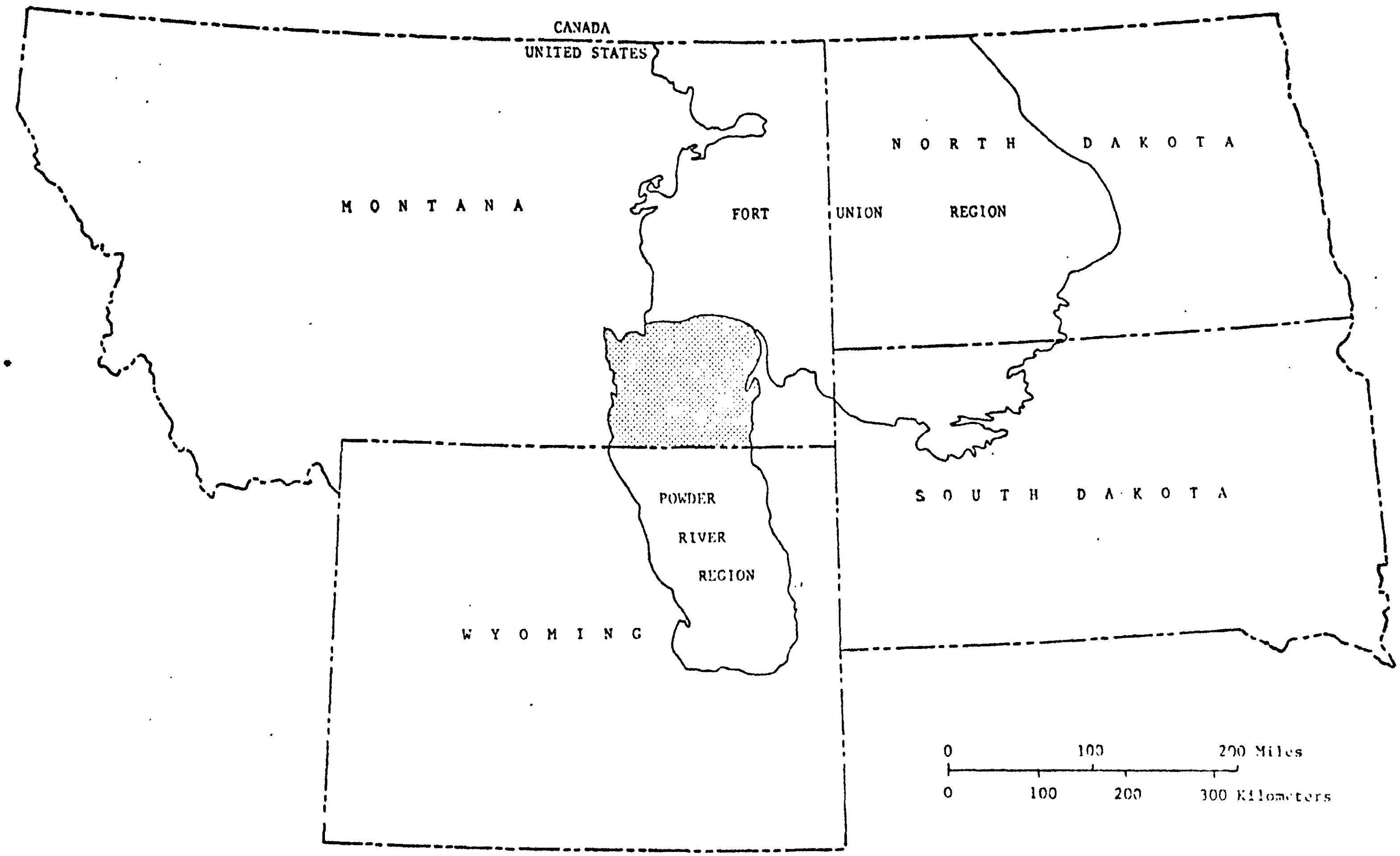

Figure 1.—Location of the northern Powder River coal region (stippled).

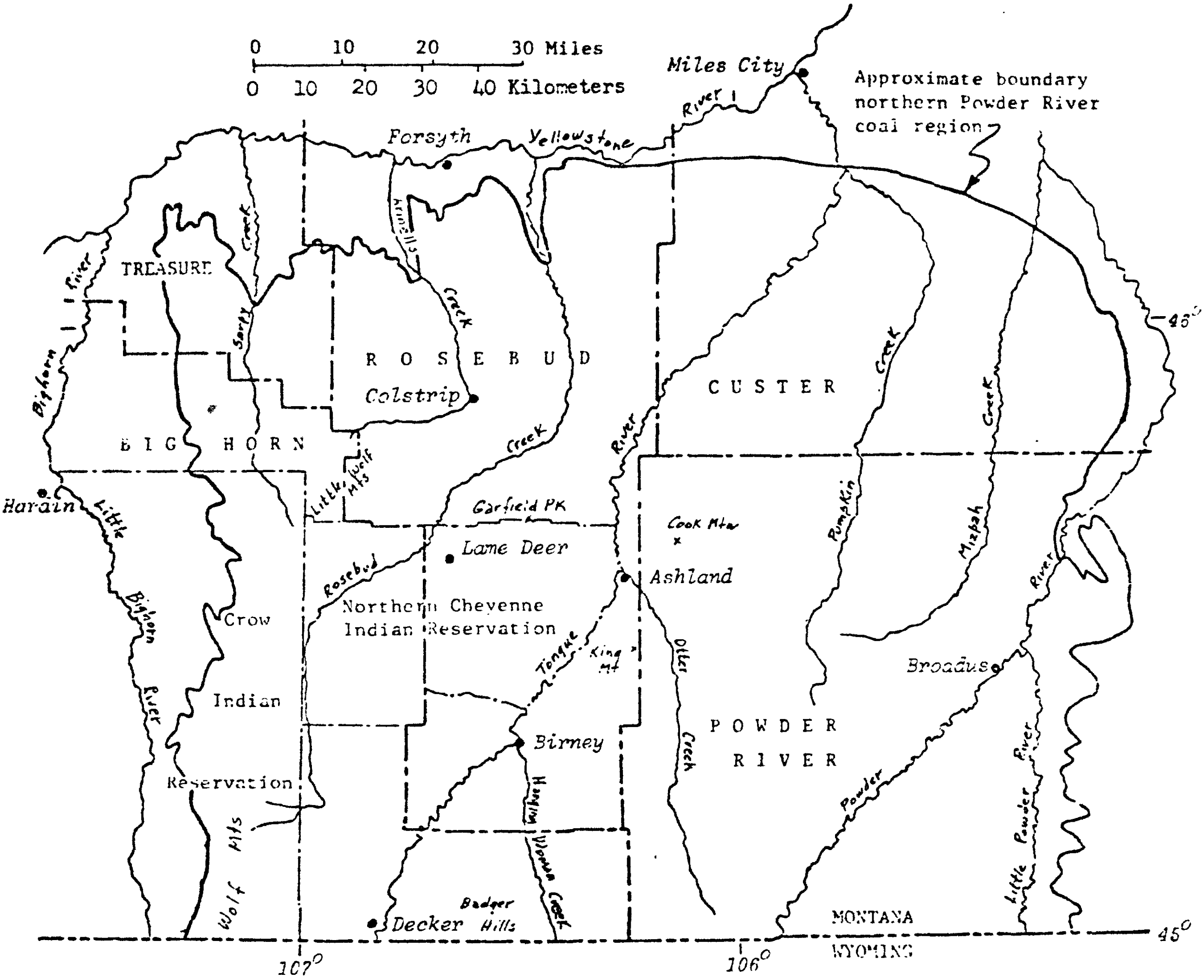

Figure 2.—Area described, northern Powder River coal region.

SOURCES OF INFORMATION

Published sources of information, principally reports of the U.S. Geological Survey and the Montana Bureau of Mines and Geology, have been used extensively in assembling this summary report. Statistical data on coal mining, oil and gas production, and the production of other mineral resources are available from the U.S. Bureau of Mines. Petroleum Information, Denver, Colorado, is a source of information on oil and gas exploration and production.

CONVERSION OF METRIC UNITS

Units of measurement used in the text of this report are in the metric system. Factors for conversion to the more customary English system are as follows:

1 meter-------------------------	3.281 feet
1 kilometer---------------------	.6214 miles
1 square kilometer--------------	.386 square miles
1 hectare-----------------------	2.471 acres
1 tonne-------------------------	1.1023 short tons
1 kilogram-calorie per kilogram----------------------	1.8 British thermal unit per pound
1 liter-------------------------	.0353 cubic feet

STATUS OF COAL STUDIES

Systematic areal studies of coal-bearing rocks in the Montana part of the Powder River coal region have been in progress intermittently for about 70 years. Except for areas covered by the Indian Reservations, the broad features of the geology, and the identification and many details of the correlation of coal beds were worked out by about 1966 with the completion of a study of the Moorhead coal field (Bryson and Bass, 1966, 1973). Very little detailed information has been published about the coal geology in the Crow and Northern Cheyenne Indian Reservations in the western and central parts of the region, except for a reconnaissance study in the Crow Indian Reservation made in the 1920's (Thom and others, 1935). From about 1968, detailed studies have been undertaken at many places in the region with the objectives of determining more accurately the continuity of the coal beds, refining coal-bed correlations, locating more accurately the positions of coal beds where they were originally mapped on inadequate base maps, determining the locations and tonnages of coal in the thicker beds where they are present under shallow cover, and determining more precisely the physical and chemical character of the coal. Information on coal in the present report is a compilation of information from these many studies, as shown on figures 3 and 4.

GEOLOGIC SETTING

The Powder River coal region coincides closely with the Powder River structural basin, a broad, northeast-trending synclinal feature at least 400 km long and as much as 160 km wide in eastern Wyoming and southeastern Montana. In Montana the basin is bounded on the north by the Bull Mountains Basin, Porcupine Dome, and by a broad, low, poorly defined structural saddle known as the Miles City Arch that connects the Porcupine Dome with the northern end of the Black Hills Uplift to the southeast. The Miles City Arch separates the Powder River Basin from the large Williston Basin to the northeast. The Big Horn Mountains-Pryor Mountains Uplift borders the Powder River Basin on the west, and the Black Hills Uplift borders it on the east (fig. 5). These structural features account broadly for the distribution of rock units in the northern part of the basin, the oldest rocks being exposed on the periphery of the basin where they come to the surface on the flanks of the bordering uplifts, and the youngest rocks, excluding surficial stream terrace deposits and alluvium, being exposed where preserved in the down-folded central part of the basin.

The distribution of rock units at the surface in the northern part of the basin is shown by the geologic map (fig. 6).

ROCK UNITS

Rocks exposed in the northern Powder River coal region belong mostly to the Fort Union Formation of Paleocene age. The basal part of the Wasatch Formation of Eocene age, which overlies the Fort Union Formation, crops out in small areas along the Montana-Wyoming border in the southern part of the region, and the Late Cretaceous Hell Creek Formation, which underlies the Fort Union Formation, crops out in the valley of the Powder and Little Powder Rivers on the eastern side and in the valley of the Yellowstone River and some of its tributaries in the northern part and along the western side. Surficial deposits of alluvium slope wash, landslide material, and stream gravel are found along the sides and on the floors of the main stream valleys.

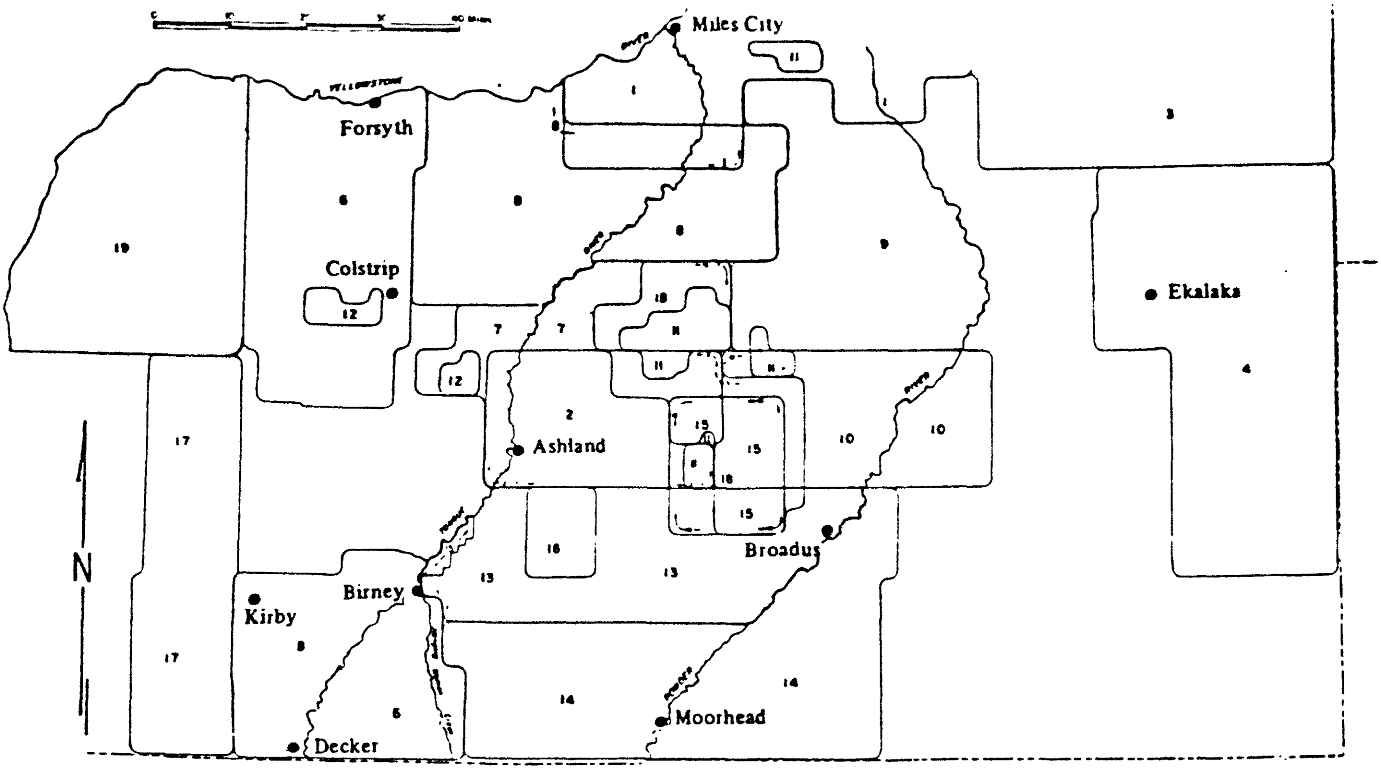

Figure 3.—Areas covered by earlier coal reports, released 1909-1969. From Matson and Blumer, 1973.

1. 1909. COLLIER, A.J., and SMITH, C.D., The Miles City coal field, Montana: U.S. Geol. Survey Bull. 341-A, p. 36-61.
2. 1910. WEGEMANN, C.H., Notes on coals of Custer National Forest, Montana: U.S. Geol. Survey Bull. 381-A, p. 108-114.
3. 1912. BOWEN, C.F., The Baker lignite field, Custer County, Montana: U.S. Geol. Survey Bull. 471-D, p. 202-226.
4. 1924. BAUER, C.M., The Ekalaka lignite field, southeastern Montana: U.S. Geol. Survey Bull. 751-F, p. 231-267.
5. 1929. BAKER, A.A., The northward extension of the Sheridan coal field, Big Horn and Rosebud Counties, Montana: U.S. Geol. Survey Bull. 806-B, p. 15-67.
6. 1930. DOBBIN, C.E., The Forsyth coal field, Rosebud, Treasure, and Big Horn Counties, Montana: U.S. Geol. Survey Bull. 812-A, p. 1-55.
7. 1932. BASS, N.W., The Ashland coal field, Rosebud, Powder River, and Custer Counties, Montana: U.S. Geol. Survey Bull. 831-B, p. 19-105.
8. 1936. PIERCE, W.C., The Rosebud coal field, Rosebud and Custer Counties, Montana: U.S. Geol. Survey Bull. 847-B, p. 43-120.
9. 1939. PARKER, F.S., and ANDREWS, D.A., The Mizpah coal field, Custer County, Montana: U.S. Geol. Survey Bull. 906-C, p. 85-133.
10. 1952. BRYSON, R.P., The Coalwood coal field, Powder River County, Montana: U.S. Geol. Survey Bull. 973-B, p. 23-106.
11. 1954. BROWN, ANDREW, and others, Strippable coal in Custer and Powder River Counties, Montana: U.S. Geol. Survey Bull. 995-E, p. 151-199.
12. 1954. KEPFERLE, R.C., Selected deposits of strippable coal in central Rosebud County, Montana: U.S. Geol. Survey Bull. 995-I, p. 333-381.
13. 1959. WARREN, W.C., Reconnaissance geology of the Birney-Broadus coal field, Rosebud and Powder River Counties, Montana: U.S. Geol. Survey Bull. 1072-J, p. 561-585.
14. 1966. BRYSON, R.P., and BASS, N.W., Geologic map and coal sections of the Moorhead coal field, Montana: U.S. Geol. Survey Open-file Rept., 37 fig., 3 tables, in 15 sheets.
15. 1969. GILMOUR, E.H., and WILLIAMS, L.A., Geology and coal resources of the Foster Creek coal deposit, eastern Montana: Montana Bur. Mines and Geology Bull. 73, 9 p.
-----Northern Pacific Railway Company cooperative projects with the Montana Bureau of Mines and Geology in 1966 and 1967.
16. 1968. MATSON, R.E., DAHL, G.G., JR., and BLUMER, J.W., Strippable coal deposits on state land, Powder River County, Montana: Montana Bur. Mines and Geology Bull. 69, 81 p.
17. 1935. THOM, W.T., JR., HALL, G.M., WEGEMANN, C.H., and MOULTON, G.F., Geology of Big Horn County and the Crow Indian Reservation, Montana, with special reference to the water, coal, oil, and gas resources: U.S. Geol. Survey Bull. 856, 200 p.
18. 1967. CARMICHAEL, V.W., The Pumpkin Creek lignite deposit, Powder River County, Montana: Unpub. thesis, 79 p.
19. 1923. ROGERS, G.S., and LEE, WALLACE, Geology of the Tullock Creek coal field, Rosebud and Big Horn Counties, Montana: U.S. Geol. Survey Bull. 749, 181 p.

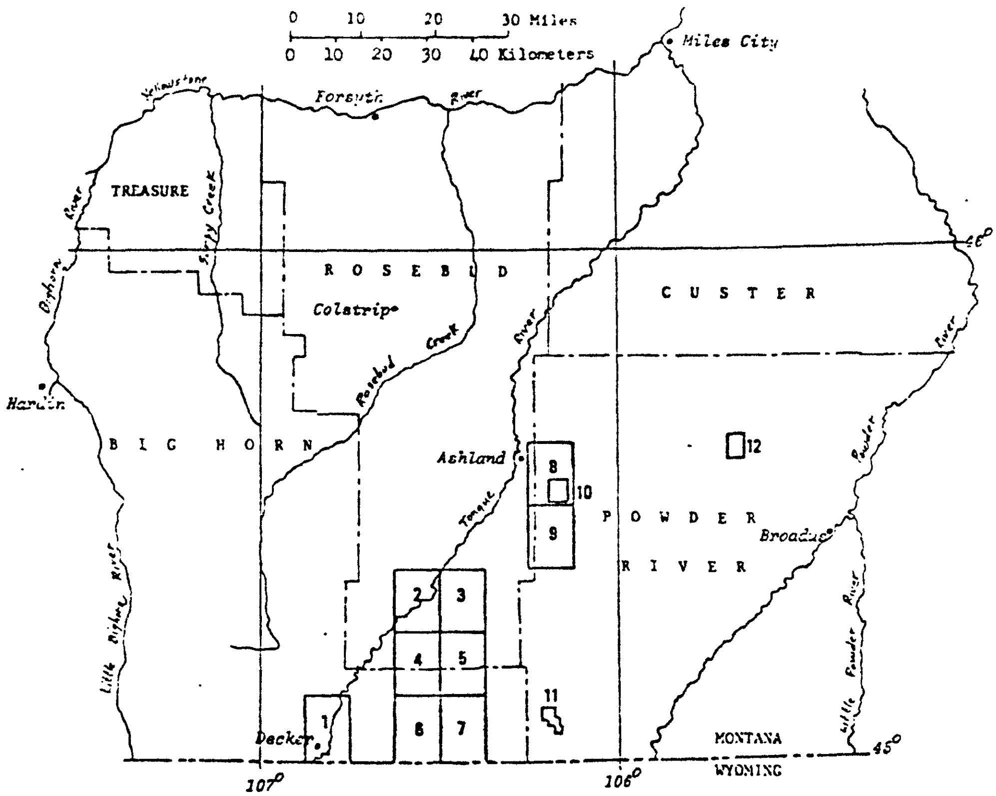

Figure 4.—Areas covered by later coal reports, released 1970–1977.

1. Law, B. E., and Grazis, S. L., 1972, Preliminary geologic map and coal resources of the Decker quadrangle, Big Horn County, Montana: U.S. Geol. Survey Open-file Rept.

2. Mapel, W. J., 1976, Geologic map and coal sections of the Birney quadrangle, Rosebud County, Montana: U.S. Geol. Survey Misc. Field Studies Map MF-813.

3. Culbertson, W. C., and Klett, M. C., 1976, Geologic map and coal sections of the Browns Mountain quadrangle, Rosebud County, Montana: U.S. Geol. Survey Misc. Field Studies Map MF-814.

4. Sarnecki, J. C., 1977, Geologic map and coal sections of the Lacey Gulch quadrangle, Rosebud and Big Horn Counties, Montana: U.S. Geol. Survey Misc. Field Studies Map MF-832.

5. Culbertson, W. C., Mapel, W. J., and Klett, M. C., 1976, Geologic map and coal sections of the Stroud Creek quadrangle, Rosebud and Big Horn quadrangle, Montana: U.S. Geol. Survey Misc. Field Studies Map MF-822.

6. Mapel, W. J., 1977, Geologic map and coal sections of the Pine Butte School quadrangle, Big Horn County, Montana: U.S. Geol. Survey Misc. Field Studies Map (in press).

7. Culbertson, W. C., and Klett, 1977, Geologic map and coal sections of the Forks Ranch quadrangle, Big Horn County, Montana: U.S. Geol. Survey Misc. Field Studies Map (in press).

8. McKay, E. J., 1976a, Geologic map and coal sections of the Willow Crossing quadrangle, Powder River and Rosebud Counties, Montana: U.S. Geol. Survey Misc. Field Studies Map MF-802.

9. McKay, E. J., 1976b, Geologic map and coal sections of the King Mountain quadrangle, Powder River and Rosebud Counties, Montana: U.S. Geol. Survey Misc. Field Studies Map MF-817.

10. U.S. Bureau of Land Management, 1975, Resource and potential reclamation evaluation, Otter Creek study site: EMRIA Rept. 1, 200 p.

11. U.S. Bureau of Land Management, 1977, Resource and potential reclamation evaluation, Bear Creek study site: EMRIA Rept. (in press).

12. U.S. Bureau of Land Management, 1977, Resource and potential reclamation evaluation, Pumpkin Creek study site; EMRIA Rept. (in press).

Not shown: Matson, R. E., and Blumer, J. W., 1973, Quality and reserves of strippable coal, selected deposits, southeastern Montana: Montana Bur. Mines and Geology Bull. 91, 135 p. Plates 1 to 32 are maps of individual deposits.

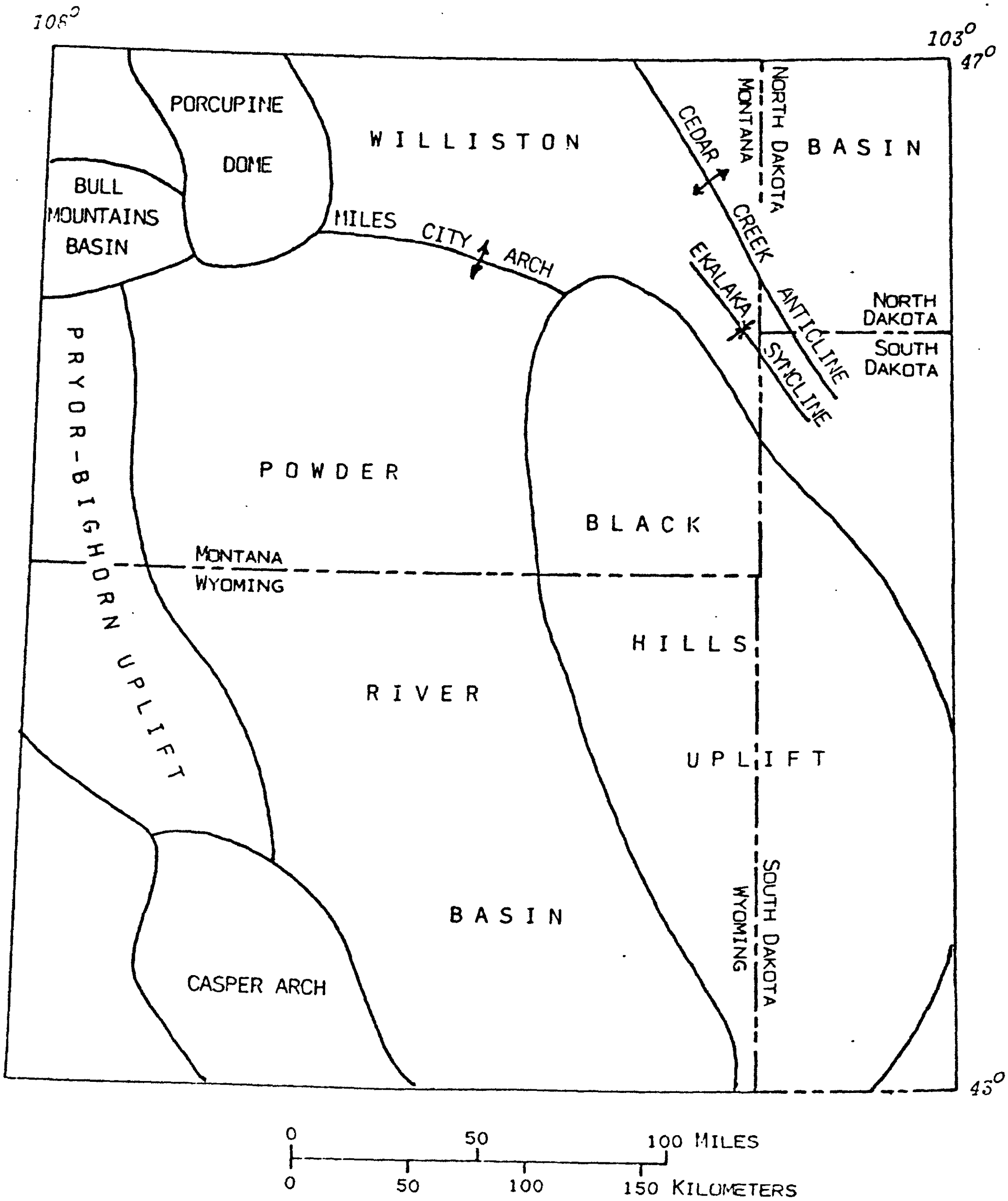

Figure 5.—Powder River Basin in relation to some nearby major structural features.

The outcropping rocks mentioned above are underlain by as much as 2,600 m of older sedimentary rocks ranging in age from Cretaceous to Cambrian. Listed in table 1 in order of increasing age and depth are rock units present at the surface and in the subsurface in the region, together with a brief description of their lithologic character and thickness.

Hell Creek Formation

The Hell Creek Formation and underlying rocks in southeastern Montana are generally non-coal-bearing. The top of the formation where it crops out is taken as the outer boundary of the Powder River coal region. The Hell Creek Formation is exposed in the valley of the Powder River from the Wyoming border northward to a point near the junction of the Powder River and Mizpah Creek. It comes to the surface also at the northwestern edge of the basin at about the junction of Rosebud Creek and the Yellowstone River, and it is exposed from there westward along the Yellowstone and in the lower valleys of Rosebud Creek and other tributaries to the Yellowstone.

The Hell Creek is about 150 m thick along the Yellowstone River and somewhat thicker along the Powder and Little Powder Rivers although at the last named places only the upper part is exposed. The formation consists of thick beds of mostly friable yellowish-gray lenticular crossbedded sandstone, interbedded with lesser amounts of gray, greenish-gray, and brown shale, and gray siltstone. The sandstone is generally arkosic, nonresistant, and in beds locally as much as 15 m thick. The formation forms low rolling hills, interspersed with a few low mesas and benches formed by more resistant sandstone layers. Soil formed on the formation is thin and supports sparse vegetation of grasses and sagebrush.

The Hell Creek is nonmarine in origin and was deposited in ancient stream channels and on the bordering floodplains. Fossils found in the formation include dinosaur bones, fossil plants, and nonmarine mollusks.

Fort Union Formation

Almost all the surface rocks in the area described here are assigned to the Fort Union Formation of earliest Tertiary (Paleocene) age. The Fort Union has a total thickness of about 760 m, and it consists chiefly of sandstone, siltstone, mudstone, claystone, and combinations of these rock types. Parts of the formation contain substantial amounts of coal.

Table 1.—Rock units at the surface and in the subsurface in the northern Powder River coal region, Montana.

[Descriptions mainly from American Stratigraphic Co. sample logs; thickness of Cretaceous and older rocks mostly from the Superior Oil Co. 22-19 Northern Cheyenne well, sec. 10, T. 2S., R. 40 E.]

Quaternary System.

Holocene Series.

Valley-fill deposits. Unconsolidated silt, sand, and gravel on the flood plains of the larger streams. Includes low stream-terrace deposits within about 20 feet of the present stream levels, and slope wash, colluvium, and small alluvial fans along the valley sides. Locally more than 30 m thick.

Quaternary and Tertiary Systems.

Miocene (?) to Pleistocene Series.

Stream terrace deposits. Mostly unconsolidated silt, sand, and gravel on discontinuous benches at several levels from about 40 feet to as much as 1,100 feet above the present streams. The thickest and most extensive deposits are along the Tongue and Yellowstone Rivers within about 300 feet above the present streams. Commonly 6 m or more thick.

Tertiary System.

Eocene Series.

Wasatch Formation. Yellowish-gray friable fine-grained sandstone, yellowish-gray and gray siltstone, gray mudstone, brown carbonaceous shale, and coal. A bed of yellowish-gray limestone composed of the shells of fresh-water mollusks near the base and similar lenticular limestone beds in the upper part. Thickness at least 150 m thick.

Fort Union Formation.

Tongue River Member. Ledge-forming light-gray and light yellowish-gray sandstone; light-gray siltstone; dark-gray shale, sandy shale, and mudstone; brown carbonaceous shale; and coal. Distinguished from the underlying parts of the Fort Union Formation by having a predominance of light yellowish-gray sandstone and thick persistent beds of coal. Thickness 450-600 m; thins southward in the subsurface.

Lebo Shale Member. Dark-gray mudstone and claystone; contains abundant ferruginous concretions and a few lenticular beds of light-gray sandstone; coal bed at the base. Not recognized separately from the underlying Tullock Member west of Pumpkin Creek. Thickness 45-210 m; thickens southward in the subsurface.

Tullock Member. Light-gray calcareous sandstone and gray sandy and silty shale; minor amounts of coal. Not differentiated from the Lebo Shale Member west of Pumpkin Creek. Thickness about 75 m.

Lower Member. Generally nonresistent brownish gray fine-grained ferruginous sandstone, light-gray to dark-gray siltstone and mudstone, lesser amounts of yellowish-gray sandstone, thin beds of brown to black carbonaceous shale, and thin lenticular beds of coal. Includes equivalents of the Tullock and Lebo Shale Members east of Pumpkin Creek. Thickness about 120-300 m; thickens southward in the subsurface.

Cretaceous System.

Upper Cretaceous Series.

Hell Creek Formation. Dark-gray and dark greenish-gray shale and light-gray fine-grained micaceous sandstone, commonly contains a coal bed at the base. Called the Lance Formation in some early reports. Thickness about 150 m.

Fox Hills Sandstone. Light-gray to very light gray friable sandstone interbedded with medium-gray to dark-gray shale and siltstone. Thickness about 60 m.

Cretaceous System -- Continued.

Upper Cretaceous Series -- Continued.

Bearpaw Shale. Medium-gray to dark-gray bentonitic slightly micaceous shale; several thin beds of white to very light gray bentonite. Thickness about 235 m.

Parkman Sandstone. Very light gray glauconitic slightly calcareous fine-grained to medium-grained sandstone; interbedded gray shale and sandy shale. Correlates with the Judith River Formation of central Montana. Thickness about 55 m.

Claggett Shale. Gray bentonitic shale containing a few stringers of light-gray siltstone and thin beds of bentonite. Thickness about 105 m.

Eagle Sandstone and Telegraph Creek Formation, undivided. Gray shale and interbedded light-gray siltstone; a few beds of light-gray fine-grained to medium-grained micaceous glauconitic sandstone near the middle including the Shannon Sandstone Member, about 10.5 m thick, about 91 m above the base of the unit. Thickness about 215 m.

Niobrara and Carlile Shales, undivided. Dark-gray alternately calcareous and noncalcareous shale and bentonitic shale; a few thin beds of light-gray fine-grained sandstone; scattered fish bones and scales. Thickness about 265 m.

Greenhorn Formation. Dark-gray bentonitic shale containing a few beds of bentonite, and, in the upper part, thin beds of light-gray fine-grained calcareous glauconitic sandstone and gray shaly limestone. Thickness about 87 m.

Belle Fourche Shale. Dark-gray shale containing several beds of light-gray and grayish-green bentonite; some interlaminated light-gray siltstone. Equivalent to the Frontier Formation of areas to the west. Thickness about 95 m.

Lower Cretaceous Series.

Mowry Shale. Dark-gray shale, siliceous near the top of the formation; some interbedded light-gray fine-grained micaceous sandstone and thin beds of bentonite. Thickness about 120 m.

Newcastle Sandstone. Light-gray very fine grained to medium-grained calcareous locally glauconitic sandstone; some interbedded light-gray siltstone and dark-gray shale. Called the Muddy Sandstone in some parts of the Powder River Basin. Thickness about 21 m.

Skull Creek Shale. Dark-gray bentonitic shale. Thickness about 25 m.

Fall River Formation. Light-gray very fine grained to fine-grained micaceous sandstone interbedded with gray siltstone and dark-gray shale. Upper half is generally more silty and shaly than the lower half, and in some wells the upper part is called the "basal Colorado silt". Thickness about 65 m.

Lakota Formation. Light-gray, green, and maroon claystone interbedded mostly in the lower part with gray and brownish-gray medium-grained to coarse-grained sandstone. Upper, variegated claystone interval called the Fuson Shale in some wells. Thickness about 60 m.

Jurassic System.

Morrison Formation. Purplish red and green claystone, calcareous in the lower part; interbedded very light gray fine-grained to medium-grained calcareous sandstone near the base. Thickness about 37 m.

Jurassic System -- Continued.

Swift Formation. Greenish-gray flaky noncalcareous shale interbedded with light-gray calcareous glauconitic very fine grained to fine-grained sandstone; a few thin beds of brownish-gray oolitic limestone. Thickness about 84 m.

Rierdon Formation. Greenish-gray calcareous shale and marl. Thickness about 45 m.

Piper Formation and underlying Jurassic rocks, undivided. Red and green calcareous claystone in upper part; light-gray limestone and dolomite in the middle part; and orange-red claystone interbedded with anhydrite in the lower part. Thickness about 50 m.

Triassic System.

Spearfish Formation. Orange-red very fine grained and fine-grained dolomitic sandstone and sandy claystone. Thickness about 43 m.

Triassic and Permian Systems.

Goose Egg Formation. Interbedded orange-red calcareous siltstone, white anhydrite, and thin beds of light-gray cherty dolomite. Thickness about 29 m.

Pennsylvanian System.

Tensleep Sandstone. Light-gray and pinkish-gray very fine grained to fine-grained dolomitic sandstone, light-gray and tan cherty dolomite, and light-gray sandy dolomite. Locally cemented by anhydrite in the subsurface. Thickness about 29 m.

Amsden Formation. Light-gray and light pinkish-gray cherty dolomite; interbeds of red shale. Thickness about 26 m.

Mississippian System.

Mission Canyon Formation. Light-gray and light grayish-tan cherty bioclastic dolomite; locally contains beds of light-to dark-gray anhydrite. Equivalent to the upper part of the Madison Limestone of the Bighorn Mountains to the west. Thickness about 235 m.

Lodgepole Limestone. Light-gray and brownish-gray oolitic bioclastic limestone and dolomite. Equivalent to the lower part of the Madison Limestone of the Bighorn Mountains to the west. Thickness about 115 m.

Devonian System.

Duperow Formation. Light-gray, grayish-brown, and pinkish-gray dolomite; a few shaly partings. Equivalent to the Jefferson Formation of nearby areas to the west. Thickness about 50 m.

Silurian System.

Interlake Formation. Light-tan to very light gray fragmental dolomite. Thickness as much as 23 m; pinches out westward.

Ordovician System.

Red River Formation. Light-gray and light-tan granular dolomite. Equivalent to the Bighorn Dolomite of nearby areas to the west. Thickness about 96 m.

Winnipeg Sandstone. Grayish-white very fine grained to fine-grained quartzose sandstone. Thickness about 20 m

Cambrian System.

Cambrian rocks, undivided. Tan and gray glauconitic limestone; partings of green micaceous shale. Thickness about 9 m.

Precambrian rocks.

Igneous and metamorphic rocks.

The Fort Union is divided in ascending order into the Tullock, Lebo Shale, and Tongue River Members in the northwestern part of the Powder River Basin and in outcrops along the northern margin as far east as Pumpkin Creek south of Miles City (Rogers and Lee, 1923; Dobbin, 1930; Pierce, 1936). The Tullock and Lebo Shale Members cannot be separated from each other in the northeastern and eastern parts of the region. There they are combined in a unit known as the "somber colored beds" (Parker and Andrews, 1939) or the Lower Member (Bryson, 1952; Bryson and Bass, 1973). Coal occurs in all the members of the formation, but the thickest and most persistent beds are in the Tongue River Member.

Fossil remains in the Fort Union include many kinds of plants, fresh-water mollusks, fishes, crocodile-like reptiles, and turtles (Brown, 1952, p. 91; 1958, p. 112). Among the plants are mosses, ferns, cycads, conifers, palms, water lilies, birches, hazels, hickories, oaks, viburnums, and other dicotyledons (Brown, 1952, p. 91). Rocks comprising the Fort Union were deposited at elevations of perhaps a few tens of feet above sea level in a vast area of shifting flood plains, sloughs, swamps, and lakes that occupied the central part of United States in latest Cretaceous and early Tertiary time.

Wasatch Formation

The Wasatch Formation consists of friable yellowish-gray sandstone, gray shale and mudstone, and thin beds of carbonaceous shale. The formation includes a coal bed as much as 2.7 m thick about 110 m above the base (Badger coal bed of Baker, 1929, p. 33) and a few stringers of coal at lower horizons. A total of about 140 m of the Wasatch crops out in the Badger Hills, an area of moderately high hills between the Tongue River and Hanging Woman Creek, and the formation is present at other places along and near the Montana-Wyoming border. The formation contains the remains of many kinds of plants, locally abundant nonmarine mollusks in thin beds and lenses of limestone, and, in the Wyoming part of the basin, the bones and teeth of mammals.

Terrace gravels

Stream-deposited gravel is present in isolated deposits at several levels along the Yellowstone River and nearly all its north-flowing tributaries, including, in particular, Rosebud Creek, the Tongue River, Little Pumpkin, Pumpkin, and Mizpah Creeks, and the Powder and Little Powder Rivers. The highest and oldest gravels are as much as 335 m above the Tongue River near Ashland (Dobbin, 1929, p. 20-22). Younger and much more extensive deposits are found at lower elevations from a few feet to about 90 m above the present streams. The deposits range in thickness from a meter to as much as 27 m (Rogers and Lee, 1923, p. 44) and commonly are 6 m or more thick. The gravels record stream levels at various stages during a long-continued period of erosion and dissection that has been in progress in the region at least since middle Tertiary time.

Gravels on benches along the Yellowstone, Tongue, and Powder Rivers contain large proportions of pebbles and cobbles of limestone, dolomite, chert, and igneous and metamorphic rocks derived from Paleozoic and Mesozoic formations in the Bighorn and Pryor Mountains. Other streams that head in Tertiary rocks of the Powder River Basin contain material derived mostly from the Fort Union Formation, including fragments of iron- and calcite-cemented sandstone, quartzite, limestone, and clinker.

The distribution, origin, and history of the perched stream gravels in eastern Montana, including the gravel deposits in the northern Powder River coal region, have been described by Alden (1932).

Valley-fill deposits

The larger streams in the northern Powder River Basin occupy wide flat-floored valleys containing deposits of alluvium along the present floodplains of the streams, and low stream-terrace deposits, alluvial fans, sheet-wash deposits, and other unconsolidated surficial deposits along the valley sides. These valley-fill deposits at places are several meters to tens of meters thick, and they form a band commonly 1-3 km wide in the valleys of the Tongue and Powder Rivers and 1/2-1 km wide in the valley of the Rosebud Creek and some of the other large streams. The deposits consist of mostly unconsolidated silt, sand, and gravel, the bulk of which was locally derived; however, pebbles and cobbles on the flood plains and low terraces of the Powder and Tongue Rivers include igneous and metamorphic rocks and other resistant rock types derived from pre-Tertiary formations exposed in the headwater regions of these rivers.

STRUCTURAL FEATURES

Folds

The Powder River Basin in Montana is a very broad southwestward plunging synclinal fold having a structural relief of about 900 m in the area between the Wyoming border and Yellowstone River at Forsyth, or an average southward dip along the axis of the fold of about 6 m per km. The axis of the basin is very poorly defined, but in general it trends northeastward about coincident with the Tongue River. West of the Tongue River the surface rocks generally are inclined eastward or southeastward, and east of the river they generally are inclined westward or southwestward. As shown by figure 7, many small, very low amplitude subsidiary folds are superimposed on the major basinal structure. Minor folds in the surface rocks do not necessarily faithfully reflect the configuration of folds at depth because of differential compaction and other stratigraphic variations in the rock column, but minor folds in the surface rocks tend to have low dips and the same vague structural trends as the folds depicted by the irregular structure contours on figure 7.

Faults

Faults having displacements of a few feet to as much as 60 m cup the upper part of the Fort Union Formation and the basal part of the Wasatch Formation at numerous places in the northern Powder River Basin, principally on the west flank and axial part of the basin, and at other places within a few km of the Wyoming border on the east flank of the basin (fig. 6).

The faults are important because they displace coal-bearing rocks, and thus may limit the extent of some coal deposits in mining. The faults typically trend northeastward, and some have been traced for several kilometers. The faulting probably occurred in early or middle Tertiary time.

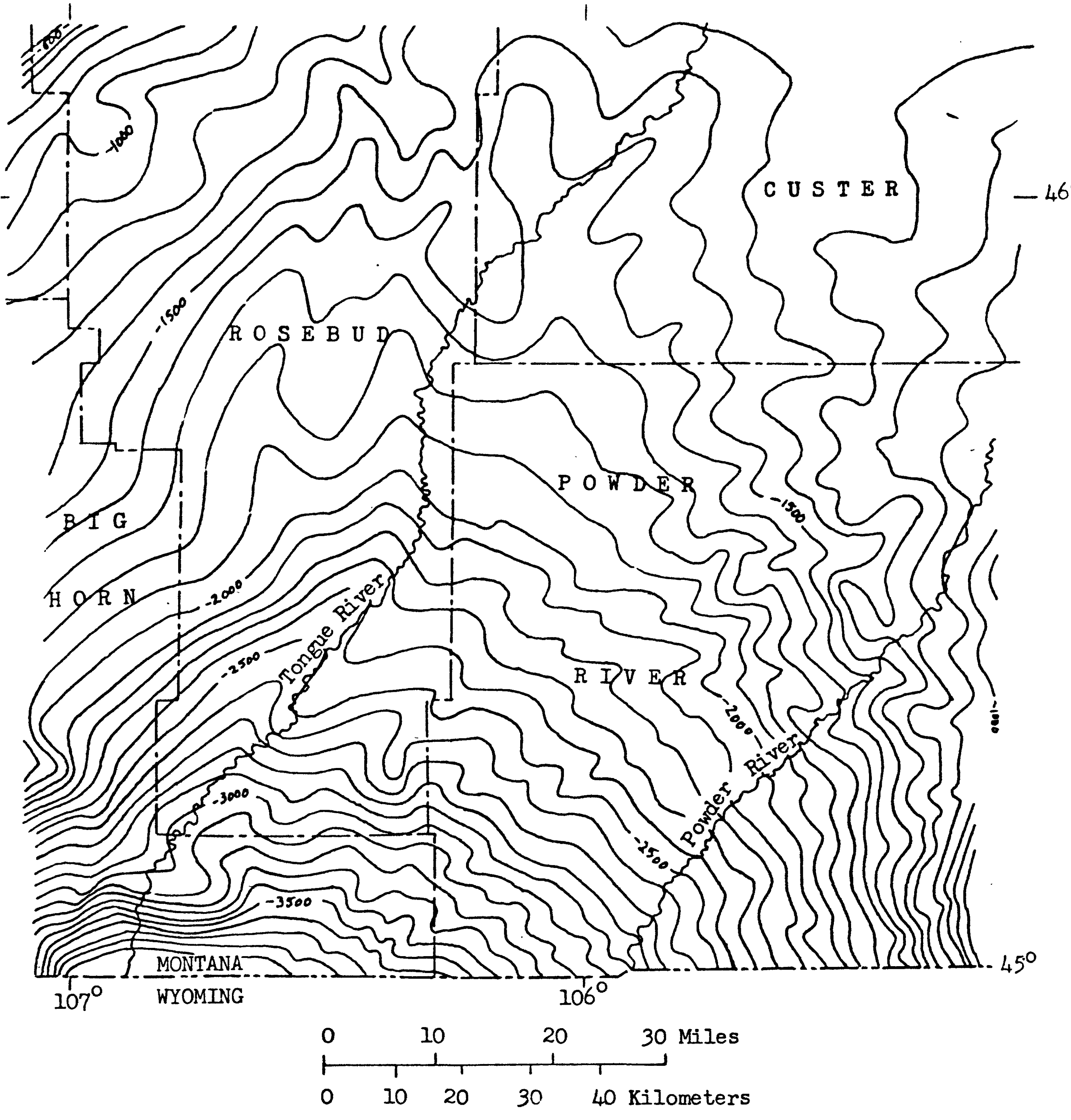

Figure 7.—Structure contour map, Upper Cretaceous rocks, northern Powder River coal region. [From Balster, 1973]

COAL DEPOSITS

Coal occurs in all three members of the Fort Union Formation, but principally in the Tongue River Member where it is found in several thick persistent beds and in many thinner ones. The Wasatch Formation, which overlies the Fort Union Formation, contains one coal bed of possible interest for mining in the northern Powder River coal region.

Figures 8, 9, and 10 show the sequence of coal beds in different parts of the northern Powder River coal region, and their approximate correlations as worked out mainly by reconnaissance surface mapping. Some of the coals occupy fairly consistent stratigraphic positions and, although their thicknesses vary from place to place, they can be traced for many miles in outcrops and drill holes. Others are local lenses. The intervals between the coal beds also vary. Locally, beds merge or split into separate benches, which in poorly explored areas makes correlations uncertain.

Coal in the lower part of the Fort Union Formation

Coal beds characteristically are few in number and are thin and lenticular in the lower part of the Fort Union Formation, including coal in the Tullock and Lebo Shale Members and in their undifferentiated equivalent, the Lower Member. With a few exceptions, the coal beds range in thickness from a few centimeters to about 1 m and commonly contain thin partings of shale.

In the Tullock coal field southwest of Forsyth, coal has been distinguished at 10 stratigraphic levels in the Tullock Member of the Fort Union Formation, and at two levels in the Lebo Shale Member, including one bed in the Tullock that is as much as 1.5 m thick (Rogers and Lee, 1923, p. 31, 32, 73).

In the Forsyth coal field south of Forsyth, the Wright coal bed, which lies at the base of the Tullock Member, is locally about 1 m thick, and the Big Dirty coal bed, at the base of the Lebo Shale Member, is locally as much as 3.5 m thick. The last named locality is along the East Fork Armells Creek south of Forsyth (Dobbin, 1929, p. 26).

In the Rosebud coal field southeast of Forsyth, a coal in the lower part of the Tullock Member is locally almost 1.5 m thick, and the coal at the base of the Lebo Shale Member, the Big Dirty bed, is locally slightly more than 1.5 m thick (Pierce, 1936, p. 77, 78).

In the Mizpah coal field, adjacent to the Rosebud coal field on the east, several thin coal beds in the Lower Member of the Fort Union Formation have been given names, but at only a few places are any of them more than 1 m thick.

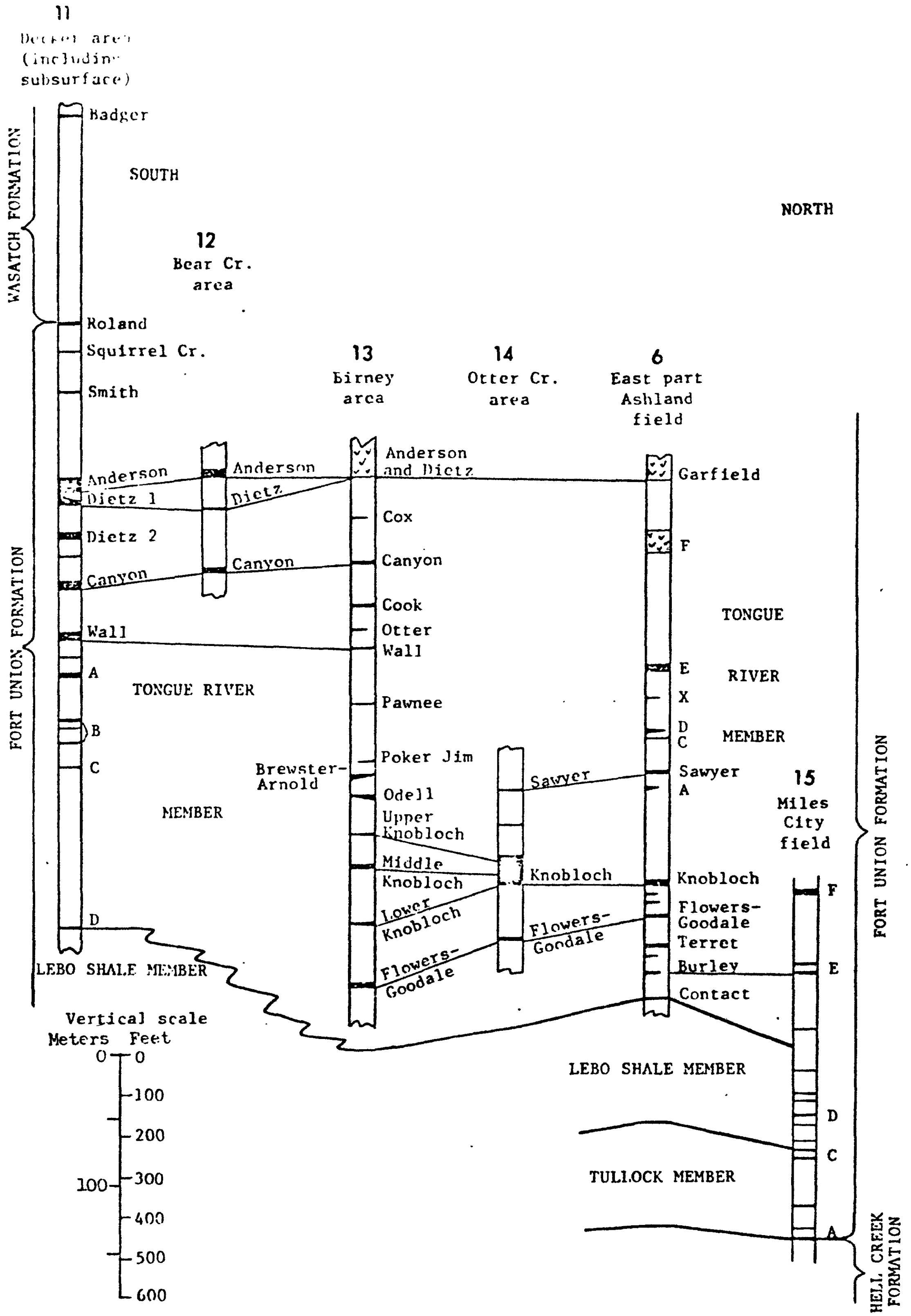

Figure 8.—Diagram showing relations of coal beds from south to north in the northern Powder River coal region. Location of sections on figure 10.

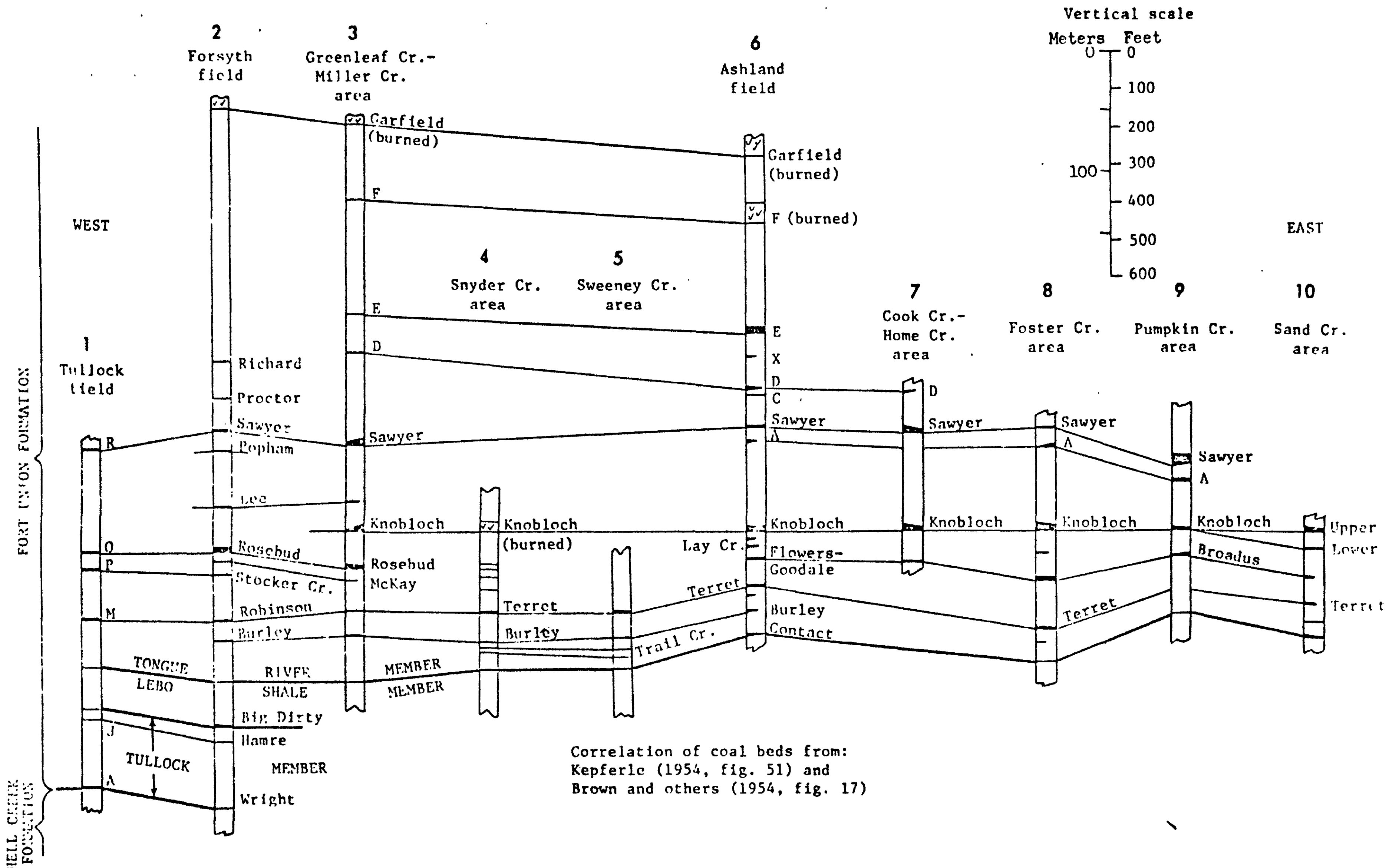

Figure 9.—Diagram showing relations of coal beds from west to east in the northern Powder River coal region. Locations of sections on figure 10.

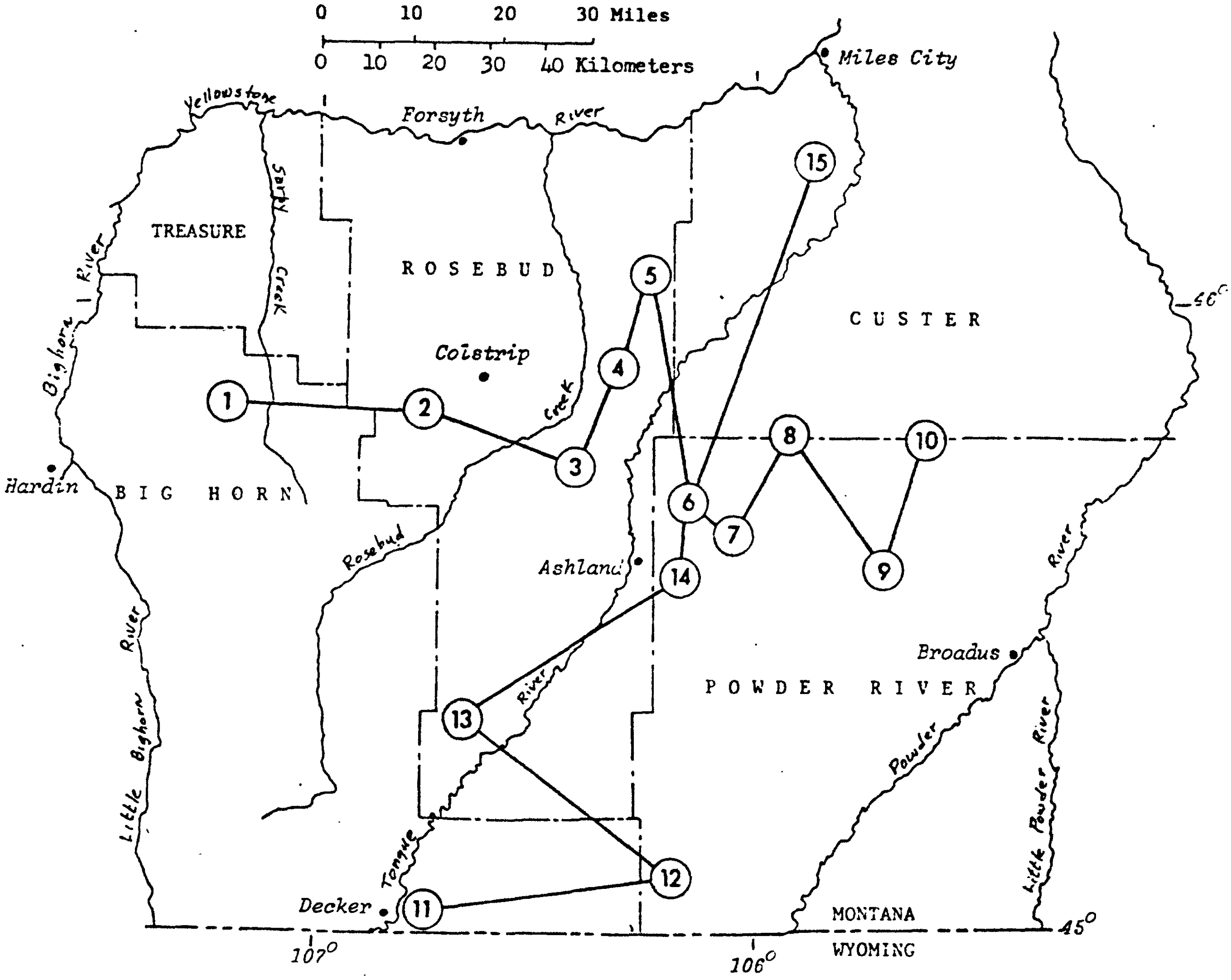

Figure 10.—Locations of stratigraphic sections shown on figures 8 and 9.

Where thickest, the coal is about 1.8 m thick in the Elmhurst bed in T. 2 N., R. 52 E. At least two other beds in the Lower Member have about the same thickness for short distances along their outcrops in other parts of the Mizpah coal field (Parker and Andrews, 1939, p. 107-110).

Bryson (1952, pl. 1) and Bryson and Bass (1973, pl. 1) distinguish a few discontinuous lenses of coal in the Lower Member of the Fort Union along the Powder and Little Powder Rivers south of the Mizpah coal field, but all the coal is in beds that are regarded by them as too thin or shaly to have much commercial value.

Coal in the Tongue River Member of the Fort Union Formation

The Tongue River Member of the Fort Union Formation contains practically all the workable coal in the northern Powder River coal region. The coal is distributed at fairly regular intervals throughout the member as shown by figures 8 and 9. Many of the coals are more than 3 m thick, and several attain thicknesses of more than 6 m in areas of many square km. A single coal deposit locally is about 21 m thick near Ashland in the central part of the region, and another deposit is more than 24 m thick in the vicinity of Decker in the southwestern part.

Figure 11 shows the distribution of 35 thick accessible deposits of coal, as outlined by Matson and Blumer (1973). The deposits are briefly described in table 3 (page 28). The distribution of a few of the thickest and most extensive of the coal beds are discussed below.

Rosebud and associated coal beds.--The Rosebud coal bed is an important coal in the northwestern part of the region. It lies about 110 m above the base of the Tongue River Member, and it crops out mainly near the heads of Sarpy Creek and the East and West Forks of Armells Creeks, and along Rosebud Creek south of Colstrip (Dobbin, 1929; Kepferle, 1954). Bed Q of Rogers and Lee (1923) is its continuation in the Tullock coal field in the northwestern corner of the area. In much of this area the coal is 6-9 m thick. The coal thins rapidly southward in the northern parts of the Crow and Northern Cheyenne Indian Reservations. It also appears to thin from Rosebud Creek eastward toward the Tongue River. Its stratigraphic position east of the Tongue River is approximately at the level of the Flowers-Goodale bed (Bass, 1932, p. 51). The Flowers-Goodale bed has been correlated with the Broadus bed farther to the east (Brown and others, 1954, p. 170). The Flowers-Goodale bed attains a thickness of about 3.6 m in outcrops between the Tongue River and Pumpkin Creek, and the Broadus bed is as much as 7.9 m thick west of Broadus in the northeastern part of the region (Matson and Blumer, 1973, pl. 17).

Knobloch coal bed.--The Knobloch bed (spelled Knoblock in early reports) lies about 30-45 m above the Rosebud bed in the western part of the region, and about the same interval above the Flowers-Goodale and Broadus beds in the eastern part of the region. The Knobloch is present over a wide area in the northern part of the basin. It attains a maximum known thickness of about 21.3 m near Ashland (U.S. Bureau of Land Management, 1975), and is 6 m or more thick at many other places in the region. The Knobloch splits into three benches a short distance south of Ashland according to Matson and Blumer (1973, pl. 34). Three coal beds in a stratigraphic interval of about 75 m are thought to be the southward continuation of the three benches in the subsurface in the southern part of the region south of about T. 5 S. Drilling is sparse in the southern part of the region, however, and correlations cannot be made with any great assurance.

Sawyer coal bed.--The Sawyer bed is a widespread coal in the central part of the area described here. It occurs about 65 m above the Knobloch coal bed, and is 3-6 m thick west of the Tongue River in the southern part of the Ashland coal field (Bass, 1932, p. 52-53). East of the Tongue River a coal mapped as the Sawyer bed is about 40 m above the Knobloch bed and is locally as much as 10 m thick on the Pumpkin Creek-Mizpah Creek divide (Brown and others, 1954, p. 171). The Sawyer bed thins southward in the uplands east of the Tongue River, and has not been recognized south of T. 4 S., Rs. 49-50 E. (Warren, 1959, pl. 19).

Brewster-Arnold and Cache coal beds.--The Brewster-Arnold coal bed lies about 75-80 m above the middle or main coal of the Knobloch coal sequence in the vicinity of Birney. It reaches a thickness of 6-8 m along the Tongue River in an area of about 100 square km, mostly west and southwest of Birney. Coal at the Brewster-Arnold horizon appears to thin rapidly east and southeast of Birney in outcrops and in the subsurface.

The Cache coal bed is at least 4.2 m thick locally, south of Broadus in the valley of the Powder River where it crops out 90-105 m above the Broadus bed (Warren, 1959, p. 572). It is a thin but recognizable bed about 90 m above the Knobloch bed south of Ashland in the lower Otter Creek drainage (Warren, 1959, pl. 19; McKay, 1976a), where it is about 90 m above the Knobloch coal bed. The Cache bed appears to be the approximate correlative of the Brewster-Arnold bed of the area near Birney.

Wall coal bed.--The Wall bed, which is 75 m above the level of the Brewster-Arnold bed, is a thick and potentially important coal south of the Northern Cheyenne Indian Reservation in the southwestern part of the northern Powder River coal region area. The coal is as much as 9.8 m thick in an outcrop along the Tongue River a few km south of Birney (Baker, 1929, p. 37). Holes drilled by the Montana Bureau of Mines and Geology found from 9 to 18 m of coal at the horizon of the Wall bed in the vicinity of this outcrop and at other places along both sides of the Rosebud Creek-Tongue River divide south of the Reservation (Matson and Blumer, 1973, pls. 5A and 6). Coal in the Wall bed can be followed in the logs of oil and gas wells from Birney southwestward to the Wyoming border with a thickness commonly in excess of 6 m.

The Wall bed appears to split into two or more coal beds eastward in the subsurface beneath the Tongue River-Hanging Woman Creek divide. Present information is not adequate to define the southeastern limit of the thick coal in the Wall bed, or to determine precisely the relation of several possible correlatives of the Wall in the eastern part of the region to the main body of coal in the Wall bed in the western part.

Canyon coal bed.--The Canyon coal bed is 45-60 m above the Wall bed. It crosses the south-central part of the northern Powder River coal region with a thickness commonly between 3.5 and 6 m, locally attaining a thickness of as much as 9 m. Available information from drilling suggests that the Canyon is present in the subsurface with a thickness of 3-6 m at least as far south as the Montana-Wyoming boundary.

Dietz 2 and 1 coal beds.--The Dietz 2 and overlying Dietz 1 are separate coal beds, each 4.5-6 m thick on the east side of the Tongue River near Decker where they lie 30-45 m above the Canyon bed (Matson and Blumer, 1973, pl. 1). At places on the west side of the Tongue River, the two beds appear to coalesce into a single thick coal; at other places the Dietz 1 or both the Dietz 1 and 2 beds coalesce with the overlying Anderson coal bed in combinations not yet fully determined except in a few areas of closely spaced drilling. More than 15.2 m of coal is assigned to the combined Dietz 1 and 2 beds west of Decker in the southwestern corner of the region (Matson and Blumer, 1973, pl. 1). A few km east of the Tongue River, in the upper reaches of Hanging Woman Creek, one coal bed 2.4-6 m thick is present in the Dietz interval (Matson and Blumer, 1973, pl. 33).

Anderson coal bed.--The Anderson coal bed is a persistent coal about 60 m above the Canyon bed and 75 m below the top of the Tongue River Member of the Fort Union Formation. The Anderson commonly is 6-11 m thick where present in the southern part of the region. Locally, the underlying Dietz 1 bed merges with the Anderson. The two coals form a single bed at least 15.2 m thick on high divides east of Birney (Matson and Blumer, 1973, pl. 11). The Anderson combines with both the Dietz 1 and Dietz 2 beds in the vicnity of Decker to form a single bed of coal as much as 24.4 m thick (Matson and Blumer, 1973, pl. 33).

The Anderson and Dietz 1 beds are probably equivalent to the Garfield bed of the Ashland and Birney-Broadus coal fields (Olive, 1957, pl. 4).

Roland coal bed.--The Roland coal bed, as mapped by Baker (1929), is 30-33 m above the top of the Anderson coal bed. The Roland bed crops out near the Badger Hills in the south-central part of the region where it commonly attains thicknesses of 1.7-4 m. In most reports on the geology of the region, the top of the Roland bed of Baker (1929) is designated as the contact of the Fort Union with the overlying Wasatch Formation, although there appears to be little or no lithologic basis for distinguishing two separate formations at this horizon at most places.

COAL RESOURCES

The original coal resources in the northern Powder River coal region, including resources at some places in beds as thin as 0.46 m, are currently estimated to be about 161 billion tonnes, distributed as shown in table 2.

The resources for different parts of the region have not all been classified in the same detail, and therefore are not strictly comparable. For instance, the thinnest beds for which resources are calculated are 0.48 m in the Tullock and Rosebud coal fields, 0.61 m in the Ashland and Moorhead coal fields, 0.76 m in the Birney-Broadus coal field, 0.91 m in the Forsyth coal field, and 1.52 m in the Crow and Northern Cheyenne Indian Reservations.

Coal in beds deeper than 460 m is not included in the resource estimates.

COAL RESOURCES IN THICK, ACCESSIBLE DEPOSITS

As currently calculated by Matson and Blumer (1973, p. 11) and Matson (1975, p. 578), the resources of coal in the northern Powder River coal region in thick, accessible deposits that are potentially strippable are about 32.7

Table 2.—Estimated original coal resources in the northern Powder River coal region

[In millions of short tons; estimates are rounded; overburden 0-1,500 feet]

Coal field	Demonstrated and inferred resources	Hypothetical resources	Source of estimate
Tullock	1,200	—	Rogers and Lee, 1923, p. 78.
Forsyth	5,440	4,240	Dobbin, 1929, p. 36.
Rosebud	1,120	—	Pierce, 1936, p. 83.
Ashland	10,760	—	Bass, 1932, p. 58.
Mizpah	1,370	—	Parker and Andrews, 1939, p. 112.
Coalwood	1,600	—	Bryson, 1952, p. 77-81.
Northern estension Sheridan	38,500	—	Baker, 1929, p. 67.
Birney-Broadus	21,500	—	Warren, 1959, p. 575-584.
Moorhead	21,600	30,000	Bryson and Bass, 1973, p. 34-44.
Northern Cheyenne and Crow Indian Res.	3,500	36,500	1/
Totals (rounded)	107,000	71,000	

1/ Demonstrated and inferred resources are in strippable deposits as listed in table 3; hypothetical resources are unpublished estimates by W. J. Mapel based on extrapolation of information into the Reservations from nearby known coal-bearing areas.

1 short ton equals 0.9072 tonnes.

billion tonnes. These deposits underlie an area of somewhat less than 340,000 hectares or 2,930 square km, as shown by figure 11. Coal in these deposits is under less than about 45 m of overburden, and the thickness of coal in individual deposits averages from 2.7 to 15.2 m. More than 20 different named beds are represented. The deposits are distributed widely within the area in which the Tongue River Member of the Fort Union Formation is present.

Deposits having the highest average tonnes of coal per hectare are the Ashland and Cheyenne Meadows deposits in the Knobloch bed, and the Decker deposit in the Anderson, Dietz 1, and Dietz 2 beds (table 3). The Kirby and Canyon Creek deposits in the Wall bed, and the Otter Creek deposit in the Knobloch bed are almost as large. All of these large deposits are in the western part of the area, and four of the six are along the valley of the Tongue River. The area disturbed by mining per ton of coal extracted would be relatively low for such deposits compared to many of the others in which the average tons of coal available per acre is substantially less.

Additional exploration by mapping and drilling can be expected to outline additional strippable deposits in the region, and to modify the tonnages estimated for the presently known deposits.

COAL PRODUCTION

Scattered small underground mines and prospects have been intermittently in operation for many years, mostly to supply coal for the domestic use of local residents. In addition, four large strip mines were in production in 1976 to supply coal for electric power generation. The locations of the principal mines are shown on figure 12, and the production of coal from them for 1975 is given in table 4.

COAL QUALITY AND COMPOSITION

Coal in the northern Powder River coal region ranges in rank from lignite A through subbituminous A, and the heat value on an as-received basis from 6,350 to 9,940 Btu per pound. The coal is non-coking and non-agglomerating. The coal shows a roughly systematic variation in rank from lignite A with a relatively low heat value and high moisture content in the northeastern part of the region, increasing southwestward through subbituminous C to subbitumininous B and locally to subbituminous A coal having a higher heat value and lower moisture

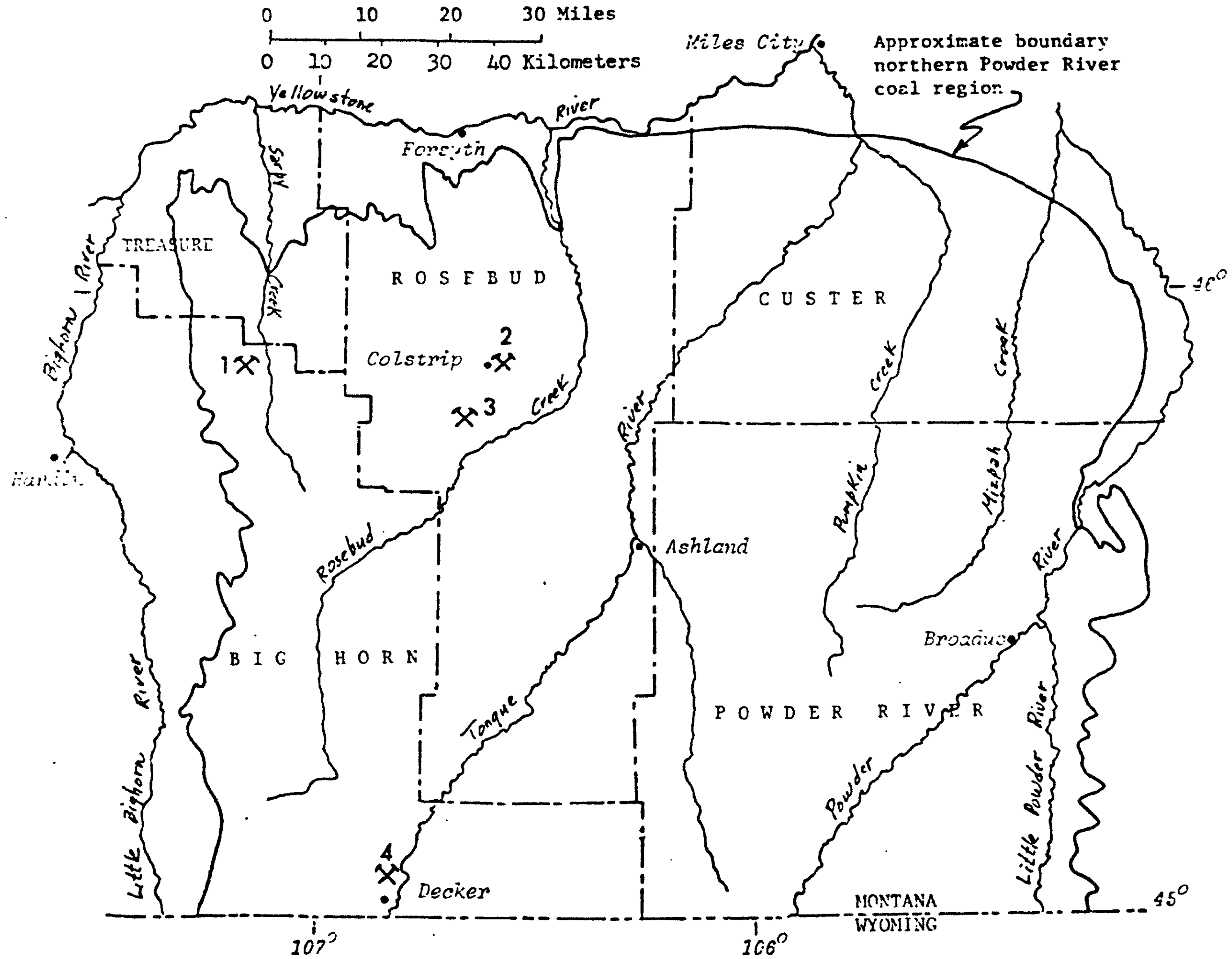

Figure 12.—Producing coal mines, 1976. 1, Westmoreland Coal Co., Sarpy Creek mine; 2, Western Energy Co., Colstrip mine; 3, Peabody Coal Co., Big Sky mine; 4, Decker Coal Co., Decker no. 1 mine.

Table 3.—Reserves of coal in strippable deposits.

[From Matson and Blumer, 1973, table 1; Matson, 1975, table 1; all numbers are rounded].

Coal deposit	Map no.	Coal bed	Average thickness of coal, feet	Reserves, million tons	Acreage	Average tons/acre [1]
Decker	1	Anderson and Dietz 1 & 2	50	2,240	25,520	83,800
Deer Creek	2	Anderson and Dietz 1 & 2	20	495	14,210	35,400
Roland	3	Roland	10	218	12,080	18,100
Squirrel Creek	4	Roland	12	133	6,210	21,500
Kirby	5	Anderson	22	217	5,660	38,300
		Wall	45	474	6,950	79,600
		Dietz	27	834	17,520	47,600
		Canyon	22	159	4,070	39,000
Canyon Creek	6	Wall	45	1,880	23,860	79,000
		Brewster-Arnold	18	66	2,070	31,900
Birney	7	Brewster-Arnold	15	181	6,970	25,900
Poker Jim Lookout	8	Anderson and Dietz	25	873	19,610	44,500
Hanging Woman Creek	9	Anderson	29	1,580	30,550	51,800
		Dietz	15	1,120	43,650	25,700
West Moorhead	10	Anderson	25	884	19,670	44,900
		Dietz	11	379	20,420	19,500
		Canyon	17	690	22,550	30,600
Pokar Jim Creek-O'Dell Creek	11	Knobloch	27	373	7,890	47,300
		Knobloch	44	565	7,190	78,600
Otter Creek	12	Knobloch	45	2,080	25,790	80,500
Ashland	13	Knobloch	56	2,700	27,200	99,100
		Sawyer, A and C	10	357	20,260	17,600
Colstrip	14	Rosebud	24	1,440	33,380	43,100
Pumpkin Creek	15	Sawyer	30	2,430	45,700	53,100
Foster Creek	16	Knobloch	14	708	27,800	25,500
		Terret	9	461	27,460	16,800
		Flowers-Goodale	10	259	14,440	17,900
Broadus	17	Broadus	23	740	18,430	40,100
East Moorhead	18	T	19	525	15,560	33,800
Diamond Butte	19	Canyon	10	418	21,360	19,600
Goodspeed Butte	20	Cook	26	629	13,450	46,800
Fira Gulch	21	Pawnee and Cook	21	337	8,490	39,700
Sweeney Creek-Snyder Creek	22	Terret	17	326	10,920	29,900
Yager Butte	23	Elk and Dunning	25	1,180	26,920	43,700
		Cook	12	312	14,510	21,500
Threemile Buttes	24	Canyon and Ferry	9	225	13,840	16,300
Sonnette	25	Pawnee	22	320	8,220	38,900
		Cook	20	363	10,470	34,700
Home Creek Butte	26	Canyon and Ferry	25	217	4,850	44,800
Little Pumpkin Creek	27	A, Sawyer, C and D, X, and Z	14	216	8,530	25,300
Sand Creek	28	Knobloch	25	267	5,950	44,900
Beaver Creek-Liscom Creek	29	Flowers-Goodale, Terret, and Knobloch	14	628	25,930	24,200
Greenleaf Creek-Miller Creek	30	Rosebud, Knobloch, and Sawyer	17	454	14,920	30,400
Sarpy Creek	31	Rosebud and McKay	20	1,500	42,370	35,400
Little Wolf	32	Rosebud and McKay	24	314	7,410	42,400
Cheyenne Meadows	33	Knobloch	50	1,200	13,560	88,500
Jeans Fork	34	Bed name not given	13	90	3,800	23,700
Wolf Mountains	35	Anderson, Dietz 1, Dietz 2	35	1,920	31,000	62,000
Totals				36,000	839,000	

[1] 1 short ton equals 0.9072 tonnes; 1 acre equals 0.405 hectare

Table 4.—Coal production from operating strip mines in 1975

[Data from the U. S. Bureau of Mines]

Company and mine	Production, in short tons[1]
Decker coal Co., Decker no. 1	9,175,434
Western Energy Co., Colstrip	6,407,307
Westmoreland Coal Co., Sarpy Cr.	4,048,082
Peabody Coal Co., Big Sky	2,080,412

[1] 1 short ton equals 0.9072 tonnes

content in the southwestern part of the region. Many local variations are seen in this general pattern, depending on the age and depth of burial of the coal. The oldest and most deeply buried coals in local areas tend to have the highest rank.

Most of the coal is classed as low-ash and low-sulfur coal, consistently containing 4 to 8 percent ash and 0.4 to 0.8 percent sulfur (table 5). Samples from some beds or parts of beds contain as much as 3 percent sulfur because of local concentrations of pyrite, or have more than 12 percent ash, but coal with such high sulfur and ash contents is exceptional. The remarkable Knobloch bed in the central part of the region locally contains more than 2 billion tons of potentially strippable coal that averages less than 0.2 percent sulfur and 4.8 percent ash (Ashland deposit, table 5).

The coal tends to lose moisture on exposure to air, to slack, and to ignite spontaneously.

Concentrations of selected trace elements and major and minor oxides in coal in the Northern Great Plains, including the northern Powder River coal region, are shown on tables 6 and 7.

Complete chemical analyses of the coal, including analyses for trace elements, are available from the Colstrip, Ashland, and Decker areas, as summarized in tables 8 to 13. In addition, the U.S. Bureau of Mines (1932), and the Montana Bureau of Mines and Geology (Matson and Blumer, 1973) have published several hundred proximate and ultimate analyses of the coal, including analyses of coal from nearly all of the more than 25 major coal beds in the region. Reports on individual coal fields, listed on figures 3 and 4, contain analytical data on the coal.

Colstrip area

Coal being mined or scheduled for mining in the Colstrip area is in two beds--the upper, Rosebud bed which is generally 7.6 to 9.1 m thick, and the lower, McKay bed which is generally 2.4 to 3.7 m thick. The two beds are separated by 4.6 to 20 m of rock. The rank of coal in both beds is subbituminous B.

The average composition of the coal in each bed, and the range in the concentrations of each component, are listed in table 8. Sulfur is more abundant than in most coal in the northern Powder River coal region, and sulfur in the McKay coal bed generally is 0.3 to 0.5 percent higher than sulfur in the Rosebud bed. The distribution of sulfur is erratic, however, mainly due to local concen-

Table 5.—Average ash, sulfur, and heat value in coal deposits in the northern Powder River coal region.

[As received basis; ash and sulfur in percent; data from Matson, 1975]

No. on map	Name of field	Coal bed	Ash	Sulfur	Btu
1	Decker	Anderson-Dietz 1&2	4.0	.40	9,652
2	Deer Creek	Anderson-Dietz 1&2	4.0	.50	9,282
3	Roland	Roland	9.2	.74	8,164
4	Squirrel	Roland	5.5	.29	7,723
5	Kirby	Anderson	4.2	.32	8,328
		Wall			
		Dietz	5.8	.59	8,509
		Canyon	5.8	.24	8,789
6	Canyon	Wall	4.6	.30	9,088
		Brewster-Arnold	7.5	.40	8,444
7	Birney	Brewster-Arnold	5.1	.41	9.055
8	Poker Jim Lookout	Anderson-Dietz	5.2	.37	7.925
9	Hanging Woman Cr.	Anderson	4.9	.29	8.496
		Dietz	5.5	.33	8.078
10	West Moorhead	Anderson	5.3	.36	8.296
		Dietz	4.1	.41	7.990
		Canyon	5.6	.45	8.055
11	Poker Jim O'Dell	Knobloch	5.1	.22	8.846
12	Otter Creek	Knobloch	4.7	.36	8.468
13	Ashland	Knobloch	4.8	.15	8,421
		Sawyer A & C	4.9	.49	7.883
14	Colstrip	Rosebud	9.5	.70 1/	8.836
15	Pumpkin Creek	Sawyer	7.5	.34	7.438
16	Foster Creek	Knobloch	7.8	.76	7,573
		Terret	5.8	.21	7,770
		Flowers-Goodale	7.8	.51	7,553
17	Broadus	Broadus	7.2	.27	7,437
18	East Moorhead	T	6.2	.57	7,120
19	Diamond Butte	Canyon	4.8	.43	7,330
20	Goodspeed Butte	Cook	10.6	1.63	6,771
21	Fire Gulch	Pawnee & Cook	3.8	.33	7,739
22	Sweeney-Snyder	Terret	9.1	.11	8,175
23	Yager Butte	Elk & Dunning	4.8	.33	7,646
		Cook	6.7	.63	7,254
24	Threemile Buttes	Canyon & Ferry	5.5	.94	6,867
25	Sonnette	Pawnee	9.8	.88	6,964
		Cook	8.1	1.23	6,891
26	Home Creek Butte	Canyon & Ferry			
27	Little Pumpkin Creek	Sawyer A&C, D, X, & E			
28	Sand Creek	Knobloch	6.6	.30	7,340
29	Beaver-Liscom	Flowers-Goodale & Terret	8.1	.96	8,102
		Knobloch	7.7	.50	8,027
30	Greenleaf-Miller Creek	Rosebud, Knobloch, and Sawyer	7.5	.71	8,422
31	Sarpy Creek	Rosebud-McKay	6.5	.50	8,600
33	Cheyenne Meadows	Knobloch	4.1	.40	8,400
32	Little Wolf	Rosebud-McKay			
34	Jeans Fork				
35	Wolf Mountains				

1/ Taken from Matson and Blumer, 1973, p. 78-79.

Table 6.—Arithmetic mean, observed range, geometric mean, and geometric deviation of 36 elements in 490 Northern Great Plains province coal samples (whole-coal basis). For comparison average shale values are listed (Turekian and Wedepohl, 1961). Data from U. S. Geological Survey.

[As, F, Hg, Sb, Se, Th, and U values used to calculate the statistics were determined directly on whole-coal. All other values used were calculated from determinations made on coal ash. L means less than the value shown]

Element	Arithmetic mean (abundance)	Observed range Minimum	Observed range Maximum	Geometric mean (expected value)	Geometric deviation	Average shale
Si %	1.4	0.01 L	25	1.0	2.3	7.3
Al %	.73	.11	11	.61	1.8	8.0
Ca %	1.2	.086	7.8	1.0	1.6	2.21
Mg %	.238	.013	.758	.218	1.5	1.55
Na %	.122	.001	.672	.067	3.0	.96
K %	.042	.001L	1.2	.018	3.7	2.66
Fe %	.55	.010	14	.36	2.5	4.72
Mn ppm	50	9.0 L	440	33	2.5	850
Ti %	.040	.004	.13	.034	1.7	.46
As ppm	4	1 L	45	2	2.5	13
Cd ppm	.08	.02	2.7	.04	2.8	.3
Cu ppm	10.5	.34	76	8.2	2.0	45
F ppm	47	20 L	340	38	1.9	740
Hg ppm	.11	.01 L	3.8	.08	2.2	.4
Li ppm	5.6	.32 L	49.2	3.6	2.6	66
Pb ppm	5.9	1.2 L	76	4.8	1.9	20
Sb ppm	.6	.1 L	43	.4	2.6	1.5
Se ppm	.9	.1 L	13	.6	2.4	.6
Th ppm	4.3	.04	28	3.4	2.0	12
U ppm	.9	.07	7.5	.6	2.6	3.7
Zn ppm	17.9	1.0	218	9.4	3.1	95
B ppm	70	15	300	70	1.8	100
Ba ppm	500	10	2,000	300	2.3	580
Be ppm	.7	.1 L	15	.5	2.4	3
Co ppm	2	.3 L	20	2	2.1	19
Cr ppm	5	.5	100	3	2.3	90
Ga ppm	2	.5	20	2	1.9	19
Mo ppm	2	.3 L	70	1.5	2.4	2.6
Nb ppm	1.5	.7 L	30	.7	3.3	11
Ni ppm	5	.5 L	300	2	2.5	68
Sc ppm	2	.5 L	20	1.5	1.8	13
Sr ppm	300	15	1,500	200	2.3	300
V ppm	15	1	150	10	2.3	130
Y ppm	5	.7 L	30	3	2.1	26
Yb ppm	.3	.07 L	3	.3	2.0	2.6
Zr ppm	15	2	150	15	1.8	160

Table 7.—Arithmetic mean, observed range, geometric mean, and geometric deviation of 15 major and minor oxides and trace elements in the ash of 490 Northern Great Plains province coal samples. Data from U. S. Geological Survey

[All samples were ashed at 525°C; L after a value means less than the value shown]

Oxide or element	Arithmetic mean (abundance)	Observed range			Geometric mean (expected value)	Geometric deviation
		Minimum		Maximum		
Ash %	9.8	3.2		84.9	9.0	1.5
SiO_2 %	29	1.0	L	69	24	1.8
Al_2O_3 %	14	2.6		30	13	1.5
CaO %	19	.36		49	16	1.8
MgO %	4.59	.28		14.3	4.00	1.7
Na_2O %	2.07	.27		12.4	1.00	3.3
K_2O %	.45	.022		3.1	.22	3.3
Fe_2O_3 %	7.5	.12		77	5.6	2.1
MnO %	.060	.02	L	.45	.034	2.9
TiO_2 %	.67	.082		1.61	.59	1.6
SO_3 %	17	.28		45	15	1.8
Cd ppm	.8	1.0	L	20	.5	2.4
Cu ppm	114	4.6		685	91	2.0
Li ppm	54	5	L	186	40	2.2
Pb ppm	62	25	L	1,660	49	2.0
Zn ppm	186	12		2,480	106	2.8

Table 8 .--Composition of coal in the Rosebud and McKay beds, Colstrip area, Montana, based on standard coal analyses (proximate, ultimate, Btu, and forms-of-sulfur analyses, reported in percent on as-received basis).

[Analyses by Coal Analysis Section, U.S. Bureau of Mines, Pittsburgh, Pa.]

	Rosebud Bed (12 samples)		McKay Bed (5 samples)	
	Arithmetic mean	Range	Arithmetic mean	Range
Moisture	21.5	15.8-26.4	24.9	19.7-27.0
Vol. matter	29.5	27.1-31.4	27.1	26.3-28.3
Fixed C	39.9	33.3-43.5	40.0	37.5-46.3
Ash	9.1	4.3-15.5	7.9	6.5- 9.9
Hydrogen	6.0	5.5- 6.4	6.0	5.5- 6.3
Carbon	52.8	44.4-56.5	50.5	46.8-56.4
Nitrogen	.8	.7- .9	.7	.7- .8
Oxygen	30.0	22.8-34.3	32.9	30.4-34.9
Sulfur	1.3	.5- 4.1	1.9	.4- 4.2
Btu/lb	9,120	7,810-9,720	8,660	8,250-9,380
Sulfate S	0.01	0.00- .2	0.01	0.01- .03
Pyritic	1.01	.11-3.98	1.66	.09-4.05
Organic S	.29	.13- .38	.28	.15- .42

trations of pyrite. Large tonnages of coal in the Rosebud bed contain 0.7 to 0.9 percent sulfur. The McKay bed is thinner and has a slightly lower average heat value than the Rosebud bed. Analyses providing results similar to those in table 8 are given by Matson and Blumer (1973, table 43).

The composition of the ash of the coal and the concentrations of trace elements in the coal are given in table 9. The Rosebud and McKay coals contain distinctly less of the alkali metals than other coal in the Powder River coal region; the Rosebud coal contains only about 6 percent as much Na_2O as does the Anderson and Dietz 1 and 2 coals in the Decker area (the degree of boiler fouling in steam plants increases with the amount of sodium in the coal). Of all 27 trace elements shown in table 9 only Zn is appreciably higher in the Colstrip area than it is in other Powder River Basin coal (Swanson and others, 1976). Chadwick and others (1975) give a detailed review of the distribution of 14 trace elements in the Rosebud and McKay coal beds, especially their distribution as related to the amount and forms of sulfur. They conclude (p. 175) that Sb, As, Cd, Cu, Hg, Ni, and Zn tend to concentrate in the parts of the coal high in pyritic sulfur.

Ashland area

The coal of primary interest in the Ashland area[1] is in the Knobloch coal bed, which is generally 15.2 to 20 m thick (U.S. Bureau of Land Management, 1975). The Flowers-Goodale bed underlies and is separated from the Knobloch by 23 to 38 m of rock. It is 0.9 to 4.6 m thick, but because it is deeply buried it has received little interest for future mining in this area. The rank of coal in both the Knobloch and Flowers-Goodale beds is subbituminous C.

The average composition of the coal in each bed, and the range in concentration of each component, are listed in table 10, as determined from samples collected by the U.S. Bureau of Land Management (1975). The most remarkable value shown in this table is the average of 0.2 percent sulfur in the Knobloch coal; this may be the lowest average sulfur value for any major coal deposit in the United States. Though the average heat value is relatively low--8,140 Btu per pound--the average ash content is also exceptionally low, 5.7 percent. Analyses reported by Matson and Blumer (1973, table 37) give approximately the same results; an average of 0.17 percent sulfur, 4.5 percent ash, and 8,445 Btu

[1] Called the Otter Creek area by the U.S. Bureau of Land Management (1975).

Table 9.--Average (arithmetic mean) composition of ash (10 major and minor oxides and 20 trace elements), and contents of seven additional trace elements in coal of the Rosebud and McKay beds in Colstrip area, Montana.

[Ashed at 525°C on air-dried coal. All trace-element determinations on ash, except Cd, Cu, Li, Pb, and Zn, by semiquantitative spectrographic method. All analyses by U.S. Geological Survey, Denver, Colo.]

Coal bed (number of samples)	Major and minor oxides in ash (percent)										
	Ash	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3	MnO	TiO_2	SO_3
Rosebud (42)	13.1	41	15	11	3.5	0.24	0.48	8.8	0.09	0.64	14
McKay (29)	9.8	22	13	10	3.2	1.05	.18	20	.04	.37	20

	Trace elements in ash (ppm)																			
	B	Ba	Be	Cd	Co	Cr	Cu	Ga	Li	Mo	Nb	Ni	Pb	Sc	Sr	V	Y	Yb	Zn	Zr
Rosebud (42)	700	5,000	3	1.0	10	30	63	30	107	20	20	15	40	10	1,500	70	30	2	385	150
McKay (29)	1,000	5,000	10	1.7	15	20	58	30	56	15	20	20	33	10	2,000	50	30	3	601	50

	Trace elements in whole coal (ppm)						
	As	F	Hg	Sb	Se	Th	U
Rosebud (42)	3	63	0.11	0.7	0.7	2.6	1.1
McKay (29)	3	33	.08	1.4	.9	1.8	.7

Table 10.--Composition of coal in the Knobloch and Flowers-Goodale beds, Ashland area, Montana, based on standard coal analyses (proximate, ultimate, Btu, and forms-of-sulfur analyses, reported in percent on as-received basis).

[Analyses by Coal Analysis Section, U.S. Bureau of Mines, Pittsburgh, Pa.]

	Knobloch Bed (22 samples)		Flowers-Goodale Bed (3 samples)	
	Arithmetic mean	Range	Arithmetic mean	Range
Moisture	30.3	26.0-35.1	27.6	26.4-28.8
Vol. matter	28.8	26.4-32.5	27.6	26.2-28.7
Fixed C	35.2	31.3-37.9	36.6	34.4-39.1
Ash	5.7	4.0- 7.4	8.2	5.8-11.9
Hydrogen	6.7	6.4- 6.9	6.2	5.6- 6.5
Carbon	47.6	43.3-49.8	48.4	45.8-51.2
Nitrogen	.7	.6- .8	.8	.7- .9
Oxygen	39.2	37.4-41.7	35.9	35.0-37.2
Sulfur	.2	.1- .3	.5	.4- .6
Btu/lb	8,140	7,270-8,480	8,240	7,790-8,710
Sulfate S	0.01	0.00- .07	0.01	0.01- .01
Pyritic S	.06	.01- .12	.10	.07- .15
Organic S	.10	.01- .26	.36	.29- .43

per pound heat value (one anomalous high-ash, high-sulfur sample was excluded in deriving these averages). The Knobloch coal near Ashland is truly an exceptional coal, unique in its quality in the Powder River Basin, and in the United States.

The composition of the ash of the coal, and the concentrations of trace elements in the whole coal are given in table 11. Coal in the Ashland area contains two to 10 times more of the alkali metals (Ca, Mgn, Na, and Ba) than the average coal in the United States, which is usual in the subbituminous coal in the Powder River coal region (Swanson and others, 1976). Most of the transition and heavy metals are near or slightly below the average concentrations in other coal. The ash of three samples of the Knobloch coal contain 70 ppm Ge and one contained 1.5 ppm Ag; the ash of one Flowers-Goodale sample contained 30 ppm Ge, and the ash of another 7 ppm Ag. These values are appreciably higher than is common for coals in the Western States, according to analyses of United States coals compiled by Swanson and others (1976).

Decker area

Coal currently being mined and scheduled for mining in the Decker area generally is in the Anderson, Dietz 1, and Dietz 2 beds (Matson and Blumer, 1973). By rank, the coal in all of these beds is subbituminous B.

The composition of the coal, by bed, and the range in concentrations of each component, are listed in table 12. These analyses and additional data presented in the Environmental Impact Assessment reports prepared by the Decker Coal Co. for the Decker area, indicate that the following ranges apply to coal in the Decker area (on an as-received basis); 23-25 percent moisture, 29-33 percent volatile matter, 38-40 percent fixed carbon, 3-9 percent ash, 0.3-0.5 percent sulfur, and 9,000-9,500 Btu per pound heat value.

The composition of the coal ash and the concentrations of trace elements in the coal are presented in table 13. Compared to the average coal in the United States, the following constituents are two to 10 times more abundant in the coal of the Decker area; CaO, MgO, Na_2O, Ba, Cu, Pb, and Sr. On the other hand, the coals at Decker contain less than average amounts of SiO_2, Al_2O_3, Hg, Se, and U.

Table 11.--Average (arithmetic mean) composition of ash (10 major and minor oxides and 20 trace elements), and contents of seven additional trace elements in coal of Knobloch and Flowers-Goodale beds in the Ashland area, Montana.

[Ashed at 525°C on air-dried coal. L, less than value shown. All trace-element determinations on ash, except Cd, Cu, Li, Pb, and Zn, by semiquantitative spectrographic method. All analyses by U.S. Geological Survey, Denver, Colo.]

Coal bed (number of samples)	Major and minor oxides in ash (percent)										
	Ash	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3	MnO	TiO_2	SO_3
Knobloch (55)	8.3	36	16	16	4.2	4.8	0.64	3.1	0.026	0.71	7.4
Flowers-Goodale (8)	9.3	37	20	13	2.4	4.7	.72	4.2	.037	.66	13

	Trace elements in ash (ppm)																			
	B	Ba	Be	Cd	Co	Cr	Cu	Ga	Li	Mo	Nb	Ni	Pb	Sc	Sr	V	Y	Yb	Zn	Zr
Knobloch (55)	700	5,000	3	1.0L	10	30	71	30	80	10	20	15	65	15	3,000	70	20	2	121	150
Flowers-Goodale (8)	1,000	7,000	10	1.0	10	30	97	30	65	10	20	15	51	15	5,000	70	30	3	80	200

	Trace elements in whole coal (ppm)						
	As	F	Hg	Sb	Se	Th	U
Knobloch (55)	1	41	0.05	0.4	0.4	2.5	0.7
Flowers-Goodale (8)	3	48	.06	1.2	.5	3.2	1.7

Table 12.--Composition of coal in the Anderson, Dietz 1, and Dietz 2 beds, Decker area, Montana, based on standard coal analyses (proximate, ultimate, Btu, and forms-of-sulfur analyses, reported in percent on as-received basis).

[Analyses by Montana Bureau of Mines and Geology (Matson and Blumer, 1973, table 3) and Coal Analysis Section, U.S. Bureau of Mines, Pittsburgh, Pa.]

	Anderson bed (11 samples)		Dietz 1 bed (7 samples)		Dietz 2 bed (3 samples)	
	Arithmetic mean	Range	Arithmetic mean	Range	Arithmetic mean	Range
Moisture	23.7	19.3-27.1	23.6	17.3-27.1	22.9	20.9-23.9
Vol. matter	31.3	21.1-35.6	29.4	21.2-31.6	29.9	26.3-32.5
Fixed C	38.5	32.3-41.6	38.5	26.7-43.4	39.7	35.8-42.9
Ash	6.3	2.9-27.3	8.5	2.6-34.8	7.5	2.5-16.7
Hydrogen	-----	---------	6.2	---------	----	--------
Carbon	-----	---------	57.1	---------	----	--------
Nitrogen	-----	---------	.9	---------	----	--------
Oxygen	-----	---------	30.9	---------	----	--------
Sulfur	.4	.2- .8	.4	.3- .7	.4	.2- .7
Btu/lb	8,990	6,590-9,850	8,860	6,020-9,880	9,100	8,080-9,690
Sulfate S	0.01	0.00- .03	0.01	0.01- .02	0.01	0.00- .02
Pyritic S	.09	.02- .31	.10	.03- .15	.14	.04- .31
Organic S	.28	.14- .54	.31	.24- .57	.27	.09- .40

Table 13.--Average (arithmetic mean) composition of ash (10 major and minor oxides and 20 trace elements), and contents of seven additional trace elements in coal of Anderson, Dietz 1, and Dietz 2 beds in the Decker area, Montana.

[Ashed at 525°C on air-dried coal. L, less than value indicated. All trace-element determinations on ash, except Cd, Cu, Li, Pb, and Zn, by semiquantitative spectrographic method. All analyses by U.S. Geological Survey, Denver, Colo.]

Coal bed (number of samples)	Major and minor oxides in ash (percent)										
	Ash	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3	MnO	TiO_2	SO_3
Anderson (7)	4.92	35	35	15	5.7	4.1	1.0	4.4	0.03	1.0	11
Dietz 1 (7)	5.4	32	16	15	4.6	4.0	.7	5.7	.03	1.0	17
Dietz 2 (1)	7.5	48	16	7	1.4	7.0	1.4	3.4	----	.8	11

	Trace elements in ash (ppm)																			
	B	Ba	Be	Cd	Co	Cr	Cu	Ga	Li	Mo	Nb	Ni	Pb	Sc	Sr	V	Y	Yb	Zn	Zr
Anderson (7)	700	10,000	3	1.0L	15	50	294	20	49	70	20L	30	569	15	5,000	150	30	3	153	150
Deitz 1 (7)	700	5,000	3L	1.1	20	70	276	30	81	50	20	50	193	30	7,000	200	50	3	137	200

	Trace elements in whole coal (ppm)						
	As	F	Hg	Sb	Se	Th	U
Anderson (7)	2	23	0.06	6.7	0.2	2.0L	0.5
Dietz 1 (7)	3	32	.08	15.5	.4	2.0	.5

COMPOSITION OF OVERBURDEN

The chemical composition of overburden above the Knobloch and Flowers-Goodale beds in the Otter Creek-Ashland area is shown by table 14 (U.S. Bureau of Land Management, 1975). The average compositions of the three principal rock types--sandstone, siltstone, and shale--resemble the average compositions of these rock types in sedimentary basins elsewhere (Turekian and Wedepohl, 1961, table 2). The rocks consist dominantly of silica and alumina, with minor amounts of calcium, magnesium, potassium, and iron oxides, which is typical of rocks composed dominantly of quartz, clay minerals, and minor calcite and dolomite. Further, the ranges in amounts of particular trace elements are within the normal ranges; for example, in shale, less than 10 to 52 ppm Cu (av. 28 ppm), 20 to 100 ppm B (av. 50 ppm), 3.1 to 8.5 ppm U (av. 4.2 ppm); in sandstone, less than 10 to 26 ppm Cu (av. 13 ppm), 1.8 to 3.5 ppm U (av. 2.8 ppm), and 30 to 78 ppm Zn (av. 49 ppm).

About the same ranges in values as those given above have been found in 21 core samples of the Tongue River Member of the Fort Union Formation in the eastern Powder River Basin in Wyoming (U.S. Geological Survey and Montana Bureau of Mines and Geology, 1974), and on this basis the values can probably be considered typical of non-coaly rocks in the Tongue River Member of the Fort Union Formation.

Table 15 gives chemical analyses of 16 samples of claystone and mudstone from the Tongue River Member of the Fort Union Formation at the localities shown on figure 13. Sample 698 is a claystone about 9 m above the Broadus coal bed (Berg and others, 1970, p. 24). The other samples are all from the part of the member lying above the Knobloch coal bed; most of them are from the upper part of the member above the level of the Canyon coal bed. Kaolinite is present in all but three of the samples, and is the predominant clay mineral in many of them (according to X-ray analyses reported by Berg and others, 1970, 1973). Illite is also present in most of the samples and smectite or montmorillonite is present in about half of them, generally in trace amounts.

Table 14.--Average (arithmetic mean) chemical composition of sandstone, siltstone, and shale that comprise the overburden rock above the Knobloch coal bed near Ashland, Mont. Samples are from three drill cores; 23 sandstone samples, 16 siltstone samples, and 27 shale samples.

[L, less than the value indicated. All analyses by U.S. Geological Survey, Denver, Colo.]

	In percent				In percent		
	Sandstone	Siltstone	Shale		Sandstone	Siltstone	Shale
SiO_2	62	59	55	As	6	6	13
Al_2O_3	10	12	15	Cd	1.0 L	1.0 L	1.0 L
CaO	7.3	6.9	6.5	Cu	13	22	28
MgO	3.20	3.41	3.07	F	556	714	896
Na_2O	.88	.78	.63	Hg	.06	.06	.09
K_2O	2.0	2.4	2.9	Li	21	28	36
Fe_2O_3	2.6	3.6	4.4	Pb	25	25 L	25
MnO	.025	.045	.053	Sb	.8	1.3	.2
TiO_2	.40	.46	.55	Se	.1	.2	.1
C (total)	2.90	2.60	3.35	Th	7.5	9.4	10.9
C (org.)	.4	.3	.8	U	2.8	3.6	4.2
C (min.)	2.50	2.30	2.55	Zn	49	69	91
S (total)	.03	.07	.29				
	In parts per million				In parts per million		
B	30	50	50	Ni	10	15	20
Ba	500	500	700	Sc	7	7	10
Be	1 L	1.5	2	Sr	100	150	150
Co	7	7	7	V	50	70	100
Cr	30	50	70	Y	10	20	20
Ga	10	15	15	Yb	1.5	2	2
Mo	3 L	3	5	Zr	150	150	100
Nb	5	5	15				

Table 15.—Chemical analyses of clay samples from the Tongue River Member of the Fort Union Formation.

[In percent of the total sample; from Berg and others, 1970, 1973]

Sample no.	SiO_2	Al_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	Fe[1]
683	54.0	18.75	3.36	3.90	0.69	1.31	0.30	5.20
684	59.7	13.4	1.68	2.40	0.60	1.30	0.25	3.80
685	49.4	17.4	2.63	1.65	0.49	2.46	0.30	6.40
686	67.4	13.8	1.11	0.70	0.35	1.28	0.25	2.40
687	56.7	16.95	1.91	1.00	0.61	1.31	0.30	4.80
688	59.4	16.9	1.91	1.35	0.59	1.32	0.33	4.70
689	60.5	16.45	1.57	0.78	0.53	1.30	0.35	3.60
690	59.6	10.95	3.55	6.3	0.78	1.29	0.25	3.20
691	59.6	12.1	3.15	5.15	0.78	1.30	0.25	3.60
692	57.0	14.8	2.42	5.00	0.65	1.29	0.25	4.60
693	57.5	17.25	1.85	0.78	0.54	1.28	0.30	2.70
694	53.5	11.6	1.92	2.10	0.61	1.29	0.35	4.70
695	70.3	10.45	1.70	2.15	0.80	1.30	0.25	3.10
696	64.1	12.45	1.16	1.30	0.80	1.25	0.35	6.40
697	55.6	15.85	2.64	5.45	0.72	1.29	0.27	4.30
698	43.7	11.35	4.35	13.55	0.81	1.30	0.26	4.00
728	50.7	18.7	2.39	3.0	0.74	2.40	0.65	4.05
729	56.1	15.3	2.43	2.6	0.78	2.52	0.30	6.20
730	57.3	12.6	3.10	4.55	0.84	1.85	0.30	3.70
731	56.3	12.8	3.00	4.05	0.98	2.10	0.35	3.60
732	54.2	13.7	3.14	4.50	1.08	2.64	0.30	3.80
733	53.6	15.6	2.25	4.80	0.74	2.52	0.40	4.40
734	54.8	14.4	2.67	3.35	0.94	2.88	0.35	3.60
735	53.1	14.3	3.32	5.05	0.95	1.98	0.40	2.70
736	53.8	13.5	3.10	4.70	0.83	2.28	0.35	3.80
737	49.6	14.8	3.10	4.30	0.88	2.58	0.40	3.95
738	52.2	14.75	2.07	3.45	0.88	2.76	0.40	4.85
739	58.9	14.8	1.86	2.25	0.71	2.52	0.55	3.05
740	63.3	16.1	1.88	1.60	0.78	2.76	0.45	2.60
741	62.0	13.0	2.52	3.30	0.68	2.34	0.35	2.25
742	59.1	13.9	2.92	2.80	0.58	2.46	0.50	3.40
743	64.8	13.2	2.49	3.65	0.56	2.22	0.45	2.70
744	57.9	16.9	2.17	1.80	0.58	2.70	0.55	3.15
745	68.8	12.4	1.38	1.05	0.56	2.10	0.40	3.05
746	64.8	14.1	1.19	1.00	0.61	2.30	0.70	3.15
747	62.8	14.2	2.46	2.05	1.01	2.16	0.45	2.70
748	65.2	13.9	2.64	2.95	1.42	2.18	0.35	3.85
749	61.2	10.6	2.24	2.60	0.93	2.86	0.40	3.15
750	64.4	13.6	2.67	2.90	1.12	1.74	0.45	2.50
751	54.5	16.5	2.88	3.25	0.98	2.18	0.45	4.50
752	64.3	14.4	1.59	2.10	0.78	2.58	0.60	3.25
753	65.0	10.25	1.88	3.35	0.68	2.36	0.50	2.80
754	62.3	8.50	1.85	6.95	0.63	2.02	0.40	2.90
755	62.3	11.50	1.95	4.20	0.58	2.22	0.50	2.90
756	60.2	12.45	2.28	3.25	0.50	1.82	0.60	3.70
757	60.2	13.4	2.75	3.35	0.58	2.26	0.60	3.35
758	62.5	11.25	2.82	4.30	0.57	2.28	0.55	3.35
759	57.5	11.75	2.82	5.60	0.80	2.46	0.55	3.25
760	55.8	10.7	3.84	7.50	0.90	2.52	0.50	4.25
761	63.6	14.75	1.45	1.40	0.95	2.90	0.70	2.70
762	59.8	13.75	1.92	2.54	0.84	2.58	0.50	3.60
763	49.5	10.55	3.95	7.40	0.86	2.40	0.55	4.70
764	53.0	13.25	3.73	6.20	0.89	2.94	0.55	4.35
765	55.6	11.45	3.66	6.50	0.92	2.48	0.50	4.05
766	55.6	13.50	3.29	5.05	0.98	2.94	0.50	3.95
767	64.1	12.60	1.34	1.75	0.74	2.20	0.60	3.05
768	50.3	11.15	3.69	9.85	0.84	2.72	0.45	4.05
769	52.2	9.40	4.56	10.45	0.82	2.18	0.30	3.05
770	50.0	11.95	4.27	9.85	0.76	2.59	0.50	3.15
771	54.3	11.70	3.37	8.70	0.84	2.92	0.45	3.25
772	66.3	14.15	1.27	1.85	0.84	2.46	0.55	3.05
773	62.7	11.80	2.32	4.30	0.90	2.50	0.50	3.25
774	59.2	11.95	1.57	6.25	0.84	2.30	0.50	3.50
775	60.3	15.60	1.01	2.80	0.65	2.52	0.70	3.25
776	58.0	13.8	1.85	4.30	0.78	2.40	0.60	3.70
777	61.2	12.85	2.18	4.35	1.15	2.44	0.55	3.80

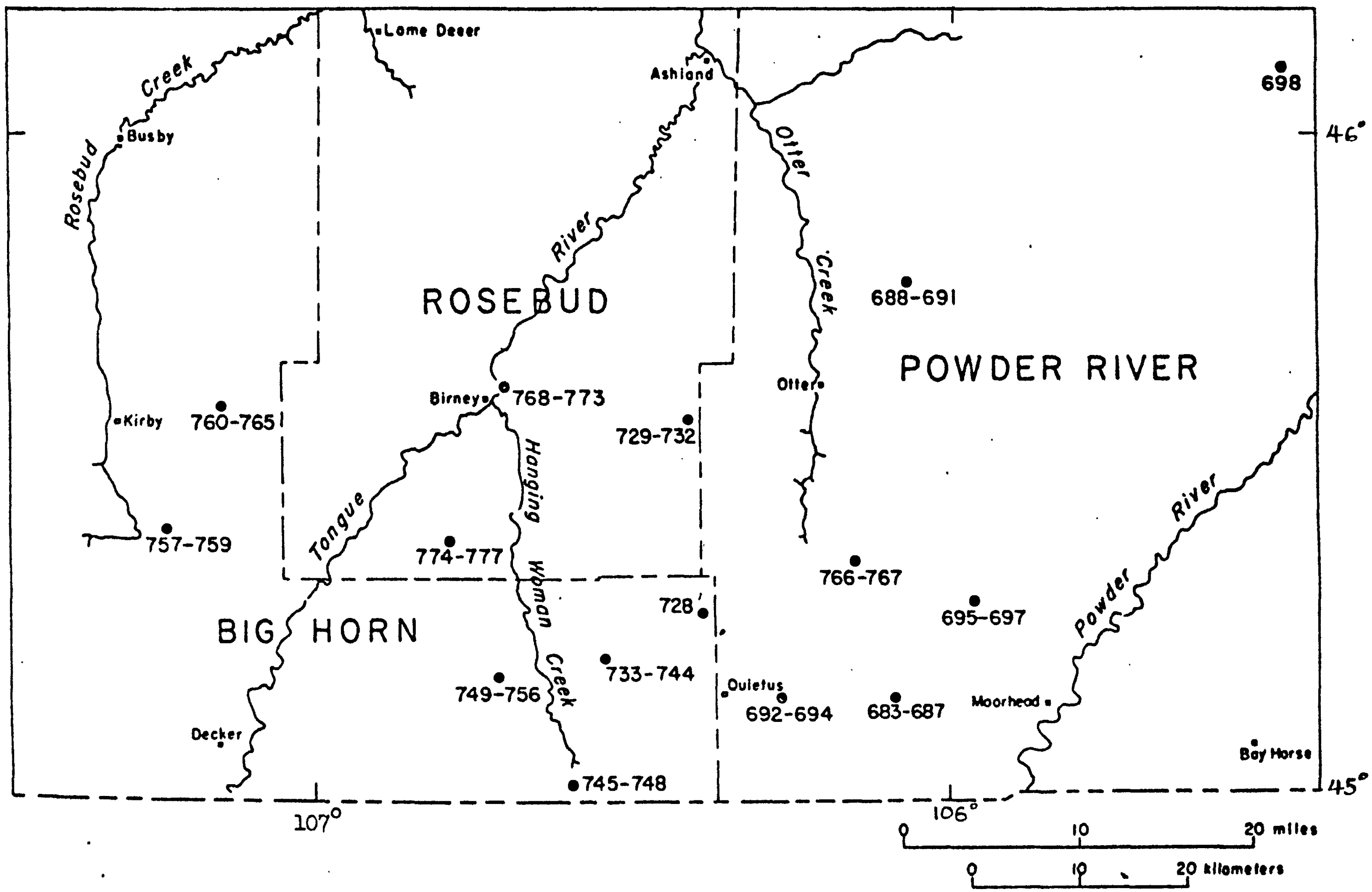

Figure 13.—Location of clay samples from the Tongue River Member of the Fort Union Formation. (From Berg and others, 1973).

OIL AND GAS

The northern Powder River coal region has been prospected for oil and gas intermittently since the 1920's. About 650 wells have been drilled in the region including about 160 wells drilled in developing the Bell Creek and seven other smaller fields and about 490 unsuccessful wildcat wells widely scattered across the basin. Nine oil and gas fields have been discovered on or near the periphery of the region in Montana to 1976, as shown by figure 14 and table 16. Rocks continuous with those that underlie the northern part of the basin are prolific producers of petroleum in the adjacent part of Wyoming.

Formations that contain oil and gas in and adjacent to the northern Powder River coal region include in descending order the Shannon Sandstone Member of the Cody Shale, the Frontier Formation, the Newcastle Sandstone, and the Tensleep Sandstone. Several rock units other than those mentioned above contain petroleum in the Wyoming part of the basin, including rock units of Cretaceous, Jurassic, Permian, and Pennsylvanian ages (Strickland, 1958; Kinnison, 1971).

The main target of oil exploration in the Powder River Basin has been deposits in Cretaceous rocks. Kinnison (1971, p. 607) summarized Cretaceous production and potential in the following terms:

> "The Cretaceous System has accounted for approximately two-thirds of the produced oil in the Powder River basin and has the highest potential for additional reserves. Some production is found in basically structural anomalies on the rims of the basin, but most reserves have been found in stratigraphic traps on the gently dipping east flank. With the exception of the Lance Formation, all the sandstone units are hydrocarbon-productive. The upper Inyan Kara (Fall River) and Muddy-Newcastle zones hold more than 90 percent of the total Cretaceous reserves."

Figure 15 shows the density of drilling in the northern Powder River coal region. Cretaceous rocks as old as the Newcastle Sandstone have been moderately well explored locally in the southern and eastern parts of the area, and much less well explored in the northwestern part. Only about 15 percent of the wells drilled to 1976 have tested rocks older than the Jurassic Morrison Formation. An appreciable volume of rock that is prospective for petroleum, therefore, is inadequately tested, and the prospects for discovering new resources of petroleum are considered favorable both in Cretaceous and pre-Cretaceous rocks.

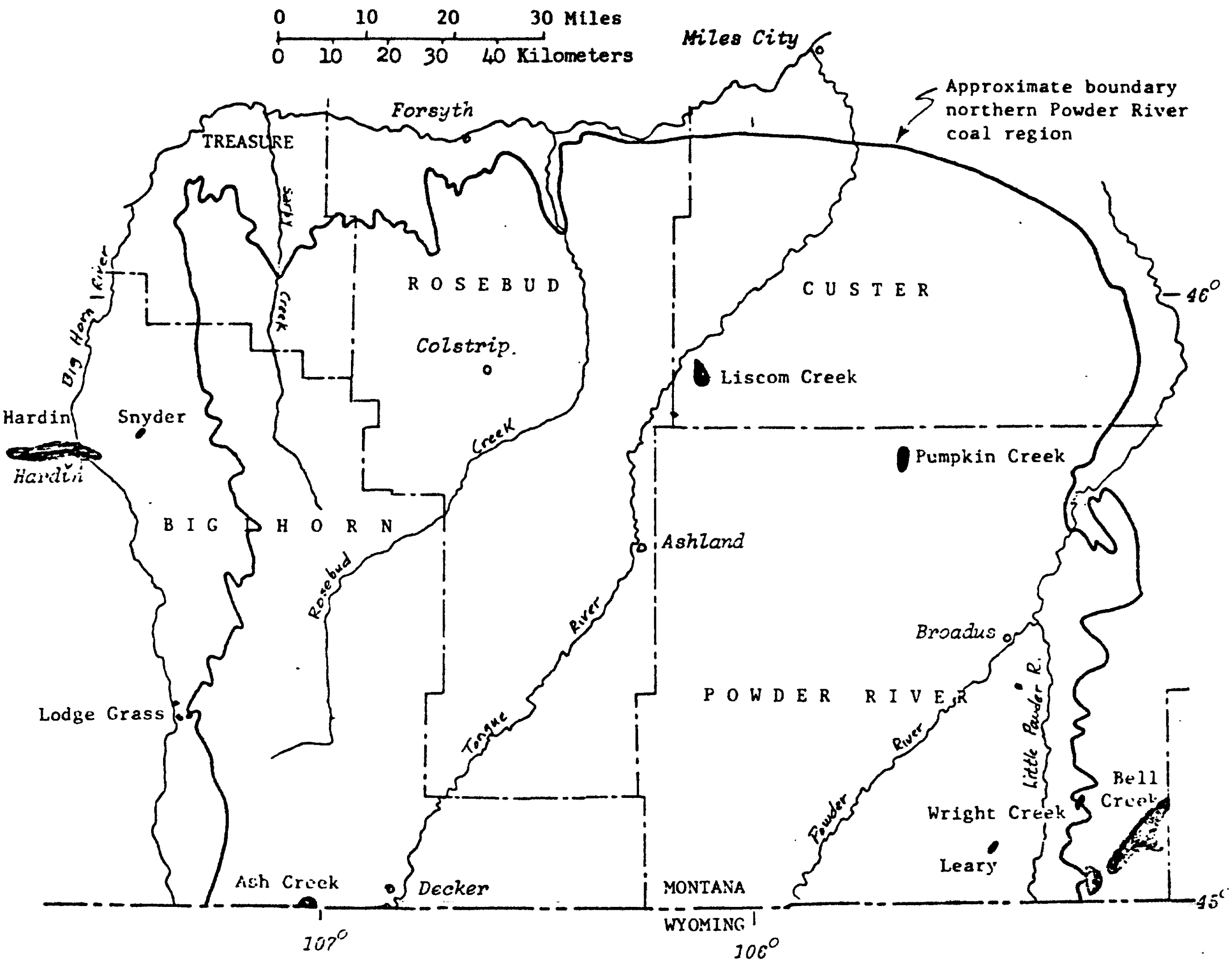

Figure 14.—Oil and gas fields (solid black areas) in and near the northern Powder River coal region.

Table 16.—Oil and gas fields in and near the northern Powder River coal region, Montana

[Data as of September, 1974; from Petroleum Information, Denver, Colorado]

Name	Location: Township	Location: Range	Producing formation	Year discovered	Cummulative production: Oil, bbls[1]	Cummulative production: Gas, MFC[2]	Number of producing wells
			Big Horn County				
Snyder	1 S.	35 E.	Tensleep	1954	391,338	———	3
Hardin	1 S.	33, 34 E.	Frontier (Belle Fourche)	1913	———	1,232,529	34
Lodge Grass	6 S.	35, 36 E.	Tensleep	1964	205,558	———	1
Ash Creek	10 S.	38 E.	Shannon Sandstone Member, Cody Shale	1952	723,996	4,679	5
			Custer County				
Liscom Creek	1,2 N.	45 E.	Shannon Sandstone Member, Cody Shale	1959	———	844,324	7
			Powder River County				
Pumpkin Creek	1 S.	49, 50 E.	Telegraph Creek	1954	———	no record	8
Leary	8, 9 S.	51 E.	Newcastle Sandstone	1969	160,059	122,477	3
Wright Creek	8 S.	53 E.	Newcastle Sandstone	1969	159,658	167,839	5
			Powder River and Carter Counties				
Bell Creek	8, 9 S.	53, 54, 55 E.	Newcastle Sandstone	1967	66,431,569	34,405,673	228

[1] Barrels [2] Thousand cubic feet

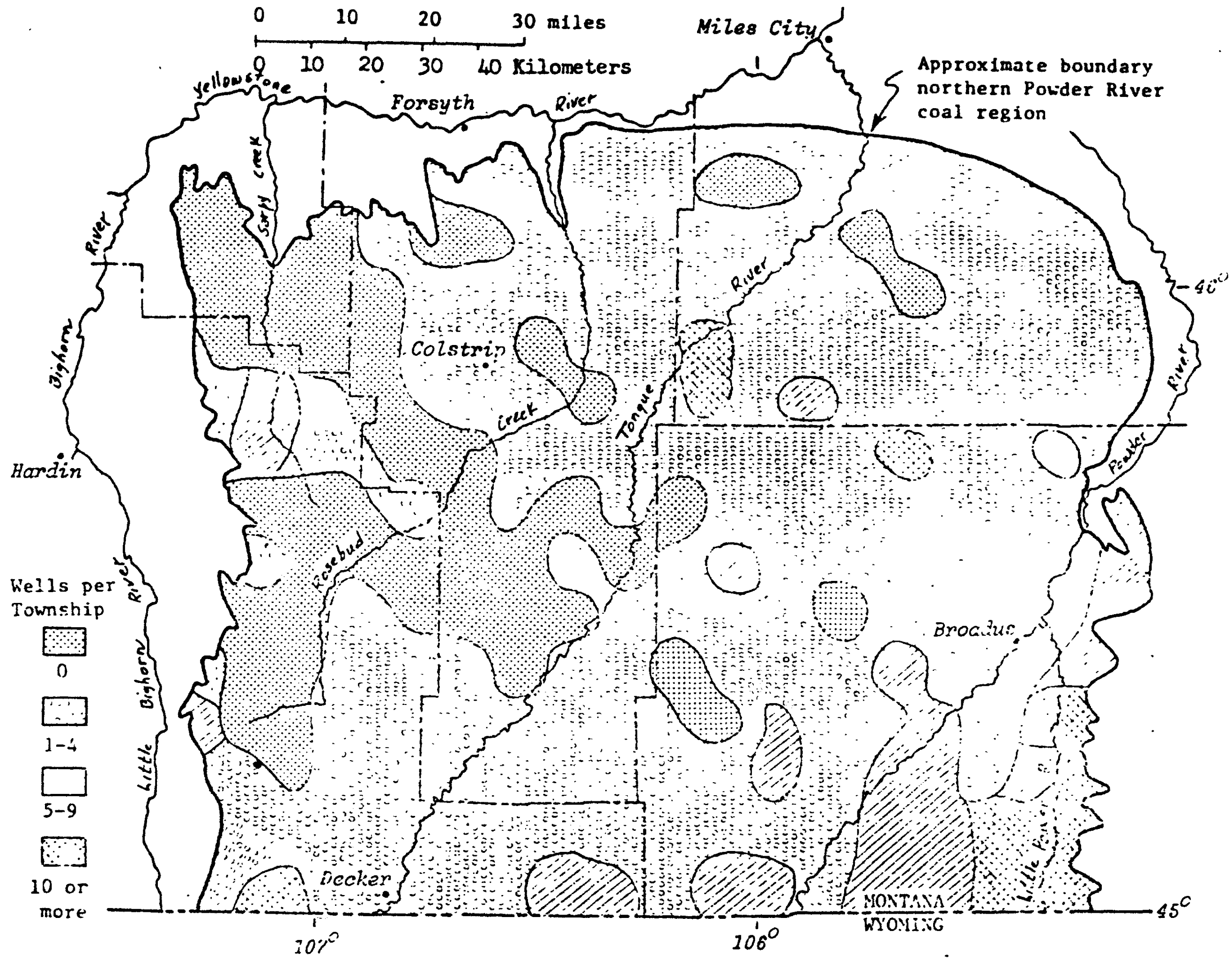

Figure 15.—Density of drilling for oil and gas, northern Powder River coal region.

The depth to the Shannon Sandstone Member of the Cody Shale, or its equivalents, beneath the base of the coal-bearing Tongue River Member of the Fort Union Formation in the northern Powder River coal region is about 760 m and the depth to the Newcastle Sandstone beneath the Tongue River is about 1,370-1,430 m. Older formations of potential interest for petroleum are deeper. Coal mining in the Tongue River Member will have no effect on petroleum resources in Cretaceous or older rocks at these depths. However, mining may cause exploration to be deferred at a few localities not prospected previous to mining. It is possible, and perhaps likely that oil and gas will be discovered in areas coincident with minable coal deposits. In any such areas, coal and petroleum might have to be produced sequentially. Because oil and gas fields have yet to be discovered in areas having good potential for coal mining, the extent of possible conflicts in producing the two resources cannot be accurately assessed.

NATURAL GAS IN COAL

Methane gas derived from coal has been produced from shallow wells in the Tongue River Member of the Fort Union Formation in the Wyoming part of the Powder River coal region and used for domestic purposes, according to Olive (1957, p. 23). Three shallow wells are reported by him to have had initial productions of gas of 500,000-1,000,000 cubic feet per day. Methane gas from coal or associated permeable sandstone beds may constitute a minor resource in some parts of the northern Powder River coal region. The potential of this resource is unevaluated.

BENTONITE

Bentonite is a clay material formed from the alteration of volcanic ash. It has a wide variety of industrial uses as described by Hosterman (1973, p. 127-128). Lenses of bentonite have been found at a few places in the Fort Union Formation in the northern Powder River coal region. Bryson (1952, p. 65) gives the following description of a bentonite deposit in the valley of the Powder River in the Lower Member of the Fort Union.

Shale, silty.

	Ft	In.
Bentonite (nonswelling type)	0	8
Bentonite (nonswelling type), dark olive-green; acid-activable oil-bleaching clay	2	4
Bentonite (nonswelling type) olive-green	2	11
Bentonite (nonswelling type), olive-green; contains fossil leaf; both natural and acid-activable bleaching clay	2	10
Bentonite (nonswelling type), olive-green, in alternating hard and soft layers; both natural and acid-activable bleaching clay	2	11
Bentonite (swelling type), olive-green, in alternating hard and soft layers	4	0
Bentonite (swelling type), olive-green, in alternating hard and soft layers	2	0
Bentonite (swelling type), light olive-green	1	1
	18	9

Shale, siliceous, hard.

Bentonite of fair to poor quality has been noted in the lower part of the Tongue River Member of the Fort Union Formation at three localities in the Northern Cheyenne Indian Reservation. The bentonite occurs in beds ranging in thickness from 1.8 to 6 m. Test data on samples from these beds is given in table 17.

A few undescribed deposits of bentonite probably occur at other places in the northern part of the region, both in the Tongue River and Lebo Shale Members of the Fort Union Formation. The potential for appreciable resources of good quality material cannot be evaluated accurately, but the scarcity and mediocre quality of the known deposits indicate the potential is low. On the basis of available information, strippable deposits of coal do not occur in close association with valuable deposits of bentonite in the Fort Union.

CONSTRUCTION MATERIALS

Clinker

Clinker is a common rock type in the Tongue River Member of the Fort Union Formation and is widely used for road metal and railroad ballast. Its origin and composition have been described by Brown and others (1954, p. 166) as follows:

Table 17.—Test data on bentonite samples

[From Magill and others, 1969, p. 28. Sample 1, sec. 2, T. 3 S., R. 43 E.; sample 2, sec. 17, T. 2 S., R. 41 E.; sample 3, sec. 6, T. 5 S., R. 43 E.]

Sample No.	Swelling capacity in millilitres of 2.0 gram sample	Percent grit (+325 mesh)	Yield (bbl per ton)
1	6.5	4.0	26.8
2	1.5	7.4	13.0
3	4.5	14.8	13.4

Viscosity for slurries containing various clay percentages

Sample No.	Percent clay	Viscosity (centipoises)	Percent clay	Viscosity (centipoises)	Percent clay	Viscosity (centipoises)
1	6.0	1.7	15.0	6.2	21.0	19.6
2	6.0	1.2	15.0	1.7	35.0	6.4
3	6.0	1.4	15.0	2.1	35.0	16.6

Wall building properties - for slurries containing 6 percent clay by weight

Sample No.	Filtrate in ml for indicated time in minutes 2	15	30	Thickness of cake in 1/32 in.
1	8.0	26.0	37.5	1.5
2	91.5	240.0	328.0	.4
3	40.0	106.0	137.0	.5

The term clinker includes the several types of rock that have been produced from sandstone and shale by the melting, partial fusion, and baking resulting from the intense heat of gases that rise from burning coal beds. Clinker masses show a rough zoning of thermal alteration that ranges upward from complete melting to simple baking. The melted rock resembles common furnace clinker or volcanic lava. It has a vitreous appearance, shows flow lines, and contains frothy vesicular masses. The baked rock retains its original texture and bedding, but the individual grains are fused together, giving it a much greater hardness than unaltered rock. An intermediate type is a breccia of fused angular blocks of baked rock. This type is produced when rocks overlying a burning coal bed crack and slump as their support is burned away. The dominant color of clinker is a brick red, but in the fused zone many parts are gray, black, yellow, or greenish. Clinker strongly resists weathering and erosion; it forms the cap rock on most of the buttes and mesas in the area and makes rough escarpments on many slopes.

The thick coal beds in the region have all burned extensively along their outcrops and under shallow cover, producing masses of clinker locally more than 30 m thick. The use for clinker is small compared to the large supply available in the region, and the value of the resource that would be lost in mining coal is small.

Sand and gravel

Major sand and gravel deposits occur in the stream terraces along the major streams as shown on the geologic map, figure 6. Gravel from some of these deposits has been used locally for road subgrade and road surfacing. Because many of the deposits contain clinker, ferruginous sandstone fragments, and other possibly deleteriously reactive or structurally weak rock types, much of the gravel may not be suitable for making good quality concrete.

At places, such as along the Tongue River near Birney, stream gravels overlie strippable coal deposits, and at such places useful gravel deposits might be lost in mining the coal.

Clay and shale

The ceramic and bloating properties of 65 samples of clay and shale from the Tongue River Member of the Fort Union Formation, collected at 15 widely scattered localities in southeastern Montana, have been described by Berg and others (1970, 1973), including mineralogical and chemical analyses of the samples, and tests forwaterof plasticity, drying shrinkage, fired color, hardness, and other physical properties. Berg and others (1970, p. 27; 1973, p. 18) conclude that most of the clay and shale tested showed little suitability for use in manufacturing bricks or other fired products, but that shale represented by about a third of the samples was suitable for use as lightweight aggregate.

Coal mining would not be expected to affect appreciably the availability of clay and shale of the quality known to be present in the region.

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PART B.--LANDSCAPE GEOCHEMISTRY

by J. J. Connor

SYNOPSIS

Coal-based energy development in the Northern Powder River Basin is expected to impact the geochemical landscape most importantly by changing the chemistry of vegetation. Two examples of such impact observed to date in this or nearby regions are (1) altered copper/molybdenum ratios in sweetclover growing on spoil banks, and (2) accumulations of selenium and fluorine and, probably, other trace elements in native vegetation growing within 5-10 km of coal-fired electric-generating plants. Altered copper/molybdenum ratios can induce molybdenosis in ruminants, and both selenium and fluorine are known poisons. In general, while natural scientists can define an "excessive" trace element level in natural materials, medical scientists are the only ones capable of assessing a "health hazard" based on such levels.

DISCUSSION

The two greatest geochemical impacts on the western landscape resulting from large-scale coal development are likely to be geochemical alteration at strip mine sites by overturn, and geochemical alteration adjacent to electric-generating sites through coal combustion. The first tends to be a rather localized effect but the second may have regional impact.

The environmental interest in the chemical composition of the natural landscape arises solely from fears that disturbed (or restored) landscapes may exhibit visibly changed compositions. For all practical purposes, this interest focuses on the chemical potential of disturbed or restored materials in supporting a desirable vegetative cover, which in turn can support animal life of interest (including animals used directly by humans).

If the area to be disturbed by mining or related activity presently supports vegetation, the chemical composition of the substrate (soil or rock) obviously meets at least the minimum requirements of this vegetation. Therefore, a primary geochemical need in impact assessment is a knowledge of the chemistry of these substrates in terms of geochemical backgrounds or "baselines." Such baselines in essence define the minimum levels of total nutrient elements, and maximum levels of "toxic" elements, to which this vegetation is exposed, although not necessarily to the extreme that this vegetation can endure. They also provide a basis for estimating the chemical potential of abandoned or reclaimed land to support the same vegetation.

Many studies have shown that the elemental composition of bulk soil is only weakly reflected by element levels in plant tissue under ordinary landscape conditions. Therefore, work in plant geochemistry should focus on levels in the plant that may be toxic to wildlife or domestic animals. Because the plants that are there, by their very presence, demonstrate that any current levels of elemental concentration found in the supporting soil can be tolerated by the vegetation, the major botanical problem then becomes whether or not such plants can be expected to grow on some new kind of substrate (resulting from man's activities) and whether or not such growth will result in changed tissue concentrations of elements.

The first part of this question can only be answered by a study of the geochemistry of the new substrate. The chemical composition of these materials may indicate levels of nutrient elements below, or levels of toxic elements above, the concentrations found in the original ("native") substrate. It is true that chemical requirements or chemical tolerances of vegetation are determined by the "available" amounts, not total amounts, of certain elements in the substrate, but the experimental difficulties of determining or stating in a general way the criterion of element availability without reference to species-selective membrane response make the concept very difficult or impossible to apply to native ecosystems.

While nutrient deficiencies are not uncommon in the plant and animal world, public concern over trace element impact of coal development tends to focus on element excesses ("toxicities"). The definition of what constitutes an "excess" in a landscape material is less difficult than that of the definition of availability, but it is nevertheless a difficult one. Ideally, an excess is that amount above "normal," but because normal concentrations can and do vary over considerable ranges in nature, a normal concentration at one spot (or in one sample) could be viewed as excessive at another nearby spot (or in another sample of the same or similar material).

Considerable evidence is available (U.S. Geological Survey, 1974, 1975, 1976) that the range in normal concentrations in soil and plant tissue typical of the coal regions of Wyoming, Montana, and North and South Dakota is manifested largely at very local or short-range scales in nature; that is, the range in concentration noted in a suite of samples from one localized area in the region (like a strip mine), is likely to be similar to the range noted at other, far-distant sites. Under such circumstances, an elemental excess may be viewed as concentrations above some upper limit typical of the normal range.

Such a provisional limit is estimated in table 1 (page 7) for some 10 ordinary landscape materials likely to be encountered in the Northern Powder River coal region. Each limit is defined as a concentration above which only about one sample in 20 is expected to fall under "natural" conditions. Because of uncertainties inherent in the method of estimation, each limit is given to one significant figure only and, as such, represents an interval equal to perhaps 10-20 percent of the listed value. Regardless, these limits may prove useful in assessing geochemical impact. For example, observed ranges in concentration of elements in 10 samples of top-dressed spoil materials from the Big Sky mine in Rosebud County are as follows:

Element	Range (ppm)
Silicon	210,000-340,000
Fluorine	600-1700
Carbon	16,000-160,000
Mercury	.01-.12
Thorium	5.7-11
Uranium	2.3-3.7
Calcium	18,000-44,000
Magnesium	8200-17,000
Lithium	21-55
Sodium	2800-23,000
Potassium	15,000-20,000
Manganese	101-294
Zinc	42-66
Aluminum	46,000-76,000
Sulfur	280-6700
Rubidium	59-85
Titanium	2300-3000
Iron	17,000-32,000

The higher concentrations of fluorine, mercury, thorium, calcium, lithium, sodium, and aluminum noted in these reclaimed materials exceed the upper limits for natural soil given in table 1. They also exceed the upper limits of mercury, magnesium, lithium and sodium given for one or more fractions of sediment in the Powder River (table 1). In the simplest terms of substrate element concentration, these data indicate something of the impact of mining.

In addition, the potential impact of vegetative cover is suggested in an examination of the copper/molybdenum ratios in sweetclover growing on spoil materials (table 2). This ratio is seen to range from about 0.4-6.5 and for six of the eight mines listed on table 2 is less than 4.0 as compared to an "optimal" ratio of about 5.0-7.0. Clearly, a browse diet formed largely of such a plant might induce symptoms of a copper/molybdenum imbalance. Grama grass in natural landscapes of the Powder River Basin has an average ratio of 4.7.

A miscellaneous collection of analyses of landscape materials from the Northern Powder River Basin shows a geochemical diversity that stands in strong contrast to the rather uniform geochemical nature of the surface soils of the basin.

Regional geochemical impacts are likely to result largely from windborne transport of extraneous materials. Two sources of such materials are unreclaimed or abandoned disturbed areas and stack emissions from coal-fired generating plants. Again, the focus of such impact is on potential changes in the vegetative cover. It is reasonable to suppose that powerplant emissions contain at least small amounts of every naturally occurring element, but any practical assessment of their impact can only be based on elemental effects observed in the landscape adjacent to or downwind from the stack. Such effects were looked for in both sagebrush and soil lichen downwind of the Dave Johnston powerplant at the southern edge of the Powder River Basin (figs. 1 and 2). The strongest effect, as measured by regression techniques, was that due to selenium, a particularly important element because of its known toxic effects to browsers. In both vegetation species, selenium appears to be elevated out to distances of 5-10 kilometers. Other suspect elements include strontium, vanadium, uranium, and fluorine, and, perhaps, titanium, zinc, lithium, and cobalt. Except for uranium in sagebrush and selenium in lichen, the observed concentrations thought to reflect contamination are similar to or less than the upper limits for natural conditions given in table 1.

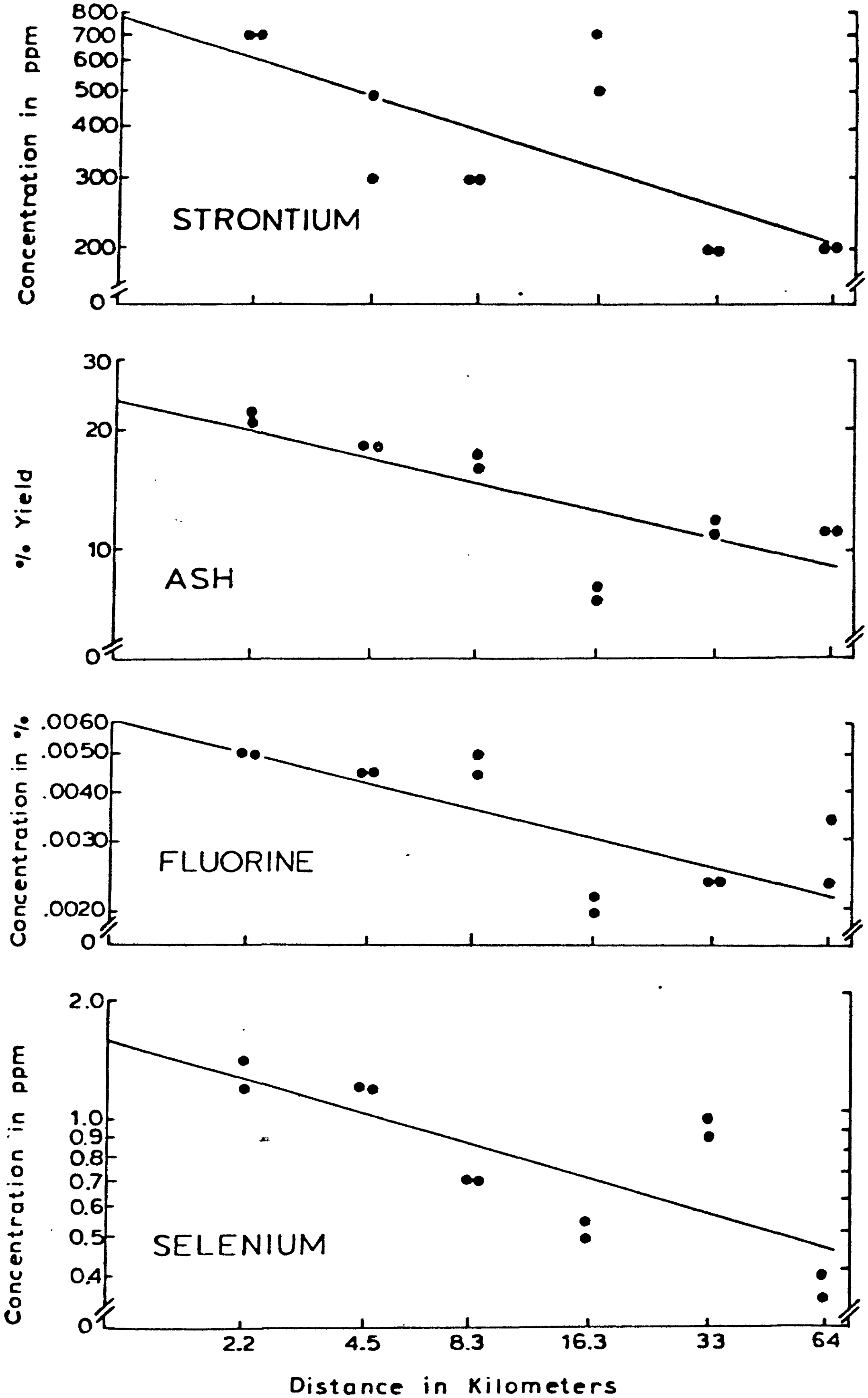

Figure 1.--Regression trends in Parmelia chlorochroa for concentrations of fluorine, selenium, strontium, and ash progressing east from the Dave Johnston Powerplant. Slopes are significantly different from zero at the 0.01 probability level.

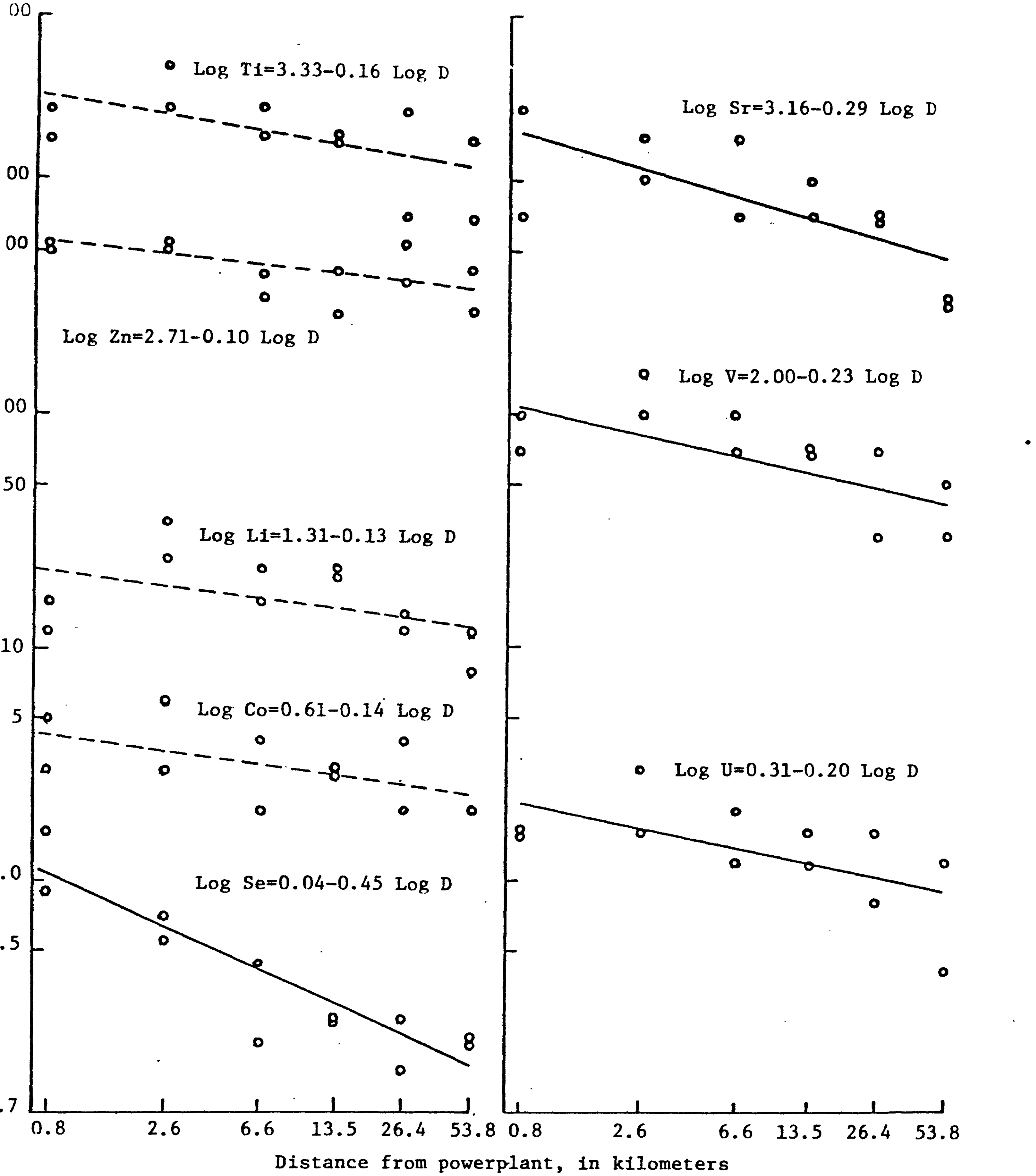

Figure 2.--Metel trends in sagebrush away from powerplant. Slopes of solid regression lines are statistically significant at the 0.05 or lower probability level of dashed regression lines at the 0.05 to 0.10 probability levels; both define trends in concentration. Concentrations of selenium measured in dry weight; all other concentrations measured in ash weight. From Connor and others, 1976.

Table 1.—Approximate maximum limits of chemical concentrations and derivative geochemical properties in some ordinary landscape materials in the Powder River Basin. Data on ground water and wheat drawn in part from the Northern Great Plains as well. Concentrations in parts per million except for water which are given as milligrams per liter 1/; dashes (- - -) indicate data are not available.

	Powder River sediments 2/ >200	100-200	63-100	<63	Soil 2/	Sagebrush 2/	Lichen 2/	Grama grass 2/	Wheat 3/	Shallow ground water 4/
Aluminum	-----	-----	-----	-----	70,000.0	70,000.0	60,000.0	50,000.0	-----	------
Antimony	-----	-----	-----	-----	2	------	------	------	-----	------
Arsenic	-----	-----	-----	-----	10	------	1 5/	2 5/	-----	------
Barium	-----	-----	-----	-----	1,000	1,000	700	800	-----	------
Beryllium	-----	-----	-----	-----	2	------	------	------	-----	------
Boron	-----	-----	-----	-----	60	400	------	200	-----	------
Bromine	-----	-----	-----	-----	-------	------	------	------	-----	0.8
Cadmium	-----	-----	-----	-----	-------	16	9	2	6.0	------
Calcium	-----	-----	-----	-----	20,000	100,000	------	60,000	------	200
Chlorine	-----	-----	-----	-----	-------	------	------	------	------	80
Chromium	-----	-----	-----	-----	80	40	70	70	------	------
Cobalt	-----	-----	-----	-----	10	5	7	9	4	------
Copper	-----	-----	-----	-----	30	------	100	200	300	-------
Fluorine	-----	-----	-----	-----	700	20 5/	50 5/	100 5/	------	1
Gallium	-----	-----	-----	-----	20	------	------	20	------	-------
Germanium	-----	-----	-----	-----	2	------	------	------	------	-------
Iodine	-----	-----	-----	-----	-------	------	6 5/	------	------	------
Iron	-----	-----	-----	-----	40,000	------	20,000	20,000	------	2
Lead	-----	-----	-----	-----	30	100	200	40	8	------
Lithium	40	20	20	30	30	30	10	20	------	------
Magnesium	20,000	7,000	9,000	10,000	20,000	------	10,000	20,000	------	100

Table 1.—Approximate maximum limits of chemical concentrations and derivative geochemical properties in some ordinary landscape materials in the Powder River Basin—Continued

	Powder River sediments[2/] >200	100-200	63-100	<63	Soil[2/]	Sagebrush[2/]	Lichen[2/]	Grama grass[2/]	Wheat[3/]	Shallow ground water[4/]
Manganese ----------	-----	-----	------	-----	700	900	600	1,000	------	.2
Mercury ------------	.4	.05	.05	.05	.03	.03[5/]	.1[5/]	.04[5/]	------	-------
Molybdenum ---------	-----	-----	------	-----	--------	20	-------	20	200	-------
Nickel -------------	-----	-----	------	-----	30	30	20	10	40	-------
Nitrogen										
Organic, as N ----	-----	-----	------	-----	--------	------	------	------	------	4
NH_4, as N --------	-----	-----	------	-----	--------	------	------	------	------	3
NO_3, as N --------	-----	-----	------	-----	--------	------	-------	------	-------	4
Phosphorus ---------	------	-----	------	-----	--------	------	-------	10,000	-------	--------
Potassium ----------	------	-----	------	-----	30,000	400,000	-------	30,000	-------	20
Rubidium -----------	100.0	80.0	90.0	90.0	100.0	-------	-------	40.0	------	------
Scandium -----------	------	------	------	------	10	-------	-------	------	------	------
Selenium -----------	------	------	------	------	.5	2.0[5/]	0.6[5/]	.5[5/]	2.0[5/]	------
Silicon ------------	------	------	------	------	400,000	10	20	40	------	30[6/]
Sodium -------------	9,000	7,000	7,000	7,000	9,000	2,000	600	1,000	------	------
Strontium ----------	------	------	------	------	300	1,000	900	300	------	------
Sulfur -------------	------	------	------	------	-------	2,000[5/]	1,000[5/]	700[5/]	------	1,000[7/]
Thorium ------------	------	------	------	------	10	--------	-------	-------	------	------
Tin ----------------	------	------	------	------	3	-------	-------	--------	------	------
Titanium -----------	------	------	------	------	4,000	2,000	3,000	3,000	------	------
Uranium ------------	------	------	------	------	5	1	6	2	------	------
Vanadium -----------	------	------	------	------	100	80	90	100	------	------

Table 1.—Approximate maximum limits of chemical concentrations and derivative geochemical properties in some ordinary landscape materials in the Powder River Basin—Continued.

	Powder River sediments 2/ >200	100-200	63-100	<63	Soil 2/	Sagebrush 2/	Lichen 2/	Grama grass 2/	Wheat 3/	Shallow ground water 4/
Ytterbium ----------	------	------	------	------	2	-------	-------	------	------	------
Yttrium ------------	------	------	------	------	20	--------	50	------	------	-------
Zinc ---------------	100	60	60	90	100	600	-------	1,000	3,000	4
Diss. Solids, 180°C.	------	------	------	------	------	-------	-------	------	------	3,000
Total hardness (as $CaCO_3$) -----------	------	------	------	------	------	-------	--------	------	------	1,000
pH -----------------	------	------	------	------	7.9	-------	--------	------	------	8.3
Radioactivity (pCi/gm) 8/	------	------	------	-------	60	-------	-------	------	------	--------
Sp. conductance (micromhos/cm) -----	------	------	------	-------	------	-------	-------	------	------	4,000

1/ All estimates except pH given to only one significant figure.

2/ Adapted from table 1, U.S. Geological Survey (1975), modified in part by data in U.S. Geological Survey (1974, 1975, 1976).

Numbers under Powder River sediments are size fractions in microns.

3/ Adapted from Shacklette, Erdman, Harms, and Papp (1976).

4/ Estimated from data in table 13, U.S. Geological Survey (1975).

5/ Determined on dry weight of plant material.

6/ as SiO_2.

7/ as SO_4.

8/ Computed as 4.81(ppmV)+1.1(ppmTH)+8.5(%K), from John Rosholt, written comm. (1976).

Table 2.--Copper and molybdenum in sweetclover (Melilotus spp.), and pH in spoil materials from eight coal mines in the Northern Great Plains

[Geometric mean (GM) concentrations and observed ranges expressed as parts per million in dry material; arithmetic mean (AM) of pH expressed in standard units; GD, geometric deviation; SD, standard deviation; mines listed in order of increasing Cu:mo ratios]

Mines, or baseline data	Sweetclover, above ground parts									Mine spoils		
	Copper			Molybdenum			Cu:Mo ratio			pH		
	GM	GD	Observed range	GM	GD	Observed range	GM	GD	Observed range	AM	SD	Observed range
Big Sky -------	8.2	1.16	6.5-9.8	13.0	1.23	10-20	0.61	1.21	0.44-0.75	7.6	0.53	6.5-8.5
Utility -------	6.9	1.14	5.3-9.0	11	1.33	6.4-18	.62	1.29	.43-1.0	7.8	1.30	4.4-9.0
Velva ---------	7.2	1.18	5.9-9.5	7.9	1.25	5.3-12	.92	1.27	.63-1.4	7.8	.40	7.0-8.5
Savage --------	5.9	1.27	4.1-9.3	6.4	1.30	4.8-10	.92	1.47	.50-1.9	8.2	.49	7.0-8.5
Kincaid -------	9.0	1.20	6.7-13	6.5	1.84	2.8-18	1.4	1.70	.65-2.8	7.8	.71	7.1-9.4
Beulah --------	5.5	1.14	4.4-6.7	2.6	1.60	1.2-8.3	2.1	1.60	.63-3.8	7.0	.69	6.2-8.7
Dave Johnston -	7.0	1.19	5.2-9.5	3.1	2.18	1.5-14	2.3	2.34	.47-6.5	6.2	1.59	4.0-8.5
Welch ---------	8.1	1.27	5.6-11	3.4	1.68	1.9-9.5	2.4	1.77	1.2-5.0	6.6	.96	5.4-7.8
Baseline data 2/	7.6	1.66	2.8-21 1/	2.1	2.57	.32-14 1/	3.6	2.35	.65-20 1/	7.2	.46	6.3-8.1 1/

1/ Ranges given for baseline data are not the "observed" ranges, but the expected central 95-percent ranges as described in the text.

2/ Sweetclover baseline based on eight samples collected throughout the United States; pH baseline based on 64 A-horizon soil samples collected across the Powder River Basin (Tidball and Ebens, 1976).

In any event, the fears aroused by such accumulations reflect less a concern with absolute amounts introduced as with the availability to plants of such emissions. Because the lichen samples were cleaned prior to analysis, the selenium accumulation noted there probably reflects biological accumulation, not simple physical entrapment. Some reported toxic effects of selected trace elements on plants and animals are listed in table 3.

Presumably, the most abundant emissions from power plants would be the oxides of sulfur, carbon, nitrogen, and hydrogen (water), but as essential constituents of vegetative tissue, it is unlikely that such impact on plant material could be measured as simple distance-related accumulation (although it might be measured in general terms of plant "health"). Interestingly, any geochemical effects of power generation need not necessarily reflect only stack emissions. A sagebrush traverse north of the Jim Bridger powerplant indicated appreciable accumulations in sagebrush of iron, titanium, nickel, silicon, fluorine, and selenium, as well as increased ash contents. All of these effects were measured before any of the generating units went officially "on-line," and they tended to be greatest within 1-3 kilometers of the plant. They probably reflect either a construction impact (windborne dust) or natural (substrate) fluctuations, or both.

The hydrologic impact of energy development is expected to be substantial, although the greatest changes will likely be on the quantity or flow direction of water supplies, rather than on chemical quality (at least in a regional sense). Table 1 gives some expected upper limits of a variety of geochemical properties in the shallower (30 or so meters) domestic or livestock water supplies of the Northern Great Plains. Landscape similarities of southeastern Montana and western North Dakota suggest that these limits may serve as provisional guides in the Northern Powder River Basin, also.

The most difficult aspect of impact assessment on the trace-element character of the landscape is that of assessing the broad-scaled regional effects. This is so because while changes in trace-element concentrations far from mines or powerplants will almost certainly be very small, the fear exists that such changes may still pose a potential hazard to plant, animal, or human health. This fear arises largely from the fact that the exact roles played by many trace elements in living tissue remain unclear or unknown and the relation of the local geochemical environment on health or disease is even less well known (cf. Hopps and Cannon, 1972; Cannon and Hopps, 1971).

Table 3.—Some reported trace-element toxicities in plants and animals

[Adapted from summaries compiled by U. S. Geological Survey, 1976, Appendix IV, and by R. C. Severson and L. P. Gough, written communication, 1976]

Element	In plants	In animals
Cadmium	Growth reduction when nutrient solution contained 0.2 ppm (beets, beans, turnips), 5 ppm (tomato, barley), and 9 ppm (cabbage).	Reduced growth in sheep with 30-60 ppm in diet for 191 days; toxic to rats at 45 ppm in diet for 6 months or 0.5 mg Cd^{++} in 10g/day dry weight diet; 16 mg Cd^{++} in 10g/day dry weight diet lethal to rats.
Cobalt	Toxic to crops at 0.1 ppm in culture solution. Sudan grass (containing 19-32 ppm in dry weight) showed toxic effects when grown in soil to which 2,000 pounds/acre had been added.	1 mg/kg of body weight per day toxic to cattle.
Fluorine	Reduced growth at 30-300 ppm (dry weight?) of plant tissue; yield reduction in citrus at leaf levels (dry weight?) of 200 ppm.	Normal performance may be affected if dietary dry matter contains 40 ppm (beef or dairy heifers), 60 ppm (horses), 100 ppm (finishing cattle), 300 ppm (broiler chickens), and 400 ppm (breeding hens and turkeys).
Uranium	Except for radiation effects, none reported.	None reported.
Zinc	Toxic? to corn, soybeans, wheat, barley, and oats at leaf levels of 150 ppm (ash weight?); toxic to citrus at leaf levels of 200 ppm (ash weight?); decreased yields of navy beans at levels above 50 ppm in the bean (ash weight?).	Growth depression and anemia in rats at dietary levels of 5,000 ppm, lethal at 10,000 ppm; growth depression in weanling pigs at dietary levels of more than 1,000 ppm; mortality at 4,000-8000ppm; reduced gains in lambs at dietary levels of 1,000-1,500 ppm; reduced gains in steers at dietary levels of 900 ppm; 150 mg Zn^{++} in 10g/day dry weight diet lethal to rats.
Selenium	Chlorosis of wheat leaves at leaf levels less than 250 ppm (dry weight?) if content of leaf sulfur "low".	Growth rates depressed at dietary levels more than 4-5 ppm; selenosis in young pigs within 2-3 weeks at dietary levels of 10-15 ppm. Dietary levels of 5-10 ppm in rats and dogs induce chronic poisoning.

Moreover, such assessment must be an interdisciplinary one. While it is the role of the natural scientist to determine the relative magnitude of man's contributions to the geochemical environment, it is the role of the medical scientist to determine what, if any, health hazard may ensue from that contribution.

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PART C.--ENGINEERING GEOLOGIC CHARACTERISTICS

Compiled by

F. W. Osterwald

A knowledge of the engineering geologic characteristics of the lower Tertiary rocks is basic to assessing the effects of anticipated large-scale economic development in the northern Powder River coal region. Large-scale mining of coal will result in the building of railroads, highways, residences, and commercial and industrial installations, as well as surface and underground coal mines. Engineering geologic characteristics of the rocks and soils will affect all of these types of development.

Engineering geologic characteristics, as used in this report, include the geotechnical properties of the earth materials, and the behavior of these materials in natural and artificial slopes; in particular their behavior in the slopes and openings created in surface and underground coal mines. The geotechnical properties of the rocks both above and below the coal beds control the behavior of the bedrock in response to either surface mining or underground mining and are important factors to consider in planning mining activities. Rocks at the outcrop commonly are so altered by weathering that geotechnical test results on surface rocks can be false and misleading. It is commonly necessary to test fresh rock from drill cores to obtain useful geotechnical information.

The response of rocks both above and below the coal beds, either to surface mining or underground mining, is controlled by: (a) the strength and deformational properties of the materials; (b) the orientation, abundance, and distribution of bedding planes, joints, and faults; and (c) the distribution, movements, and fluctuations of ground water.

SEISMIC RISKS

by H. C. Miller

The historical seismicity of both felt and instrumentally measured earthquakes in Montana and Wyoming has been compiled by Micro Geophysics (1973, 1974), Golden, Colo. Seismic risk maps (Perkins, 1974) and probabilistic estimates of maximum acceleration in rocks (Algermissen and Perkins, 1976) have also been compiled from historical seismic data. These data indicate that the northern Powder River Basin of Wyoming and Montana is seismically quiet. From about 1870 to 1976, the northern part of the basin was a zone of few earthquakes of low magnitudes and intensities and is classed as an area of none to minor earthquake damage.

GEOTECHNICAL PROPERTIES OF THE FORT UNION FORMATION

by E. E. McGregor

Geotechnical properties of the Fort Union Formation were generally not of interest until the energy crisis of the early 1970's made large-scale mining of the coal in the formation seem imminent; consequently, published data on the geotechnical properties of the Fort Union are sparse. The following conclusions are based on approximately 700 physical-properties tests made in 1974-76 on samples from four drill holes in the northern Powder River Basin (fig. 1). The results of the tests for two drill holes have been made public (McGregor, 1975). Data on the Bear Creek study area near Quietus, Montana (fig. 1) were compiled in 1976. Tertiary rocks in the Recluse, Buffalo, Sheridan, and Acme areas of northern Wyoming were also sampled for their engineering properties.

The rocks tested include siltstone, silty sandstone, sandy siltstone, sandy shale, and silty shale. Light-gray, friable sandstone is present at most places, and accounted for about half of the rock tested. The other half was shale, concretionary shale, marl, carbonaceous shale, and indurated sandstone. Coal samples were not tested because the coal was fractured, either naturally or during the drilling, and crumbled into small fragments when it was removed from the core barrel. Insufficient sample was available for tests. All samples at the drill-hole sites were tested at their natural moisture condition.

With only a few exceptions, rocks of the Fort Union Formation are so weak that they can be considered in the same category as strong soils. In general, the siltstone and shale are somewhat plastic when wet, and some samples behave as plastic soils, as defined in the Unified Soil Classification System; all samples behaved more as overconsolidated[1] soils than as rocks.

[1] The term overconsolidation is used to describe a soil that is loaded to a lesser degree than it was at some earlier time during its geologic history. Common causes of overconsolidation include past loadings from glaciers or from preexisting overburden now eroded away. The strength and compressibility of soils are influenced not only by the loads currently acting on them, but also by the maximum loads to which they have been subjected in the past. Overconsolidated soils are stronger and less compressible than comparable soils that have not been overconsolidated.

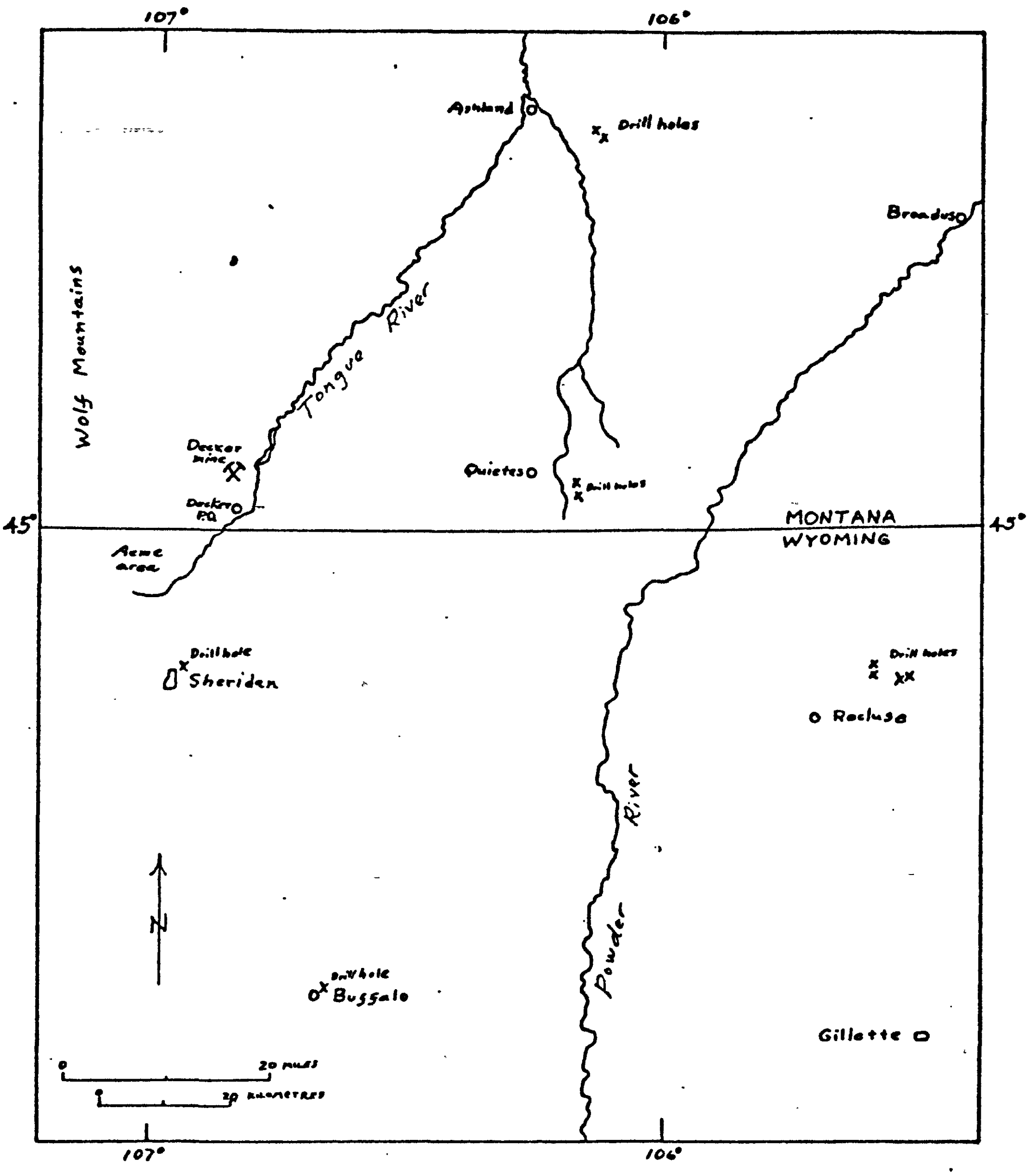

Figure 1.—Index map of the northern Powder River Basin showing locations of drill holes from which cores were tested.

The sandstone and silty sandstone generally had almost no strength; all cores of these two rock types either crumbled upon removal from the core barrel or were plastic. Examination of outcrops of sandstone and silty sandstone indicates that these rocks are better cemented and harder at and near the ground surface than they are at depth.

A PRELIMINARY BASIS FOR PREDICTION OF NATURAL SLOPE STABILITY

by T. C. Nichols, Jr., and A. F. Chleborad

Reconnaissance studies have revealed extensive landsliding on steep slopes in Tertiary rocks at the northwestern edge of the Powder River Basin, from Piney Creek, south of Story, Wyo., to the northern part of the Wolf Mountains in Montana. Most of the slope failures occur in clay-rich rocks of the Wasatch Formation; less commonly they are found in the Lebo and Tongue River Members of the Fort Union Formation. In the part of the Powder River Basin where the coal-rich Tongue River Member of the Fort Union Formation is exposed, landslides are rare.

The Wasatch Formation consists mostly of carbonaceous shale and silty clay shale interbedded with coal, lenticular siltstone, and friable sandstone. The Lebo Shale and Tullock Members of the Fort Union Formation consist of silty shale, clay shale, weakly indurated lenticular sandstone and siltstone, and occasional thin beds of coal and carbonaceous shale. The rock types in these units are prone to fail by landsliding on steep natural or artificial slopes or where they are water saturated. In the northwestern part of the basin, natural conditions that promote landsliding, as listed by Chleborad and others (1976), are:

1) Fine-grained plastic bedrock and colluvial materials.

2) Gently-dipping, sandy and silty, water-saturated rocks interlayered between clay shales on east-facing slopes.

3) Natural moisture-collecting basins provided by terrace gravels and scarp depressions of existing slides, and other shallow depressions on the leeward side of both natural and artificial slopes.

4) Wet spring snows that locally pile up in deep drifts; melt-water from which is available to saturate the ground.

Hillsides north and northeast of Sheridan, Wyo., show numerous small to large landslides. Many slides are on the western side of the southern Wolf Mountains in what has been mapped as the Lebo Shale Member by Barnum (1975). Landslides in similar rocks, also on the west side of the Wolf Mountains, occur at least as far north as Lodgegrass, Mont. The relative importance of factors such as lithology, hydrology, structure, and local climate on the stability of the Tullock and Lebo Members north of Sheridan has not been determined, although the hydrologic characteristics of the Lebo Member are such that sufficient water to initiate sliding can penetrate the rocks through sandstone and coal aquifers. The Tongue River Member of the Fort Union Formation where mapped by Barnum (1975) in the Ranchester quadrangle of Wyoming is conspicuously less susceptible to landsliding than is the underlying Lebo Shale Member. This difference in susceptibility is due to the strength imparted by relatively competent beds of sandstone, and beds of mudstone, sandstone, and carbonaceous shale hardened by burning of coal in the Tongue River Member. Cementing of sandstones near the ground surface (case hardening) also may increase their resistance to failure in natural slopes. Rocks of the Wasatch Formation exposed at the Wyoming-Montana border north of Sheridan contain baked sediments, or clinker, similar to those in the Tongue River Member of the Fort Union Formation. Like the Tongue River Member, these rocks show little evidence of landslide susceptibility.

FOUNDATION CONDITIONS

by R. A. Farrow and F. W. Osterwald

Foundation conditions for major construction projects generally are good in the northern Powder River coal region. Foundation conditions in the Sheridan-Buffalo area of Wyoming, a few miles south of the southern boundary of Montana (fig. 1), are known to be good, except for minor swelling and settling in local areas. The amount of swelling soil in the alluvium along Tongue River increases northward near the Montana boundary, probably because of increasing amounts of montmorillonitic clay in the alluvium, derived either from the Fort Union Formation or from thick bentonite beds present in the Cretaceous rocks to the west near the Bighorn Mountain flank. Bentonite beds, locally present in the Fort Union, and montmorillonitic clays in the Fort Union and Wasatch Formations, might produce swelling soils that would be hazardous to heavy construction projects. The potential for rebound is high in foundation excavations for large installations in rocks that are highly overconsolidated; however, little is known of the load-bearing characteristics of any of the rocks in the Fort Union and Wasatch Formations.

Because of a wide range in physical properties of clinker, buildings founded in clinker may settle differentially. Different types of clinker, having an extreme range in geotechnical properties, commonly are found within a few tens of feet laterally, and within a few feet vertically. Clinker includes such diverse types as dense fused flintlike porcellanite; higher vesicular fractured material; bricklike and massive rocks in which features such as slickenslides and fossil casts are well preserved; and material that is baked red, but is otherwise like the original unaltered claystone and sandstone. Clinker may contain sparse, black, strongly magnetic nodules, possibly formed by the natural smelting of pyrite. The type of clinker depends upon the original rock type and upon the temperature to which the rocks were subjected during heating. Sandstone is more resistant to alteration than is claystone. Chimneys, where hot gases were concentrated, apparently produced the most highly altered clinker.

OPEN-PIT COAL MINE SLOPE STABILITY

by W. Z. Savage and W. K. Smith

Introduction

Proper pit-slope design will help insure the safety of coal mining in the northern Powder River coal region. Proper design will become increasingly important as stripping depths become greater. From late 1974 until the present (1976), a study of pit-slope stability has been in progress in the area north of Sheridan, Wyo. Data obtained from this study are very incomplete; however, some generalizations can be made that can be extended to mining areas with similar geologic and climatic conditions.

General observations

No large slope failures were observed at any of the operating mines examined in 1974-76. Several small and incipient failures, however, were observed and have led to recognition of two factors that appear to play a major role in pit-slope behavior; these are, the length of time rocks are exposed to the air, and presence of ponded or channelized water that can infiltrate rocks forming the pit-slope surface.

Upon exposure to the air, clay-rich rocks tend to desiccate which causes them to become intensely fractured near the pit face. Tension cracks also develop on some slopes after several months of exposure to air. It is clear that the period of time during which a slope is required to be stable is an important design consideration.

Piping was observed at several places where water collected in surface depressions above a pit face. At one place, a hole more than 1.8 m deep and 0.9 m in diameter that resulted from piping was observed within 46 m of the crest of a highwall. A small slump failure of the lower part of the pit face was caused by surface water flowing out on a bench below this pipe.

Two regional fracture sets are revealed by a study of pit slopes and natural outcrops. Analysis of 531 fractures, almost equally divided between the Decker mine (fig. 1) and natural outcrops of the lower Tertiary rocks showed one principal set striking N. 44° W., and another striking N. 38° E., both vertically oriented. Fractures and other discontinuities, other than bedding, that are inclined more than 5° from the vertical are rare in the area studied. It is not known whether these fracture systems have an appreciable effect on slope stability in this region.

Pit geometry also plays a part in determining slope behavior. For example, at the Decker mine more raveling of the pit slopes was noted at the corner points of the walls than elsewhere.

Ground water probably affects slope behavior in ways other than by piping, but the extent of the effects is not known. The effects of mining in drawing down groundwater near Decker have been described by Van Voast (1974) and Van Voast and Hedges (1975).

A phenomenon which has been widely reported in the Fort Union Formation, but for which quantitative data are lacking, is that of overconsolidation and rebound (Lee and others, 1976). Many of the rocks of the basin are clay shales, a type of rock that is particularly apt to be overconsolidated. Greater deformations would be experienced in overconsolidated rocks after an opening is excavated than would otherwise be expected, with consequent detrimental effects on slope stability. The probability that highly over-consolidated rocks occur in the Powder River Basin, particularly the clay shales, should not be overlooked in predicting engineering behavior.

Physical properties of Fort Union rocks

In 1975, rocks from the Decker mine area were sampled and tested to determine engineering properties useful in predicting slope behavior (Fahy and Smith, 1976; Lee and others, 1976). Properties determined for several typical rock types include bulk density, confined and unconfined compressive strengths, Young's modulus, Poisson's ratio, and Brazilian tensile strengths. Results of triaxial tests are summarized in table 1, uniaxial tests (Poisson's ratio) in table 2, and Brazilian tension tests in table 3.

Table 1.--Results of triaxial tests, Decker mine

Sample Number	Rock Type	Density g/cm^3	Density lb/ft^3	Confining pressure kN/m^2	Confining pressure lb/in^2	Peak strenth kN/m^2	Peak strenth lb/in^2	Residual strength kN/m^2	Residual strength lb/in^2	Young's modulus 10^9N/m^2	Young's modulus 10^6 lb/in^2
1-1		2.38	149	0	0	7,810	1,130	0	0	0.54	0.0783
1-2		2.33	145	345	50	9,540	1,380	3,750	544	.447	.0648
1-3		2.30	144	690	100	6,270	910	-	-	.236	.0347
1A-4[1]		2.33	145	0	0	22,800	3,300	0	0	.757	.110
1-5	SHALE	2.34	146	1,380	200	5,830	845	5,200	754	.215	.0312
1A-6		2.34	146	2,070	300	8,230	1,190	7,880	1,140	.351	.0509
1A-7		2.31	144	2,760	400	8,250	1,200	7,190	1,043	.336	.0487
1-8		2.33	145	3,450	500	6,040	876	5,850	848	.269	.0390
1-9		2.60	162	5,170	750	40,400	5,860	-	-	2.26	.327
1-10		2.33	145	6,900	1,000	7,060	1,020	5,800	841	.209	.0303
1-11		2.54	159	10,300	1,500	39,400	5,710	33,800	4,900	2.41	
				Cyclic loading							
1-12		2.39	149	0	0					.244	.0354
				1,720	250					.444	.0644
				3,450	500					.611	.0886
				6,900	1,000					.652	.0945
				10,300	1,500	10,400	1,510			.690	.100
3A-1		2.28	142	0	0	18,100	2,630	0	0	1.29	.187
3A-2		2.27	142	690	100	19,100	2,770	9,100	1,320	1.28	.186
3A-3	SHALE	2.33	145	345	50	24,400	3,540	7,500	1,090	1.88	.272
3A-4		2.29	143	1,720	250	20,600	2,990	11,300	1,640	1.29	.187
3A-5		2.25	140	3,450	500	24,700	3,580	17,200	2,490	1.60	.232

Table 1.--Results of triaxial tests--Continued

Sample Number	Rock Type	Density g/cm³	Density lb/ft³	Confining pressure kN/m²	Confining pressure lb/in²	Peak strength kN/m²	Peak strength lb/in²	Residual strength kN/m²	Residual strength lb/in²	Young's modulus $10^9 N/m^2$	Young's modulus $10^6 lb/in^2$
3A-6	SHALE	2.38	149	1,380	200	15,300	2,220	10,200	1,480	1.28	.186
3A-7		2.29	143	2,070	300	27,200	3,940	13,000	1,890	1.67	.242
3A-8		2.25	140	2,760	400	25,600	3,710	15,000	2,180	1.50	.218
3A-9		2.31	144	5,170	750	31,400	4,550	16,300	2,360	1.90	.276
3A-10		2.34	146	6,900	1,000	38,100	5,530	23,100	3,350	2.12	.307
3A-11		2.30	144	10,300	1,500	36,600	5,310	26,400	3,830	1.95	.283
				Cyclic loading							
3A-12		2.28	142	0	0					1.29	.187
				1,720	250					1.84	.268
				3,450	500					2.24	.324
				5,170	750					2.53	.366
				10,300	1,500	40,200	5,830	28,300	4,100	2.94	.426
3A-14	SHALE	2.33	145	0	0	19,100	2,760	0	0	1.81	.263
3A-15[1]		2.38	149	0	0	16,300	2,360	0	0	1.64	.238
3B-2	SILTSTONE	2.08	130	0	0	7,750	1,124	0	0	.884	.128
3B-3[1]		2.14	134	0	0	7,250	1,050	0	0	.867	.126
3B-4		2.13	133	345	50	8,310	1,210	3,150[2]	457	.879	.127
3B-5		2.04	127	690	100	9,350	1,360	5,250[2]	761	1.00	.145
3B-6		2.17	135	1,380	200	11,000	1,600	6,350[2]	921	.775	.112
3B-7		2.16	135	2,070	300	16,700	2,420	10,600	1,540	1.55	.225

Table 1.--Results of triaxial tests--Continued

Sample Number	Rock Type	Density g/cm^3	Density lb/ft^3	Confining pressure kN/m^2	Confining pressure lb/in^2	Peak strength kN/m^2	Peak strength lb/in^2	Residual strength kN/m^2	Residual strength lb/in^2	Young's modulus $10^9 N/m^2$	Young's modulus $10^6 lb/in^2$
3B-8	SILTSTONE	2.11	132	2,760	400	17,500	2,540	13,100	1,900	1.71	.248
3B-9		2.08	130	3,450	500	21,600	3,130	15,000	2,180	1.98	.287
3B-10		2.11	132	5,170	750	25,000	3,630	18,400[2]	2,670	2.16	.313
3B-11		2.10	131	6,900	1,000	25,000	3,630	20,500	2,970	2.26	.328
3B-12		2.11	132	10,300	1,500	27,500	3,990	26,300	3,810	2.27	.330
				Cyclic loading							
3B-13		2.09	130	0	0					.965	.140
				1,720	250					1.91	.277
				3,450	500					2.47	.358
				6,900	1,000					3.26	.473
				10,300	1,500	28,400	4,120	27,500	3,990	4.15	.603
3B-1		2.09	130	0	0	4,000	580	0	0	.799	.116
3C-2	SHALE	2.42	151	0	0	17,300	2,500	0	0	1.50	.218
				Cyclic loading							
3C-3		2.36	147	0	0					1.28	.186
				1,720	250					1.55	.220
				3,450	500					1.90	.276
				6,900	1,000					2.50	.360
				10,300	1,500	38,000	5,500	34,000	4,950	3.26	.472
				Cyclic loading							
3D-1[1]	LIMY SILTSTONE	2.82	176	0	0					9.98	1.43

Table 1.--Results of triaxial tests--Continued

Sample Number	Rock Type	Density g/cm³	Density lb/ft³	Confining pressure kN/m²	Confining pressure lb/in²	Peak strength kN/m²	Peak strength lb/in²	Residual strength kN/m²	Residual strength lb/in²	Young's modulus $10^9 N/m^2$	Young's modulus $10^6 lb/in^2$
	LIMY SILTSTONE			1,720	250					12.2	1.77
				3,450	500					14.1	2.05
				5,170	750	97,000	14,100	48,100	6,980	12.5	1.81
3D-2		2.58	161	0	0	45,000	6,530	0	0	6.60	.957
3D-4		2.60	162	1,720	250	50,000	7,250	22,300	3,230	6.02	.874
3D-5		2.73	170	3,450	500	103,000	14,900	35,200	5,110	14.1	2.04
3D-6		2.79	174	6,900	1,000	135,000	19,600	48,500	7,030	15.3	2.22
4-4	COAL	1.34	83.6	0	0	20,000	2,900	0	0	2.20	.320
4-5		1.32	82.4	0	0	25,500	3,700	0	0	2.03	.294
4A-6		1.33	83.0	0	0	19,000	2,760	0	0	1.51	.219
4A-7		1.33	83.0	345	50	23,100	3,350	9,000	1,300	1.74	.252
4A-8		1.33	83.0	690	100	28,800	4,180	10,000	1,450	1.97	.286
4-9		1.33	83.0	1,380	200	24,400	3,540	14,100	2,040	1.63	.244
4-10		1.31	81.7	2,070	300	28,800	4,180	18,400	2,670	1.63	.236
4-11		1.31	81.7	2,760	400	31,400	4,550	20,000	2,900	1.93	.279
4A-12		1.32	82.4	3,450	500	37,800	5,480	19,400	2,810	2.24	.325
4-13		1.29	80.5	5,170	750	40,000	5,800	22,800	3,310	1.75	.254
4-14		1.32	82.4	6,900	1,000	35,900	5,210	30,000	4,350	2.16	.313
4A-15		1.32	82.4	10,300	1,500	33,100	4,800	29,700	4,310	2.02	.293

[1] Samples were previously loaded for Poisson's ratio (uniaxial) tests.

[2] Samples exhibited sudden increase in residual strength after post-peak drop
Residual strength recorded is the minimum stress immediately following the post-peak drop.

[3] Sample 3B-14 cored parallel to bedding.

Table 2.—Results of Poisson's Ratio tests.

Sample number	Rock type	Poisson's Ratio
1A-4	Shale	0.49
1-13	Shale	.56
3A-13	Shale	.15
3A-15	Shale	.44
3B-1	Siltstone	.57
3B-14[1]	Siltstone	.36
3C-1	Calcareous shale	.40
3D-1	Calcareous siltstone	.81
3D-3	Calcareous siltstone	.47
4-1	Coal	.36
4-2	Coal	.37
4A-3	Coal	.43

[1] Cored parallel to the bedding; all other samples were cored perpendicular to bedding.

Table 3.--Results of Brazilian Cylinder tests

Sample group	Rock type	Number of samples tested	Average tensile strength kN/m^2	Average tensile strength lb/in^2	Direction to bedding
1	Shale	10	2,460	357	Perpendicular
1A	Shale	5	1,390	202	Oblique
2	Shale	4	407	59	Perpendicular
3A	Shale	15	2,280	331	Perpendicular
3A	Shale	6	930	135	Parallel
3B	Siltstone	12	496	72	Perpendicular
3B	Siltstone	6	363	53	Oblique
3C	Calcareous shale	12	2,520	366	Perpendicular
3C	Clayey limestone	4	18,600	2,700	Perpendicular
3D	Calcareous siltstone	10	11,200	1,620	Perpendicular
3D	Calcareous siltstone	4	10,300	1,490	Oblique
4	Coal	15	1,760	255	Perpendicular
4	Coal	3	2,000	290	Oblique

Slope stability calculations

Safety factors have been calculated for a typical open-pit design in the Fort Union Formation of the Powder River Basin using the conventional method of slices; that is, by the formula:

$$F_s = \frac{\Sigma[dN\tan\phi = cdL]}{\Sigma dT},$$

where F_s is the safety factor, which must be greater than 1 for the slope to be stable; dN and dT are, respectively, the normal and shear forces acting on each slice; ϕ is the angle of internal friction; c is the cohesion; and dL is the length of the slip surface on a slice. Summation is from 1 through the total number of slices. Side forces and the effect of forces from seepage were not considered in these calculations. Material properties used for the calculations along with an idealized open-pit cross section are shown on figure 2.

Potential surfaces of failure for which safety factors were calculated are shown on figure 3. The dashed line on the figure indicates the geometry after removal of a coal bench. Safety factors both before and after removal of the bench were determined.

We considered the effects on the safety factors of changing the rock properties for two cases: In case 1, the values for the properties given on figure 2 were used; in case 2, the cohesion of each layer was reduced to zero. The second case would simulate effect of fractures on the strength of rock layers, and should be considered as an extreme case. The cohesion of an actual rock layer will probably lie somewhere between zero and the laboratory values given on figure 2.

Safety factors for the five potential failure surfaces are given in table 4. Note that when the average laboratory values are used (case 1), the safety factors are high for all surfaces--whether a coal bench is present or absent. On the other hand, when the cohesions are zero (case 2), safety factors are drastically reduced and surfaces 2 and 5 are least stable; surface 2 is seen to be marginally stable when the coal bench is removed. Water seepage would further reduce the stability, but further study of the effects of water saturation is needed.

The most critical conditions for slope stability seem to occur with removal of the coal bench, especially along failure surfaces 2 and 5. Failure along either surface during the final stages of coal-bench removal would endanger miners and mining equipment.

ROCK TYPE	YOUNG'S MODULUS E (10^9 N/M^2)	POISSON'S RATIO ν	BRAZILIAN TENSILE STRENGTH T_B (KN/M^2)	DENSITY ρ (KG/M^3)	COHESION C (KN/M^2)	ANGLE OF INTERNAL FRICTION ϕ (°)
A. SILTSTONE	0.85	0.38	430	2,300	1,700	44.8
B. SHALE	1.3	.30	1,600	2,300	4,990	32.3
C. SANDSTONE	7.0	.47	10,750	2,700	3,220	69.4
D. CLAY	.22	.49	407	2,390	642	52.0
E. COAL	1.98	.39	1,880	1,320	5,040	42.4
F. SHALE	.22	.30	3,850	2,380	642	52.0

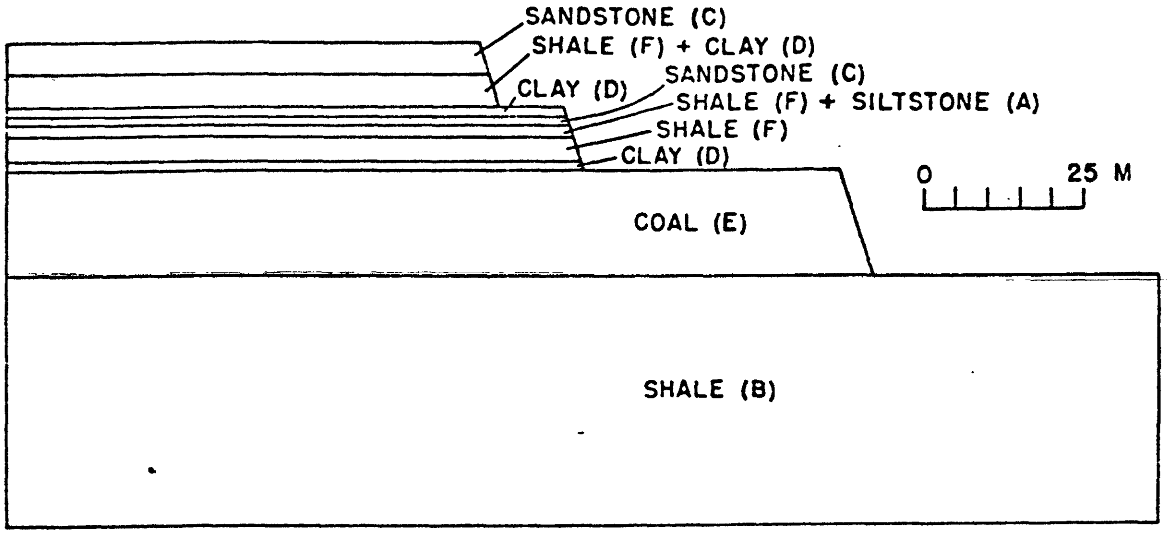

Figure 2.--Idealized cross section through an open pit in the Fort Union Formation. The average of laboratory-determined properties for the layers are shown in the table.

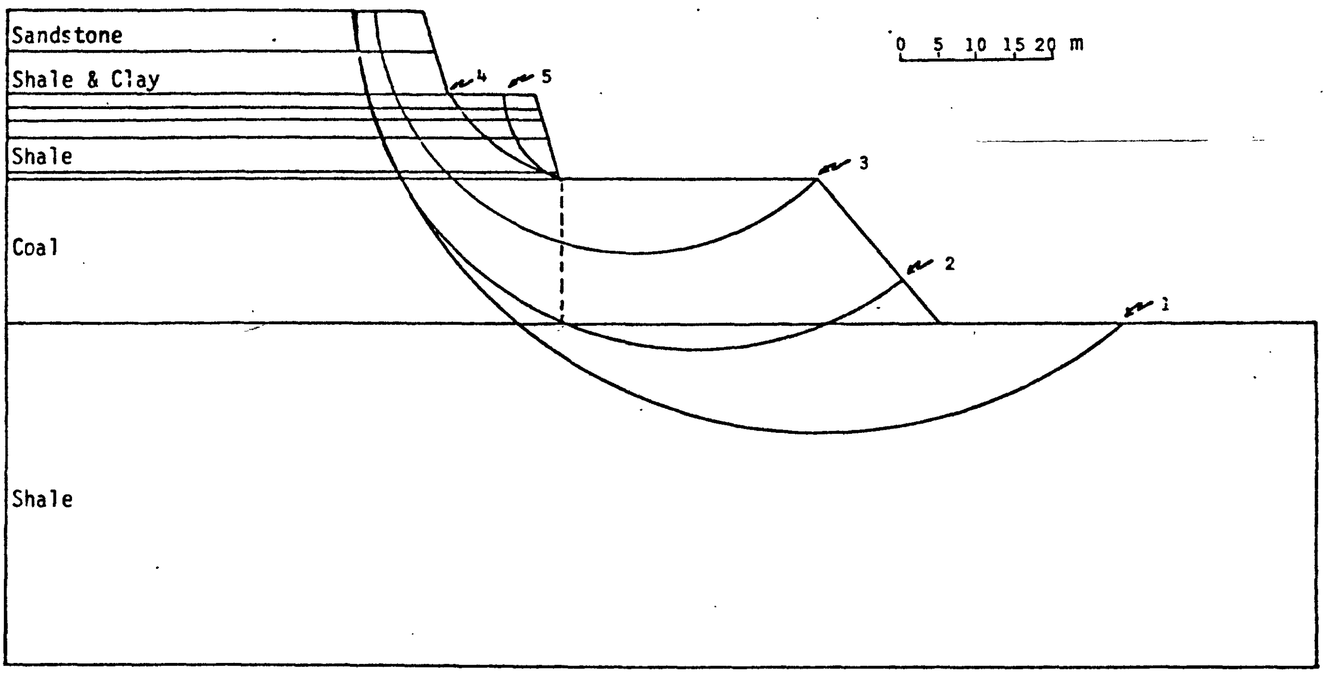

Figure 3.--Potential surfaces of failure for which safety factors were calculated. The dashed line indicates the geometry after removal of the coal bench.

Table 4.--Safety factors calculated by the method of slices for the five potential failure surfaces shown in Figure 3

	Coal bench present		Coal bench absent	
	Case 1	Case 2	Case 1	Case 2
Surface #1	24.28	2.21	29.55	2.07
Surface #2	43.10	1.53	24.84	1.09
Surface #3	89.77	2.13	35.39	1.55
Surface #4	24.03	2.25	24.03	2.25
Surface #5	25.35	1.28	25.35	1.28

Conclusions

Open-pit coal mines of the Fort Union Formation that we have examined generally have stable highwalls. The highwalls deteriorate with time, and small postmining failures commonly are observed. These failures would not be severe enough to be particularly hazardous unless mining were delayed and then resumed after a period of several months.

Seepage and piping from pools that are allowed to collect above the highwall lead to small failures, and during especially wet weather could contribute to failures on surfaces such as 2 or 5 on figure 3.

STABILITY OF UNDERGROUND COAL MINE WORKINGS

by F. W. Osterwald

Stability of roofs in underground mines is an important factor bearing upon the safety of miners, upon the economics of the coal extraction, and upon the conservation of the coal resources. Stability of roofs in any particular mine depends primarily upon the depth of mining, the geotechnical properties of the coal and rocks, upon the mining plan and mining sequence, and upon the method of artificial roof support. Good mining plans are predicted upon eventual collapse of the roof into the mine openings. Mining to the point of collapse yields the greatest percentage of coal extracted and relieves overburden loads that might be placed on pillars and faces by bridging of stresses across uncollapsed areas.

All of the known underground coal mines in the northwestern Powder River Basin had a few hundred meters or less of overburden; some had less than 30 m. The rocks above most mines were very weak, and a few mines were worked beneath almost unconsolidated stream alluvium. Little artificial support (nearly all timber) was used, probably because the mining depths were shallow, and very little stress was placed on the mine workings. Roofs were stabilized by leaving a meter or so of coal above the workings, thereby preventing air slaking of the rocks. No bumps or similar failures are known to have occurred, although gas explosions and fires were not uncommon. The old Monarch mine was closed in 1914 because of an explosion. The Carney mine was burning in the 1930's, and is still burning.

All the mines used room-and-pillar mining methods, as far as is known, probably with very incomplete extraction of coal, because most pillars were left standing. The coals slack and crumble in air, and mine pillars probably have deteriorated slowly underground causing collapse of the mine roofs. Most mining heights were very low, probably 3 m or less, although 8.5 m of coal is reported to have been extracted from one place in the Acme mine. This was less than half of the thickness of the coal that was present in the bed that was being mined.

Future large-scale underground mining in the Powder River Basin will require techniques enabling effective removal of coal beds as much as 30 m thick under overburden locally more than 300 m thick. Stresses on weak rocks in mine roofs, ribs, faces, and floors will be much greater than in the old mines. Consequently, deformation of mine workings also can be expected to be much greater than in the old mines. Squeezing of plastic clay shales into the workings probably will be widespread, and where the rocks are over-consolidated, large deformations are probable. At mining depths of more than 300 m, or possibly of only several meters, bumps (rock bursts) may occur, although little is known of the behavior of coal and associated rocks in the Fort Union Formation at depth. Longwall mining techniques, which permit uniform collapse of mine roofs immediately behind the face, probably will be the most effective under the expected weak roof rocks. Automatic equipment for longwall mining may, however, not operate well if plastic or highly over-consolidated clay-rich rocks occur in the mine floor.

SURFACE SUBSIDENCE EFFECTS FROM UNDERGROUND COAL MINING

by C. R. Dunrud

Much controversy stems from the question of whether mining coal by underground methods is less damaging to the environment than mining by surface methods. Many miners and land-use planners argue that the billions of tons of strippable coal deposits (generally under less than 60 m of cover) in the northwestern Powder River Basin can be mined more safely and much more completely by surface methods than by underground methods. Those convinced that surface mining would be more damaging to the environment than underground mining generally do not consider the long-term subsidence effects of underground mining.

Surface mining operations totally disturb the land surface of the mine area during the mining cycle. The overburden is removed to expose the coal; the coal is then removed; the overburden is piled in the void after the coal is removed; the overburden is graded; the topsoil is put back; and the land is revegetated. In a few years or a few tens of years, depending on the climate and on the chemical composition and geotechnical properties of the overburden, the land surface can be restored to agricultural or other land use.

Underground mines, on the other hand, appear initially to disturb the surface only in the vicinity of the mine portals, the coal processing and loading facilities, and mine support buildings. In the western Powder River Basin, near Sheridan and Buffalo, Wyo., however, subsidence, or the differential settlement of the land surface over long-abandoned underground mines commonly has damaged the land surface much more severely and permanently than has mining by surface methods in the same area. Subsidence is continuing 25-80 years after the mine workings were first driven.

In the western Powder River Basin, surface effects caused by underground mining include local depressions, tension cracks, compression bulges, and pits. The depressions overlie room-and-pillar workings where the coal in the pillars was not strong enough to support the weight of the overburden because either the coal pillars were initially too small, or the strength of the coal in the pillars has steadily decreased by exposure to air and water. The depressions range in depth from about 0.3 to 2.5 m; commonly are square or rectangular in plain view; and outline the mined-out sections of the underlying coal in areas where the overburden is less than about 25 m. In overburden greater than about 25 m, the depressions tend to be circular or elliptical. The depressions tend to be slightly larger in area than the actual mined-out areas.

Tension cracks occur at the margins of subsidence depressions as a result of a convex curvature and stretching of the ground surface. Compression ridges or bulges occur in the depressions where the ground surface is deformed by concave curvature and shortening of the ground surface. Circular openings 5 cm to as much as 3 m wide are locally present in soil and colluvium; these openings extend downward to tension cracks a few centimeters to a meter or so wide in the underlying bedrock. The bedrock is cracked along the margins of local subsidence depressions whereas the soil and colluvium has stretched without completely rupturing. Soil and colluvium cover most of the underlying fissures, except where local piping failure occurs or where the activities of animals or man start minor suface caving.

Subsidence pits occur above individual mine openings or above the intersection of two mine openings. The pits appear to result from an upward stopping process that is initiated by collapse of mine roofs. Collapse of mine roofs commonly is governed by the width of mine openings, the strength of the mine roof-rocks, and the adequacy of the roof support system used. New pits currently are forming among old pits 50 to 80 years after mine openings were driven in areas where the overburden is 15 to 40 m thick and consists of weak shale, mudstone, and local sandstone. Surface pits, even in overburden of constant thickness and strength, tend to be distributed sporadically because collapse of mine roofs tends to be irregular.

Most pits initially are semicircular holes 1 to 3 m wide that have vertical to overhanging side walls, and that range in depth from 2 to 6 m. They gradually are widened and the slopes of the walls are reduced by the processes of erosion and mass wasting, and eventually--10 to 30 years after they first form--the walls and floors become covered with range grass, vines, and other plants.

Subsidence pits may form suddenly in local surface depressions as well as in areas where no noticeable initial surface depression exists. Most of the pits within larger surface depressions are not as deep as the pits outside of the depressions. The total depth of the depressions and the pits within them are roughly equal to the depth of the pits that are present where no noticeable initial depression exists. The total depth of collapse features near Sheridan commonly varies from 3 to 6 m. The amount of collapse, therefore, appears to be as great, or perhaps greater, than the height of underlying mine openings as reported by miners. Pits commonly form within the local depressions many years after the depressions first appear. Therefore, local depressions serve as warnings to possible future collapse within the depressions. However, there may be no noticeable initial depression or change in elevation of the ground surface prior to pit collapse. The ground surface above mine workings where the remaining coal pillars has been strong enough to support the overburden may be prone to the sudden formation of pits by stopping failure with little or no advance warning unless the ground surface is periodically monitored for minute movement.

Although information regarding the type, rate, and amount of subsidence that can be expected for mined-out areas of various widths and heights for various overburden depths can be found in various handbooks, little or no information is available on the extension and compression rupture limits of various types of bedrock and soil. Studies to date in the western Powder River Basin show that the rupture limit of bedrock, comprising weak, soft shales, claystones, lenticular sandstones, and coal beds, is lower than the soil and colluvium overlying the bedrock. Cracks commonly were observed in soil and colluvium where differential settlement was more than 0.5 m in a lateral distance of 3 to 6 m in overburden 9 to 22 m thick. Cracks were not common in soil and colluvium at the margins of subsidence depressions where differential settlement was less than 0.5 m in 3 to 4 m laterally; however, it is not known whether or not the underlying bedrock was cracked.

Coal mine fires

Coal mine fires in abandoned mine workings are a threat to vegetation and grazing animals on the surface, and to adjacent coal deposits underground. At least 285 coal fires were burning out of control in the United States in 1975, of which 185 were in the Western States and about 100 were in Wyoming and Montana. Fires in at least three abandoned coal mines were burning out of control in a 400- to 450-hectare area near Acme, Wyo. (D. L. Donner, oral commun., 1975).

An increase in internal energy of the coal caused by locally increased stress levels, by oxidation of the coal, and by alternate wetting and drying of the coal appears to have elevated temperatures sufficiently to ignite the coal. Once ignited, combustion can be supported and fresh air drawn in through subsidence cracks and pits open to the surface. Gases are exhausted also through cracks and pits. Voids created as the coal is burned produce ground settlement, more tension cracks, and more surface pits, which in turn provide more oxygen to the fire.

Steam, other gases, and smoke, exhausted through tension cracks and pits in the Acme mining area were collected for analyses in the spring of 1976. Analyses revealed carbon disulfide, carbon oxysulfide, and an undetermined sulfur compound. More than 1 percent by volume of methane was detected in gases from a crack near one of the most intensely heated areas. The gases contained less nitrogen and more helium than normal atmosphere.

The fires in the abandoned mines locally have breached to the surface or are close enough to the surface to produce ground temperatures in excess of 200°C. Temperatures at depth of 0.15 m in some cracks locally exceeded 510°C. One fire, in the northern part of the Acme mine, breached in 1972 and started an extensive grass fire that burned a grove of juniper and ponderosa pine trees. A vertical column of heated rock estimated to be about 15 m in height, or equal to the thickness of the mine overburden, is probably kept hot by the burning of coal beds above the mined bed, as well as by burning of the coal in the mine.

Seismic activity

Small earth tremors commonly are generated by caving and stress readjustments above underground mine workings and coal fires in the western Powder River Basin. The seismic activity near the Acme mine was monitored from September 30 to November 4, 1975. The monitoring network consisted of ten vertically oriented 1-second period seismometers connected to a mobile recording laboratory. The ground motion magnification of the system was about 200,000 at 10 Hz. One seismometer was installed within 180 m of the fire that breached in 1972 during the first half of the recording period, and within 30 m of the fire pit during the last half of the period. A total of 20 to 90 small earth tremors (magnitude less than 2) were recorded per day with the seismometer located 180 m from the fire pit, whereas a total of 550 to 800 small earth tremors were recorded per day when the seismometer was moved to within about 30 m of the fire pit. The earth tremors apparently were caused by breaking and collapse of the strata within and at the periphery of the fire pit. Some may have been due to small underground explosions resulting from the fire.

In-place gasification

Studies of subsidence and coal-mine fires in abandoned underground mine workings illustrate some problems that might arise from controlled burning of coal to produce in-place gasification of coal. For instance, differential settlement of the overburden above burned coal beds at shallow depths probably would produce cracks to the surface, as are produced above mine fires at Acme, Wyo. Flow of oxygen through the cracks might be uncontrollable, and a runaway fire might occur. In addition to cracking, upward stopping might occur above cavities produced by consumption of the coal. Surface pits might then form with little or no warning.

The key to preventing, or at least minimizing, hazards to the environment and possibly to personnel from in-place gasification is to design the size and shape of the fire front and resulting cavity so that upward stopping and differential settlement of the overburden are prevented. Plans for a gasification project should take into account the geologic structure and the kinds and proportions of rock types at the site, as these will affect subsidence rates and amounts, and hence the surface deformation likely to be induced by different cavity dimensions.

Summary and conclusions

Experience in the western Powder River Basin in Wyoming and Montana indicates that the land surface is not necessarily more quickly, easily, and cheaply restored if thick coal beds are mined underground than if they are mined by surface methods. This is because of the difficulty in preventing subsidence above old underground mine workings. Subsidence is still occurring in the Powder River Basin above room-and-pillar workings driven 50 to 80 years ago, and subsidence will continue to be a hazard in areas of underground mining for many years to come. Some dramatic collapse episodes, which have produced deep pits, occur with little or no warning. The lack of recent or old subsidence features above underground mines is not an indication that subsidence will not occur. At some places, subsidence pits may be deeper than the original height of the mine openings because either the collapsed material compacts during subsidence, or the material spreads laterally into adjacent mine openings as it collapses.

GEOTECHNICAL STUDIES

by H. W. Olsen and J. Odum

Indices of the strength and deformation properties of the bedrock were measured on cores from two drill holes in the Acme, Wyo., area in April 1976. The tests run included the point-load strength, the Schmidt hammer index, the slake durability index, the dry bulk density, and the moisture content. Point-load tests were run both parallel and perpendicular to the bedding of the materials.

The test results to date show that most of the shales, claystones, and lenticular sandstones have strength and deformation characteristics that are typical of weak or soft rock and heavily overconsolidated soil. Point-load strength test results for these materials are shown in table 5.

Discontinuities such as bedding planes, joints, and faults are present in the bedrock. Little is known at most places about the orientation and distribution of the joints and faults. However, they are of concern because they introduce weakness in a rock that is not indicated by test results on core samples. The weakening effects of such discontinuities is magnified by both surface and underground mining activities. This is due to the removal of the confining rocks that provide support in a jointed or faulted rock mass.

Surface and underground mining commonly cause fluctuations in ground water levels. Where this results in alternate wetting and drying of the bedrock, the rock is weakened. Examples of rocks weakened by ground water fluctuations can be seen in surface mines in the western Powder River Basin. Highwalls 8 m to more than 30 m high in operating surface mines commonly stand nearly vertically for periods of weeks or months, but over periods of years they weaken, slough, slab, or otherwise degrade until the slope angle is much reduced.

Table 5.--Point load strengths of bedrock materials

	Perpendicular to bedding	Parallel to bedding
Claystone---------------------------	0.1-3 mN/m^2 *	0.01-1 mN/m^2
Shale-------------------------------	0.2-1.5 mN/m^2	0.1-1 mN/m^2
Sandstone---------------------------	0.5-1 mN/m^2	0.4-1 mN/m^2

* 1 mN/m^2 = 145 psi

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