Chapter WS

FORT UNION COAL IN THE WILLISTON BASIN, NORTH DAKOTA: A SYNTHESIS

By R.M. Flores and C.W. Keighin

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INTRODUCTION

Major coal resources of lignite rank (Wood and Bour, 1988; Britton and others, 1989) exist in the Paleocene Fort Union Formation in the Williston Basin in North Dakota (figs. WS-1 and WS-2). The Fort Union strata make up the surface bedrock over much of the Williston Basin. The strata (fig. WS-3) are conformably underlain by the Upper Cretaceous Hell Creek Formation, conformably overlain by the Paleocene/Eocene Golden Valley Formation, and unconformably overlain by Quaternary glacial till in the northern half of the basin (fig. WS-2). The coaly nature of the Fort Union strata was first documented in 1805 by Lewis and Clark (1893) along the Missouri River where they observed “burnt earth” and “earth, which seems to have been boiled and then hardened by exposure.” These rocks are now known as clinker; they are red and orange, baked and fused rocks resulting from burning of coal beds by spontaneous combustion, lightning, or range-fire ignitions. Additional accounts of coal deposits in the journals of the Lewis and Clark expedition are the observation of numerous outcrops of coal in river banks and nearby hills. During the expedition’s first winter, the party used Fort Union lignite in a blacksmith’s forge (Budge, 1954).

Meek and Hayden (1862) defined these coal-bearing strata as “Fort Union Coal Group.” Succeeding U.S. Geological Survey (USGS) appraisals of federally-owned coal lands resulted in subdivision of this “group” into “members,” which formed the basis for early coal resource estimates (Leonard and others, 1925; Campbell, 1929). Currently, these coal-bearing strata are recognized by the USGS as the Fort Union Formation; it is subdivided, from bottom to top, into the Ludlow, Cannonball, Tongue River, and Sentinel Butte Members (see fig. WS-3). The North Dakota Geological Survey (NDGS) recognized the same strata as Fort Union

Group; it is subdivided, from bottom to top, into the Ludlow, Cannonball, Slope, Bullion Creek, and Sentinel Butte Formations (see fig. WS-3). This report uses the USGS nomenclature; however, in this report we will attempt to correlate the members of the formation with formations of the group recognized by NDGS.

The Fort Union Formation exists over 32,000 square miles in the Williston Basin in North Dakota. In addition, the formation extends into the westernmost part of the basin in eastern Montana, southernmost part of the basin in northwestern South Dakota, and northernmost part of the basin in the southern part of the Saskatchewan Province, Canada, where the strata are called the Ravenscrag Formation (Whitaker and others, 1978; see fig. WS-3). This study investigates only the Fort Union Formation in the Williston Basin in North Dakota because associated coal (for example, Harmon, Beulah, and Hagel coal) is mined here and has contributed more than 30 million short tons or about 3 percent of the U.S. total coal production in 1998 (Resource Data International, Inc., 1998). Also, during the next few decades the coal is expected to fuel four mine-mouth power plants and three other power plants that transmit electricity to Iowa, Minnesota, South Dakota, and Wisconsin. Drill-hole data of the minable coal are available for analysis only in North Dakota.

In the 1950's a number of subsurface data points from petroleum exploration, exploration for uranium-enriched strata (including lignite beds), and drilling associated with lignite mining and utilization became available for the Fort Union Formation in North Dakota. In the 1970's, increased demand for low sulfur Fort Union lignite led to shallow drilling by coal companies, USGS-NDGS cooperative projects, North Dakota State Water Commission, North Dakota Subsurface Minerals program, and Montana Bureau of Mines and Geology. The shallow drilling (as deep as 500 ft) from the joint USGS-NDGS cooperation (U.S.

Geological Survey and North Dakota Geological Survey, 1976; 1977; 1978; 1979; 1980), coal companies, the water commission, and subsurface minerals program provided surface and subsurface stratigraphic information on the Fort Union Formation in North Dakota for our coal assessment. Log reports of these drilling activities are archived in the North Dakota Geological Survey, and more than 6,000 drill-hole records were converted into digital files, which were used in this assessment. (For a discussion concerning database creation and resource evaluation methodology see Chapter DB in this CD-ROM.). The non-proprietary digital files of drill holes are available through the U.S. Geological Survey's National Coal Resources Data System in Reston, Virginia (email: mdcarter@usgs.gov).

HISTORY OF COAL MINING

Mining of Fort Union coal in the Williston Basin in North Dakota began in 1873 near Sims about 35 miles west of Bismarck. The railroad played an important role in the development of the first recorded underground mine. The mine was abandoned after several attacks by the Sioux despite military escorts provided by Lt. Colonel George A. Custer, who was stationed in Fort Lincoln, southwest of Bismarck (Oihus, 1983). The Northern Pacific Railroad, which created the Northern Pacific Coal Company, purchased and developed the abandoned mine. Five lignite beds totaling about 22 ft in thickness yielded the first recorded production in the basin of 100 tons daily, which was used for locomotive fuel and by area consumers for heat (Leonard, 1926). The Northern Pacific Railroad played a major part in further development of lignite in the Williston Basin due to a Congressional land grant of about 10 million acres that included the coal resources beneath that land grant (Brekke, 1992).

Other underground mining followed prior to 1900 near Minot. This underground mine was the first to use compressed air tools, fan ventilation, and cable cars (Oihus, 1983). The mine produced about 600 tons of coal, which was shipped via rail to eastern North Dakota. A mine near Dickinson used the room and pillar method of mining for a coal bed that was as much as 26 ft thick. Small open-pit mines worked by either a few miners or one person also opened prior to 1900. Some of these underground and open-pit mines operated mainly during the winter, supplying heating fuel for nearby towns (Wilder and Wood, 1903).

The Williston Basin lignite industry blossomed from 1900 to 1920 with new interests in the coal quality and quantity, by-products, briquetting, and gasification of the coal deposits (Brekke, 1992). Commercial mine operations were established in Beulah, Bowman, Center, Coalbank, Columbus, Glen Ullin, Hanks, Hazen, Hebron, Medora, New Salem, Noonan, Scranton, Underwood, and Zap. There was an emergence of strip mining in these areas, from 1920 to 1940 with the introduction of the steam shovels. The shovel simplified mining operation and increased production capacity to as much as 700,000 tons per year (Oihus, 1983).

The period of 1940-1966 was marked by a decline in mining activity in the Williston Basin (Brekke, 1992). Three hundred twenty mines were working in 1940 but that number had declined to 38 mines by 1965. Production peaked during this period to 3,280,000 tons in 1951 (Carlson and Laird, 1964). Most of this production went to fueling coal-fired electric generation plants. The decline in coal mining was directly related to a shift from coal to reliance on oil and natural gas and installation of dams for generation of electric power.

New and expanded coal-fired power plants required the rapid growth of the lignite mining industry from 1966 to the present. Currently, seven coal-fired power plants supply electricity for in-state and out-of-state customers. Production peaked to as much as 32,000,000 short tons in 1996 (E.C. Murphy, NDGS, oral commun., 1998). Currently the number of active coal mines has dwindled to six mines, four lignite and two leonardite (oxidized lignite). The four coal mines are large surface mines. No underground mining is being done.

GEOLOGICAL SETTING

The Williston Basin is a structural and sedimentary basin located on the western edge of the craton in central North America. It contains more than 15,000 ft of Cambrian to Quaternary age rocks (Carlson and Anderson, 1966). These rocks dip on the average 20 ft/mi toward the basin center in northwestern North Dakota. The Miles City arch separates the southwestern margin of Williston Basin from the Powder River Basin in Montana and Wyoming (see fig. WS-1). Late Laramide or middle to late Eocene positive structures representing basement-block movements (Anna, 1986; Clement, 1987) include the Nesson and Cedar Creek anticlines and the Poplar dome along the western and northern parts of the basin (see fig. WS-1). These movements were followed by a regional epeirogenic uplift leading to the current topographic expression (Gerhard and others, 1982). The relatively thin Fort Union Formation, as much as 1,868 ft thick (Carlson, 1985), suggests that regional subsidence of the Williston Basin may not have strongly influenced sediment accumulation.

Although the basin is structural in origin and formed during periodic tectonic movements, regional Fort Union sediment accumulations were mainly controlled by depositional settings. However, local accumulation of Fort Union sediments may have been partly influenced by local tectonic movements along both the Cedar Creek anticline, which may have diverted streams flowing from the west and southeast from the Powder River Basin, and the Nesson anticline, which may have controlled the orientation of stream channels (Daly and others, 1985; Flores, 1986; Diemer and others, 1992). Downwarping of intervening areas between the Cedar Creek and Nesson anticlines may have ponded and concentrated accumulations of thick peat deposits as exemplified by the Harmon and Hansen coal zones. Timing of these tectonic movements and corresponding overthickening of chronostratigraphically contemporaneous Fort Union sediments are not well documented.

The Fort Union Formation is thick along the basin axis in the northwestern part of North Dakota (Carlson, 1985; Cherven and Jacob, 1985; Daly and others, 1985, 1992). Beds dip at low angles (1-2 degrees) toward the basin axis. Based on the NDGS classification of Fort Union Group, Daly and others (1992) informally divided it into lower and upper parts. The lower part is as much as 656 ft thick and is composed of the Cannonball Formation, which is stratigraphically equivalent to the Ludlow, Slope, and lower Ravenscrag Formations (stratigraphically equivalent to the Ludlow Member of the USGS). The upper part is as much as 1,312 ft thick and is composed of the Bullion Creek and Sentinel Butte Formations (stratigraphically equivalent to the Tongue River and Sentinel Butte Members of the USGS), and upper Ravenscrag Formation (fig. WS-3). The coal beds in the upper part of the Fort Union are thicker than those in the lower part (Daly and others, 1992). Subdivision of Fort Union strata is based on color and marker beds. For example, drab-gray rock units include the Slope, Ludlow, and Sentinel Butte, and bright yellow rock units include the Bullion Creek/Tongue River. In addition, coal beds (for example, Harmon coal bed), thick sandstone beds (for example, basal sandstone), and white siliceous beds (for example, Rhame bed; see fig. WF-2 in Chapter WF of this CD-ROM) mark boundaries of these rock units (Royse, 1970; Jacob, 1975; Rehbein, 1977, 1978; Wehrfritz, 1978; Groenewold and others, 1979).

DEPOSITIONAL SETTING

The physical variations of the Fort Union strata are mainly controlled by their depositional environments (Royse, 1970; Jacob, 1973; Warwick, 1982; Belt and others, 1984; Cherven and Jacob, 1985; Warwick and others, 1997). The strata of the lower part of the Fort Union (Ludlow and Cannonball) were deposited mainly in deltaic and marine environments, respectively (Belt and others, 1984; Cherven and Jacob, 1985). Ludlow coal beds (fig. WS-4) were interpreted as deposits that accumulated in swamps in interdistributary and abandoned deltaic areas. However, the work by Flores (1992) on stratigraphically equivalent rocks in the northwestern part of the Williston Basin in Montana suggests alluvial deposition and that the underlying Upper Cretaceous Fox Hills Sandstone and Hell Creek Formation (fig. WS-5) were deposited in delta front and delta plain environments, respectively. This Upper Cretaceous to Lower Paleocene rock package represents a regressive event trending towards the east into North Dakota. Recent work by Warwick and others (1996; 1997) on the Ludlow and Cannonball strata (figs. WS-6 and WS-7) suggest their deposition in tide-dominated (figs. WS-8, WS-9, and WS-10) and marine environments and that accumulation of Ludlow coal beds was directly influenced by eustatic sea-level rise and fall. These eustatic sea-level changes were expressed as the transgressions (toward the west) and regressions (toward the east) of the Cannonball Sea (situated mainly in the east-central part of the basin), in which the marine Cannonball strata were deposited (Cvancara, 1976). During transgressions, deltaic deposits from previous regressions were reworked by waves and tidal processes forming stacked, coarsening-upward parasequence sets of barrier bars (fig. WS-11; Warwick and others, 1997). These authors suggested that although thin coal beds accumulated in tidal-intertidal and back-barrier swamps in North Dakota and South Dakota, thicker coal beds developed in swamps associated with contemporaneous fluvial environments farther landward or to the west in Montana.

The upper part of the Fort Union strata (Tongue River and Sentinel Butte; see figs. WS-12 and WS-13) was interpreted as fluvial and deltaic deposits (Royse, 1970; Warwick, 1982; Winczewski, 1982; Jacob, 1976; Cherven and Jacob, 1985; Daly and others, 1985). Although Jacob (1976) and Winczewski (1982) interpreted the environments of deposition of the upper Fort Union sediments as deltaic and fluvial, respectively, no compelling arguments were presented to explain the accumulations of the thick and widespread coal beds and zones (for example, Harmon and Hansen, Hagel, Beulah-Zap). These coals (for example, Harmon coal) and associated rocks probably accumulated in swamps on abandoned deposits of fluvial-channel belts (fig. WS-14) that migrated into nearby interfluvial areas (fig. WS-15). Merging and splitting of these coal zones (fig. WS-16) attest to autocyclic processes associated with the fluvio-deltaic environments. This fluvio-deltaic deposition, which accompanied a widespread regression of the Cannonball Sea, developed an extensive platform from eastern Montana to western North Dakota on which the thick, white, siliceous (silcrete) Rhame Bed paleosol or ancestral soil (fig. WS-17) formed during the sea-level low stand (Wehrfritz, 1978; Christensen, 1984). This generally eastward regression was interrupted by minor transgressions (Cherven and Jacob, 1985).

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COAL GEOLOGY

The coal geology of the Fort Union Formation in the Williston Basin in North Dakota may be subdivided into that of the lower part (Ludlow through Cannonball rocks) and that of upper part (Tongue River and Sentinel Butte rocks). This dichotomy follows differences in the biostratigraphy, stratigraphy, thickness, sedimentology or depositional settings, and areal distribution of coal in these parts of the Fort Union Formation. This dichotomy is best shown by Warwick (1982) and Belt and others (1984) and by Cherven and Jacob (1985) across the west-central part of the basin.

The biostratigraphy based on palynology (analysis of spores and pollen) of the Fort Union Formation in the northern Rocky Mountains and Great Plains region was developed by Nichols and Ott (1978); see also Nichols (1994; 1996). Based on this zonation, Nichols subdivided the Fort Union Formation in the Williston Basin in North Dakota into six Zones, P1-P6 (see fig. WS-3, and Chapter WB in this CD-ROM). The Ludlow Member of the Fort Union Formation is within Zones P1-P3 (Warwick and others, 1996; 1997). The Tongue River and Sentinel Butte Members of the Fort Union Formation are within zones P4-P6 (Warwick and others, 1996; 1997).

The coal stratigraphy in the lower and upper parts of the Fort Union Formation differs in the vertical and lateral patterns of coal beds and zones and associated clastic rocks. The vertical stratigraphic pattern in the lower part of the formation consists of coal-bed-zone “bundles.” These coal “bundles” are interbedded with thick clastic intervals (as much as 240 ft thick) of sandstone, siltstone, and mudstone

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beds. The coaly “bundles” are in turn interbedded with thin clastic intervals (as much as 80 ft thick) consisting mainly of siltstone, mudstone, and subordinate sandstone. Laterally, the coal beds split and merge within a 2-7 mi distance, forming a coal zone (Belt and others, 1984). The individual coal beds of this zone vary from a few inches to 13 ft thick.

In the upper part of the formation (Groenewold and others 1979), the vertical stratigraphic pattern consists of coal-bed-zone “bundles” that are interbedded with thick clastic rock intervals (as much as 175 ft thick) of sandstone, siltstone, and mudstone. These coal “bundles” are in turn interbedded with thinner clastic intervals (as much as 125 ft thick) consisting mainly of mudstone, siltstone, and limestone, and subordinate sandstone. Laterally, the coal beds split and merge within a 9-20 mi distance, forming a coal zone (Groenewold and others, 1979). Coal beds of this zone vary from a few inches to 40 ft thick. The coal-bed-zone “bundling” is represented by Harmon and Hansen, Hagel, and Beulah-Zap beds. Coal beds and zones targeted by our assessment and their associated stratigraphy are demonstrated in Chapter WF of this CD-ROM.

The vertical and lateral patterns of the coal stratigraphy in the lower and upper parts of the Fort Union are controlled by the sedimentology or depositional environments of these rocks. In the lower part of the formation the short distance (within a 2-7 mi distance) of splitting and merging of coal beds forming a zone is controlled by the areal size and rate of sedimentation followed by avulsion or shift of the deltaic depositional systems that formed these rocks. Thus, a rapid rate of sedimentation in small depositional systems, such as in subdeltas (for example, crevasse splays), produced thin clastic intervals of mainly siltstone, mudstone, and subordinate sandstone. These sedimentary deposits formed short-lived platforms on which swamps accumulated thin peat deposits. Frequent autocyclic (lateral) shifts of these environments influenced the splitting and merging of the peat deposits and resulting thickness of peat formed on these platforms. Stacking of the peat deposits and sediments related to autocyclic deltaic systems caused coal-bed-zone “bundling” or stacked thin coal beds. The intervening thick intervals of sandstone, siltstone, and mudstone represent the major distributary channel-overbank deposits of the delta systems. These deposits in turn were reworked and modified by tidal incursions as a result of regional and local sea-level transgressions. This tidal reworking as well as restricted platforms of peat deposition may have contributed to the limited areal distribution of the peat deposits. The peat deposits formed in these environments are exemplified by coal beds in the Tongue River and Sentinel Butte Members of the Fort Union Formation.

In the upper part of the formation coal beds split and merge over a long distance (within a 9-20 mi distance) forming a coal zone. Such zones are controlled by the rapid rate of sedimentation in wide alluvial plains that were drained by meandering and braided streams and accompanying crevasse splays. Avulsion or shift and prolonged abandonment of these stream deposits formed extensive alluvial platforms on which swamps developed and very thick peat deposits accumulated. However, rapid successions of avulsion or shift and abandonment of the fluvial depositional systems along the width of the alluvial plain provided coal-bed-zone “bundling.” In addition, the vast expanse of abandoned alluvial platforms contributed to the extensive areal distribution of the peat deposits. This accounts for the widespread coal deposits of the Tongue River and Sentinel Butte Members of the Fort Union Formation.

COAL RESOURCES AND COAL QUALITY

Early estimates of the coal resources in the Williston Basin in North Dakota were based mainly on outcrop data that were stratigraphically limited. Leonard and others (1925) evaluated only the coal beds equal to or greater than 4 ft thick in the upper 300-400 ft of the Fort Union Formation, which resulted in a coal resource totaling 516 billion short tons. Campbell (1929) was the first to present comprehensive coal resource estimates in the Williston Basin in North Dakota. Utilizing coal beds 3 ft thick or greater, Campbell (1929) estimated the coal resource in North Dakota as 600 billion short tons. Using subsurface data from 0-3,000 ft below the surface and coal beds 2.5 ft thick or greater, Brant (1953) estimated the remaining identified coal resource in the Williston Basin in North Dakota to be more than 350 billion short tons. Pollard and others (1972) identified and mapped strippable lignite resources in North Dakota. Averitt (1975), using coal beds 2.5 ft thick or greater, estimated the total identified and hypothetical coal resources 0-6,000 ft below the surface in North Dakota to be more than 530 billion short tons. In addition, Averitt (1975) estimated the surface coal reserve base determined by potential mining methods (for example, strip mining) to be more than 16 billion short tons.

Most of the coal resources of the Williston Basin in North Dakota are contained in the Harmon and Hansen coal beds and zones in the southwestern part of the area, and in the Hagel and Beulah-Zap coal beds and zones in the east-central part. These coal beds and zones (for example, Harmon and Hansen, Hagel, and Beulah-Zap) were assessed in the Bowman-Dickinson, Center-Falkirk, and Beulah-Zap coalfields; assessment is limited by the extent and distribution of available drill-hole data. The coal beds and zones may exist beyond the coalfield limits. Estimates of coal resources of the Harmon and Hansen, Hagel, and Beulah-Zap coal beds and zones are presented in Chapter WN in this CD-ROM. Estimates of coal resources in beds thicker than 2.5 ft are: Harmon and Hansen coal beds and zones—67 billion short tons; Hagel coal beds and zones—4.4 billion short tons; and Beulah-Zap coal beds and zones—4.8 billion short tons; a total for the North Dakota part of the basin—76.2 billion short tons (see Chapter WN of this CD-ROM). These coal resource estimates are broken down by thickness, overburden, ownership, and county (see Chapter WN). The methodology of calculating the resources of these coal beds and zones is discussed in Chapter DB and Chapter WN).

The Fort Union lignite in the Williston Basin in North Dakota is classified according to the percent fixed carbon and calorific value calculated on a mineral-matter-free basis. Fort Union lignite in North Dakota is low in percent (arithmetic mean) fixed carbon and calorific value, which ranges from 2,625 to 7,980 Btu/lb (n= 216 samples; as-received basis; Tewalt and others, 1992). Flores and others (1998) reported calorific value (arithmetic mean) of 6,504 Btu/lb (lignite A; n=310; as-received basis) for the Fort Union lignite in North Dakota. Sulfur and ash contents of the Fort Union lignite range from 0.2 to 4.0 and 3.5 to 30.7 percent, respectively (arithmetic means; n=216 samples; as received basis; Tewalt and others, 1992). Flores and others (1998) reported sulfur and ash contents of 0.86 and 7.99 percent (arithmetic mean), respectively (n=310; as-received basis). The coal quality and geochemistry of the Fort Union lignite in the Williston Basin in North Dakota are presented in Chapter WQ of this CD-ROM.

Tewalt and others (1992) reported that the trace elements of environmental concern in Fort Union coal, which can impact coal utilization and reclamation, include arsenic and selenium. Arsenic and selenium range from 1 to 63 ppm and 0.15 to 3.3 ppm, respectively (arithmetic mean; on a whole coal; as-received basis; Swanson

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and others, 1976; Tewalt and others, 1989). Stricker and others (1998) reported the arithmetic mean for arsenic as 9.1 ppm (on a whole coal, as-received basis) and for selenium as 0.74 ppm (on a whole-coal, as-received basis). In addition, Stricker and others (1998) compared concentrations of these trace elements and others (antimony, beryllium, cadmium, chromium, cobalt, lead, manganese, mercury, nickel, and uranium) with coal from other coal regions in the conterminous U.S. (for example, Colorado Plateau, Illinois Basin, and Appalachian Basin). They concluded that the Fort Union coal in the Williston Basin in North Dakota has low concentrations of trace elements of environmental concern.

Inorganic composition of the Fort Union lignite includes mainly pyrite, quartz, and clay minerals (Benson and others, 1992). Other minerals present in lesser amounts include gypsum, other sulfides, carbonates, barite, rutile, and hematite. The pyrite, gypsum, barite, and other sulfides contribute to the sulfur content of the coal. The clay minerals and quartz contribute to the ash content of the coal. The distribution of these minerals varies with location in the coal beds (Zygarlicke, 1987). A significant proportion of the inorganic components is organically related; that is, most of the elemental components of these minerals exist as organic coordination complexes (for example, macerals) in the coal (Benson and others, 1992).

CONCLUSIONS

The Fort Union lignite represents a significant energy resource in the Williston Basin in North Dakota. Its mining history and development spans about 125 years and continues to support local and regional consumers. The most important use of this coal resource is as fuel for mine-mouth power plants and other electric power generating plants. Presently, the Harmon and Hansen, Hagel, and Beulah-Zap coal beds and zones are mined in open pits. Production from these coal mines mainly supports seven in-state electric power plants and one degasification plant. The electricity generated from the power plants is transmitted to utilities in nearby mid-western states.

In order to continue supporting the electric power and degasification plants during the next century, assessment of the Fort Union coal in the Williston Basin in North Dakota focused on the Harmon and Hansen, Hagel, and Beulah-Zap coal beds and zones. These coal deposits are as much as 60 ft thick, lignite A in rank, and have low-sulfur, ash, and trace-element contents. Coal production in 1996 from six coal mines was more than 32 million short tons and was reduced to more than 30 million short tons from five mines in 1998. The Harmon and Hansen, Hagel, and Beulah-Zap coal beds and zones contain resources of as much as 76.2 billion short tons in coal beds more than 2.5 ft thick. The thick coal beds were deposited mainly in swamps related to fluvial and deltaic environments. The extensive areal distribution of these coal beds and zones reflects accumulation in raised swamps on abandoned alluvial platforms. The thickness, areal distribution, high quality, and chemistry of this coal make it a clean and compliant energy resource.

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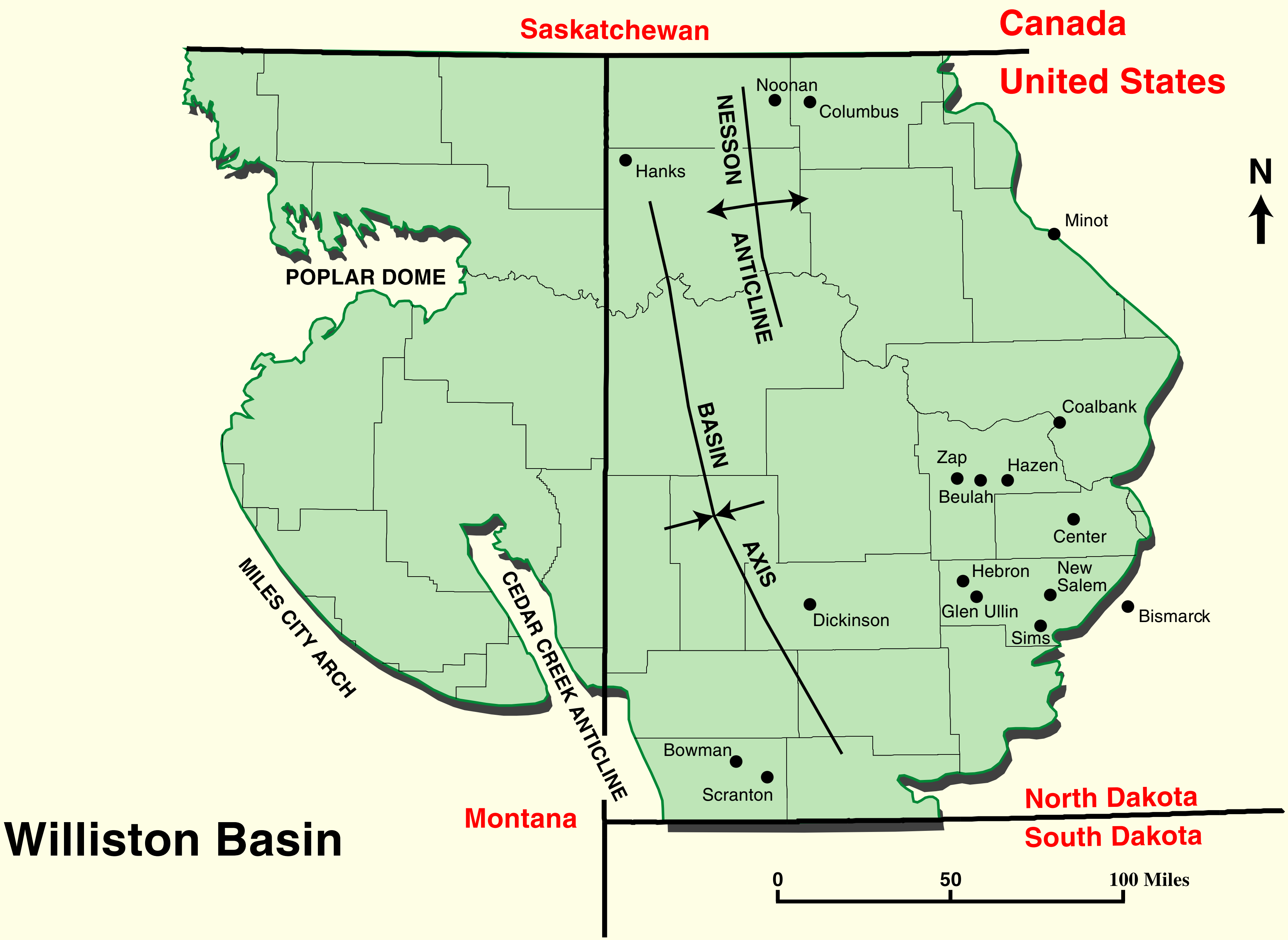

Figure WS-1. Generalized map showing the extent of the Williston Basin in North Dakota and Montana. Also shown are county boundaries, geological structures, and coal towns in North Dakota. The parts of the Williston Basin in South Dakota and Saskatchewan Province, Canada, are not shown.

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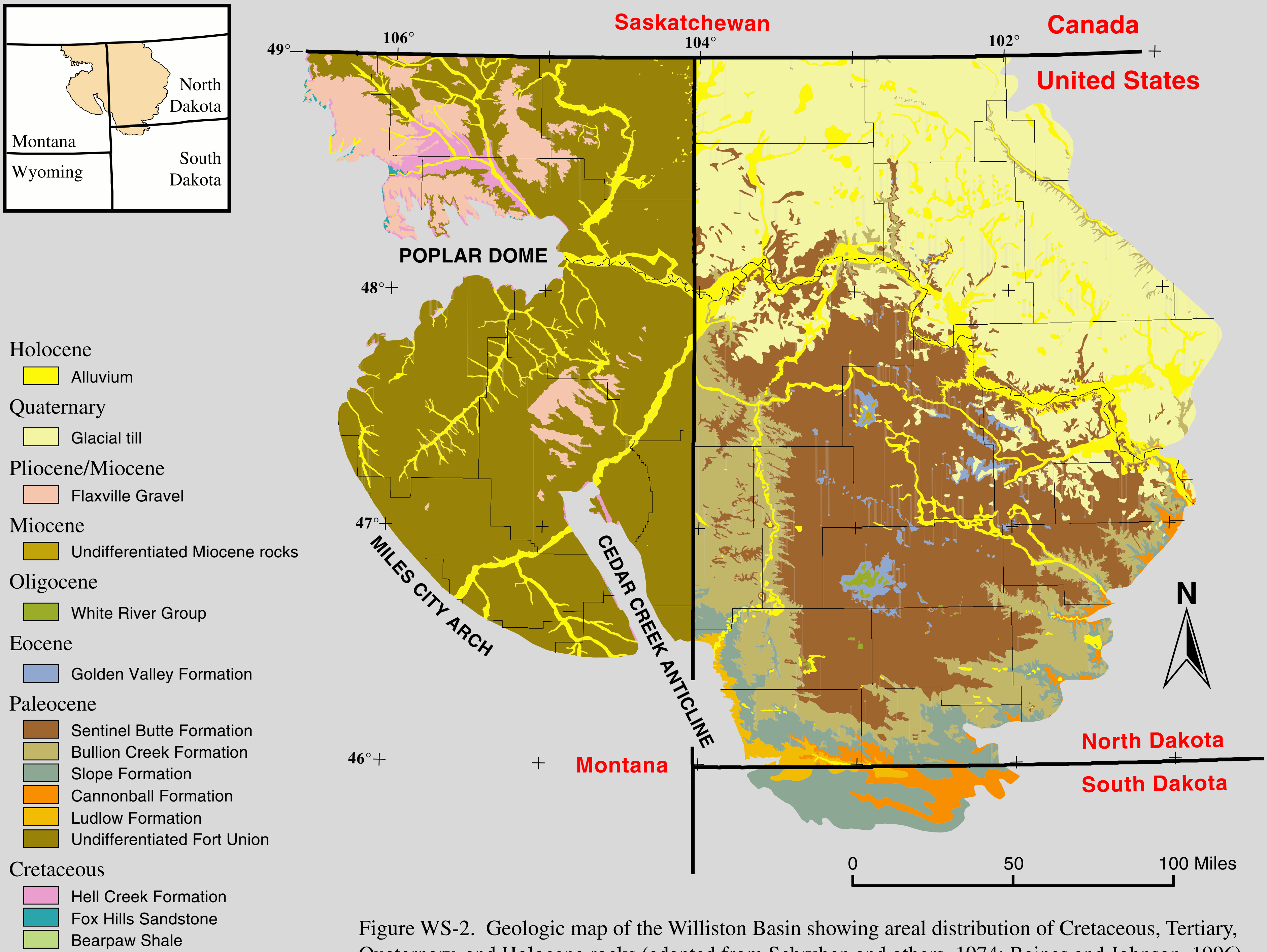

Figure WS-2. Geologic map of the Williston Basin showing areal distribution of Cretaceous, Tertiary, Quaternary, and Holocene rocks (adapted from Schruben and others, 1974; Raines and Johnson, 1996).

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Figure WS-3. Generalized stratigraphic column showing the age, palynology biozones, and nomenclature in the Williston Basin.

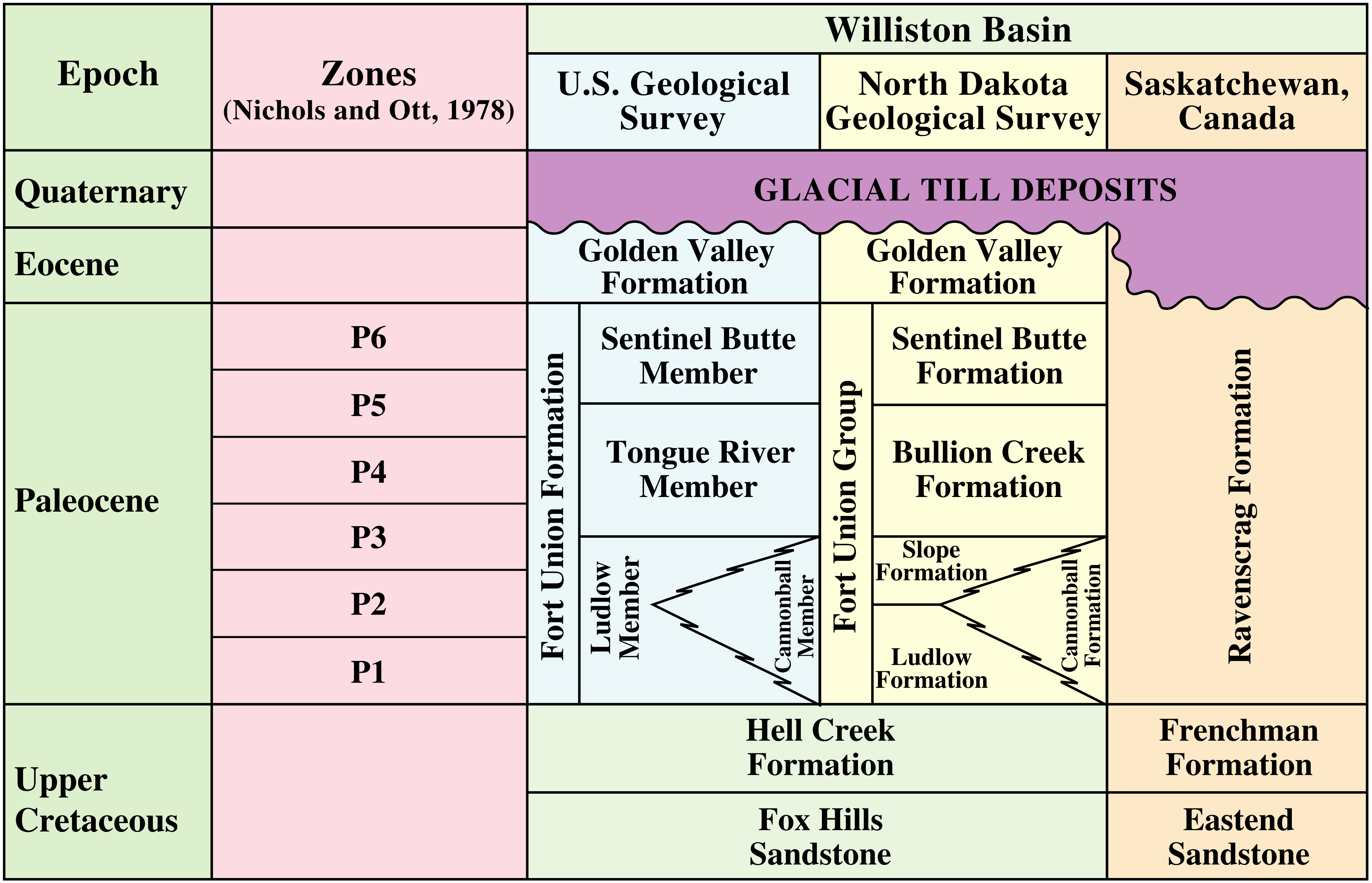

Figure WS-4. The Ludlow Member of the Fort Union Formation consisting of coarsening-upward deltaic sandstone, distributary channel sandstone, interdistributary mudstone and siltstone, and thin coal beds formed in low-lying swamps exposed along the valley of the Little Missouri River, North Dakota. Photograph by R.M. Flores.

Figure WS-5. The Cretaceous Fox Hills Sandstone (white) overlain by the Hell Creek Formation (gray Brown) exposed in the Cedar Creek Anticline, Montana. Photograph by R.M. Flores.

Figure WS-6. The Cannonball Member of the Fort Union Formation consisting of tabular, shoreface sandstone exposed along the Heart River, North Dakota. Photograph by R.M. Flores.

Figure WS-7. A tongue of the Cannonball Member consisting of oyster shell beds (brackish water) in the Ludlow Member exposed along the valley wall of the Little Missouri River, North Dakota. Photogragh by R.M. Flores.

Figure WS-8. Tidal silty sandstone, siltstone, and mudstone deposits in the Ludlow Member of the Fort Union Formation. Photograph by R.M. Flores.

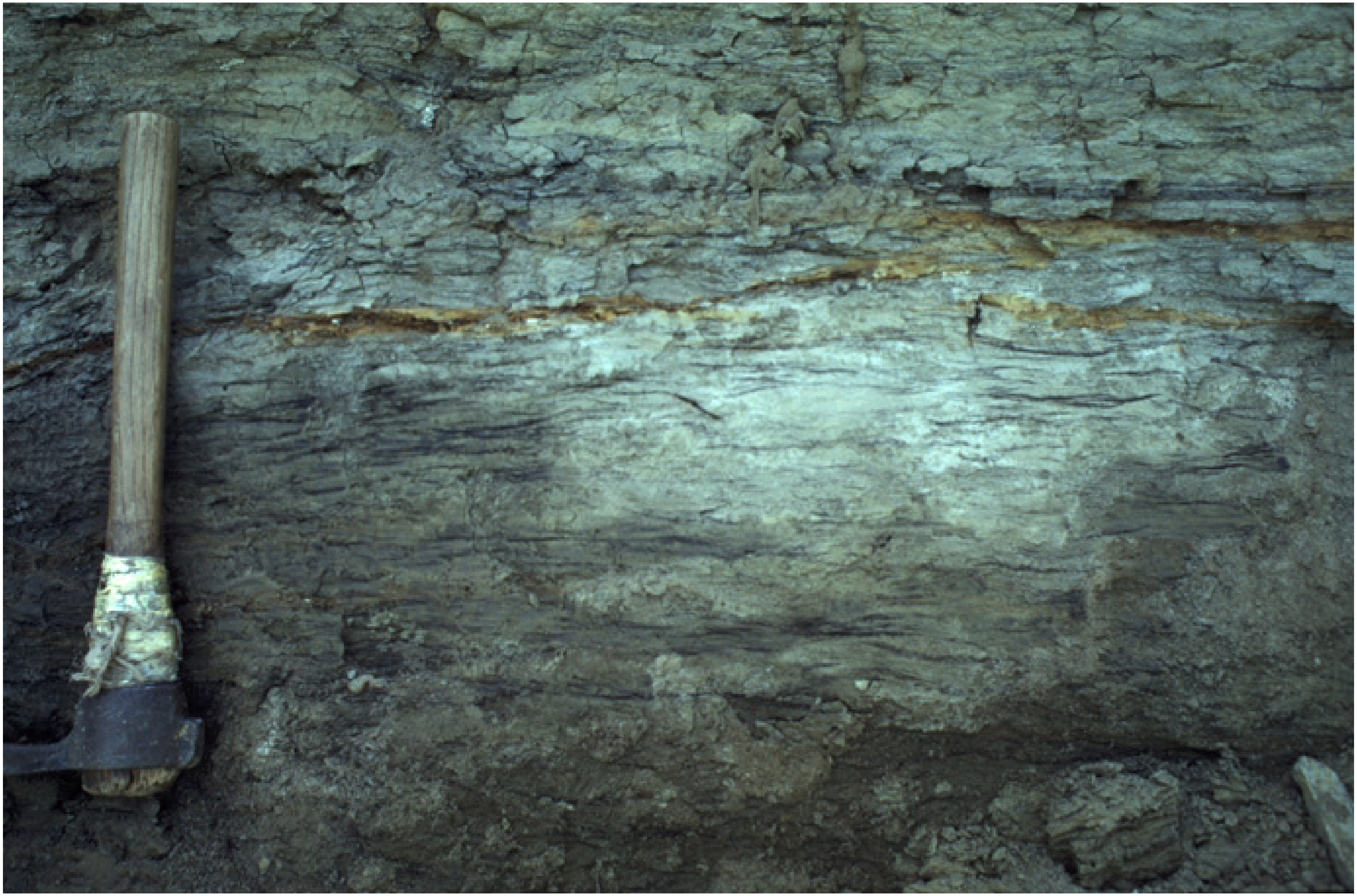

Figure WS-9. Flaser-bedded silty sandstone and siltstone draped by wispy mudstone representing tidal flat deposits in the Ludlow Member. Photograph by R.M. Flores

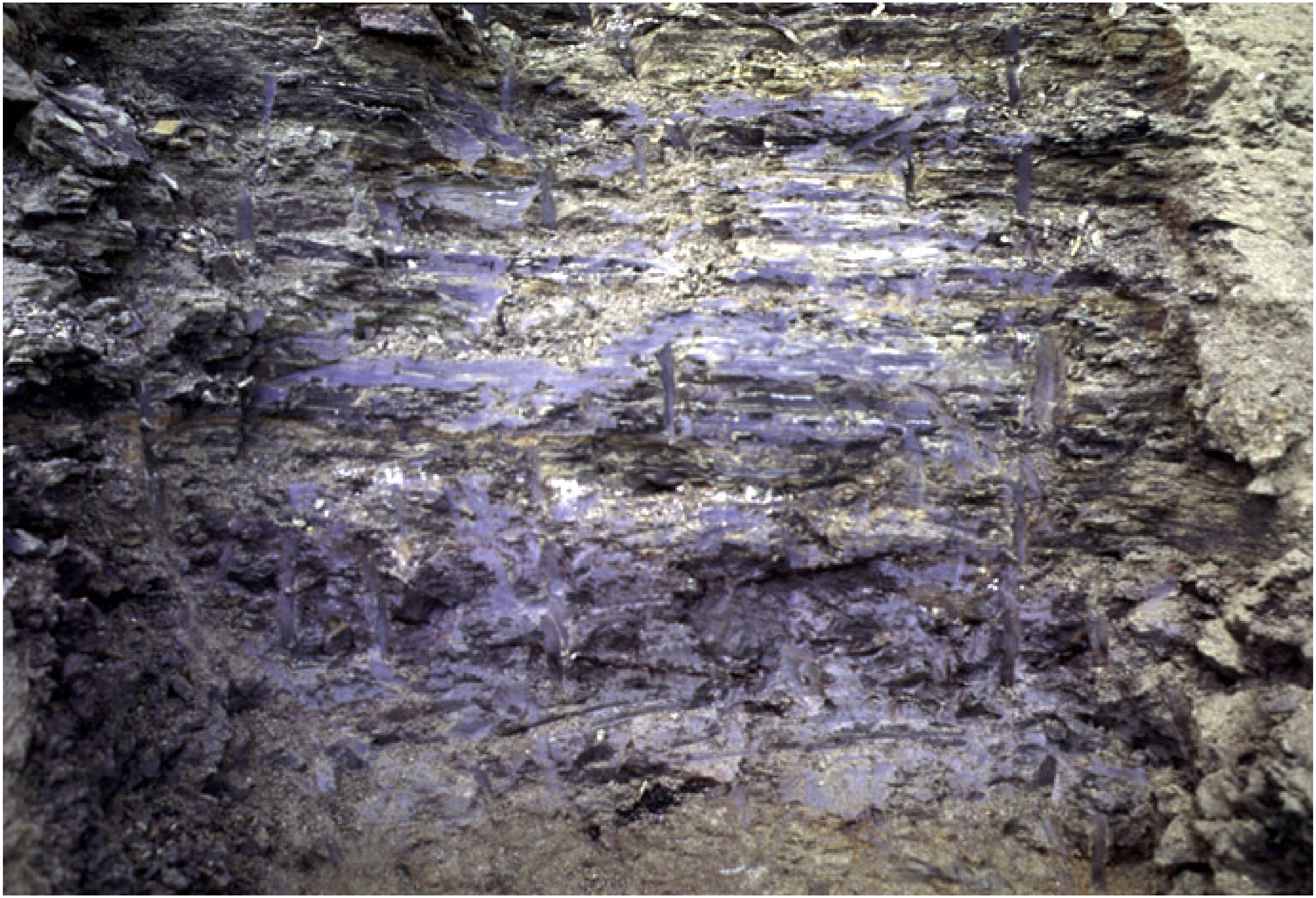

Figure WS-10. Burrowed mudstone interbedded with burrowed lenticular siltstone representing tidal flat deposits in the Ludlow Member. Photograph by R.M. Flores.

Figure WS-11. Barrier shoreface sandstone underlain by tidal flat deposits of the Cannonball Member exposed in the Cave Hills, South Dakota. The contact between the shoreface sandstone and the tidal deposits is a sequence boundary. Photograph by R.M. Flores.

Figure WS-12. The Tongue River Member of the Fort Union Formation consisting of fluvial channel sandstone, floodplain mudstone, siltstone, and silty sandstone, and thin coal beds deposited in low-lying swamps exposed along the valley wall of the Little Missouri River, North Dakota. Photograph by R.M. Flores.

Figure WS-13. The Sentinel Butte Member of the Fort Union Formation consisting of fluvial channel sandstone and interfluvial mudstone and siltstone above the valley wall of the Little Missouri River, North Dakota. Photogragh by R.M. Flores.

Figure WS-14. The Harmon and Hansen coal above fluvial channel sandstone (immediately above the river on the right of the photo) and the Rhame bed paleosol (light gray) below the coal exposed along the wall of the Little Missouri River, North Dakota. Photograph by R.M. Flores.

Figure WS-15. The Harmon (upper bed) and Hansen (lower bed) coal separated by floodplain mudstone and siltstone. Photograph by R.M. Flores.

Figure WS-16. Merged Harmon and Hansen coal interbedded with floodplain mudstone and siltstone along the valley wall of the Little Missouri River, North Dakota. Photograph by R.M. Flores.

Figure WS-17. Rhame bed paleosol is as much as 30 ft thick and consists of stacked, bleached to varicolored, rooted mudstone and interbedded carbonaceous mudstone. Photograph by R.M. Flores.