Chapter WF

FRAMEWORK GEOLOGY OF FORT UNION COAL IN THE WILLISTON BASIN

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STRUCTURAL SETTING

- The Williston Basin (fig. WF-1) underlies most of North Dakota, northwestern South Dakota, eastern Montana, and southern Saskatchewan, Canada (Whitaker and others, 1978).
- The Fort Union Formation (Paleocene) and associated beds exist at the surface and in the subsurface; they dip 1-2 degrees toward the center of the basin in western North Dakota.
- Fort Union rocks in North Dakota exist over 32,000 square mile and can be as much as 1,868 ft thick (Carlson, 1985). The Fort Union Formation makes up about 13 percent of the total sedimentary rocks in the basin, which are more than 15,000 ft in thickness (Carlson and Anderson, 1966),

STRATIGRAPHIC SETTING

- The Fort Union Formation is composed, from oldest to youngest, of the Ludlow, Cannonball, Tongue River, and Sentinel Butte Members. The nomenclature follows the U.S. Geological Survey stratigraphic classification and not that of the North Dakota Geological Survey (Jacob, 1973; 1975; 1976). The U.S. Geological Survey considers the Fort Union a formation; although, the North Dakota Geological Survey considers it a group and recognizes some different formational units within it.
- All members are coal-bearing except the marine Cannonball Member. Westward, the Cannonball Member intertongues with and pinches out into the Ludlow and Tongue River Members. The brackish-marine tongues of the

Cannonball Member may be present as far west as southeastern Montana (Warwick and others, 1998).

- Fort Union coal beds generally thicken toward the upper part of the formation. Coal beds are as much as 20 ft thick in the Tongue River Member and 26 ft thick in the Sentinel Butte Member.
- In all, 6,033 proprietary and non-proprietary drill holes were used to investigate the Fort Union coal in the Williston Basin. The stratigraphic information from drill holes was interpreted from geophysical logs (for example, gamma, resistivity, and density) and lithologic logs by geologists of the North Dakota Geological Survey and other organizations (Murphy and Goven, 1998).

DEPOSITIONAL SETTING

- Depositional environments of the Fort Union Formation include fluvial, deltaic, tidal, barrier-shoreface, and marine settings (Jacob, 1973, 1975; Cvancara, 1976; Warwick 1982; Cherven and Jacob, 1985; Warwick and others, 1996). Tidal deposits are common in the Ludlow Member, barrier deposits are common in the Cannonball Member, and fluvial-deltaic deposits are abundant in the Tongue River and Sentinel Butte Members (Warwick and others, 1996; 1998).
- Coal accumulated in peat mires or swamps in interfluvial, interdeltaic, and intertidal settings. These mires are low-lying and frequently overlain by fluvial, deltaic, and crevasse splay deposits (Warwick, 1982; Daly and others, 1985).
- Coal in the Ludlow Member, which is generally thin, occurs landward of a transgressive cycle or landward-stepping progradational events (Warwick and others, 1998). Coal in the Tongue River and Sentinel Butte Members occurs landward of a regressive cycle or seaward-stepping progradational events. Accumulation of the thin Ludlow coal was coincident to sea-level rise, which was

theoretically accompanied by a maximum addition of new accommodation space. The accumulation of the thick Tongue River and Sentinel Butte coal was coincident to sea-level fall, which was theoretically accompanied by a minimum addition of new accommodation space (Flores and Cross, 1991). Tectonic movements in the basin as suggested by Daly and others (1985) may have controlled the accommodation space during the accumulation of the Sentinel Butte coal.

COAL QUALITY

- Most of the Fort Union coal in the Williston Basin is lignite in rank (Stricker and others, 1998). However, six coal samples from our study (see Chapter WQ in this CD-ROM) indicate that some Fort Union coal in the Williston Basin is subbituminous C in rank ranging from 8,300 to 8,560 Btu/lb (moist, mineral-matter-free basis).
- Coal quality data indicate low sulfur and ash contents (Soundreal and others, 1968; Swanson and others, 1976; Stricker and others, 1998).
- Selected trace-elements of environmental concern have low concentrations (Stricker and others, 1998).

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS OF COAL UNITS AND ASSOCIATED ROCKS

STRATIGRAPHY

- The Fort Union Formation is composed primarily of sandstone, siltstone, and mudstone and subordinate carbonaceous shale, coal, and limestone. The sandstone and mudstone are common rock types of the formation. The Tongue River and Sentinel Butte Members contain up to 42 percent sandstone locally distributed throughout the members (Jacob, 1975; Warwick, 1982; Cherven and Jacob, 1985).

- Minable coal beds and zones include the Harmon, Hansen, Hagel, and Beulah-Zap (fig. WF-2). Four mines developing these deposits accounted about 3 percent of the total U.S. coal production in 1997 (Resource Data International, Inc., 1997).
- The Harmon and Hansen coal zones are in the lowermost part of the Tongue River Member and occur in the southwestern part of the basin. The Harmon coal was mined in the Gascoyne surface mine, which closed in 1996.
- The Hagel coal zone is in the middle part of the Sentinel Butte Member and occurs in the east-central part of the basin. Hagel coal is mined in the Center and Falkirk surface mines.
- The Beulah-Zap coal zone is in the upper part of the Sentinel Butte Member and exists in the east-central part of the basin. The Beulah-Zap coal is mined in the Freedom surface mine north of Beulah and in the Knife River surface mine south of Beulah.
- Coal beds of intervening coal zones such as the Antelope Creek and Kinneman Creek may be relatively thin or thick and merge with the Hagel and Beulah-Zap coal zones.
- In the Williston Basin, the biostratigraphic zonation of the Fort Union includes Zones P1-P6 (fig WF-3). The minable coal beds and zones occur in the upper part of the Paleocene in Zones P4-P6.

DEPOSITIONAL ENVIRONMENTS

- The coal of the Harmon and Hansen coal zones accumulated in peat mires or swamps in alluvial plain environments (Warwick, 1982). The Harmon and Hansen coal zones are interbedded with floodplain mudstone and siltstone (gray) and overlain by fluvial channel sandstone and interfluvial silty sandstone, siltstone, and mudstone (shown in yellow) as shown along the valley wall of the Little Missouri River (fig. WF-4). These coal zones are underlain by bleached-variegated, silcrete paleosol of the Rhame bed (fig. WF-5). The Harmon coal, which is overlain by fluvial channel sandstone, was mined at the abandoned Gascoyne surface mine (fig. WF-6). The Harmon-Hansen fluvial setting was at the western margin of the coastal plain that trailed the eastward regression of the Cannonball Sea (Cherven and Jacob, 1985). Eastward-flowing streams drained into the deltas of the coastal plain.

- Several contemporaneous, small and large fluvial channels drained the alluvial plain (Warwick, 1982). They migrated laterally by process of deposition and erosion in meander belts that shifted across the alluvial plain.
- Interfluvial peat swamps formed in lacustrine-dominated floodplains above the drainage level of bounding fluvial channels and associated levees. Swamps encroached on abandoned alluvial ridges and peat accumulated on raised platforms that were protected from sediment influx.
- These environmental conditions yielded thick, low ash, and areally elongate coal deposits formed in topographically elevated peat swamps (Warwick, 1982) and interfluvial peat swamps (Rehbein, 1977).
- The coal of the Hagel and Beulah-Zap coal zones formed in peat swamps in upper delta plain (fluvial dominated) environments. This interpretation is based on the abundance of mudstone (figs. WF-7 and WF-8) and the presence of common small and large channel-sandstone beds (figs. WF-9, WF-10, and WF-11) immediately above the coal zones. However, Daly and others (1985) suggested that deposition of the coal zones took place in a tectonic-fluvial setting.

- Low-lying interdeltaic peat swamps were bounded by large, diverging, interdistributary fluvial channels and by small crevasse channels and splays. The swamps accumulated thin and laterally discontinuous peat coal deposits.
- However, abandoned interdeltaic peat swamps resulted in the accumulation of thick and sheet-like coal deposit. The coal formed on raised swamp platforms that consisted of fluvial-channel deposits. Splitting of the coal deposits suggests intermittent flooding of the platforms by sediments.
- A few peat deposits, high in ash content and carbonaceous mud, formed in intertidal marshes drained by tidal channels and were shielded from the sea by a barrier-beach setting (Warwick and others, 1996).

BOWMAN-DICKINSON COALFIELD, HARMON AND HANSEN COAL ZONES

DISTRIBUTION

- The Bowman-Dickinson coalfield boundary approximately follows the areal extent of the Harmon and Hansen coal zone as defined by Rehbein (1977). It includes mining areas that produced from these coal zones in Bowman and Hettinger Counties (LeFever and Murphy, 1983).
- The coalfield is defined by the subsurface extent of the Harmon and Hansen coal zones, as delineated by drill holes, on the east, north, and south (Rehbein, 1977), and is defined on the west by the Montana-North Dakota state line. The state line is just west of the only known Harmon and Hansen coal outcrops along the valley walls of the Little Missouri River (Warwick, 1982; LeFever and Murphy, 1983).

- The Harmon and Hansen coal zones are found in the lowermost part of the Tongue River Member of the Fort Union Formation.
- These coal zones occur mainly in the subsurface of Bowman, Adams, Hettinger, Slope, Golden Valley, Billings, and Stark Counties in the southwestern Williston Basin, North Dakota (fig. WF-12).
- The coal zones crop out mainly along the Little Missouri River in western Billings County.

STRATIGRAPHIC FRAMEWORK

- The coal zones in the Bowman-Dickinson coalfield usually consist of a lower Hansen coal zone and an upper Harmon coal zone. These coal zones are interbedded with limestone, mudstone, carbonaceous shale, siltstone, and sandstone. The sandstone beds, which range in thickness from 8 to 74 ft and display an erosional base in outcrop, were interpreted by Warwick (1982) as a fluvial channel deposit. Warwick (1982) indicated that a crevasse splay sandstone averages 3-5 ft thick. These criteria were used as a guide in the interpretation of depositional environments of the sandstone in the coal zones and associated rocks in the subsurface.
- The thickness of the coal zones ranges from 4 to 42 ft throughout the study area.
- Laterally, the coal beds merge, split, and pinch out. The coal splits into two or more beds that gradually thin or pinch out or interfinger with other clastic rocks.
- Coal beds pinch out into wash-out areas consisting of carbonaceous shale, mudstone, siltstone, and sandstone.
- Vertically, the coal zones include as many as 4 coal beds as a result of splitting of the Harmon and Hansen coal.
- Coal beds are interbedded mainly with mudstone and carbonaceous shale partings.

- Rocks above and below the coal zones consist of mudstone, siltstone, sandstone, and limestone.
- Rocks of this zone were accumulated in fluvial channels and interfluvial environments of an alluvial plain.
- The Harmon and Hansen coal beds accumulated in interfluvial peat swamps.

HARMON AND HANSEN COAL ZONES INTERPRETIVE CROSS SECTION A-A'

- The coal beds and zones are in a 5 to 42 ft thick interval consisting of a lower Hansen coal bed and zone as much as 5 ft thick and an upper Harmon coal zone as much as 29 ft thick (fig. WF-13). Datum is the base of the Harmon coal zone. The cross section was drawn using data from 9 drill holes, which are not labeled on the cross section.
- The Harmon coal zone varies from 5 to 29 ft thick from southeast to northwest along the 51 mile extent of cross section A-A'. The coal zone locally splits in the central part of the cross section.
- The Hansen coal zone is lenticular, varies from 4 to 10.5 miles in length, and pinches out toward the northwest and southeast.
- Interburden rocks between the zones are dominantly mudstone and siltstone and subordinately sandstone.
- Sandstone bodies range in thickness from 10 to 60 ft and accumulated in either single or multiple river channels.
- These river channel deposits range from 6 to 18 mi in lateral extent and represent accumulation in laterally migrating narrow to wide channels.
- The river channels were a part of a drainage network on a delta plain (fig. WF-14), which flowed into the nearby Cannonball Sea.

- The mudstone and siltstone were deposited in overbank and floodplain environments, and the sandstone was deposited in crevasse splays (fig. WF-15) in flood basins between river channels.
- Low-lying areas between the river channels remained below water level and supported peat swamps (fig. WF-16) where peat deposits were buried by younger sediments and eventually transformed into lignite. Coal beds that formed in these peat swamps are thin and laterally discontinuous.
- Peat deposits also accumulated in swamps once occupied by river channel, overbank, floodplain, and crevasse splay environments later abandoned by the river (fig. WF-17). Peat deposited in these environments formed thick and laterally extensive coal beds exemplified by the Harmon and Hansen coal.

HARMON AND HANSEN COAL ZONES INTERPRETIVE CROSS SECTION B-B'

- These coal zones occur in an 8 to 25 ft thick interval that includes a lower Hansen coal bed and zone that is as much as 5 ft thick and an upper Harmon coal zone as much as 12 ft thick (fig. WF-18). Datum is the base of the Harmon coal zone. The cross section was drawn using data from 10 drill holes, which are not labeled on the cross section.
- The Harmon coal zone varies from 3 to 12 ft thick from northwest to southeast along the 56-mi extent of B-B'. It splits to the southeast, pinches out to the northwest but is present again at the northwest end of the cross section.
- The Hansen coal zone is as much as 5 ft thick and is lenticular along its extent in the southeast part of the cross section.
- Interburden rocks between the zones are dominantly mudstone and siltstone and subordinately sandstone.

- Other sandstone bodies shown in the cross section range from 50 to more than 100 ft thick. They were deposited in multiple river channels.
- River channel deposits range from 10 to 20 mi in lateral extent. They represent accumulation in mainly laterally migrating river channels.
- These river channels are areally contemporaneous on a delta plain (fig. WF-19). They may have merged and diverged as they drained into the nearby Cannonball Sea.
- The mudstone and siltstone were deposited in overbank and floodplain environments and the sandstone was deposited in crevasse splays in flood basins between river channels.
- These low-lying flood basins remained below water level and supported swamps that accumulated peat that eventually resulted in thin and laterally discontinuous coal beds.
- Areas once occupied by river channels and their flood basins but later abandoned by the river served as swamp platforms where the Harmon and Hansen coal accumulated as thick and laterally extensive deposits.
- The Harmon and Hansen coal zones pinch out suggesting washouts through the peat swamps.

HARMON AND HANSEN COAL ZONES INTERPRETIVE CROSS SECTION C-C'

- These coal zones occur in a 15-ft-thick interval consisting of a lower Hansen coal zone that is as much as 6 ft thick and an upper Harmon coal zone as much as 10 ft thick (fig. WF-20). They merge to form a single zone as much as 14 ft thick. Datum is the base of Harmon coal zone. The cross section was drawn using data from 7 drill holes, which are not labeled on the cross section.

- The Harmon coal zone varies from 5.5 to 10 ft thick along parts of the 72.6 mi extent of cross section C-C’. The coal zone pinches out toward the central part of the cross section.
- The Hansen coal zone is 0 to 6 ft thick and merges to the east with the Harmon coal zone (see western part of cross section).
- Interburden rocks are dominated by mudstone and siltstone and secondarily by sandstone.
- Other sandstone bodies shown in the cross section average 50 ft in thickness and probably were deposited in a multiple channel complex.
- The sandstone bodies range from 15 to 20 mi in lateral extent and represent deposition in laterally migrating river channels that drained into the Cannonball Sea.
- The mudstone and siltstone were deposited in lake (fig. WF-21) and floodplain environments and the sandstone was deposited in crevasse splays in flood basins between river channels.
- These flood basins remained below water level, supporting small peat swamps, which later formed thin and laterally discontinuous coal beds.
- The Harmon and Hansen coal zones formed in peat swamps on abandoned river channel and flood basin deposits. However, the lateral extent of these coal beds was affected by crevasse washouts in flood basins.

HARMON AND HANSEN COAL ZONES INTERPRETIVE CROSS SECTION D-D’

- These coal zones are in an interval 2 to 40 ft thick consisting of a lower Hansen coal bed and zone as much as 10 ft thick and an upper Harmon coal zone as much as 13 ft thick (fig. WF-22). These coal zones consist of up to four beds. Datum is the base of the Harmon coal zone. The cross section was drawn using data from 10 drill holes, which are not labeled on the cross section.

- The Harmon coal zone varies from 5 to 13 ft in thickness from southwest to northeast along the 45.2 mi extent of cross section D-D'. The coal zone pinches out towards the southwest.
- The Hansen coal zone is 0 to 9 ft thick and pinches out towards the southwest.
- Interburden rocks are dominated by mudstone and siltstone and subordinately by sandstone.
- Other sandstone bodies shown in the cross section range from 20 to 90 ft in thickness and form single to multiple channel complexes.
- The sandstone is 4.5 to 11 mi in lateral extent. These deposits accumulated in areally alternating narrow and wide river channels that flowed into the Cannonball Sea (See Chapter WS).
- The mudstone and siltstone were deposited in overbank and floodplain environments and the sandstone was deposited in crevasse splays in flood basins between river channels.
- Drowned flood basins supported numerous small and disconnected peat swamps that formed thin and laterally discontinuous coal beds.
- The Harmon and Hansen coal zones formed in continuous peat swamps on abandoned river-channel and flood-basin deposits abandoned by the river. However, the extent of these coal zones was controlled by washouts in the river-channel margins and flood basins.
- Flood-basin washouts may be caused by lake and crevasse-splay deposition.

CENTER-FALKIRK COALFIELD, HAGEL COAL ZONE

DISTRIBUTION

- The Center-Falkirk coalfield (fig. WF-23) boundary approximately follows the areal extent of the Hagel coal zone as defined by Groenewald and others (1979). It includes early and current mining areas that produced from this coal zone in Center and Falkirk in McLean, Mercer, and Oliver Counties (Leonard, 1908; Groenewold and others, 1979; Oihus, 1983).
- The coalfield is delineated by the subsurface extent of the Hagel coal zone on the east, west, north, and south, which were locally removed at the surface by Quaternary river and glacial processes. Data available for this study also limit the extent of the coal zone shown.
- The Hagel coal zone is in the lower part of the Sentinel Butte Member of the Fort Union Formation.
- The coal zone is in the subsurface of McLean, Mercer, and Oliver Counties in the east-central part of the Williston Basin, North Dakota.
- The coal zone crops out along the valleys of the Missouri River and Knife River and their tributaries in McLean, Mercer, and Oliver Counties.

STRATIGRAPHIC FRAMEWORK

- The Hagel coal zone is an interval usually consisting of five coal beds. These coal beds are interbedded with mudstone, carbonaceous shale, siltstone, and sandstone. The sandstone, which ranges from 16 to 131 ft in thickness and fines upward (based on subsurface geophysical and lithologic logs interpretation), was interpreted by

Daly and others (1985) and Groenewold and others (1979) as a fluvial channel deposit. Daly and others (1985) indicated that a crevasse-splay sandstone is less than 16 ft in thickness and coarsens upward. These criteria were used as a guide in interpretation of the depositional environments of the sandstone in this study.

- The interval ranges in thickness from 50 to 500 ft throughout the study area.
- Laterally, these coal beds merge, split, and pinch out. The coal splits into two or more beds and gradually interfingers with clastic rocks.
- Coal beds pinch out into washout areas of mudstone, siltstone, and sandstone.
- Coal beds are interbedded with carbonaceous shale and mudstone partings.
- The rocks above and below the coal zone consist of mudstone, siltstone, and sandstone.
- These rocks accumulated in distributary channels and interdistributary areas of an upper delta plain.
- The Hagel coal zone accumulated in interdistributary peat swamps.
- The Hagel coal zone and associated rocks were partly to totally eroded and infilled by glacial till consisting of yellowish-brown silt, clay, sand, and gravel.

HAGEL COAL ZONE INTERPRETIVE CROSS SECTION A-A'

- This west-to-east cross section (fig. WF-24) shows the Hagel coal zone in the Center mining area. Datum is the base of the lowermost coal bed of the zone. The cross section was drawn using data from 17 drill holes, which are not labeled on the cross section.
- The coal zone is a 50-ft-thick interval and consists of four coal beds. The lower bed is as much as 12 ft thick and the upper bed is as much as 7 ft thick.

- These four coal beds merge into two beds toward the western part of the cross section and split toward the east. Splitting resulted from re-occupation of floodplains by peat swamps.
- The Hagel coal zone accumulated in interdistributary swamps (fig. WF-25) and is interbedded with mudstone or other interburden rocks formed in interdistributary floodplains.
- The overburden dominantly consists of mudstone, and subordinately consists of siltstone and sandstone. The sandstone was deposited in distributary channels and the mudstone was deposited in floodplains.
- The Hagel coal zone was deposited on sandstone of abandoned distributary channels and mudstone of interdistributary floodplains.
- Glacial till infilled local surfaces of erosion on the overburden.

HAGEL COAL ZONE INTERPRETIVE CROSS SECTION B-B'

- This west-to-east cross section (fig. WF-26) shows the Hagel coal zone in the Falkirk mining area. Datum is the base of the lowermost coal bed of the zone. The cross section was drawn using data from 18 drill holes, which are not labeled on the cross section.
- The coal zone is as much as 48 ft thick and consists of four coal beds. The lower bed is as much as 6 ft thick and the upper bed is as much as 13 ft thick.
- These four coal beds merge and split repeatedly along a 24.8-mi extent of the cross section. Splitting resulted from re-occupation of floodplains by peat swamps.
- The Hagel coal beds, which accumulated in interdistributary swamps, are interbedded with mudstone or interburden rocks deposited in interdistributary floodplains.

- The Hagel coal zone was deposited on sandstone of abandoned distributary channels and mudstone of interdistributary floodplains.
- The overburden contains abundant mudstone, and subordinate siltstone and sandstone. The sandstone was deposited in distributary channels (fig. WF-27) and the mudstone formed in floodplains.
- Glacial till infilled local surfaces of erosion on the overburden.

HAGEL COAL ZONE INTERPRETIVE CROSS SECTION C-C'

- This south-to-north cross section (fig. WF-28) shows the Hagel coal zone in the Center mining area. Datum is the base of the lowermost coal bed of the zone. The cross section was drawn using data from 20 drill holes, which are not labeled on the cross section.
- The coal zone is a 90-ft-thick interval and consists of five coal beds. The lower bed is as much as 10 ft thick and the upper bed is as much as 6 ft thick.
- These five coal beds merge into two beds and split repeatedly laterally along a 20.5-mi extent of the cross section. Splitting resulted from re-occupation of floodplains by peat swamps and shifting of distributary channels.
- The Hagel coal beds, which accumulated in interdistributary swamps, are interbedded with mudstone deposited in interdistributary floodplains and with sandstone deposited in distributary channels.
- The overburden includes dominantly mudstone, and subordinately sandstone. The sandstone was deposited in distributary channels and the mudstone formed in floodplains.
- The Hagel coal zone was deposited on sandstone of abandoned distributary channels and mudstone of interdistributary floodplains.
- Glacial till infilled local surfaces of erosion on the overburden.

HAGEL COAL ZONE INTERPRETIVE CROSS SECTION D-D'

- This north-to-south cross section (fig. WF-29) shows the Hagel coal zone in the Falkirk mining area. Datum is the base of the lowermost coal bed of the zone. The cross section was drawn using data from 19 drill holes, which are not labeled on the cross section.
- The coal zone (75-ft-thick interval) consists of six coal beds. The lower bed is as much as 6 ft thick and the upper bed is as much as 3 ft thick.
- These six coal beds merge and split repeatedly along a 16.75-mi extent of the cross section. Splitting resulted from re-occupation of ancestral floodplains by peat swamps due to shifts in environments.
- The Hagel coal beds, which accumulated in interdistributary swamps, are interbedded with mudstone deposited in interdistributary floodplains.
- The overburden dominantly consists of mudstone, and very minor sandstone. The sandstone was probably deposited in crevasse-splay channels and the mudstone in floodplains.
- Sandstone and mudstone below the Hagel coal zone formed in distributary channels and interdistributary floodplains, respectively. Minor swamps developed in distal floodplains as shown by thin, lenticular coal beds.
- Glacial till infilled local surfaces of erosion on the overburden.

BEULAH COALFIELD, BEULAH-ZAP COAL ZONE

DISTRIBUTION

- The Beulah coalfield (fig. WF-30) boundary approximately follows the areal extent of the Beulah-Zap coal zone as defined by Groenewold and others (1979). It includes early and current mining areas that produced from this coal zone in the vicinity of Beulah and Zap in Mercer and Oliver counties (Leonard, 1908; Groenewold and others, 1979; Oihus, 1983).

- The coalfield is delineated by the subsurface extent of the Beulah coal zone on the east, west, and south, which were locally removed by Quaternary fluvial and glacial processes. On the north, it is delineated by the Fort Berthold Indian Reservation. Data available for this study also limit the extent of the coal zone shown.
- The Beulah-Zap coal zone is found in the middle part of the Sentinel Butte Member of the Fort Union Formation.
- The coal zone exists in the subsurface of McLean, Mercer, and Oliver Counties in east-central part of the Williston Basin, North Dakota.
- Surface occurrence of the coal zone is in the valley walls of the Knife River and its tributaries in Mercer and Oliver Counties.

STRATIGRAPHIC FRAMEWORK

- The Beulah-Zap coal zone is an interval usually consisting of five coal beds. These coal beds are interbedded with mudstone, carbonaceous shale, siltstone, and sandstone. The sandstone bodies, which range in thickness from 16 to 131 ft and fine upward (based on subsurface geophysical and lithologic logs interpretation), were interpreted by Groenewold and others (1979), and Daly and others (1985) as fluvial channel deposits. Daly and others (1985) indicated that crevasse-splay sandstone is less than 16 ft in thickness and coarsens upward. These criteria were used as a guide in interpreting the depositional environments of the sandstone in this study.
- The interval ranges in thickness from 3.5 to 50 ft throughout the study area.
- Laterally, these coal beds merge, split, and pinch out.

- The coal beds pinch out into washout areas of mudstone, siltstone, and sandstone.
- Coal beds are interbedded with carbonaceous shale and mudstone partings.
- The rocks above and below the coal zone consist of mudstone, siltstone, and sandstone.
- These rocks were accumulated in distributary channels and interdistributary areas of a upper delta plain.
- The Beulah-Zap coal beds accumulated in interdistributary and abandoned delta peat swamps.
- The Beulah-Zap coal zone and associated rocks were partly to totally eroded and infilled by glacial till consisting of yellowish-brown silt, clay, sand, and gravel.
- The Beulah-Zap coal zone is underlain by the Antelope Creek and Kinneman Creek coal zones, together consisting of as many as eight coal beds, which are each as much as 8 ft thick.

BEULAH-ZAP COAL ZONE INTERPRETIVE CROSS SECTION E-E'

- This southwest-to-northeast cross section (fig. WF-31) shows the Beulah-Zap coal zone through the Knife River and Freedom mining areas. Datum is the base of the lowermost coal bed of the zone. The cross section was drawn using data from 50 drill holes, which are not labeled on the cross section.
- The coal zone is an interval more than 30-ft-thick and consists of five coal beds. The lower bed is as much as 9 ft thick and the upper bed is as much as 18 ft thick.
- These five coal beds merge into one bed, as much as 20 ft thick, that splits repeatedly along the 73.9-mi extent of the cross section. Splitting resulted from re-occupation of floodplains by peat swamps due to shifts in environments.

- The Beulah-Zap coal, which accumulated in interdistributary swamps (fig. WF-32), is interbedded with mudstone that was deposited in interdistributary floodplains.
- The overburden includes abundant mudstone and sandstone. The sandstone was deposited in river channels and crevasse splays (fig. WF-33) and the mudstone was formed in floodplains.
- Sandstone and mudstone below the Beulah-Zap coal zone formed in abandoned distributary channels and interdistributary floodplains, respectively. Well-developed swamps accumulated the Antelope Creek and Kinneman Creek coal zones.
- Glacial till infilled local surfaces of erosion on the overburden. Locally, erosion has completely cut out the Beulah-Zap, Antelope Creek, and Kinneman Creek coal zones.

BEULAH-ZAP COAL ZONE INTERPRETIVE CROSS SECTION F-F'

- This west-to-east cross section (fig. WF-34) shows the Beulah-Zap coal zone through the Freedom mining area. Datum is at the base of the lowermost coal bed of the zone. The cross section was drawn using data from 19 drill holes, which are not labeled on the cross section.
- The coal zone is an interval more than 25 ft thick and consists of three coal beds. The lower bed is as much as 8 ft thick and the upper bed is as much as 12 ft thick.
- These three coal beds merge into mostly one bed as much as 22 ft thick. This bed splits laterally on the western and eastern parts of the 16.1 mile cross section. Splitting resulted from inundation of the ancestral peat swamps by floodplain sediments.
- The Beulah-Zap coal, which accumulated in interdistributary swamps, is interbedded with mudstone deposited in interdistributary floodplains.

- The overburden consists of mudstone and sandstone. The sandstone was deposited in river channels and the mudstone in floodplains. Minor swamps formed in distal floodplains, which accumulated peat deposits (fig. WF-35) resulting in thin, lenticular coal beds.
- Sandstone and mudstone below the Beulah-Zap coal zone formed in abandoned distributary channels and interdistributary floodplains and related swamps. Well-developed swamps formed the Antelope Creek and Kinneman Creek coal zones (consisting of eight coal beds) shown in the lower part of the cross section.
- Glacial till infilled local surfaces of erosion on the overburden. Erosion has partly to completely locally cut out the Beulah-Zap coal zone.

BEULAH-ZAP COAL ZONE INTERPRETIVE CROSS SECTION G-G'

- This west-to-east cross section (fig. WF-36) shows the Beulah-Zap coal zone north of the Freedom mining area. Datum is the base of the lowermost coal bed of the zone. The cross section was drawn using data from 16 drill holes, which are not labeled on the cross section.
- The coal zone, which is as much as 35 ft thick, consists of three coal beds. The lower bed is as much as 7 ft thick and the upper bed is as much as 11 ft thick.
- These three coal beds merge into one bed as much as 20 ft thick that splits laterally along the 12.4-mi long cross section. Splitting resulted from inundation of the ancestral peat swamps by floodplain sediments.
- The Beulah-Zap coal, which accumulated in interdistributary swamps, is interbedded with mudstone deposited in interdistributary floodplains and sandstone deposited in a crevasse splay.

- The overburden contains abundant mudstone and sandstone. The sandstone was deposited in river channels and the mudstone in floodplains. Minor swamps formed in distal floodplains, which formed thin, lenticular peat deposits.
- Sandstone and mudstone below the Beulah-Zap coal zone formed in abandoned distributary channels and interdistributary floodplains and related swamps. Well-developed peat swamps formed the Antelope Creek and Kinneman Creek coal zones.
- Glacial till infilled local surfaces of erosion on the overburden. Erosion has partly to completely cut out the Beulah-Zap coal zone locally.

BEULAH-ZAP COAL INTERPRETIVE CROSS SECTION H-H'

- This west-to-east cross section (fig. WF-37)shows the Beulah-Zap coal zone northeast of Lake Sakakawea. Datum is the base of the lowermost coal bed of the zone. The cross section was drawn using data from 14 drill holes, which are not labeled on the cross section.
- The coal zone is as much as 40 ft thick and consists of four coal beds. The lower bed is as much as 7 ft thick and the upper bed is as much as 5 ft thick.
- These four coal beds are merged and split locally along the 12.4-mi lateral extent of the cross section. Splitting resulted from inundation of ancestral peat swamps by floodplain sediments.
- The Beulah-Zap coal accumulated in interdistributary swamps and is interbedded with mudstone deposited in interdistributary floodplains.
- The overburden is dominantly mudstone and subordinately sandstone. The sandstone was deposited in river channels and the mudstone in floodplains. A swamp formed on the distal floodplain that formed thin, lenticular peat beds.

- Sandstone and mudstone below the Beulah-Zap coal zone formed in abandoned distributary channels and interdistributary floodplains.
- Glacial till infilled local surfaces of erosion on the overburden. Erosion has partly to completely cut out the Beulah-Zap coal zone locally.

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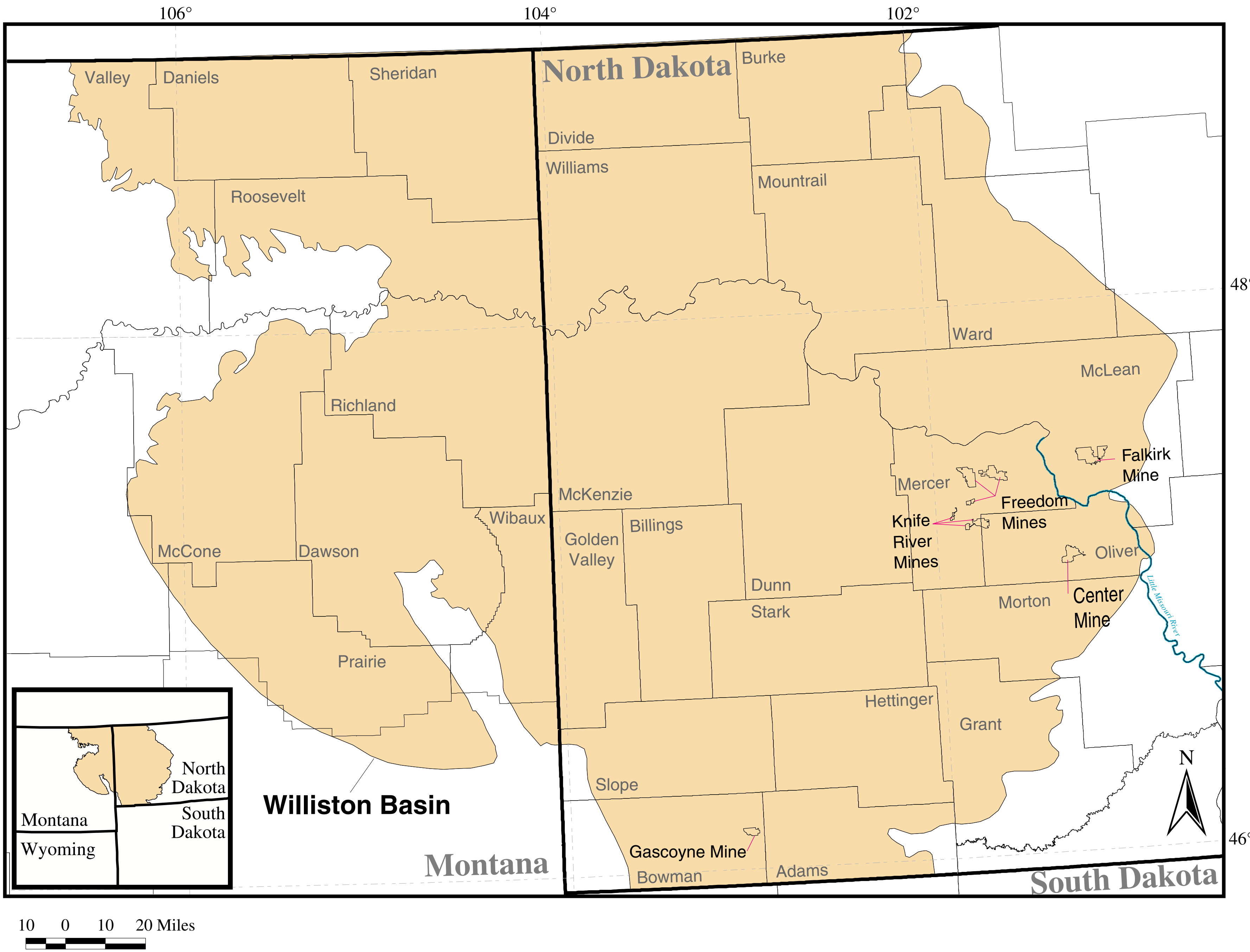
Figure WF-1. Location map showing the Williston Basin.



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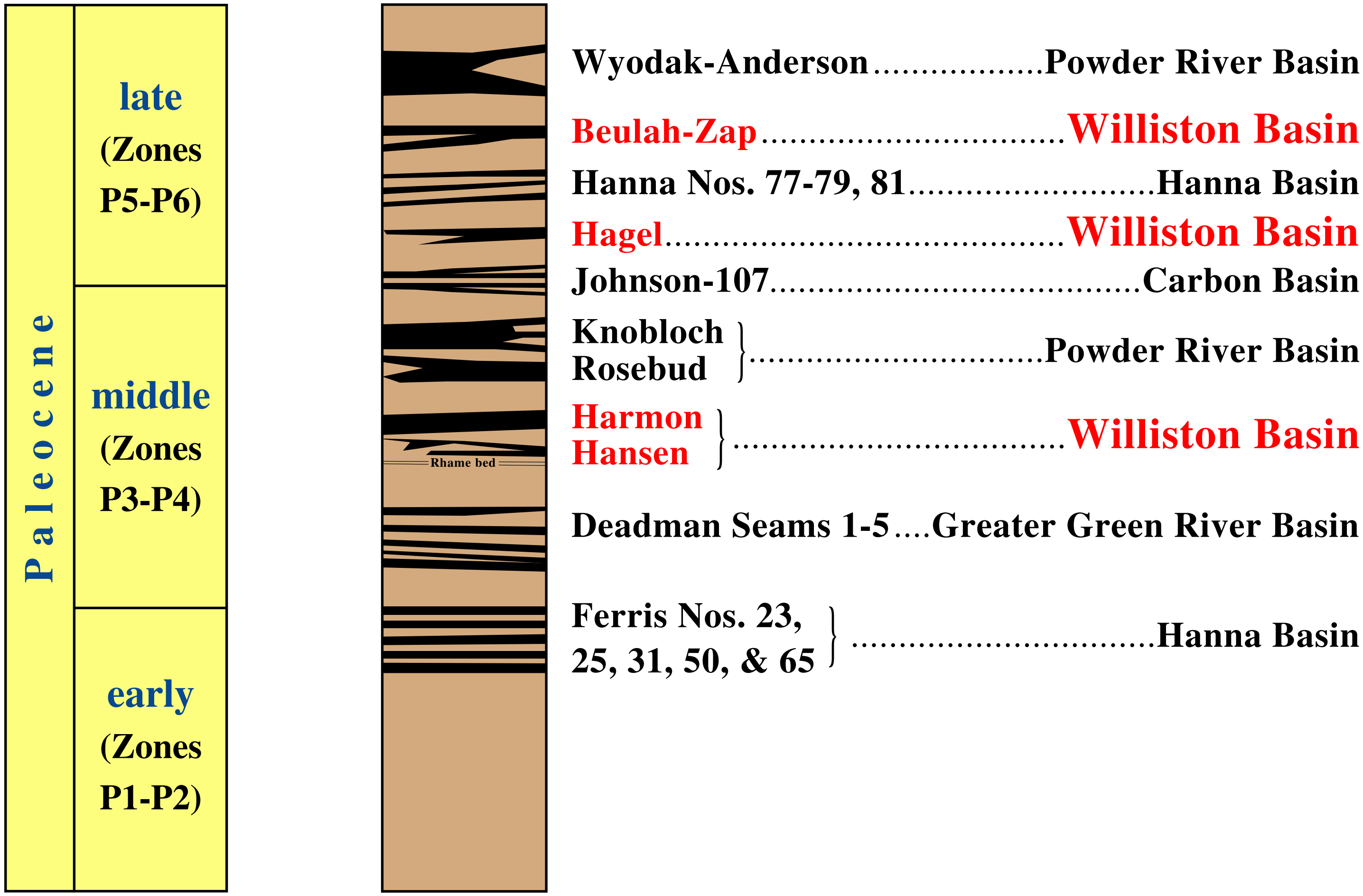

Figure WF-2. Composite stratigraphic section for the assessment region showing the studied coal beds and zones with age relationships based on palynology. Assessment units in the Williston Basin are highlighted in red.

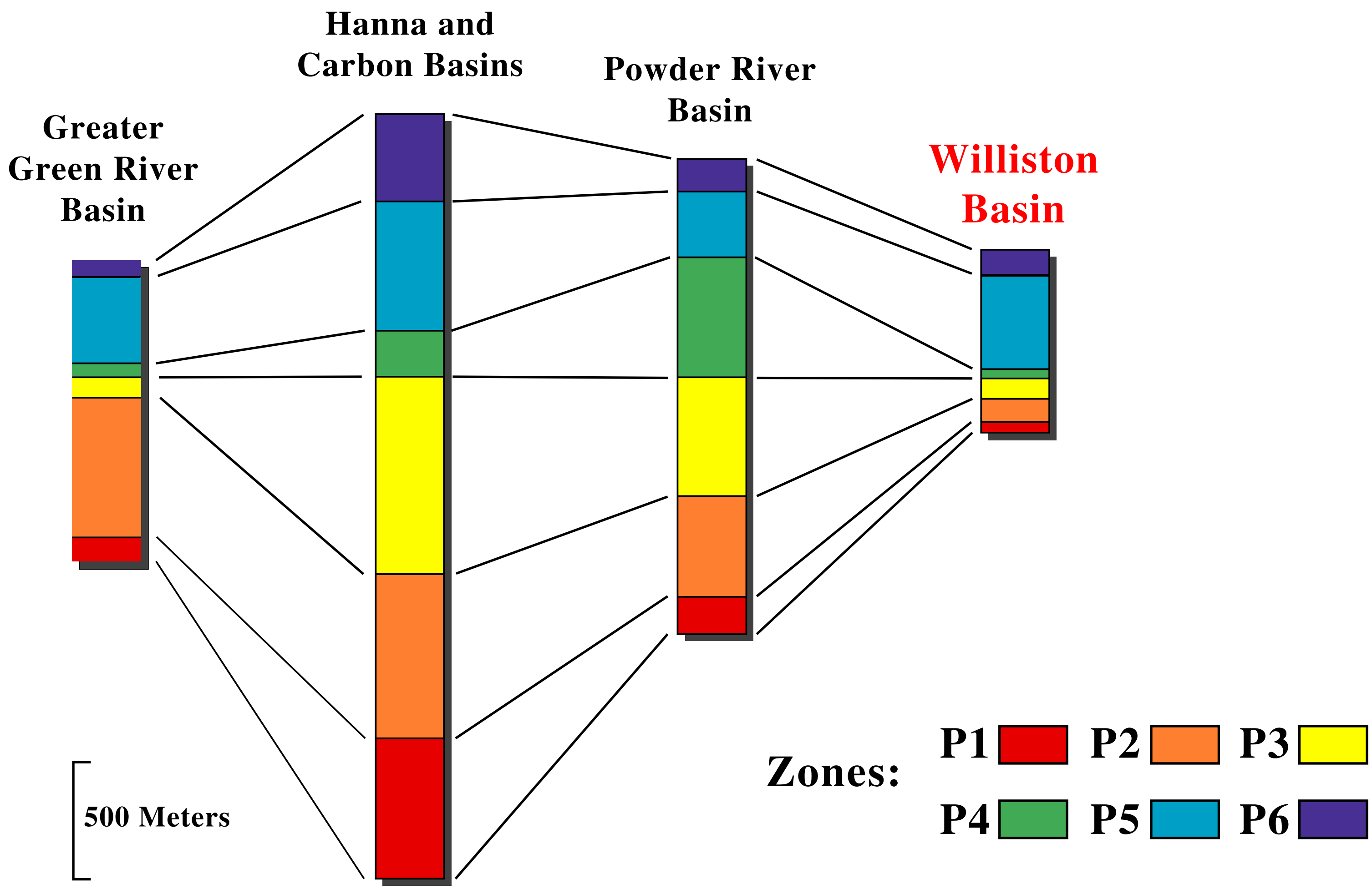

Figure WF-3. Composite correlation of Paleocene sections based on palynostratigraphy.

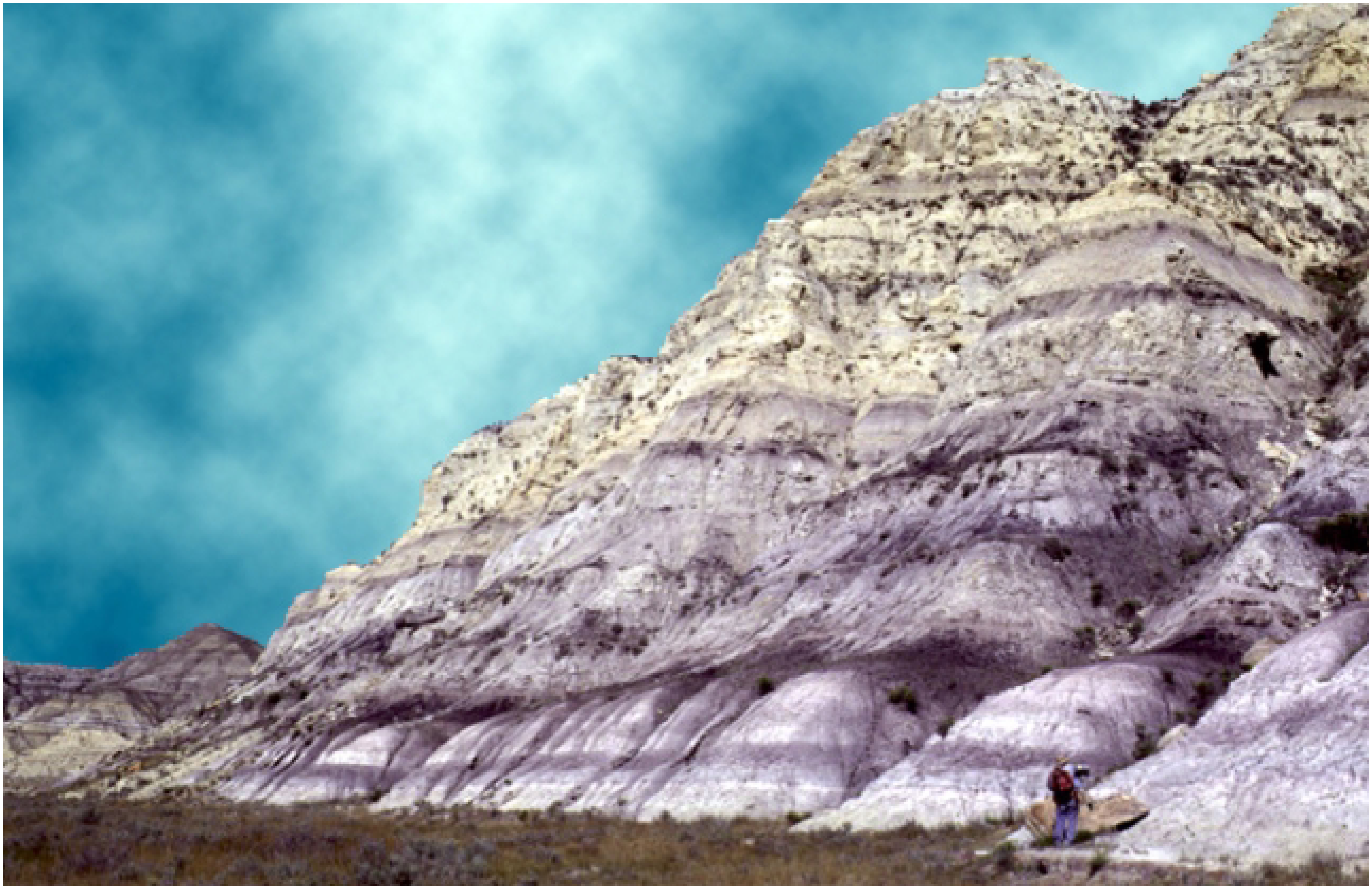

Figure WF-4. The Harmon and Hansen coal beds and zones in the lower part of the picture are exposed along the valley wall of the Little Missouri River. The coal beds and zones are overlain by fluvial deposits. Photograph by R.M. Flores.

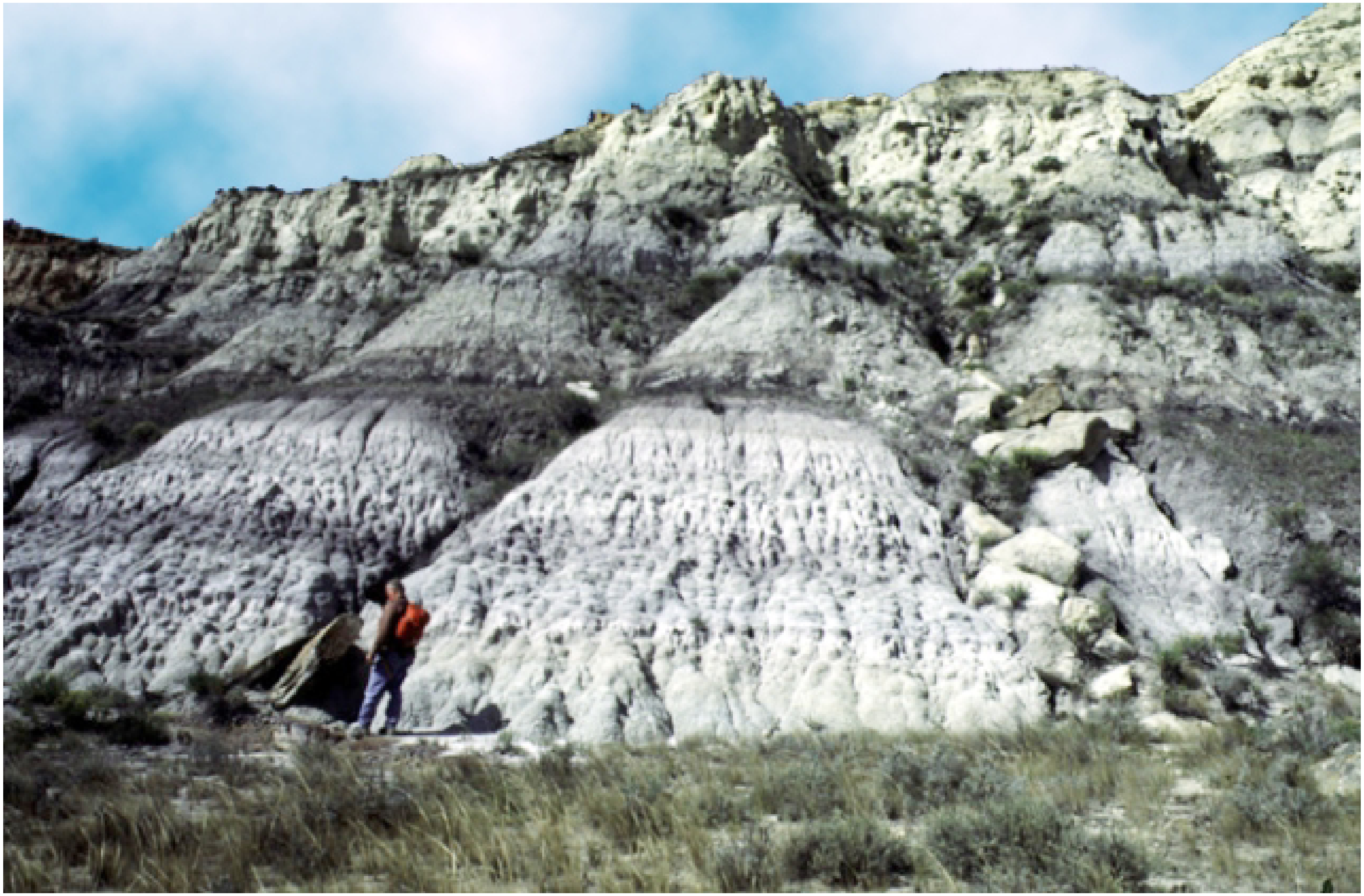

Figure WF-5. The Rhame bed in the lower part of the picture is exposed along the valley wall of the Little Missouri River. This paleosol is overlain by the Harmon and Hansen coal beds and zones.
Photograph by R.M. Flores.

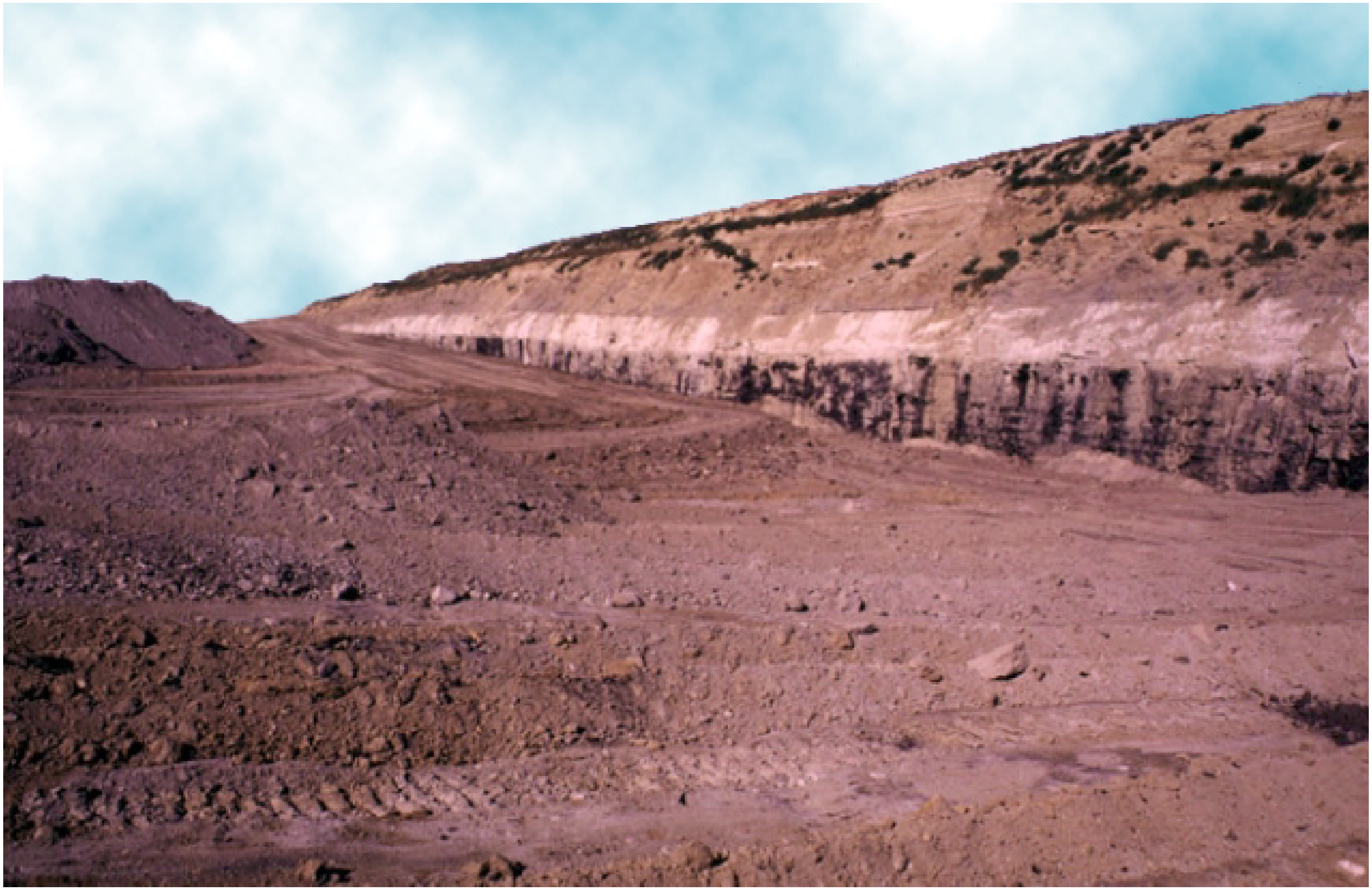

Figure WF-6. The Harmon coal zone is overlain by fluvial channel sandstone in the Gascoyne mine. Photograph by R.M. Flores.

Figure WF-7. The Beulah-Zap coal zone in the Freedom mine is overlain by mudstone. Photograph by R.M. Flores.

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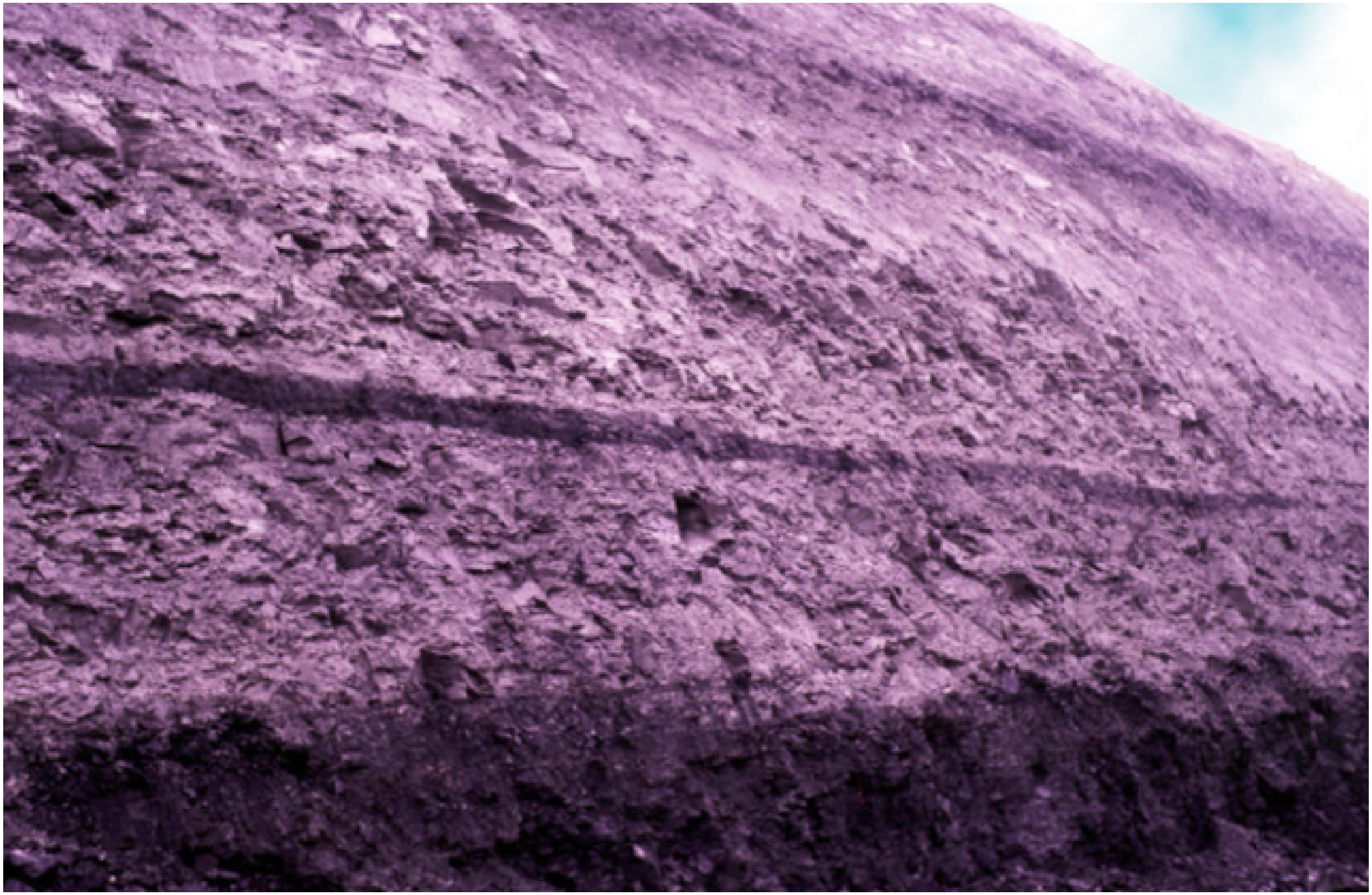

Figure WF-8. The Beulah-Zap coal zone in the Freedom mine is overlain by a thin rider coal and mudstone. Photograph by R.M. Flores.

Figure WF-9. Thin, trough-crossbedded, fluvial channel sandstone overlies the Beulah-Zap coal zone in the Freedom mine. Photograph by P.D. Warwick.

Figure WF-10. The fluvial sandstone shows a deep erosional base (see hammer for scale in the photo). Photograph by P.D. Warwick.

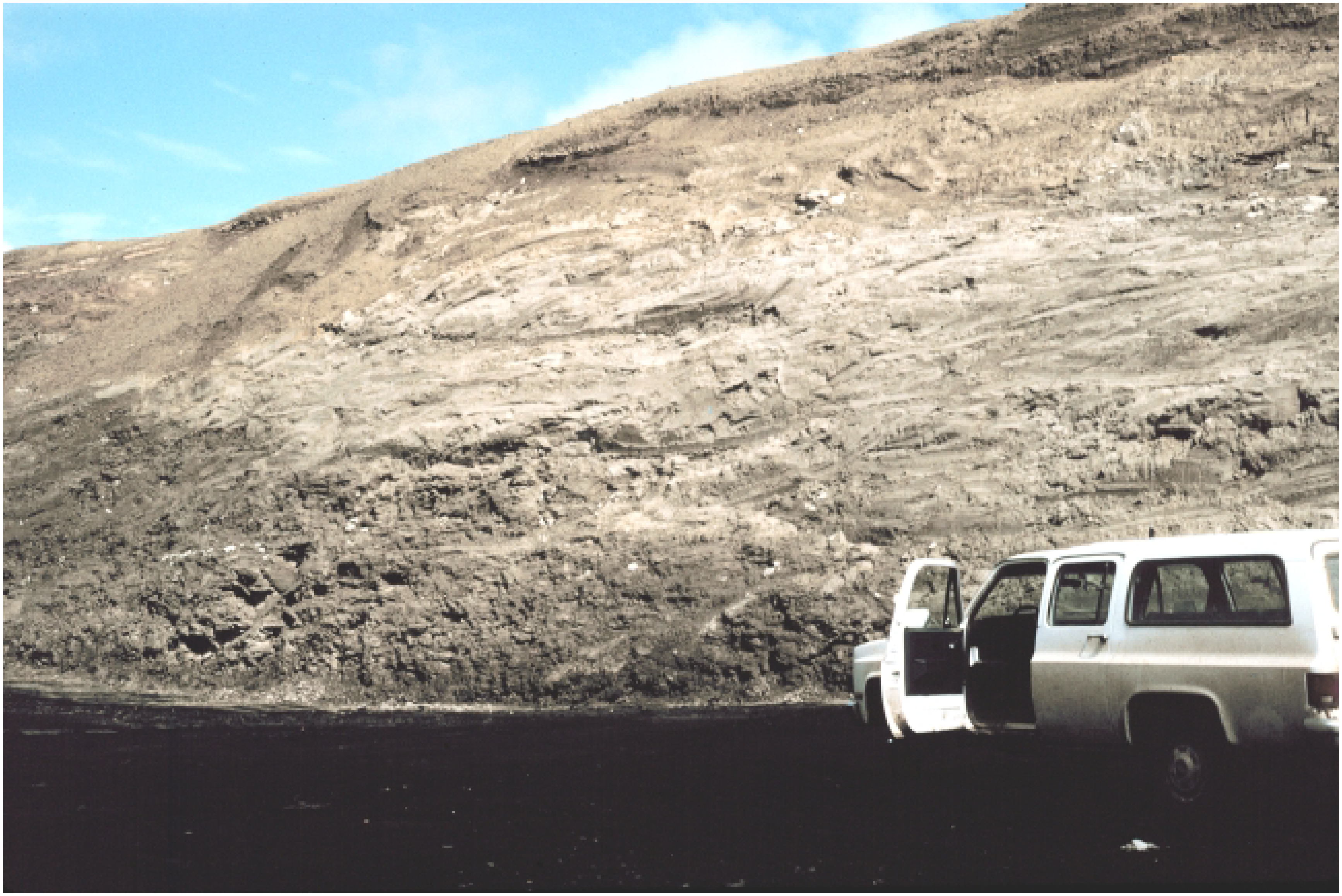

Figure WF-11. Thick, fluvial channel sandstone overlies the Beulah-Zap coal zone in the Freedom mine. Photograph by P.D. Warwick.

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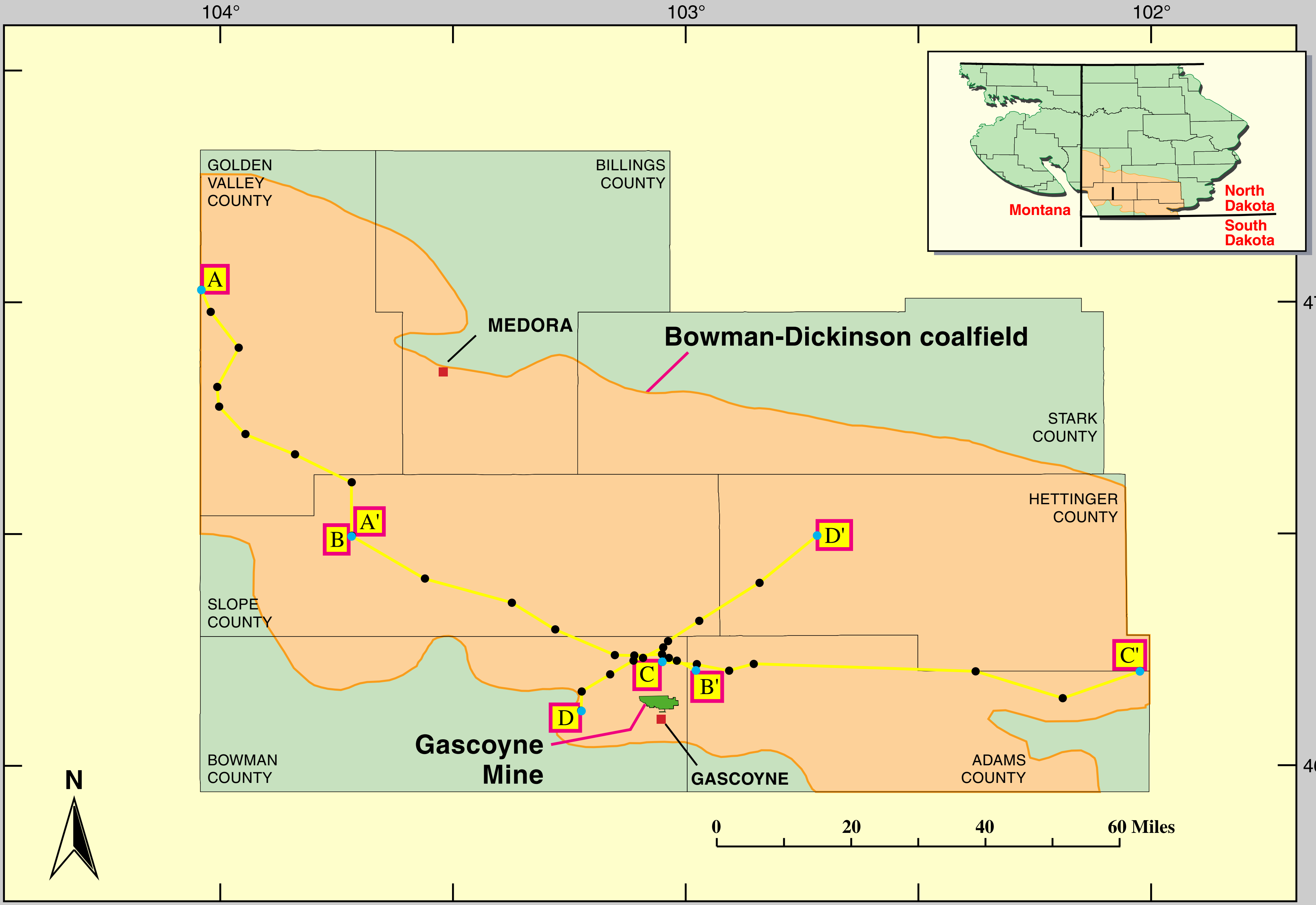

Figure WF-12. Bowman-Dickinson coalfield, Williston Basin, North Dakota, and generalized interpretive cross section layout.

Williston Basin

A A' Cross Section with nonproprietary drill holes

Bowman-Dickinson Coalfield (Harmon-Hansen Coal Zone)

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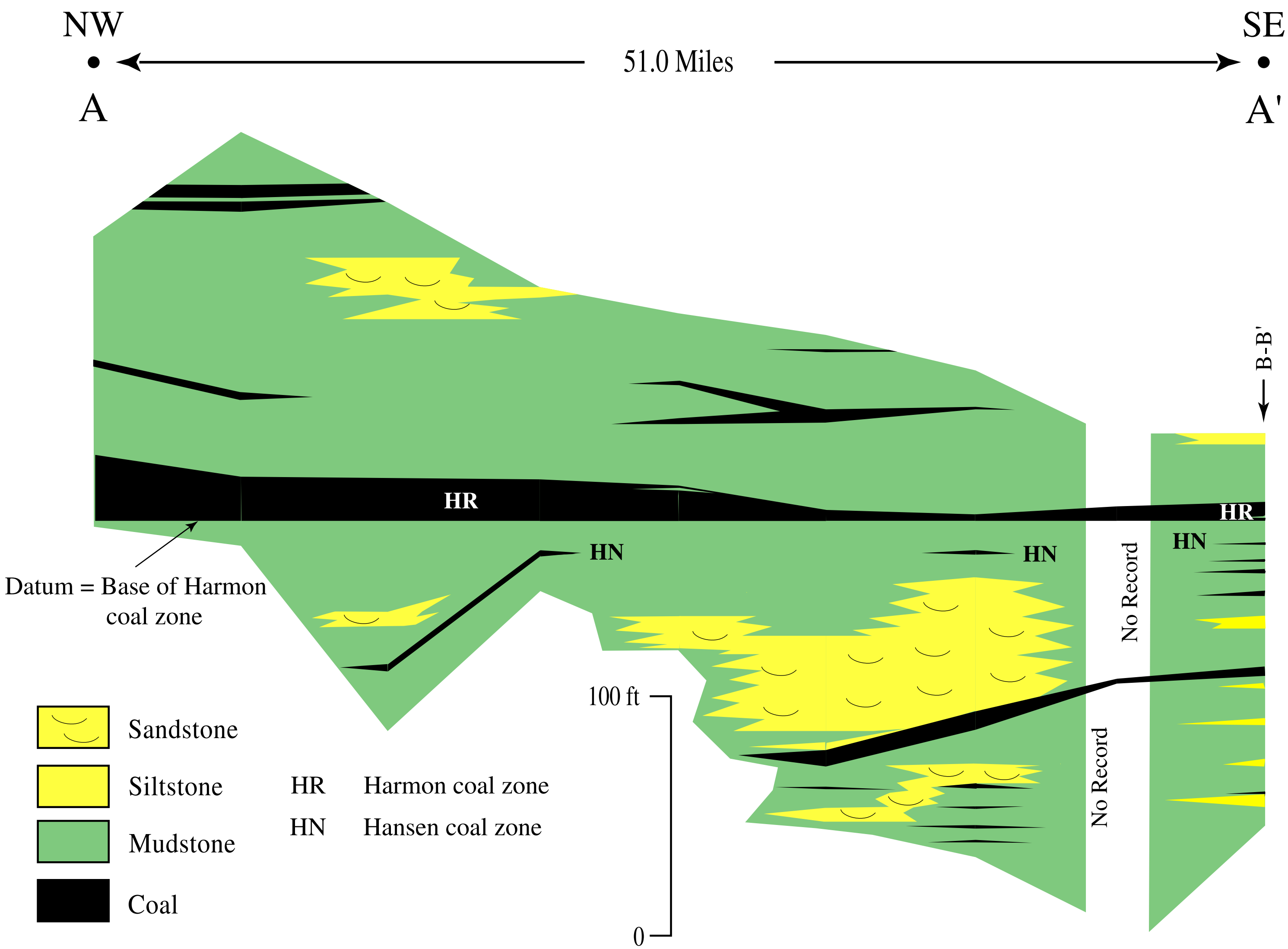

Figure WF-13. Harmon and Hansen coal zones interpretive cross section A-A', Bowman-Dickinson coalfield, Williston Basin, North Dakota.

Figure WF-14. Lower Mississippi River delta plain in Louisiana showing subdeltas and swamps.
Photograph by R.M. Flores.

Figure WF-15. Crevasse splay and associated swamps in the lower Mississippi River delta plain, Louisiana. Photograph by R.M. Flores.

Figure WF-16. Peat swamp in the upper Mississippi River delta plain, Louisiana. Photograph by R.M. Flores.

Figure WF-17. Abandoned river channel and peat swamp in the Florida Everglades, Florida. Photograph by R.M. Flores.

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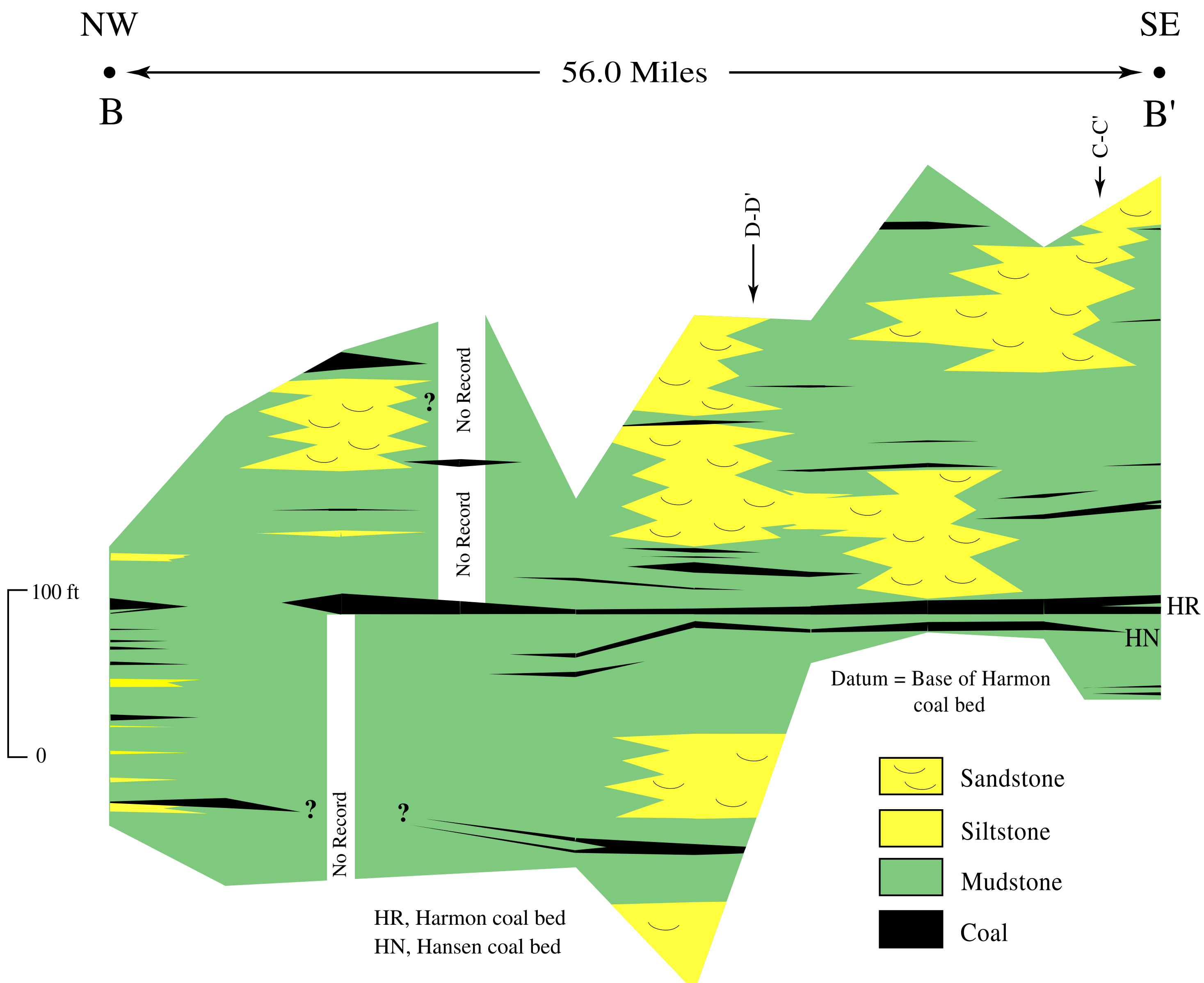

Figure WF-18. Harmon and Hansen coal zones interpretive cross section B-B', Bowman-Dickinson coalfield, Williston Basin, North Dakota.

Figure WF-19. Contemponeous delta plain swamps and river channel in the lower Mississippi River delta plain, Louisiana. Photograph by R.M. Flores.

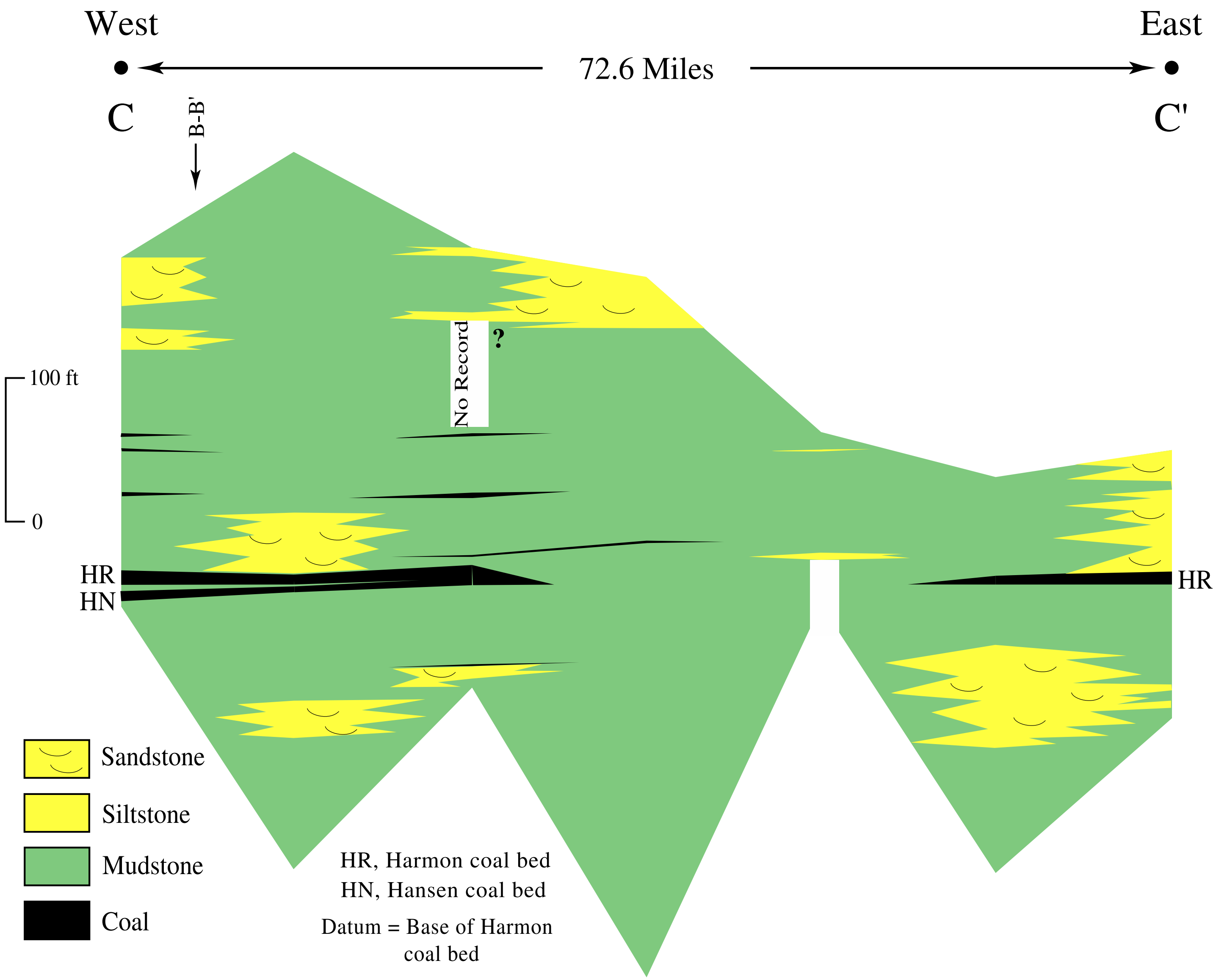

Figure WF-20. Harmon and Hansen coal zones interpretive cross section C-C', Bowman-Dickinson coalfield, Williston Basin, North Dakota.

Figure WF-21. Lake, floodplain, and swamp environments associated with the Beluga River in Alaska. Photograph by R.M. Flores.

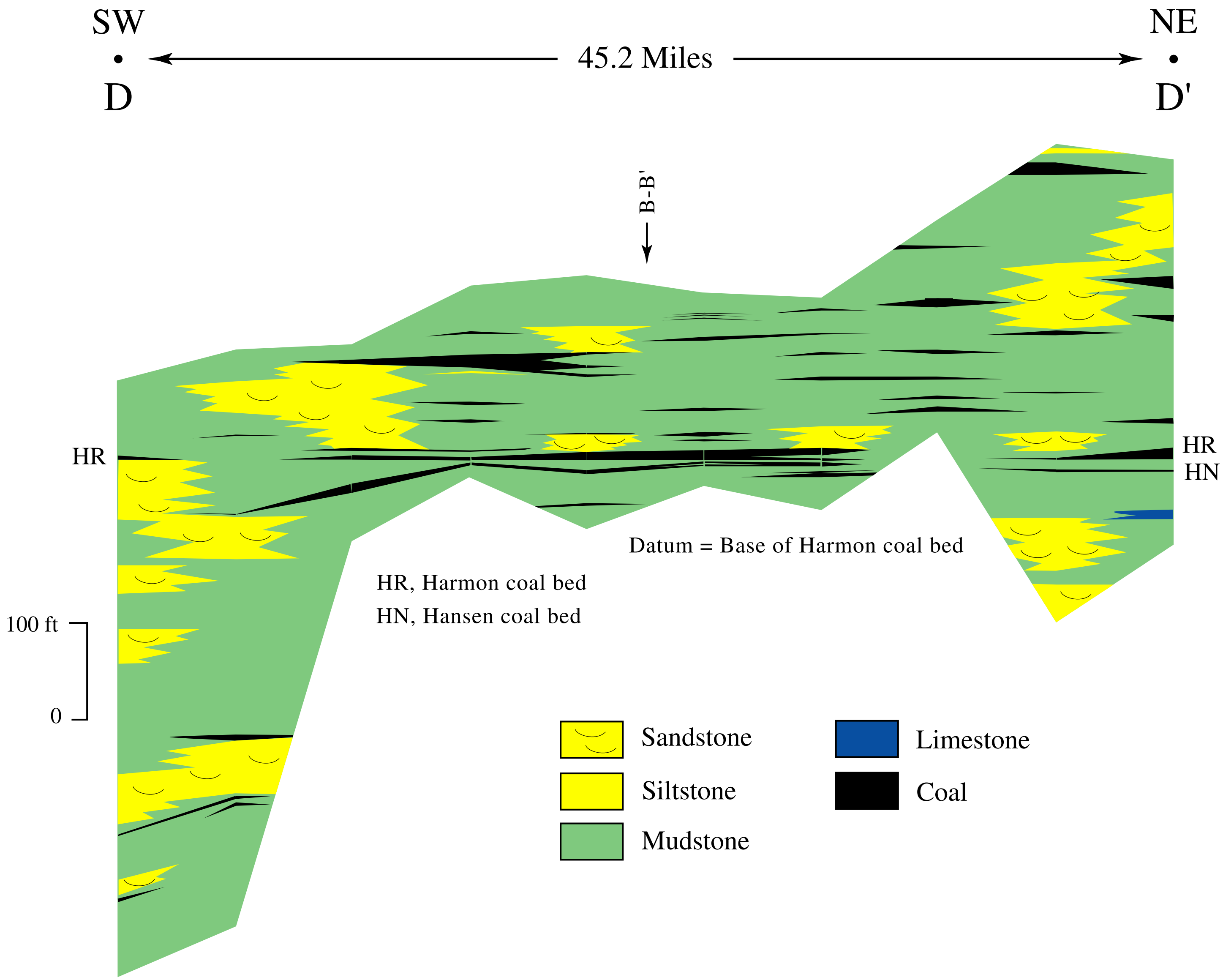

Figure WF-22. Harmon and Hansen coal zones interpretive cross section D-D', Bowman-Dickinson coalfield, Williston Basin, North Dakota.

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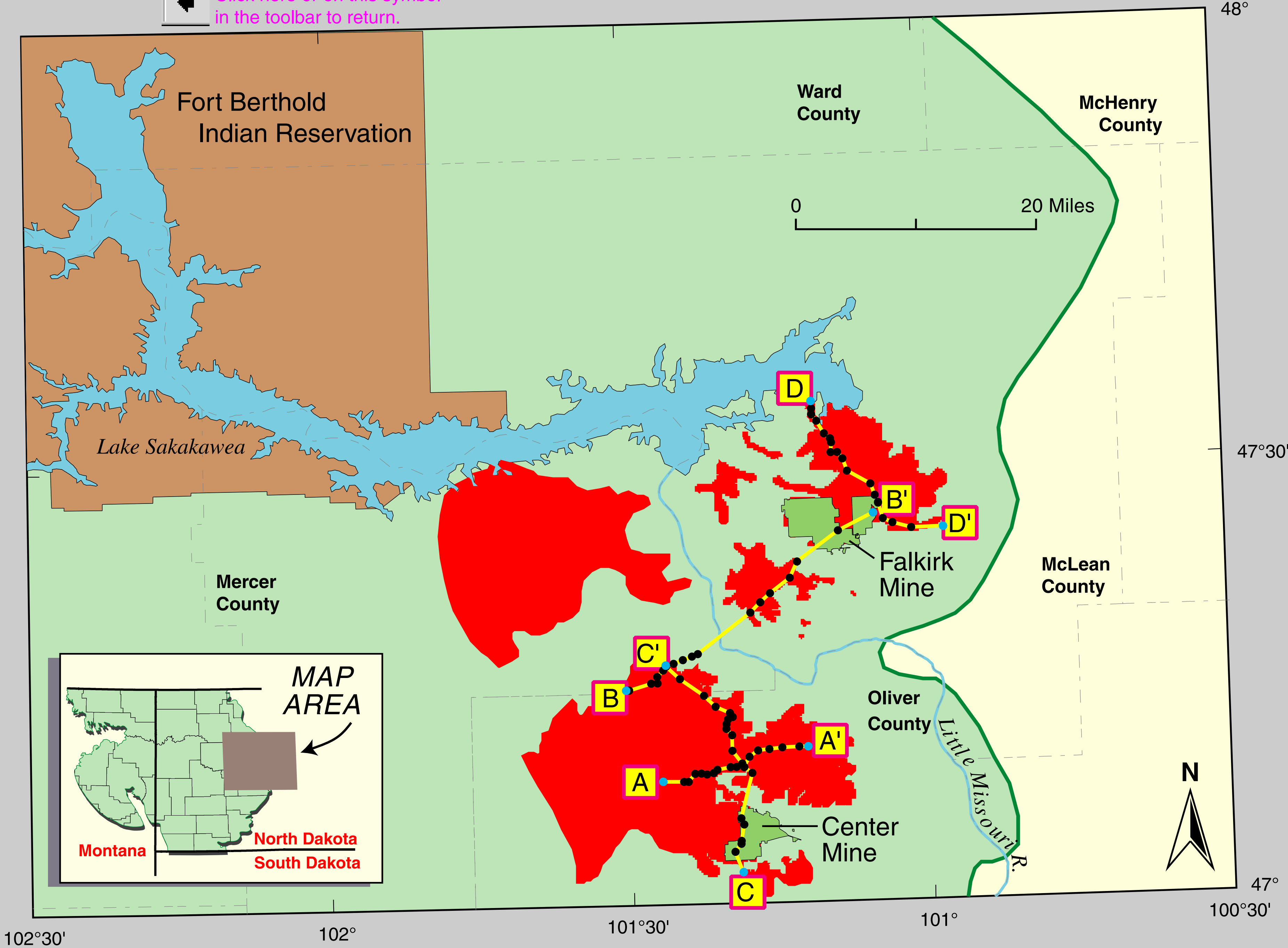

Williston Basin

Mines

Cross section with nonproprietary drill holes

Center-Falkirk coalfield (Hagel Coal Zone)

Figure WF-23. Center-Falkirk coalfield, Williston Basin, North Dakota, and generalized interpretive cross section layout.

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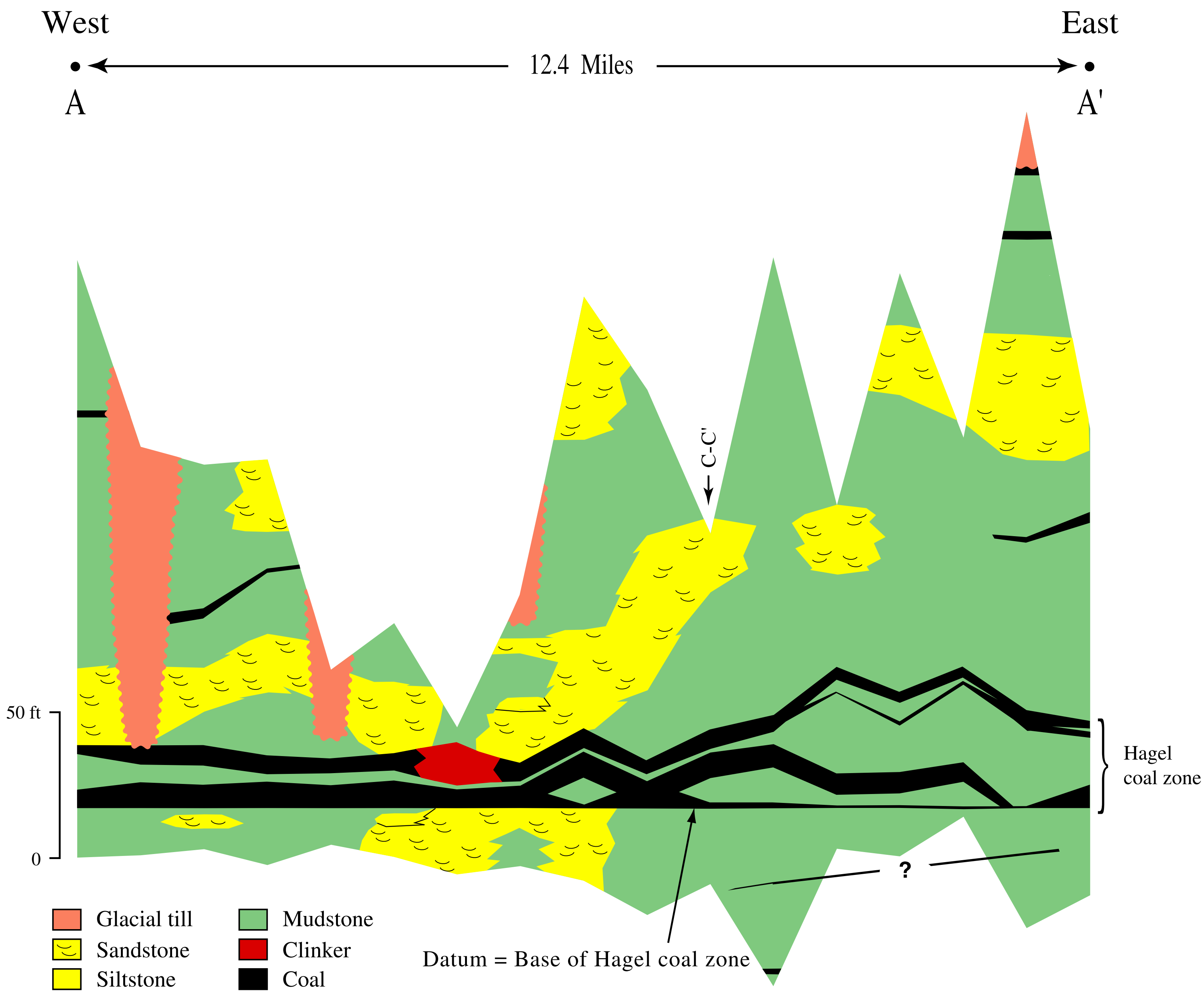

Figure WF-24. Hagel coal zone interpretive cross section A-A', Center-Falkirk coalfield, Williston Basin, North Dakota.

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Figure WF-25. Interdistributary swamps and floodplains in the upper Mississippi River delta plain, Louisiana. Photograph by R.M. Flores.

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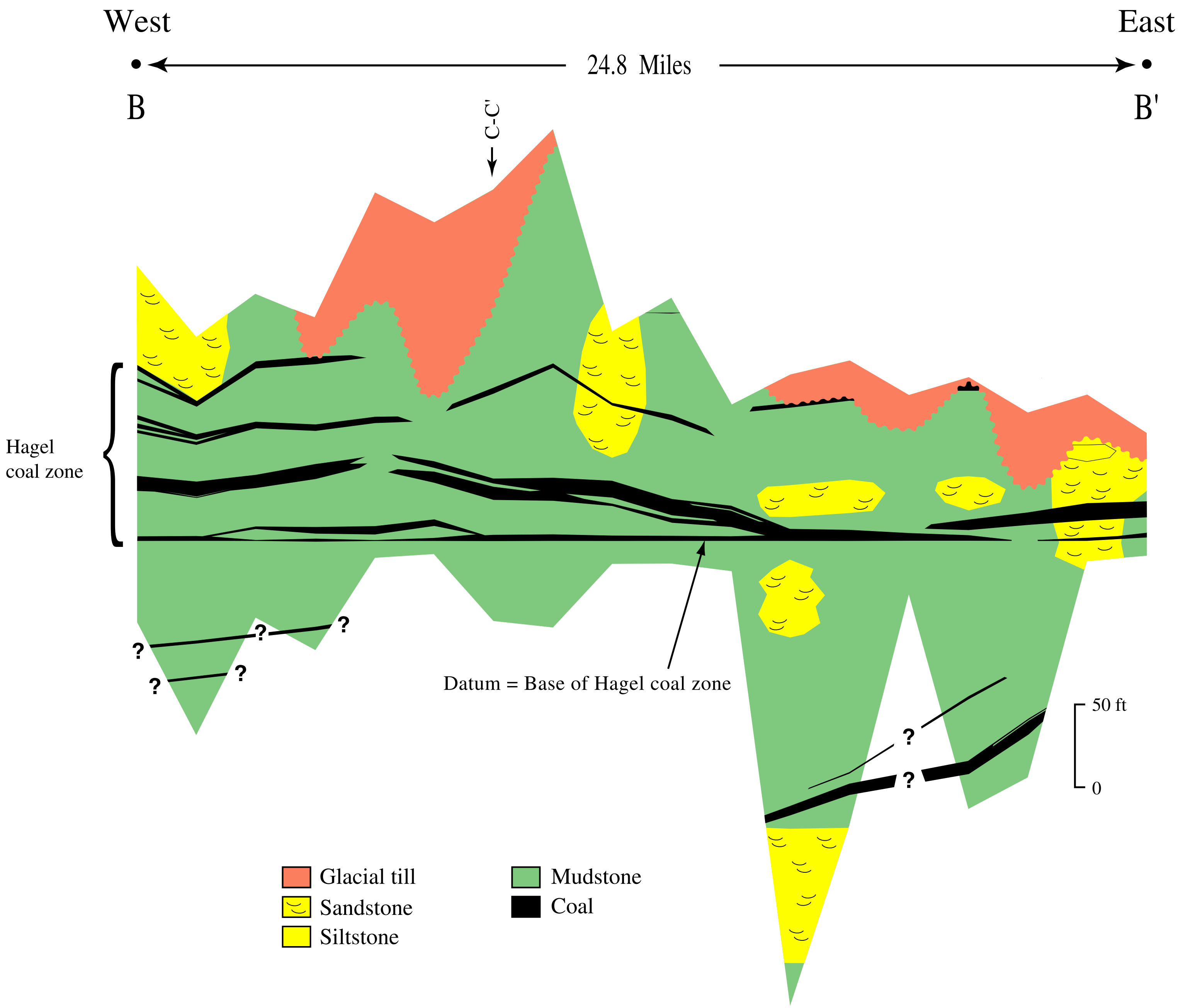

Figure WF-26. Hagel coal zone interpretive cross section B-B', Center-Falkirk coalfield, Williston Basin, North Dakota.

Figure WF-27. Interdistributary channel in the upper Mississippi River delta plain, Louisiana.
Photograph by R.M. Flores.

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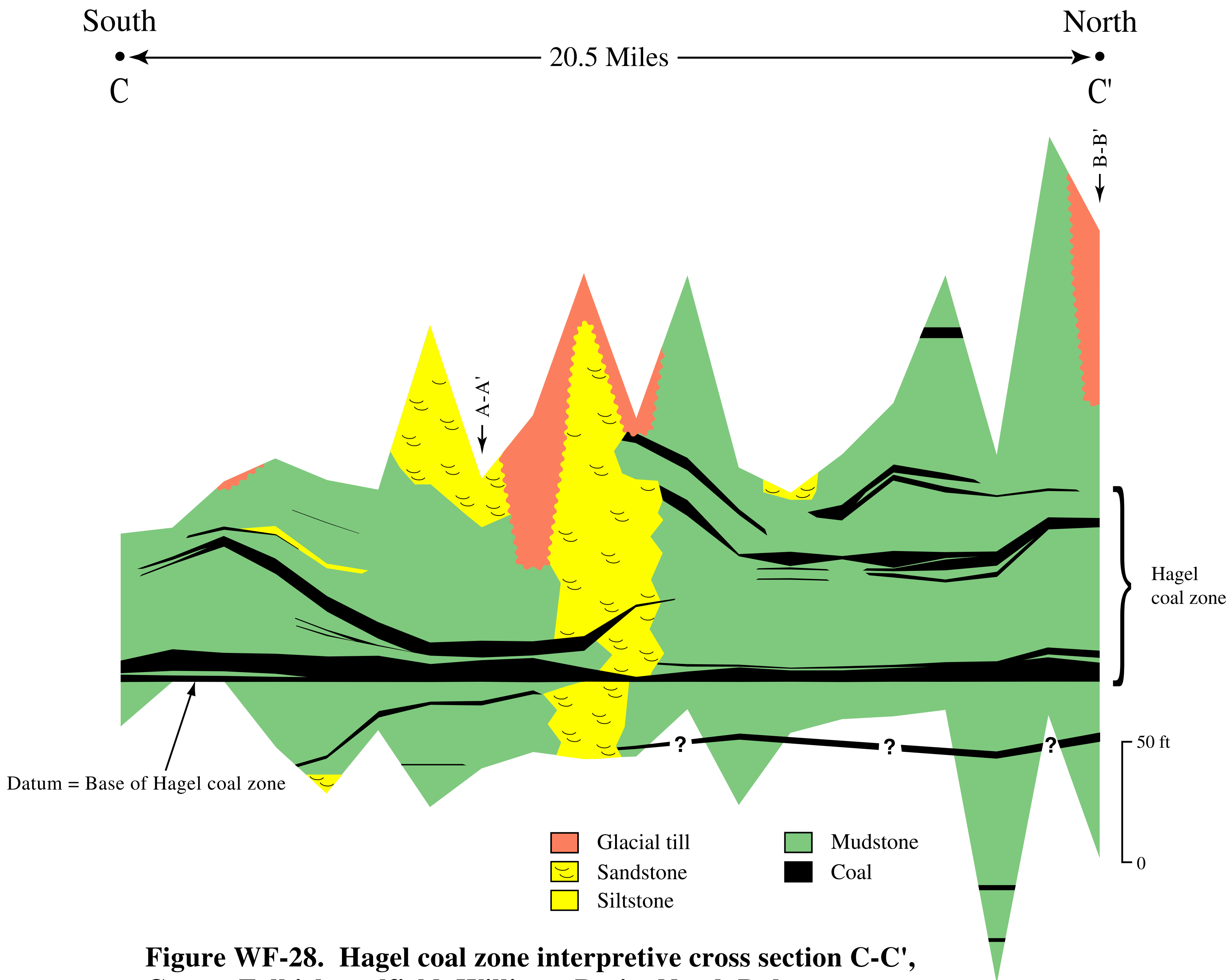

Figure WF-28. Hagel coal zone interpretive cross section C-C', Center-Falkirk coalfield, Williston Basin, North Dakota.

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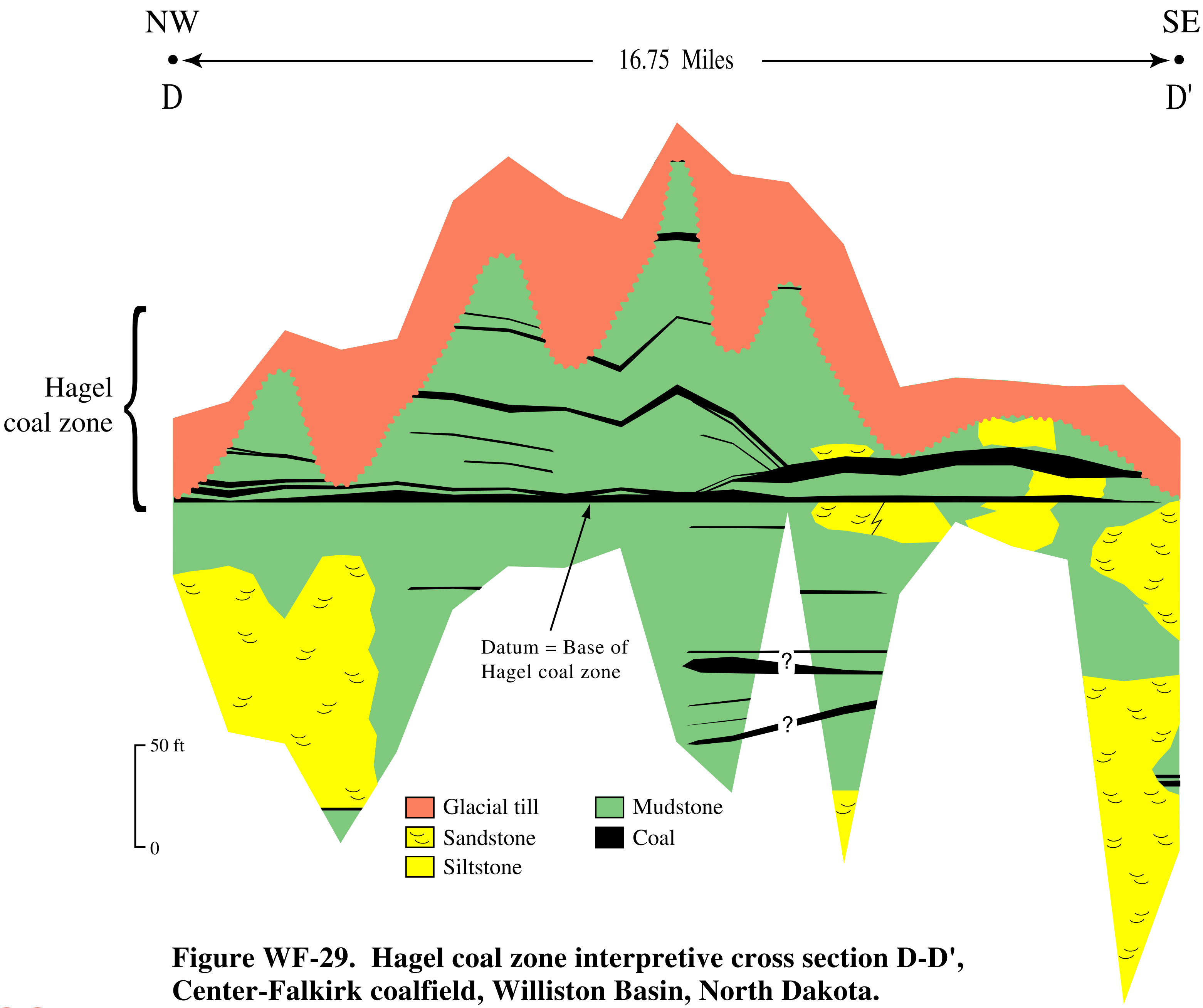

Figure WF-29. Hagel coal zone interpretive cross section D-D', Center-Falkirk coalfield, Williston Basin, North Dakota.

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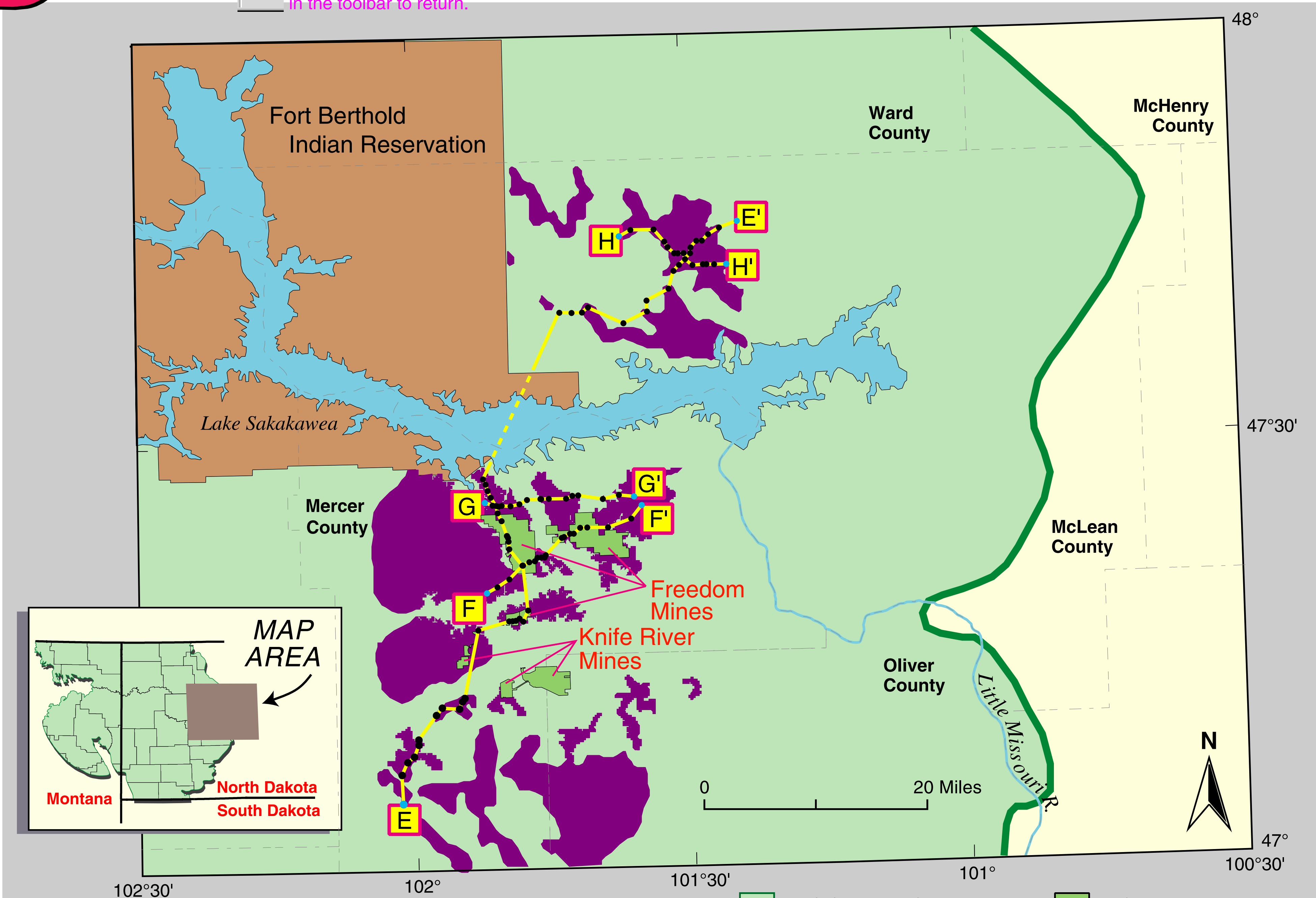

Figure WF-30. Beulah coalfield, Williston Basin, North Dakota, and generalized interpretive cross section layout.

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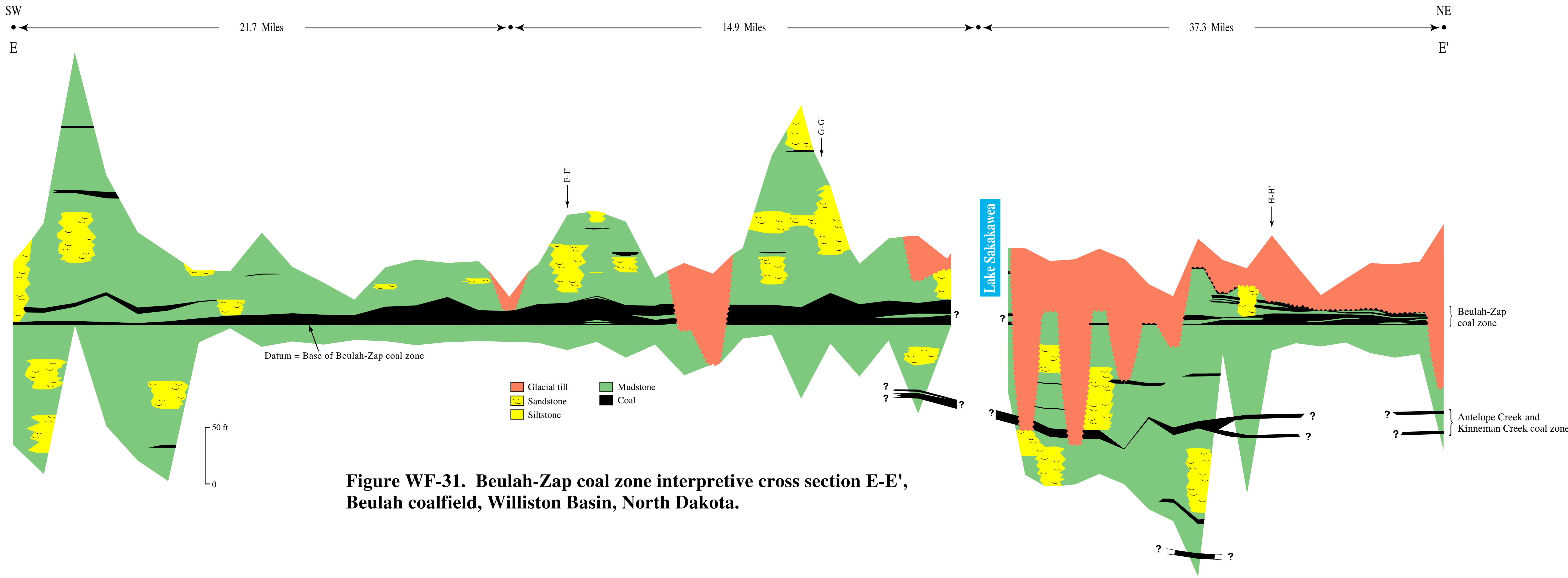

Figure WF-31. Beulah-Zap coal zone interpretive cross section E-E', Beulah coalfield, Williston Basin, North Dakota.

Figure WF-32. Interchannel swamps and floodplains in the South Carolina coastal plain.
Photograph by C. Connor.

Figure WF-33. Crevasse splays and swamps in the lower Mississippi River delta plain, Louisiana. Photograph by R.M. Flores.

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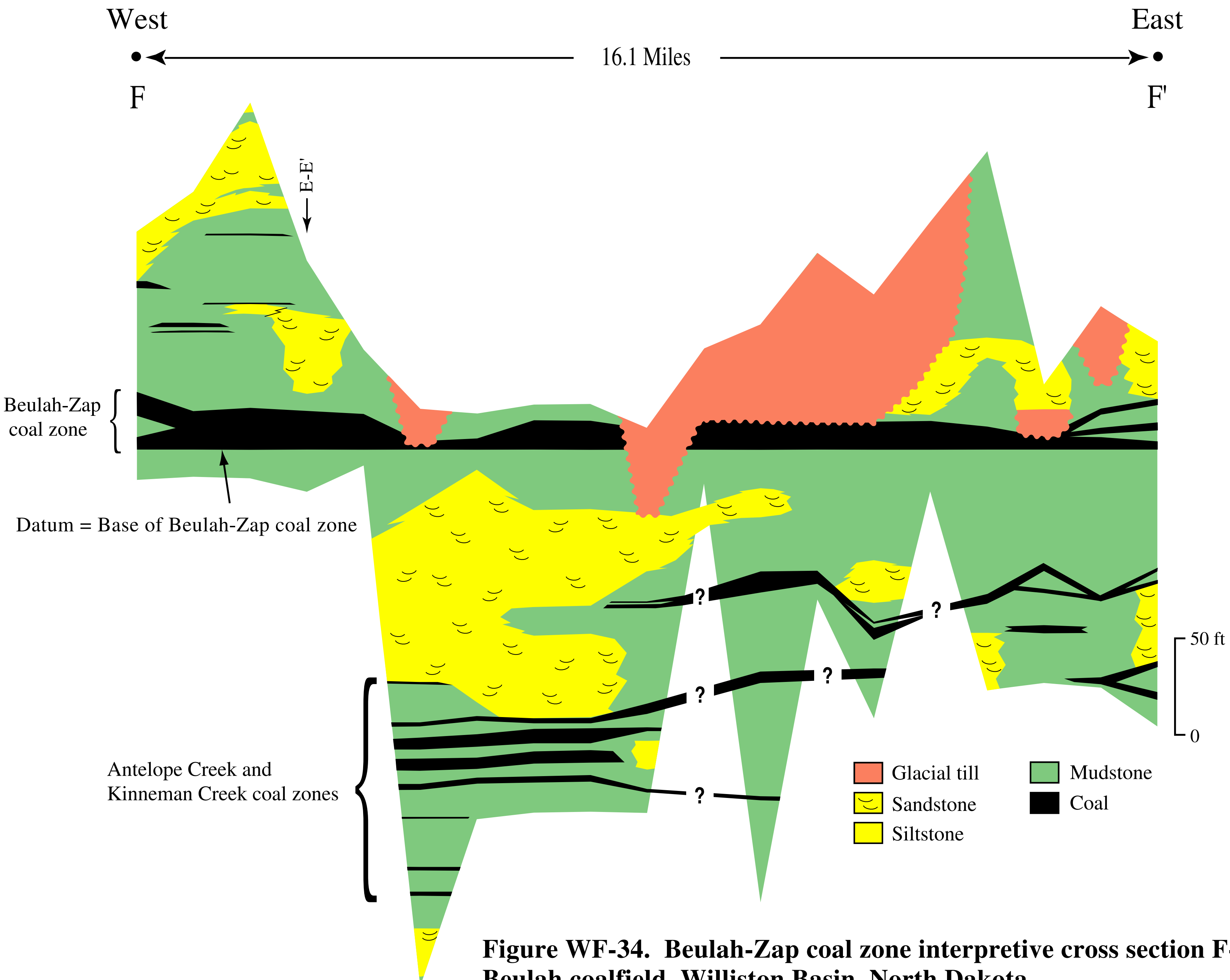

Figure WF-34. Beulah-Zap coal zone interpretive cross section F-F', Beulah coalfield, Williston Basin, North Dakota.

Figure WF-35. Peat deposits in the Florida Everglades. Photograph by R.M. Flores.

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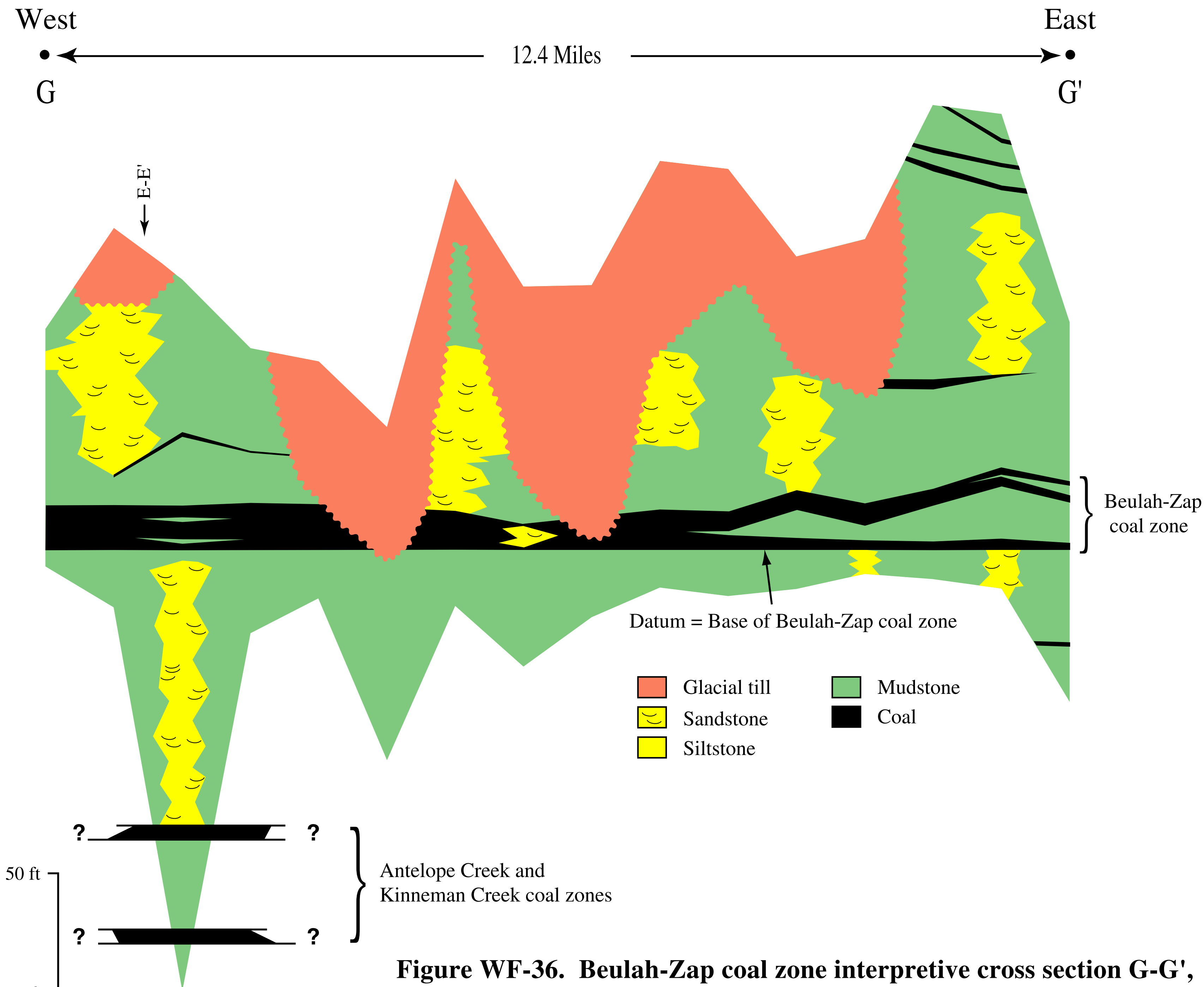

Figure WF-36. Beulah-Zap coal zone interpretive cross section G-G', Beulah coalfield, Williston Basin, North Dakota.

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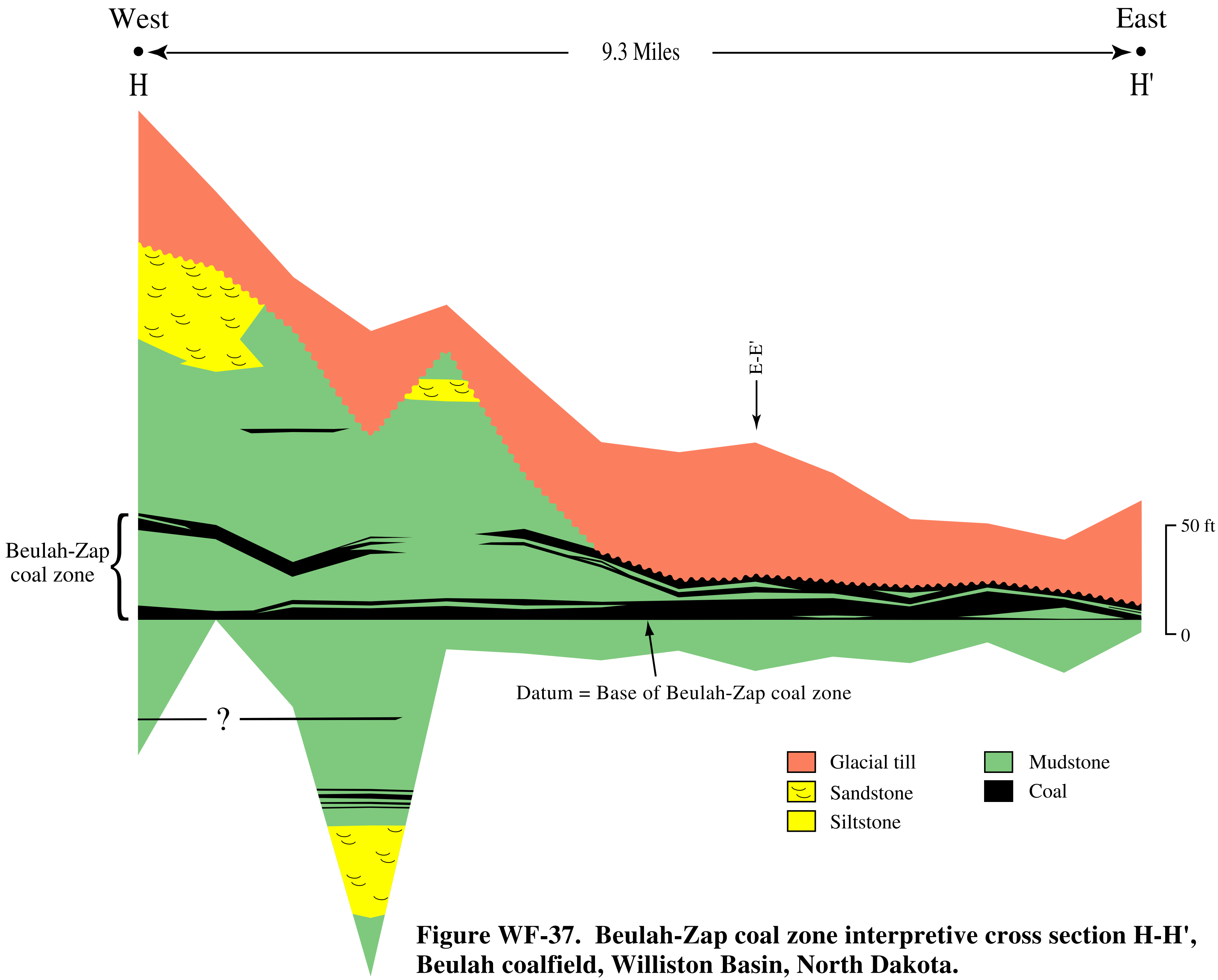

Figure WF-37. Beulah-Zap coal zone interpretive cross section H-H', Beulah coalfield, Williston Basin, North Dakota.