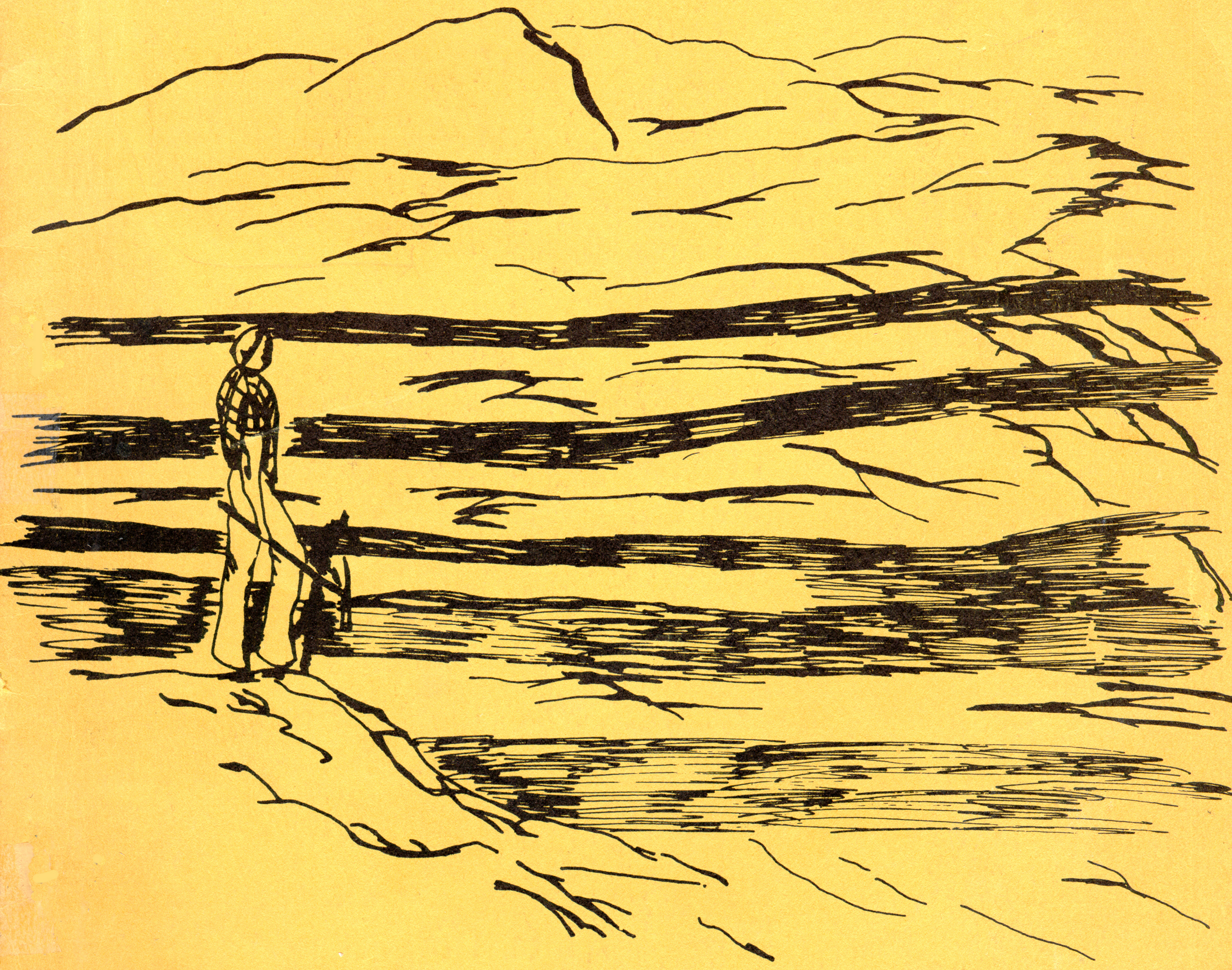
FIELD GUIDEBOOK

Prepared for Annual Field Trip,
Coal Geology Division
Geological Society of America
Minneapolis, Nov. 10-11, 1972

DEPOSITIONAL ENVIRONMENTS OF THE LIGNITE-BEARING STRATA IN WESTERN NORTH DAKOTA

F.T.C. TING, EDITOR



Guidebook No. 3
Department of Geology
University of North Dakota

Miscellaneous Series No. 50
North Dakota Geological Survey
E. A. Noble - State Geologist

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SEDIMENTARY ENVIRONMENTS OF PALEOCENE LIGNITE-BEARING STRATA IN WESTERN NORTH DAKOTA

INTRODUCTION

Early tertiary strata in the Williston Basin contain the largest accumulation of lignite in North America. Lignite beds occur in the Ludlow, Tongue River, and Sentinel Butte Formations of the Fort Union Group (Paleocene) in a stratigraphic section about 2,200 feet thick over an area of about 30,000 square miles.

Despite the vast quantity of lignite in this region, there have been relatively few published studies concerned with the origin and sedimentary environments of these lignite-bearing units. One of the reasons for this lack of study is that not until the late 1960's did the lignite play an important role in the mineral economics of North Dakota. Currently the lignite is used primarily for electrical-power generation. Extensive studies are being made by major gas companies for the gasification of lignite to supplement the growing shortage of natural gas. The interest in gasification has led to active exploration for strippable reserves in western North Dakota.

This field guidebook, with contributed papers, emphasizes the stratigraphy and environments of deposition of the lignite-bearing Paleocene strata in western North Dakota. Information provided in this guidebook should provide some insight into some of the geological processes responsible for the accumulation of the lignite deposits and their associated strata.

The first day will be spent traveling across the center of the Williston Basin examining exposures of lignite and the other lithologies of the Tongue River, Sentinel Butte, and Golden Valley Formations. The petrographic characteristics and the occurrence of sodium in lignite will be studied in strip mines.

The second day will be spent in the southern part of the basin, continuing the examination of the lignite-bearing strata; cyclic sedimentation in these strata will be examined. A stop will be made to examine the occurrence of petrified peat in a lignite bed, and a stop at an exposure of the marine Cannonball Formation will conclude the trip.

ROADLOG

Lee Clayton
Geology Department, University of North Dakota

The fieldtrip route and the surface lithostratigraphic units of southwestern North Dakota are shown in Figure R-1. A stratigraphic column is shown in Figure R-2. The topography of the state is shown in Figure R-3.

The mileages shown in the roadlog correspond to those shown on the green milepost signs at the edge of all highways.

FRIDAY

BISMARCK TO DICKINSON

Missouri River.--The Missouri River here averages about 30,000 cubic feet per second. It drains most of the northern Plains, including much of Montana and North Dakota and parts of Wyoming, South Dakota, Saskatchewan, and Alberta. It is an anomalous river in that it flows southeastward parallel to the regional slope, rather than northeastward down the regional slope from the Rocky Mountains to Hudson Bay; it was diverted into this position around the margin of the continental glaciers during late Cenozoic time. The Missouri River divides North Dakota into two general landscape areas. The west is characterized by nonglacial landforms, an integrated drainage network, concave slopes, and flat-topped buttes. The east is characterized by glacial landforms, nonintegrated drainage, abundant sloughs (marshy duck ponds), and convex slopes.

Mile 156.1.--Go west on I-94 at exit 34.

Indian village.--The top of the high bluff on the east side of the Missouri River (to the right) is the site of one of the numerous upper Missouri valley earth-lodge villages. The lodge sites are still clearly visible on the ground. These villages were occupied by the Mandan, Arikaree, and Minnetaree (Hidatsa) when Lewis and Clark came up the Missouri in 1804.

Mile 154.6.--Here we leave the floodplain of the Missouri River. The valley walls here are composed of the Cannonball Formation. The Standard Oil Refinery on the right is on a river terrace formed at the end of the last glaciation (the Wisconsinan), about 14,000 years ago. It is capped with about 10 feet of wind-blown silt of the Oahe Formation (largely Holocene).

Mile 151.6.--The flat upland here is underlain by several feet of glacial sediment of the Braddock Formation (late Pleistocene). Although the entire area from here to Killdeer (this afternoon) was glaciated, we will see little

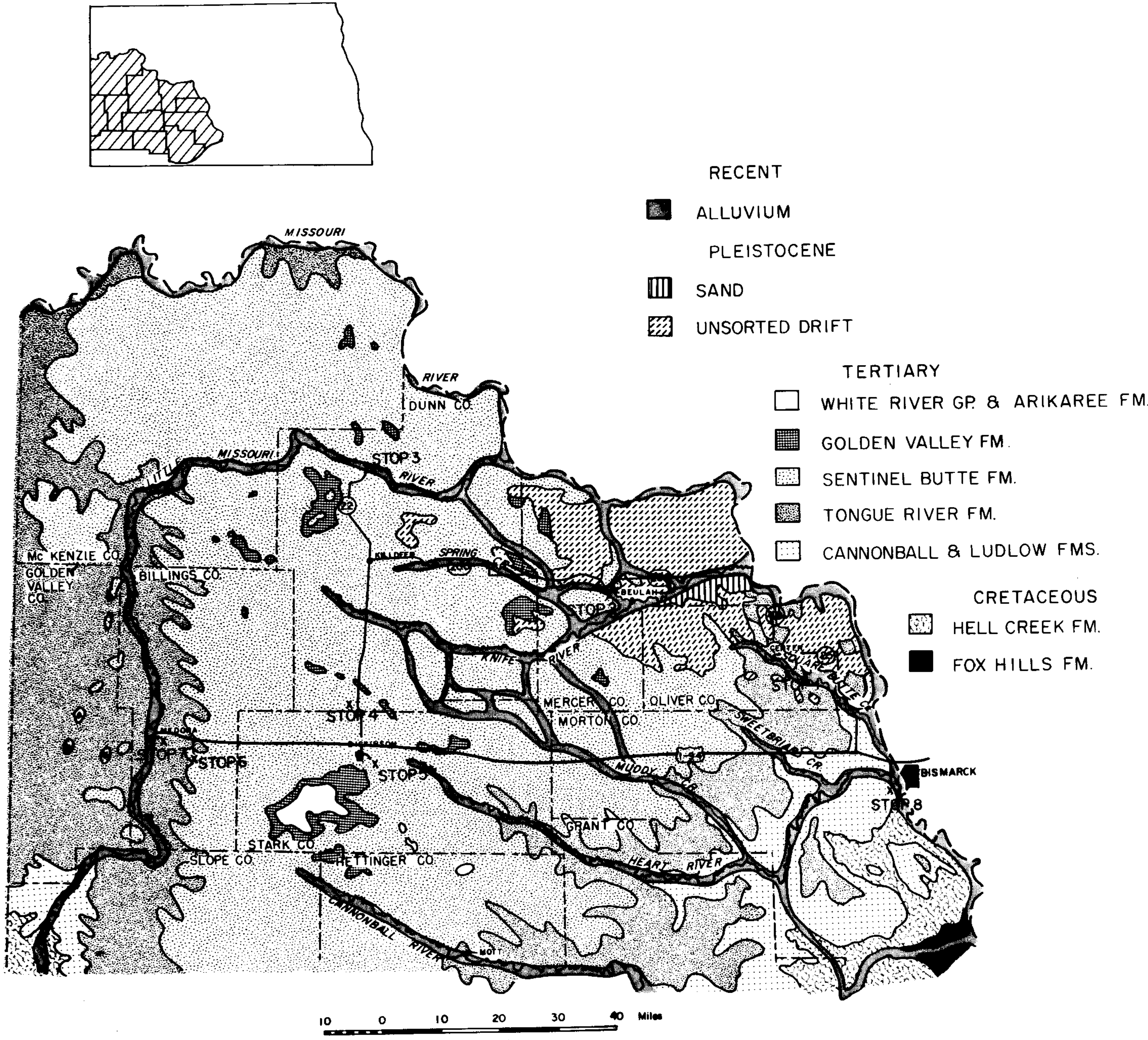

Figure R-1. Geologic map of southwestern North Dakota showing the fieldtrip route.

AGE	SEQUENCE	UNIT NAME		DESCRIPTION
PLEISTOCENE	SAKAKAWEA SEQUENCE	COLE-HARBOR GROUP	OAHE FM.	COARSE SILT: GRAY OVER REDDISH OVER TAN (EOLIAN).
			DENBIGH FM.	WELL-SORTED, MEDIUM SAND (EOLIAN).
			COTEAU FM.	ORGANIC, POORLY-SORTED, GRAVELLY, SANDY, CLAYEY SILT (FLUVIAL, ETC.).
			FOUR BEARS FM. / EMMONS FM.	NONORGANIC SAND AND GRAVEL (FLUVIAL, SHORELINE) AND NONORGANIC SILT AND CLAY (OFFSHORE).
			BRADDOCK FORMATION	SLIGHTLY GRAVELLY, SANDY, CLAYEY SILT (GLACIAL SEDIMENT) AND GRAVEL (INCLUDING GRANITE, LIMESTONE, AND BASALT), SAND, SILT, AND CLAY.
PLIOCENE	TEJAS SEQUENCE	FLAXVILLE? FORMATION		CLAYEY SILT WITH LIGNITE FRAGMENTS (FLUVIAL OVERBANK SEDIMENT) AND CROSSBEDDED SAND WITH SOME QUARTZITE, ARGILLITE, AND PORPHYRY PEBBLES (FLUVIAL CHANNEL SEDIMENT).
MIOCENE	TEJAS SEQUENCE	ARIKAREE ? FORMATION		TUFFACEOUS, LIGHT GRAY, GREENISH, OR WHITE, CROSSBEDDED, COARSE SANDSTONE AND LIMESTONE (LACUSTRINE AND FLUVIAL).
OLIGOCENE	TEJAS SEQUENCE	WHITE RIVER GROUP	BRULE FORMATION	PINKISH SILTSTONE AND CLAY (LACUSTRINE OFFSHORE) AND SOME SAND (FLUVIAL AND LACUSTRINE SHORELINE); STEEP SLOPES.
			CHADRON FORMATION	DARK CLAY WITH THIN LIMESTONE (LACUSTRINE); FLUFFY, ROUNDED SLOPES.
				CROSSBEDDED SAND WITH QUARTZITE AND PORPHYRY PEBBLES (FLUVIAL).
EOCENE	ZUNI SEQUENCE	GOLDEN VALLEY FORMATION	UPPER MEMBER	YELLOWISH, MICACOUS, CROSSBEDDED SANDSTONE, MONTMORILLONITIC SHALE, SILTSTONE, AND MINOR LIGNITE (FLUVIAL AND LACUSTRINE).
PALEOCENE			LOWER MBR.	LIGNITE OR SILICIFIED SILTSTONE. LAVENDER CLAY. WHITE OR ORANGE, KAOLINITIC CLAY. GRAY CLAY. (LACUSTRINE OR FLUVIAL).
		FORT UNION GROUP	SENTINEL BUTTE FORMATION	CROSSBEDDED SAND (PART OF GOLDEN VALLEY FM.?) (FLUVIAL).
				UPPER YELLOW BED. LOWER YELLOW BED. "BIG BLUE" CLAY BED. SOMBER BROWNISH GRAY, 60% SILT AND CLAY (FLUVIAL OVERBANK, FLOODBASIN, AND OFFSHORE LACUSTRINE); 35% SAND (FLUVIAL AND SHORELINE); 3% LIGNITE (SWAMP); SOME SANDSTONE, SCORIA, AND LIMESTONE; PETRIFIED-STUMP ZONE BELOW "BIG BLUE"; STEEP, RILLED SLOPES.
				BASAL SAND BED.
			TONGUE RIVER FORMATION	HT LIGNITE BED. YELLOWISH; 75% SILT AND CLAY (FLUVIAL OVERBANK, FLOODBASIN, AND OFFSHORE LACUSTRINE); 10% SAND (FLUVIAL AND SHORELINE); 3% LIGNITE (SWAMP); SOME LIMESTONE, SCORIA, AND SANDSTONE; GENTLE, ROUNDED SLOPES.
				BASAL SAND BED.
			LUDLOW FM.: LEBO MEMBER	LEBO: DARK-GRAY CLAY WITH FLUFFY SLOPES. SIMILAR TO TONGUE RIVER (YELLOWISH). SIMILAR TO SENTINEL BUTTE (GRAY).
			LUDLOW FM.: TULLOCK MEMBER	TULLOCK: SIMILAR TO SENTINEL BUTTE; BUT THINNER BEDDED; YELLOWISH BED AT TOP.
			CANNON BALL FM.	CANNONBALL: DARK SHALE (OFFSHORE MARINE) AND SAND (SHORELINE).
LATE CRETACEOUS		HELL CREEK FM.	PRETTY BUTTE MBR.	DARK-GRAY CLAY; FLUFFY, ROUNDED, BARE SLOPES (LACUSTRINE).
				SOMBER-GRAY, LIGNITIC SHALE AND DIRTY CROSSBEDDED SAND; DARK-PURPLE CONCRETIONS (FLUVIAL; SOME MARINE).
			COLGATE MBR.	WHITE, CROSSBEDDED SAND (FLUVIAL).
		FOX HILLS FM.	BULLHEAD MBR.	THINLY INTERBEDDED, BROWNISH-GRAY SILT AND CLAY. (MARINE COASTAL SEDIMENT).
			TIMBER L. MBR.	YELLOWISH, GLAUCONITIC, DIRTY, FINE SAND. (MARINE COASTAL SEDIMENT).
			TRAIL CITY MBR.	GRAYISH-BROWN SILT AND CLAYEY SAND. (MARINE COASTAL SEDIMENT).
		PIERRE FORMATION	VIRGIN CR. MBR.	SOFT, DARK-GRAY, FLAKEY, NONCALCAREOUS SHALE. (MARINE OFFSHORE SEDIMENT.)
			ODONAH MEMBER	HARD, SILICEOUS, NONCALCAREOUS, GRAY SHALE; REDDISH-BROWN STAINS ON JOINTS; A FOOT-THICK BED OF LIGHT-YELLOW WAXEY CLAY AT BASE; FORMS STEEP SLOPES.
			DE GRAY MBR.	SIMILAR TO ODONAH MEMBER. SOFT SHALE THAT LACKS TREES IN WOODED AREAS.
			GREGORY MBR.	THINLY-BEDDED, CALCAREOUS, GRAY TO YELLOWISH SHALE WITH FLUFFY SURFACE; COMMONLY SLUMPS.
			PEMBINA MEMBER	SLIGHTLY ORGANIC. HIGHLY ORGANIC (FISH SCALES). SOFT, NONCALCAREOUS, BLACK SHALE WITH YELLOW STAINS; POORLY EXPOSED. WITH WHITE, WAXEY, CLAY BEDS.
		NIOBRARA FORMATION		TAN TO ORANGE, CALCAREOUS SHALE; FORMS STEEP SLOPES. GRAY, CALCAREOUS SHALE WITH WHITE SPECKS.
		CARLILE FORMATION		SOFT, BLACK, NONCALCAREOUS SHALE WITH LARGE ELLIPSOIDAL CONCRETIONS; FINE SAND AT TOP.

Figure R-2. Lithostratigraphic units exposed at the surface in North Dakota. The Sakakawea Sequence and the formations of the Coleharbor Group are being named in a paper in press by Bickley, Clayton, and Moran.

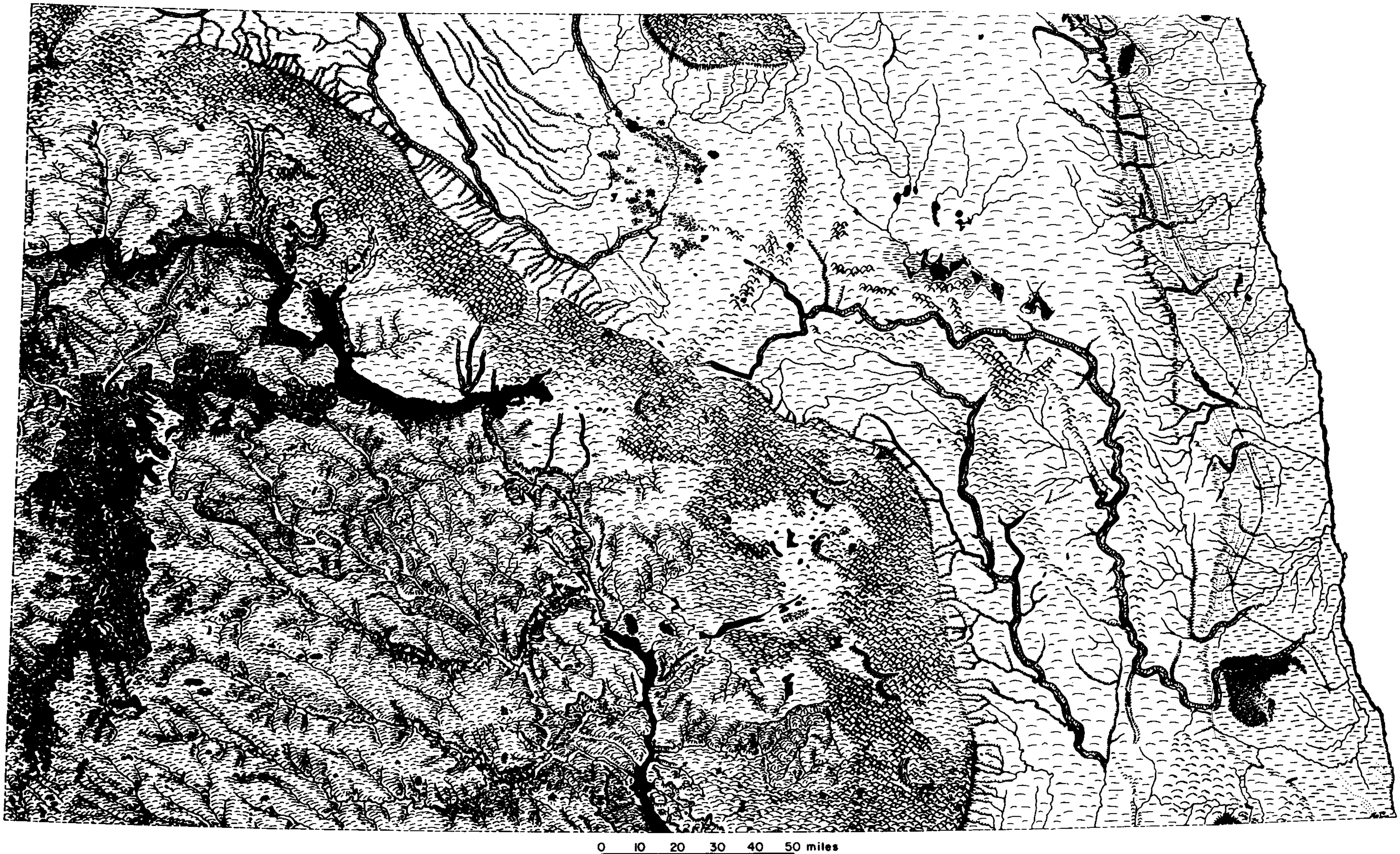

Figure R-3. The topography of North Dakota.

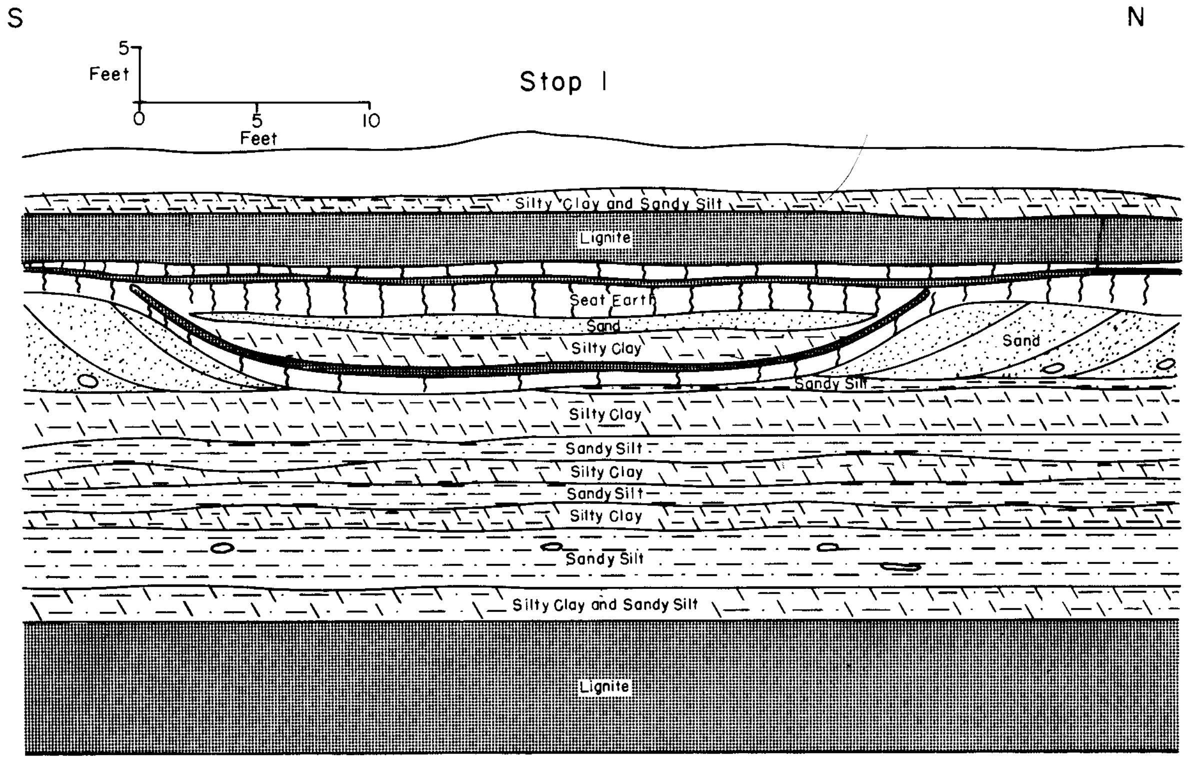

Figure R-4. Stop 1. Exposure of the highwall during the summer of 1972 at the Baukol Noonan Coal Company, Center Mine, SE¼, sec. 25, T.142 N., R.84 W., Oliver County.

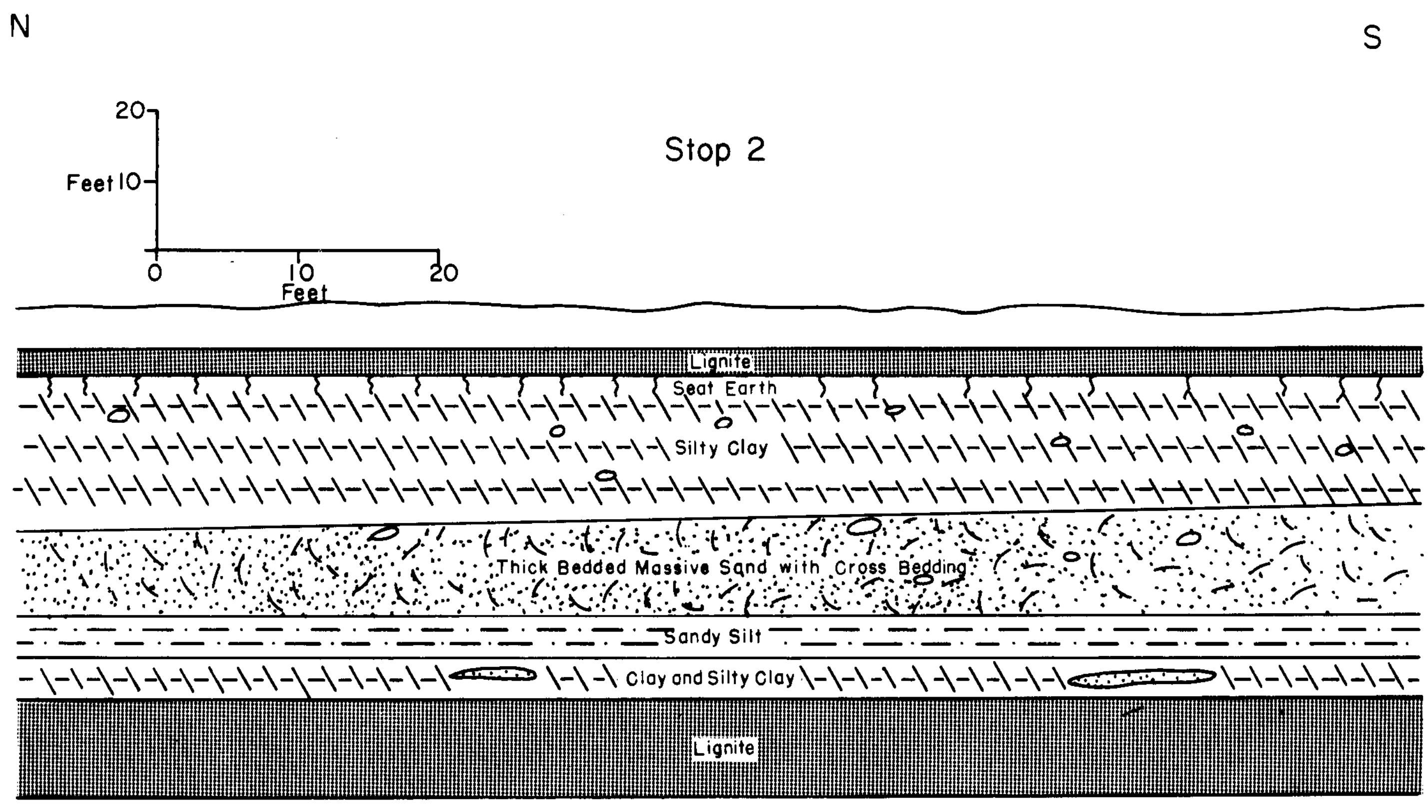

Figure R-5. Stop 2. Exposure of highwall during the summer of 1972 at North American Coal Corporation, Indianhead Mine, SE¼, sec. 31, T.144 N., R.88 W., Mercer County.

evidence for it in most areas other than scattered boulders of granite derived from the Canadian Shield; since glaciation, most of the glacial sediment has been eroded away.

Mile 150.0.--Drive down off the Braddock Formation onto the Cannonball Formation. The sides of the Heart River valley to the south (left) are underlain by the shale and sand of the Cannonball Formation.

Mile 147.2.--Turn right (north) at exit 30 onto N. D. 25 (mile 0.0). Continue north on the upland underlain by the Cannonball Formation.

Mile 1.5.--The high point in the road here is at the top of the Cannonball Formation. All of the hills to the west (left) are underlain by the Tongue River Formation.

Mile 6.5.--Drop down off the upland into Square Butte valley. The valley sides are composed of the Cannonball Formation.

Mile 8.2.--Leave Morton County and enter Oliver County. Continue on the Cannonball Formation.

Mile 13.0.--Drive up out of the Square Butte valley onto the upland, which is underlain by glacial sediment of the Braddock Formation on top of the Tongue River Formation.

Mile 17.5.--N. D. 25 turns straight west.

Mile 23.8.--Turn south (left) onto a paved county road (mile 0.0; no mileposts). Drop down into Square Butte valley. The valley sides are composed of Tongue River Formation, which is only about 100 feet thick here.

Mile 4.1.--The 250-MW Milton R. Young Generating Station, which is owned by Minnkota Power Cooperative. It burns lignite from the Baukol Noonan Mine.

Land restoration.--A program of land restoration has been begun by Minnkota and Baukol Noonan. The spoil banks are bulldozed off to form a gently rolling landscape, which is planted to grass, elm, cottonwood, ash, maple, ponderosa pine, juniper, dogwood, plum, and lilac.

Stop 1: The Baukol Noonan Mine (by F. T. C. Ting).--This is a typical minemouth power-plant complex. The mine supplies exclusively the nearby power plant. Lignite comes mainly from the Hagel Seam, which has a thickness between 10 and 14 feet. A second seam, the Keuther Seam, lies 35 to 40 feet above the Hagel Seam and is mined whenever conditions permit. The Keuther Seam is generally oxidized into leonardite or removed by erosion.

The overburden of the Hagel Seam is characterized by alternating sequences of silty clay, silt, and cross-bedded sandy silt. Oscillatory and current ripples are common in the silty clay beds. The overburden above the Hagel Seam is generally gray to light gray wherever the overlying Keuther Seam is present. The presence of a lignite or leonardite bed prevented the oxidation of the overburden. Where the upper coal is missing, the overburden of the Hagel Seam is generally oxidized buff or yellow.

The coal is characterized by the presence of abundant thick vitrain lenses, composed of lignitized conifer logs and stumps. The tree rings of the stumps are often marked by intensive mineralization of pyrite. Microscopic examination reveals that pyrite grains are closely associated with late wood and ray cells.

The sodium content of the lignite (reported as Na_2O) is low in this mine. There is strong evidence that it is related to the high-carbonate and permeable overburden. The sodium is replaced by calcium and other cations through ion exchange.

Return to N. D. 25 (mile 23.8) and go west to Center.

Mile 28.7.--Town of Center (600 population). Turn right (north) on N. D. 48 (mile 0.0).

Mile 1.0.--Rise up out of the valley onto the Sentinel Butte Formation. We will drive over Sentinel Butte Formation overlain by scattered patches of glacial sediment of the Braddock Formation for the next 8 miles.

Mile 9.0.--Leave Oliver County and enter Mercer County.

Mile 9.3.--Turn left (west) on N. D. 200 Alternate (mile 911.1). Drop down onto the 30-foot terrace of the Missouri River; it was formed at the end of the Wisconsinan Glaciation.

Mile 910.2.--Turn right onto the gravel road to Fort Clark Historic Site (mile 0.0; no mileposts).

Mile 1.0.--Turn right. The bluff to the left is the edge of the 30-foot terrace of the Missouri River.

Mile 1.2.--Turn left into the historic site.

Indian village.--The mounds and depressions in the hay field to the left are collapsed earth lodges of a Mandan village. A large proportion of the Mandans died of smallpox here in 1837.

In 1832 George Catlin, the artist, arrived aboard the steamship Yellowstone and painted scenes of Indian life. Prince Maximillian of Wied visited here in 1833; his book, Travels in the Interior of North America, provides excellent insights into the history of this area.

Mile 1.5: Fort Clark.--The stone building is an approximate reconstruction of Fort Clark, minus windows and a door; the fort was about 100 square feet. It was an American Fur Company post from 1831 to about 1860. The Missouri River flowed against the bluff below the fort in the 1800's. Brief stop.

Return to N. D. 200 Alternate.

Mile 909.0: Fort Mandan.--Lewis and Clark spent their first winter (1804-1805) 1 mile east of here, just downstream from the Mandan earth-lodge villages on the Missouri bottomland. Here they hired the French-Canadian trader Charbonneau so that his Shoshoni wife, Sacajawea (Sakakawea), could guide them over the Rocky Mountains, where she grew up.

Mile 908.4: B. E. Plant.--The Basin Electric Plant, with a capacity of 230 MW. It burns lignite from the Glenharold Mine of the Consolidation Coal Company.

Revegetation.--According to J. J. Bond (Northern Plains Research Center, U. S. Department of Agriculture, Mandan, North Dakota), preliminary laboratory studies show that the spoil-bank material is deficient in nitrogen and phosphorous. However, field studies at the Glenharold Mine show adequate nitrogen for plant growth. Apparently soil-forming activities convert ammonium in the spoil into nitrate, a form that is usable by plants, within a very short time. Phosphorous deficiency (and any nitrogen deficiency) is easily remedied using commercial fertilizers. Spoil-bank material is rich in sodium montmorillonite, which produces poor soil structure, resulting in slight infiltration of rainfall, maximum runoff, and considerable hillslope erosion. Until the sodium is naturally leached, little plant growth takes place. Poor soil structure resulting from excess sodium can be remedied with the use of mulches.

Mile 907.6: U. P. A. Plant.--The United Power Association Plant, with a capacity of 175 MW. It burns lignite from the Indian Head Mine at Zap (stop 2).

Mile 907.3 to 905.9: Missouri River.--View of the Missouri River bottomland and cottonwood forest. We are driving on a 30-foot terrace of the Missouri River.

Garrison Dam.--Fifteen miles north of here is Garrison Dam, one of six Pick-Sloan dams on the upper Missouri. It has a 400 MW hydrolectric plant. Lake Sakakawea, behind the dam, is 170 miles long.

Mile 904.9.--Junction of N. D. 200 Alternate and N. D. 31; continue on N. D. 200 Alternate. We turn west here and drive up the Knife River valley.

Mile 903.0.--Junction of N. D. 200 Alternate and N. D. 31; continue on N. D. 200 Alternate.

Mile 902.3: Dunes.--There are several square miles of middle Holocene sand dunes here on the south side of the Knife River valley. A blowout can be seen in stabilized sand dunes a quarter mile north (right).

Mile 900.0.--Junction of N. D. 200 Alternate and N. D. 200 (mile 157.7).

Mile 156.0.--Stabilized sand dunes a half mile south (left); they were active during middle Holocene time, when the climate was drier.

Mile 153.1.--Edge of Knife River bottomland.

Mile 151.0.--Town of Hazen (population 1200). We will be driving on the Sentinel Butte Formation for most of the rest of the day.

Mile 145.5 to 146.8: Beulah Mine.--The Beulah Mine is owned by the Knife River Coal Mining Company. They are having considerable success in revegetating the spoil banks.

Mile 144.3 to 143.7: Collapse holes.--The holes in the fields are the result of the collapse of underground lignite mines.

Mile 143.5.--Junction N. D. 49; continue on N. D. 200.

Mile 139.5.--Turn left (south) on gravel road (mile 0.0; no mileposts). Cross Spring Creek, the main tributary of the Knife River.

Mile 1.3.--Turn right (northwest).

Mile 2.8: Stop 2: The Indian Head Mine of the North American Coal Company by F. T. C. Ting.--The lignite mined is the Beulah-Zap Seam, which has an average thickness of about 14 feet in this region. The coal is overlain by alternating sequences of loosely consolidated, gray to light-gray, clay, silt, and sand. An unjointed, cross-bedded, gray, sand bed occurs about 10 feet above the coal. In a now-destroyed U-shaped cut, the sand had a maximum thickness of 20 feet at the south end and tapered to a thickness of 10 feet at the north end within a distance of about 1,000 feet.

The overburden is characterized by the presence of large numbers of calcareous, sideritic, and pyritiferous nodules. The nodules are extremely large in the massive sand bed, reaching 7 feet in their horizontal dimension.

Seat earth (underclay) is usually not well developed. It is usually represented by a thin, disturbed zone, which is sometimes light green.

The lignite is also characterized by abundant thick vitrain or lignitic wood. In a stripped area 25 by 50 feet selected at random, we have observed 16 lignitized tree stumps on the top of the seam. The diameters of the trunks range between 6 inches to 2½ feet. It is conceivable that, due to oxidation during the peat stage, the trees were much larger and more numerous than those encountered.

The lignite is relatively rich in sodium. Published data show an average of 8.5% Na_2O in the ash. In contrast to the overburden at Stop 1, the immediate overburden is highly impermeable clay and is low in carbonates. This may be the reason for the large amount of sodium in the lignite.

Continue west on gravel road to Zap.

Mile 3.8.--Turn right (north). Town of Zap (population 300), site of the Zip-to-Zap riot in 1969.

Mile 5.5.--Turn left (west) on N. D. 200 (mile 136.5).

Mile 129.9.--Town of Golden Valley. The type area of the Golden Valley Formation (late Paleocene and early Eocene) is 2 to 3 miles south of town.

Mile 126.4.--Leave Mercer County and enter Dunn County. Continue on the Sentinel Butte Formation.

Mile 123.6.--Dodge.

Mile 117.2.--Junction N. D. 8; continue right (north) on N. D. 200.

Mile 115.5.--Junction N. D. 8 at Halliday; continue left (west) on N. D. 200.

Mile 110.2.--Werner.

Mile 105.0: Knife River Flint.--Knife River Flint quarries on the right, just this side of the windbreak east of the farm on the north side of Spring Creek, a half mile north (right) of the highway. The flint occurs as pebbles, cobbles, and boulders in fluvial gravel of late Pleistocene age. The flint was originally derived from silicified peat in the Golden Valley Formation at the base of the Killdeer Mountains 15 miles northwest of here. The flint has a characteristic petrography and can be distinguished from other mid-continent flint. The Knife River Flint was used as raw material for tools by prehistoric man for at least the past 11,000 years. It is commonly found in archeologic sites as far away as Alberta, Missouri, and Ohio. Almost all of it came from this quarry and a few smaller nearby quarries here in the Knife River valley. The quarry here occupies about 100 acres and consists of about 3,000 pits, each about 20 feet across and 5 feet deep. Roughly 100,000 cubic feet of flint was quarried in the Knife River valley. "Knife River" is a translation of an Indian name that was given to the river because flint for knives was quarried here.

Mile 104.3: Scoria.--Scoria pit on left (south); brief stop. In North Dakota the word "scoria" is applied to the red natural brick that results from baking of the sediment overlying a burning lignite bed. Much of the scoria is now in settings where the water table is so high that the lignite could not burn; much of the scoria in North Dakota probably formed during middle Holocene time, when the climate was drier and the water tables were lower. The fires started from prairie fires or spontaneous combustion. The fire burns back into the hillside as long as the collapsing of the overburden provides cracks to let air down to the fire; when the overburden becomes more than a few tens of feet thick the fire is smothered. Many fires are still burning; they can be seen in the south unit of Roosevelt National Park near Medora and at the Burning Coal Vein and Columnar Cedar State Park 25 miles south of Medora. The scoria is used throughout southwestern North Dakota for surfacing gravel roads.

Mile 101.8.--Dunn Center.

Mile 99.0.--Lake Ilo on left (south), an artificial lake and national wildlife refuge.

Mile 98.1.--Outer (southwestern) limit of the late Pleistocene glaciation. Only rare glacial boulders will be seen beyond this point; they may be of middle or early Pleistocene age.

Mile 95.2.--Turn right (north) on N. D. 22 (mile 105.0).

Killdeer Channel.--The town of Killdeer (population 700) is in the bottom of the Killdeer Channel, which held a river (comparable in size to the Missouri) draining much of the northern Plains when the late Pleistocene glacier margin was 3 miles east of here. The Killdeer Mountains can be seen northwest of here.

Mile 107.4.--We are driving along the east edge of the Killdeer Channel.

Mile 108.8: Killdeer Battle.--The Killdeer Battle Historic Site is west of here, at the south end of the Killdeer Mountains. The "Battle of Killdeer Mountains" took place July 28, 1864, from 1:00 in the afternoon until dusk. General Sully and 2200 men used artillery on 6,000 Sioux warriors. Many Sioux were killed; tons of dried buffalo meat, dried berries, robes, skins, household utensils, and saddles were destroyed; and 1600 tepees were burned. These were Teton and Yanktonai Sioux. The "battle" was revenge for the uprising of Santee Sioux along the Minnesota River in southern Minnesota.

Medicine Hole.--At the top of the southeast spur of the Killdeer Mountains is Medicine Hole. It is about 10 feet across and over 90 feet deep. Originally the surface of the earth was without life. Then Medicine Hole opened, letting light shine on the face of a sleeping Indian woman, causing her to awake. She woke the other Indians, buffalo, and other animals and led them up to the surface.

Mile 111.0: Killdeer Mountains.--The Killdeer Mountains (on the left) rise 1,000 feet above the highway and 1,500 feet above the Little Missouri River, just to the north.

The Killdeers are capped with the Miocene (?) Arikaree (?) Formation. It consists of 400 feet of tuffaceous sandstone and limestone, probably of lacustrine origin. Beneath the Arikaree (?) is a small amount of White River (?) Group. Beneath it is the Golden Valley Formation. The Sentinel Butte Formation occurs along the highway.

Pediment surfaces can be seen sloping up to the pass between the north and south parts of the Killdeer Mountains.

Mile 112.8: Oahe Formation.--The gravel pit on the right (east) contains boulders of Knife River Flint. Capping the gravel is about 5 feet of silt of the Oahe Formation (Wisconsinan and Holocene). The silt is wind-blown dust; the dark paleosol in the Aggie Brown Member can be seen near the base of the Oahe.

Mile 115.5: Pediment.--Ahead and to the left is a gravel pit on a pediment remnant sloping up toward the Killdeer Mountains. The gravel is about 10 feet thick and contains fossil ice-wedge polygons formed under a tundra climate. The gravel is late Pleistocene (possibly early Wisconsinan) in age.

Mile 117.3: Oak forest.--The forest in the valley coming down from the Killdeer Mountains here consists of oak and smaller numbers of aspen, birch, ash, and elm. The north-facing slopes of the Killdeers are a refuge for many species of plants normally found north and east in forest regions.

Mile 121.2.--View of Little Missouri Badlands to the left (north).

Ash forest.--The forest on the north-facing slopes of the Badlands here contains ash plus smaller numbers of aspen, juniper, and birch. Willow and cottonwood occur in the more moist areas. The shrubs include buffaloberry (red berries), chokecherries, juneberries, and wild rose.

Mile 123.8: Little Missouri Badlands.--Descend into the Badlands. This is one of the narrowest (4 miles) and deepest (650 feet) parts of the Little Missouri Badlands. The entire Sentinel Butte Formation is exposed here. The Golden Valley Formation is at the highest part of the valley wall (we won't see it), and the Tongue River Formation is near river level.

Mile 124.1.--The Little Missouri Bay of Lake Sakakawea (dammed by Garrison Dam) can be seen to the right (east).

Mile 125.3: Stop 3: The Sentinel Butte Formation.--The Sentinel Butte Formation is about 600 feet thick here. About 60 percent of the formation consists of silt and clay beds. A few tens of percent of the silt and clay consists of clay minerals. The clay minerals are largely sodium montmorillonite in groundwater discharge areas and below a depth of about 200 feet in groundwater recharge areas. The clay minerals are largely calcium montmorillonite down to a depth of 200 feet in groundwater recharge areas, where the sodium has been flushed out and replaced with calcium supplied by weathering in the A1 soil horizon. Sodium montmorillonite is much more plastic than calcium montmorillonite, which causes greater erosion by mass movement in groundwater discharge areas. Other minerals in the silt and clay beds include several tens of percent of quartz and feldspar, about 5 percent calcite and dolomite, and minor amounts of other minerals, such as iron oxides, marcasite, and gypsum.

About 35 percent of the Sentinel Butte Formation consists of sand beds, which consist of quartz, feldspar, and some heavy minerals.

About 3 percent of the Sentinel Butte Formation consists of lignite beds up to 15 feet thick.

Less than 1 percent of the Sentinel Butte Formation consists of sandstone. Other minor lithologies include scoria and limestone.

The characteristic feature that distinguishes the Sentinel Butte Formation from the underlying Tongue River Formation is its color. The Sentinel Butte is grayish or brownish; the Tongue River is dull yellow. The Sentinel Butte tends to have steep, minutely rilled badland slopes, whereas the Tongue River tends to have more gently, smoother, more rounded badland slopes.

The Sentinel Butte is Paleocene and consists of nonmarine coastal-plain deposits.

C. F. Royse will supply more detailed information on the Sentinel Butte Formation at this stop. (See Table R-1.)

Mile 125.9.--Scoria pit to the left (west).

TABLE R-1

Table R-1.--The Sentinel Butte Formation in S½ sec. 26 and N½ sec. 35, T.148N., R.95W., just north of Lost Bridge. The following section was measured by C. F. Royse in 1966. The formation is thicker than normal here because it is near the center of the Williston Basin, and it contains more carbonaceous material than in most other areas. (Thicknesses are in feet.)

448-530	Poorly exposed; probably the "upper Sentinel Butte sand"; the contact of the Golden Valley Formation and Sentinel Butte Formation, 2 miles north of Lost Bridge, is poorly exposed.
422-448	Buff to brownish yellow clayey silt.
413-422	Dark silty clay.
410-413	Lignitic and clayey shale.
405-410	Light buff to gray microcrossbedded silt.
403-405	Lignite.
399-403	Clay.
397-399	Lignitic shale.
375-390	Slumped; may contain some lignite.
374-375	Lignite.
370-374	Silty clay and clayey silt.
346-370	Sand and clayey sand.
344-346	Calcareous clay.
340-344	Silt.
338-340	Lignite.
328-338	The "Upper Yellow Bed."
327-328	Lignitic shale and lignite.
323-327	Clay.
322-323	Lignitic shale and lignite.
312-322	Clayey silt.
302-312	Sand; gradational upper contact.
302	Zone of limonitic concretions.
289-302	Sand, poorly consolidated.
286-289	Very silty lignitic shale.
282-286	Silt; gradational upper contact.
280-282	Lignitic shale and lignite.
278-280	Silt.
277-278	Lignitic shale.
225-277	Gray silty clay and clayey silt; some limonitic staining along many horizons; numerous large iron-rich and carbonate-rich concretions, nodules, and lenses; most of the interval is thinly laminated.
222-225	Lignite and lignitic shale.
220-222	Clay.
220	Lignitic shale and lignite; 4 inches thick.
214-220	Crossbedded lignitic silt; gradational upper contact.
208-214	Silt.
207-208	Lignitic shale.
205-207	Silt.

203-205	Lignitic shale.
192-203	Lignite.
190-192	Silty lignitic shale.
174-190	Buff to gray, laminated clayey silt; poorly exposed.
170-174	Lignite; thin bed of sand between the lignite and underclay.
155-170	Buff-yellow to grayish brown laminated clayey silt.
149-155	Gray clay.
147-149	Zone of limonitic concretions; microcrossbedded.
145-147	Clay.
117-145	Sand and clayey sand; several limonitic horizons.
114-117	Dark clay; rich in organic material.
112-114	Dark clay and lignitic shale.
105-112	The "Lower Yellow Bed."
100-105	Lignitic shale.
82-100	Variegated silty clay and clayey silt with many limonitic layers; silty above 90 feet.
81-82	Lignitic shale.
71-81	The "Blue Bed"; clayey silt.
63-71	Lignitic shale with some lignite and shale partings.
51-63	Sand; becomes finer upward; clayey near top.
50-51	Lignite.
38-50	Sand; locally crossbedded.
36-38	Lignite; poorly exposed.
29-36	Clayey silt.
28-29	Lignite; well developed underclay.
20-28	Clayey silt with bentonitic beds and calcareous concretions.
11-20	Clay; gradational upper contact; thin limonitic zones and calcareous concretions.
10-11	Lignite; contains silicified wood.
4-10	Clayey silt.
0- 4	Clay with thin (¼ to ½ inch) calcareous and limonitic concretionary horizons; grades downward into the basal Sentinel Butte sand; the base of the section is about ¼ mile northeast and about 40 feet above the north end of Lost Bridge, or about 50 feet above the contact between the Sentinel Butte Formation and Tongue River Formation.

Little Missouri delta.--The mud flat beneath the dead cottonwood trees here is the delta of the Little Missouri River where it flows into Lake Sakakawea.

Mile 126.5: Lost Bridge.--The bridge was "lost" from 1931, when it was built, until 1954, when the road reached it. The Fort Berthold Indian Reservation, on the north side of the river, is occupied by the Mandan, Arikaree, and Minnetaree.

Turn around and return to Killdeer.

Mile 105.0.--Back at junction with N. D. 200; continue south on N. D. 22.

Mile 103.0.--Cross the Killdeer Channel again.

Mile 96.5.--Knife River.

Mile 96.0.--Manning, Dunn County seat.

Mile 90.0.--Outer (southwestern) limit of Pleistocene glaciation.

Mile 85.4: Golden Valley Formation.--The Golden Valley Formation outcrops several hundred feet to the west (right) of the highway. According to Leo Hickey, the lower member is only 14 feet thick here. It consists of kaolinitic silty clay and silt with zones of organic trash and poorly preserved plant fossils; it contains a conspicuous 7-foot orange bed. The contact between the Golden Valley Formation and the Sentinel Butte Formation is gradational.

The base of the upper member is marked by a 6-foot bed of blue-gray montmorillonitic clay. The top of the hill is channel sandstone of the upper member.

Mile 85.0: Russian Spring Escarpment.--We are here at the top of the Russian Spring Escarpment, which marks the contact between the younger stability surface to the north and the older stability surface to the south. Continue on the Sentinel Butte Formation.

Missouri Slope.--The part of North Dakota between the Missouri River and the Little Missouri Badlands is called the Missouri Slope. The more level areas, such as here south of the escarpment, are used primarily for the growing of spring wheat; the rougher areas, such as those north of the escarpment, are used for the grazing of beef cattle.

This area was originally a wheatgrass-needlegrass (midgrass) area. Woodlands (cottonwood) occur on the floodplains of the larger rivers. Juniper occur on some north-facing scarps. The soils are dominantly Chestnut or Argiborolls (Mollisols); locally alkali soils (Solonetz or Natriborolls) and Regosols (Entisols) occur.

Bison were the dominant mammal in this area until 1880; their trails are still one of the most conspicuous minor landforms seen on air photos of this area.

The Sioux were the dominant tribe west of the Missouri in the 1880's.

Mile 79.5.--Turn right (west) onto gravel road. Continue 1 mile to Camels Butte.

Stop 4: Golden Valley Formation by Leo Hickey.--Both members of the Golden Valley Formation are well exposed here (Fig. R-6). (The lower contact of the formation is covered.) The 21-foot lower member is divided into three conspicuous color zones. A light gray, kaolinitic, silt and sand unit makes up the lower zone. This is followed by a silty and sandy orange and yellow zone containing limonite spherules, gypsum crystal crusts, and limonite and gypsum joint fillings. Eighteen feet above the base of the outcrop the member becomes increasingly carbonaceous, taking on a dark yellowish-gray weathering color and culminating in a 6-inch bed of lignitic, silty shale. This unit marks the upper contact of the lower member of the Golden Valley Formation and lies on the Paleocene-Eocene boundary.

The upper member immediately above the contact consists of parallel-bedded silt, shale, fresh-water limestone nodules, and lignite with a small assortment of megafossil plants including *Salvinia preauriculata*, *Isoetites*, and monocots. The lithologies and plants of this zone appear to indicate a paludal and lacustrine origin for these beds. A lignite bed about 30 feet above the base of the upper member is partly replaced by chert. The abundance of lignite across the Paleocene-Eocene boundary in this section should make pollen sampling very rewarding. The upper member becomes steadily coarser upward. The upper 40 feet of the butte consist of cross-bedded micaceous sandstone and includes a 20-foot channel filled with intraformational conglomerate having clasts up to 2½ feet in diameter.

Mile 78.4.--Leave Dunn County and enter Stark County. Drop down into the Green River valley. The high buttes in this area are capped by the Golden Valley Formation and White River Group.

Mile 74.8.--The Dickinson oil field.

Mile 72.5.--Junction I-94 and N. D. 22.

Dickinson (population 10,000). End of first day.

SATURDAY

DICKINSON TO BISMARCK

Mile 0.0.--Junction of I-94 and N. D. 22. Go south through Dickinson on N. D. 22 (no mileposts).

Mile 1.2.--Turn left (east) on Villard Street (Business 94).

Mile 2.3.--Straight ahead (don't angle left on Business 94) on paved road.

Mile 4.2.--Turn right (south) on gravel road.

Mile 5.0.--Old mine cars on hillside to left (east).

Mile 5.2.--Heart River.

Mile 6.0.--Turn left (east) into plant entrance.

Stop 5: Depositional Environments of the Sentinel Butte Formation, Husky Lignite Mine.--Husky Industries obtains lignite from this mine for the production of lignite-char barbecue briquettes. The lignite is distilled and the residuum (char) is used to manufacture the briquettes. By-products of the distillate are creosote oil, used for wood preservation, and pitch (coal tar), used as a binding agent in heating-type briquettes.

Figure R-7 is a sketch of the south wall of the mine as it appeared in the spring of 1972. The lower sand bed becomes silty eastward. This change may not be visible at the time of our visit because mine operations may have altered the exposed section. The upper sand bed is continuous across the entire mine wall.

The sand beds probably are high-sinuosity stream deposits. Epsilon cross-strata (large foresets that are concave downward, extend from the top to the bottom of the bed, and have clay and silt on their surfaces), such as shown on Figure R-7, result from lateral accretion on point bars in high sinuosity streams. Epsilon cross strata are not common in these sands, but they are present. Don't confuse them with shovel marks, which are concave upward. The vertical sequence of sedimentary structures and the fining upward also are characteristic of point bars.

Figure R-8 illustrates the origin of the sand beds. The thickness of the sand bed in Figure R-8 is equivalent to the depth of the stream in the bend where it was deposited. The bed shear stress on the stream bottom decreases toward the convex side of the bend. So the sand bed resulting from lateral accretion becomes finer upward.

The sediment surrounding the sand beds at the Husky Mine probably was deposited on natural levees adjacent to the streams and in flood basins (including swamps and small lakes and ponds) away from the streams. Climbing ripples and plane bedding occur in the silt adjacent to the lower sand. These sedimentary structures are particularly characteristic of natural levees.

A shoreline origin for the sand is unlikely. If it were shoreline sediment it would be a transgressive deposit because the sand becomes finer upward. So the sediment overlying the sand should be offshore lake sediment (the sediment is non-marine). But the sediment over the sand is lignitic silty clay, which is swamp sediment, not lake sediment.

An eolian origin of the sand is unlikely because of its close association with lignite, which indicates an environment too wet for eolian transport. Ripple stratification, which is present in this sand, does not occur in eolian deposits. Abundant plant debris in the sand also argues against an eolian origin, and the high silt and clay content of the sand is not typical of eolian deposits.

Return to Dickinson.

Mile 61.5.--Junction of N. D. 22 and I-94 (exit 13). Go west on I-94.

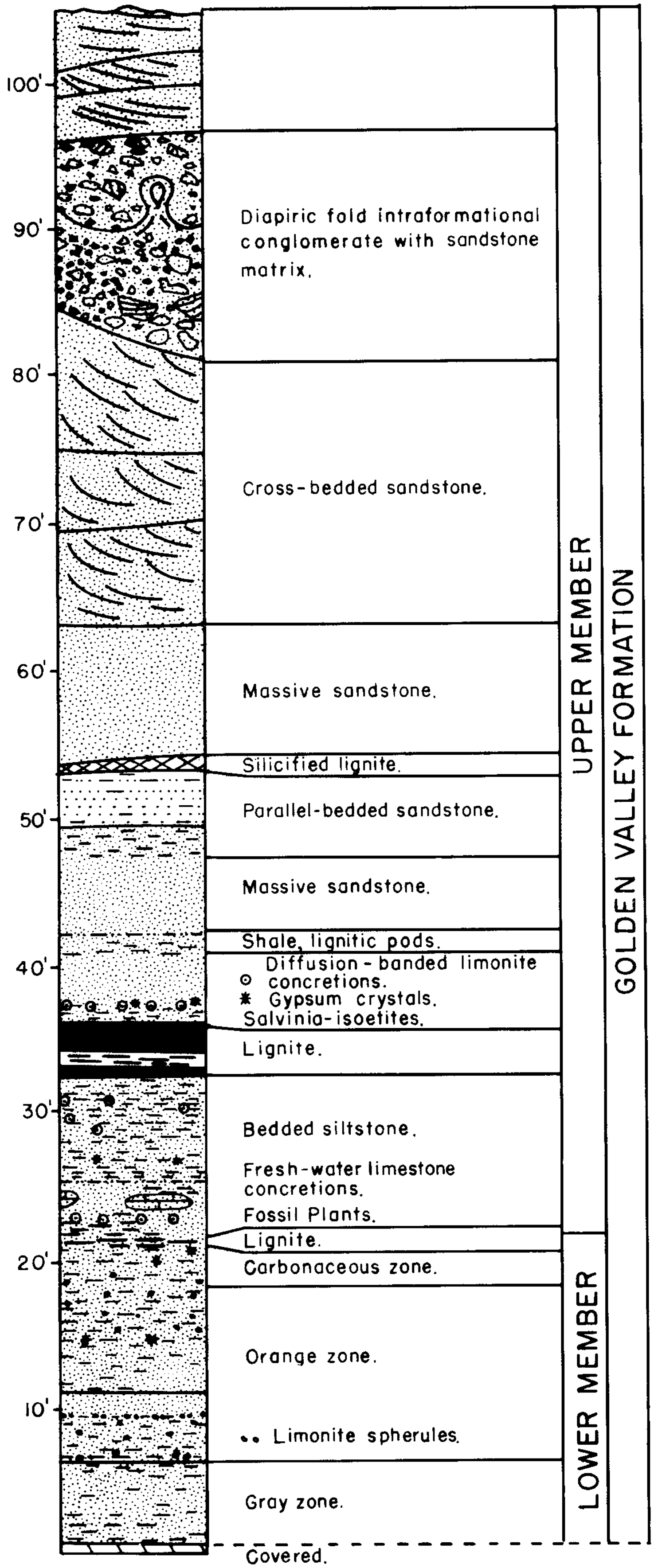

Figure R-6. Stop 4. The Golden Valley Formation at Camels Butte.

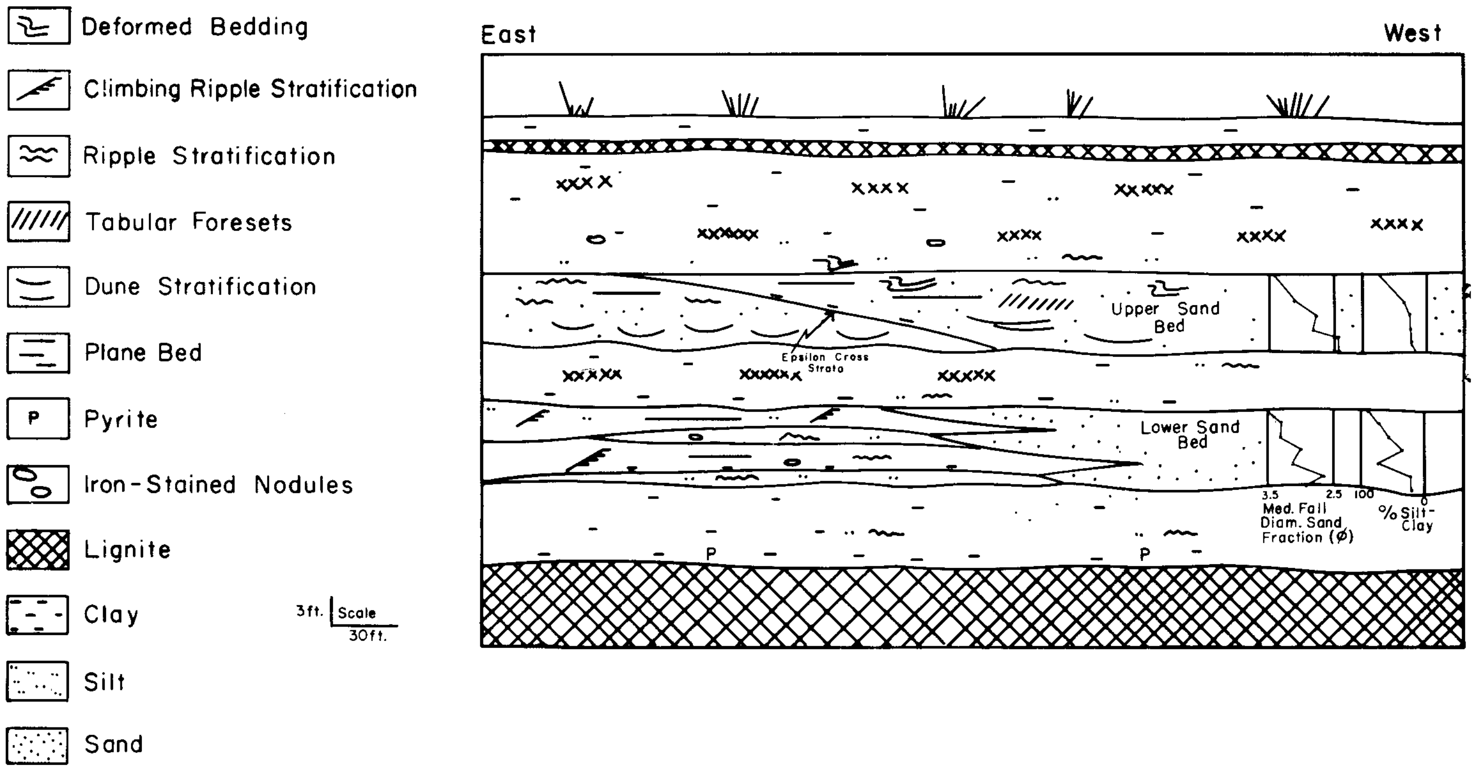

Figure R-7. Stop 5. Diagram of the western part of the south wall of the Husky Mine during the spring of 1972.

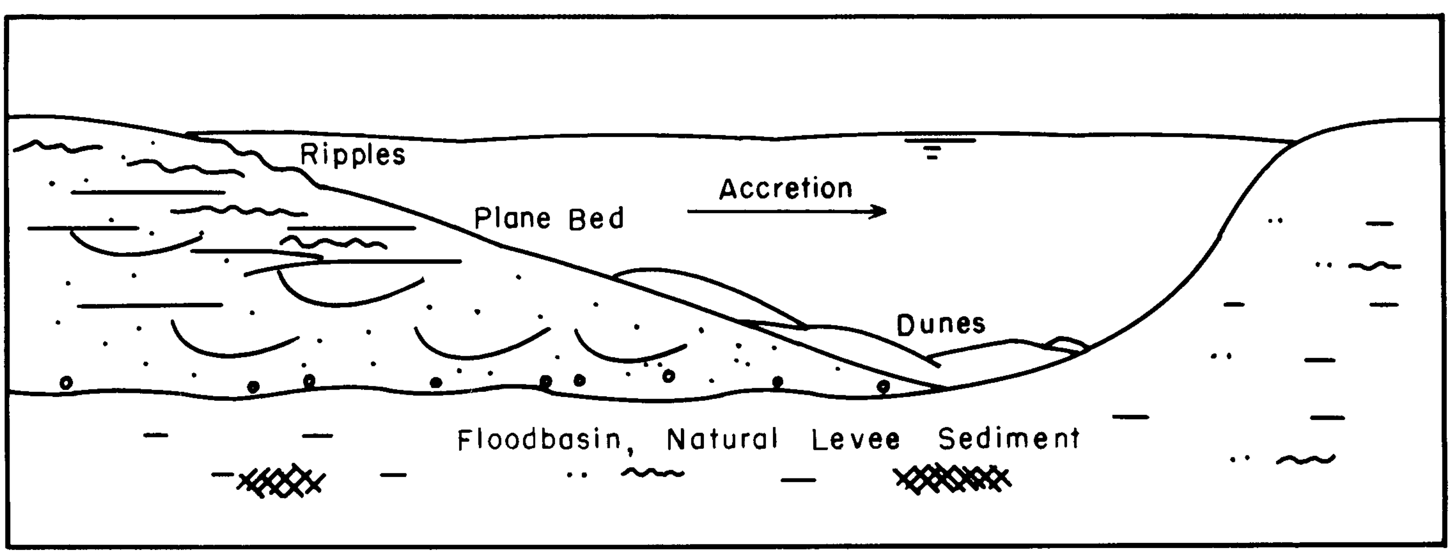

Figure R-8. Stop 5. Model for the origin of the sand beds in the Husky Mine. Accretion is taking place toward the concave side of a point bar.

Drive over upland underlain by the Sentinel Butte Formation until mile 28.7.

Mile 60.8 to 55.3: Dickinson Oil Field.--Oil-well pumps of the Dickinson oil field. Production is from the Pennsylvanian Tyler Formation; one well has also produced from the Mississippian Madison Group.

Mile 40.4.--Leave Stark County and enter Billings County.

Mile 35.1.--Approach the east edge of the Little Missouri Badlands.

Mile 33.6.--Turn off on exit 8 to Painted Canyon Scenic overlook. Brief stop.

Go over the overpass (at mile 33.0). Then descend into the Badlands and continue on the gravel road about 2½ miles to the road junction just across the railroad tracks. Turn right (south) and continue on the gravel road 1.1 mile to stop 6.

Stop 6: Petrified Forest in the Sentinel Butte Formation by F. T. C. Ting.--The purpose of this stop is to observe the occurrence of petrified Paleocene peat in a lignite bed in the lower part of the Sentinel Butte Formation. The petrified peat occurs as slabs in the upper part of a 3-foot lignite bed. A 5-inch clay parting divides the lignite bed into two parts 15 inches below the top of the coal bed. Several petrified stumps are also visible in the upper part of the coal bed. Nearby, there are numerous petrified stumps scattered within an area of several square miles and occupying the same stratigraphic horizon. Most of them are not associated with lignite beds.

The petrified peat at this locality is the first reported, well preserved, petrified peat in North America. The state of preservation is comparable to that of "coal ball" of Pennsylvanian age. Part of the slab shown at the left side of figure R-10-A has yielded abundant well preserved plant remains including roots, stems, seeds, well preserved xylem, phloem, bordered pits, fern annuli, and many unidentified tissues and organs. This peat offers a valuable intermediate material for the study of coalification of Tertiary lignite in particular and coal in general.

The petrified stump shown in figure R-10-A also offers a good opportunity to measure the compaction of lignite after the peat stage. Figure R-10-B illustrates the compaction ratio since at least the time of the petrification of the conifer stump. The stump shows very little sign of compaction. Thus, the ratio 4 represents a good measure of the compaction of North Dakota lignite.

Return to I-94.

Mile 33.0.--Go west (left) onto I-94.

Mile 31.5.--Descend into the Badlands again.

Mile 29.4: HT bed.--The red rock here is scoria resulting from burning of the lignite of the HT Bed at the base of the Sentinel Butte Formation.

Figure R-9. (A) Cross section of siliceous "coal ball" showing many roots in cross section and oblique section (X 0.5). (B) Section of a possible conifer seed (X 100). (C) Transverse section of a young root (?). The secondary wood and one layer of phloem cells are well preserved. The cambium was not preserved. Ephidermal cells are evident (X 100). (D) Unidentified parenchymatous tissue (X 120). (E) Transverse section of a portion of a root (?) showing secondary xylem and several layers of well preserved stone cells (X 150). (F) Rootlets (X 120). (G) Radial section of secondary wood showing tracheids with bordered pits and rays (X 300). (H) Fern annuli (X 300). (I) Tangential section of wood showing uniseriate ray cells and tracheids (X 150). (Ting, 1972, Reprinted from Science with permission)

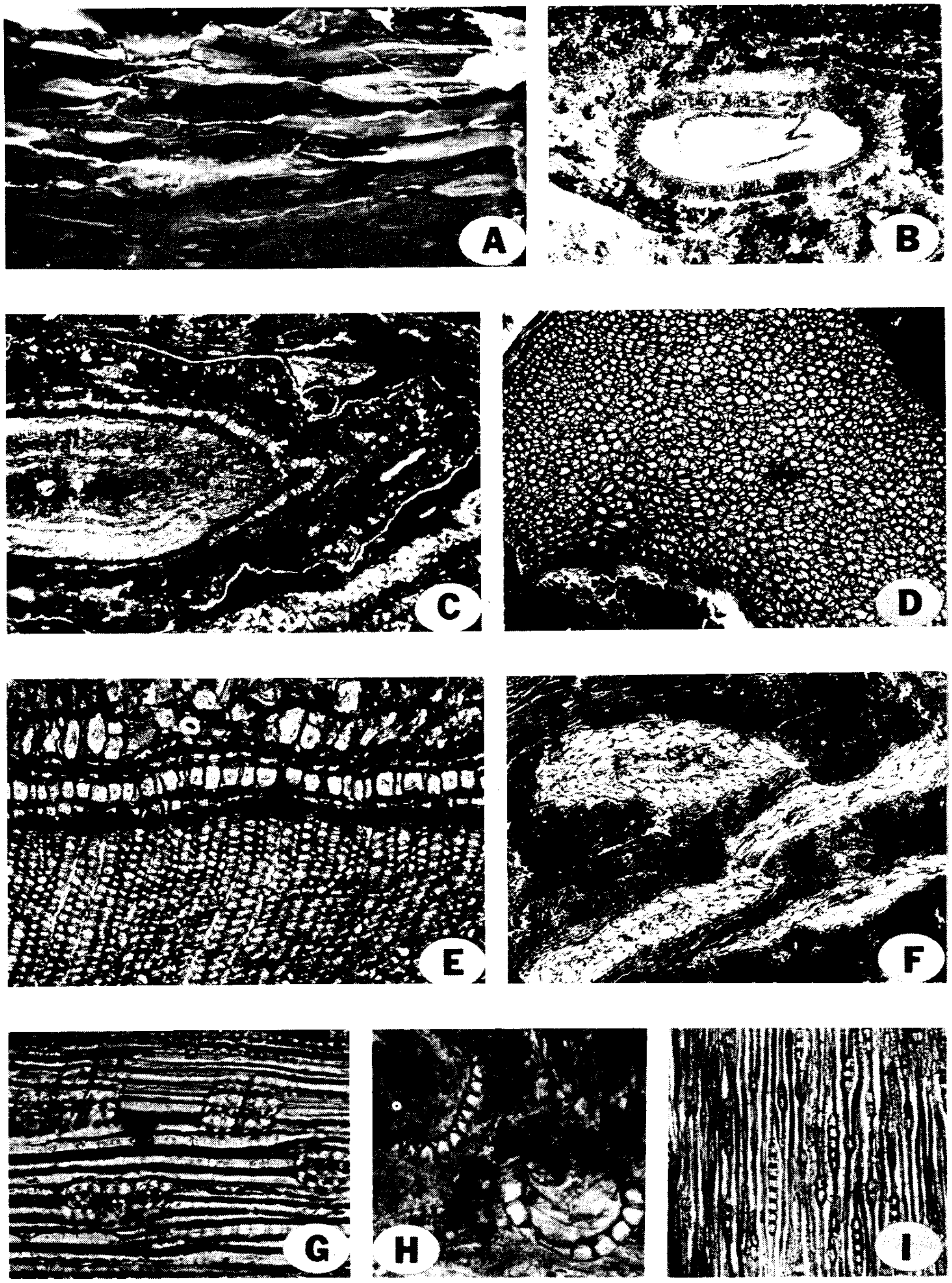

Figure R-9. Stop 6. (A) Cross section of siliceous "coal ball" showing many roots in cross section and oblique section (X 0.5). (B) Section of a possible conifer seed (X 100). (C) Transverse section of a young root (?). The secondary wood and one layer of phloem cells are well preserved. The cambium was not preserved. Epidermal cells are evident (X 100). (D) Unidentified parenchymatous tissue (X 120). (E) Transverse section of a portion of a root (?) showing secondary xylem and several layers of well preserved stone cells (X 150). (F) Rootlets (X 120). (G) Radial section of secondary wood showing tracheids with bordered pits and rays (X 300). (H) Fern annuli (X 300). (I) Tangential section of wood showing uniseriate ray cells and tracheids (X 150). (Reprinted from Science with permission, Ting, 1972)

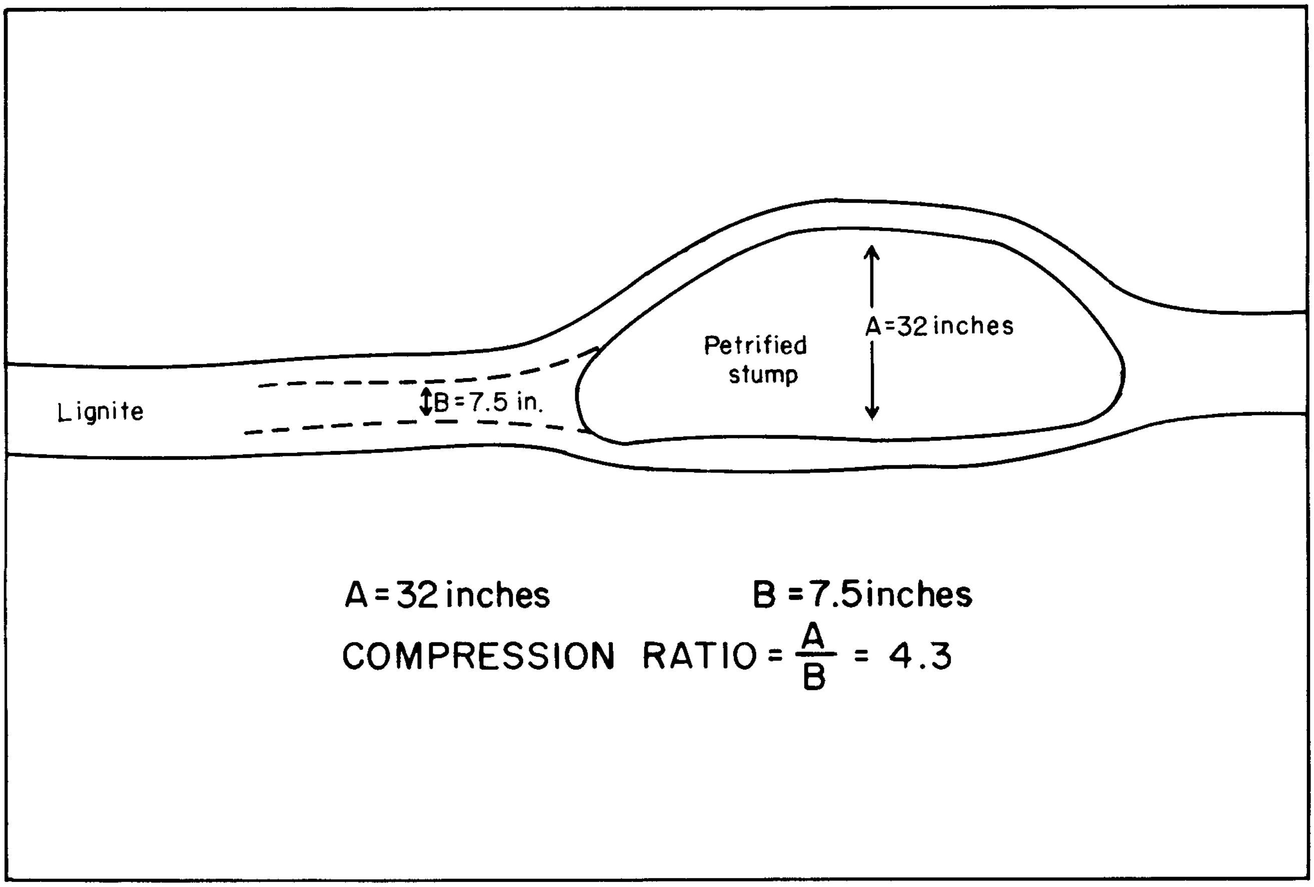

Figure R-10. Stop 6. A. Road cut exposure showing the occurrence of petrified peat (left) and a petrified conifer stump in a lignite bed. B. Schematic sketch illustrating the compaction of lignite since peat stage.

Mile 28.7: Tongue River Formation.--Drop down into the Tongue River Formation. The Sentinel Butte Formation is dull grayish brown; the Tongue River Formation is grayish yellow.

Gypsum.--The sparkles on the roadside are not broken glass; they are crystals of gypsum (selenite) from the Tongue River or Sentinel Butte Formations.

Mile 28.3 to 27.5: Ponderosa Pine.--The Ponderosa pine on the left (south) are the most northeasterly representatives of a population that extends throughout the semiarid west. Juniper are the most common trees on steep slopes throughout the Badlands. Other plants characteristic of dry soils in the Badlands include small cactus, yucca, and sagebrush.

Medora.--The town of Medora (population 150) is at the entrance of the South Unit of Theodore Roosevelt National Memorial Park.

Roosevelt ranched from 1883 to 1886 at the Elkhorn Ranch (north of here) and the Maltese Cross Ranch (south of here).

Medora was named after the wife of the Marquis de Mores, who started a meat-packing plant (the chimney remains near the park entrance) in 1883.

The winter of 1886-1887 broke the cattle industry. Both Roosevelt and de Mores returned to politics. De Mores, who had hoped to make a fortune on cattle to help him gain the French crown, was eventually slain by desert tribesmen in North Africa. The Chateau de Mores is just west of Medora.

Stop 7: Depositional environments of the Tongue River Formation at Medora by A. F. Jacob.--In the paper in this guidebook entitled "Depositional Environments of Parts of the Tongue River Formation, Western North Dakota," the Tongue River Formation around Medora has been interpreted as being mostly alluvial in origin. The purpose of this stop will be to examine some of the evidence used for the interpretations made in that paper.

First, from the west bank of the Little Missouri River we will view the exposures on the east bank above the town of Medora. These exposures are diagrammed in figure 5 of the paper mentioned above. Several examples of the basic alluvial cyclic unit described in that paper will be visible. We will then return to the east bank where we can closely examine rocks interpreted as having been deposited in the natural-levee, crevasse-splay, floodbasin, high-sinuosity-channel, and low-sinuosity-channel environments.

Return to Dickinson on I-94.

Mile 61.5.--Dickinson; junction with N. D. 22. Continue east on I-94. Continue on the Sentinel Butte Formation.

Mile 86.--Leave Stark County and enter Morton County.

Mile 94.--The Killdeer Channel, a late Pleistocene glacier-margin channel.

Mile 109.--Another glacier-margin channel. The Tongue River Formation occurs near the bottom of the channel walls.

Mile 115.--The Tongue River Formation occurs near the bottoms of four small valleys that we will cross during the next 10 miles.

Mile 132.--Drive off the Sentinel Butte Formation onto the Tongue River Formation.

Mile 136.--Sweet Briar Dam. Cannonball Formation at the bottom of the valley.

Mile 139.--Drive off the Tongue River Formation onto the Cannonball Formation.

Mile 153.--Exit 32. Go south of Mandan on N. D. 80 to Fort Lincoln.

Fort Lincoln.--Custer left Fort Lincoln in May, 1876, to meet the Sioux at the Little Bighorn a month later.

Several Indian earth lodges have been reconstructed here on the site of a village that was active in the 1700's.

The first known European to enter this area was the French-Canadian trader Pierre de la Verendrye, who visited the Mandans at one of their earth-lodge villages in this area in 1738.

Stop 8: The Cannonball Formation at Fort Lincoln by A. M. Cvancara.--The lower to middle part of Cannonball Formation (Paleocene) is exposed in a roadcut in the NW¼ sec. 13, T. 138 N., R. 81 W., 0.1 mile north of north boundary of Fort Lincoln State Park, and about 4¼ miles south of Mandan, northeastern Morton County. At this locality (Fig. R-11), 44.8 feet of sandstone (upper 16.8 feet mostly concealed) overlies 101.3 feet of mudstone. The poorly consolidated, mainly fine-grained sandstone is light grayish green when moist and weathers (dry) light brownish yellow. In the upper part are lenticular, well indurated sandstone beds (medium blue-greenish gray, weather light to medium brownish yellow). These resistant beds form conspicuous, flattened uplands and topographic "benches" or "shoulders" at different levels, especially in the area south and west of Mandan. In the lower, well-exposed part of the poorly consolidated sandstone are lenticular, well indurated beds of sandstone (up to 0.6 foot thick) and claystone (up to 0.2 foot thick). The claystone (shown as dark beds in Fig. R-11) forms a dark, orange-yellow rubble on the surface of the exposure. Mostly fragmental, marine bivalves and gastropods are the most common fossils in this sandstone unit.

The underlying mudstone unit is poorly consolidated,medium tan-gray to very dark gray when moist and weathers (dry) light brownish-yellowish gray to light gray. Sand is present in variable amounts throughout and occurs also commonly in thin beds (mostly less than 0.1 to 0.2 foot; one bed is 1.5 feet thick) that are lenticular and may show cross-bedding. Near the lower part of the unit is lenticular to concretionary, well indurated,

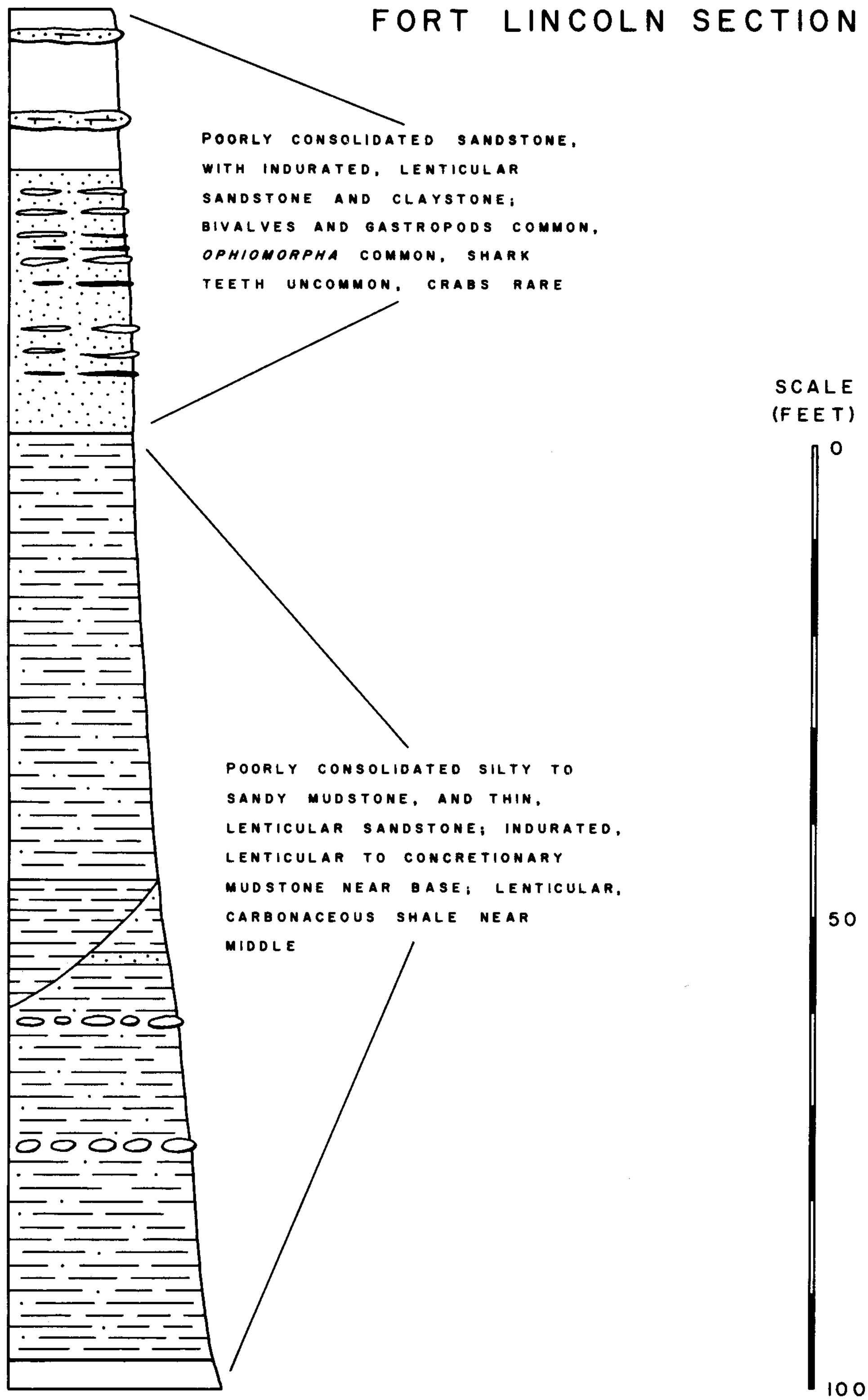

Figure R-11. Stop 8. Fort Lincoln section; Cannonball Formation, west roadcut exposure (NW¼, sec. 13, T.138 N., R.81 W.), 0.1 mile north of Fort Lincoln State Park or about 4¼ miles south of Mandan. Blank areas indicate concealed parts of section. Light beds in the poorly consolidated sandstone unit are of sandstone and the dark beds are of claystone.

highly calcareous, sandy mudstone up to 1 foot thick. It is light gray and weathers whitish gray. Throughout the unit are scattered marcasite nodules and selenite along bedding fractures; small plant fragments are common.

About 43 feet below the top of the mudstone units is a lenticular (0 to 13.4 feet thick), fissile, slightly calcareous, carbonaceous shale. It is very dark brownish gray to black and weathers light brownish gray. This shale body may represent an abandoned tidal channel.

Return to Mandan; return to Bismarck. End of field trip.

BISMARCK TO MINNEAPOLIS

ON I-94

Mile 157.--The Cannonball Formation is overlain by thin patches of glacial sediment of the Bradock Formation for the next 11 miles.

Mile 168.--Collapsed superglacial lake sediment of the Fourbears Formation for the next 10 miles.

Mile 178.--The glacial sediment of the Coleharbor Group is about 100 feet thick for the next several miles.

Mile 201.--Steele is in the middle of a flat ice-walled-lake plain, which is 2 miles across and elevated tens of feet above the surrounding glacial sediment.

Mile 206: Kidder Sand Plain.--The Kidder Sand Plain is largely collapsed superglacial stream sediment of the Fourbears Formation. The sand was deposited 13,000 to 10,000 years ago on stagnant glacial ice at the end of the Wisconsinan Glaciation.

Mile 217: Missouri Coteau.--The Missouri Coteau (or Coteau du Missouri, or "hills of the Missouri") is an area of collapsed thick superglacial glacial sediment having hummocky topography. The Coleharbor Group is 200 to 400 feet thick over the shale of the Cretaceous Pierre Formation. This is one of the main wild duck breeding areas in the United States.

Mile 242: Glacial plain.--An undulating glacial plain extends eastward to the Red River Valley. The Coleharbor Group is 100 to 400 feet thick in most of this area. The glacial sediment of the late Wisconsinan advance averages about 10 feet thick. The bedrock is the Pierre Formation.

Mile 260: James trench.--The James River trench here is about a mile wide. In late Wisconsinan time it held a river the size of the lower Mississippi River. It drained much of the midcontinent area to the Rockies. Shale of the Pierre Formation is exposed in the slumped sides of the trench.

Mile 265.--A smaller melt-water channel.

Mile 291: Sheyenne trench.--The Sheyenne River trench is similar to the James River trench at mile 260.

Mile 319: Lake Agassiz.--The Red River Valley here is the plain of glacial Lake Agassiz. Several low beach ridges can be seen near mile 320, 321, 323, and 324. Lake Agassiz existed from 13,500 to 8,000 years ago. Much of the time its outlet was to the south through the Minnesota River. Between 11,000 and 10,000 and after 9,500, this part of the lake became dry as the ice melted back and opened a lower outlet into northern Lake Superior. The Coleharbor Group is 200 to 300 feet thick here. The bedrock consists of several lower to upper Cretaceous formations. Precambrian rocks subcrop beneath the Pleistocene sediment from near Fargo most of the way to Minneapolis.

Mile 335: Maple Ridge.--Maple Ridge is the result of the compaction of Lake Agassiz offshore sediment around a body of less compactive channel sediment. The channel sediment was deposited on the unconformity between the offshore sediment that was deposited from 13,500 to 11,000 and the offshore sediment that was deposited from 10,000 to 9,500.

Mile 353.--Red River of the North, a tributary of the Nelson River, which empties into Hudson Bay. Enter Minnesota (mile 0.0).

Mile 20 to 24.--Lake Agassiz beaches.

Mile 28.--East edge of plain of Lake Agassiz. Drive across undulating glacial plain for 4 miles.

Mile 33.--Hummocky collapsed superglacial sediment (as on the Missouri Coteau from mile 217 to 242) for the next 68 miles.

Mile 101.--Undulating glacial plain and fluvial deposits largely of Late Wisconsinan Age, from here to Minneapolis. Precambrian rocks outcrop in a few places. Granite quarries can be seen in the St. Cloud area.

THE TONGUE RIVER AND SENTINEL BUTTE FORMATIONS (PALEOCENE) OF WESTERN NORTH DAKOTA: A REVIEW

Chester F. Royse, Jr.

INTRODUCTION

In western North Dakota, the Tongue River and Sentinel Butte Formations comprise the upper portion of a stratigraphic sequence that constitutes a depositional continuum from late Cretaceous time through the Paleocene. Upward the sequence is transitional from marine to terrestrial. Collectively, the sequence constitutes a "clastic wedge" spread eastward from the Rocky Mountains during successive episodes of Laramide orogeny that may be referred to as exogeosynclinal (Royse, 1970) or as "continental replacement" (Dunbar and Rodgers, 1963).

No discussion of these strata would be complete without at least a brief reference to the controversy that has colored their history from the time of the early Territorial Surveys. The earliest geological reports referred to these coal-bearing beds as the "Great Lignite Sequence." Meek and Hayden (1862) supplanted this usage with Fort Union Group for strata along the confluence of the Yellowstone and Missouri Rivers near the present North Dakota-Montana line. The term "Lignitic Group" was also replaced by the term "Laramie Group" in the vicinity of the fortieth parallel by King (1876). This duplication of terminology was soon recognized and (presumably) King and Hayden agreed to include all strata between the Fox Hills Sandstone and the Wasatch (or its equivalents) within the "Laramie Group." For reasons that are not entirely evident, this compromise failed and the term Fort Union persisted. Subsequent workers began to restrict the usage of Fort Union and Laramie and to apply new terms to portions of this interval. Weed (1893) defined the Livingstone Formation in Montana as an interval between the Fort Union and Laramie beds. In Converse County, Wyoming, Hatcher (1903) applied the name "Lance Creek beds" to the dinosaur-bearing beds between the Fox Hills and Fort Union; similar strata in eastern Montana were named "Hell Creek beds" by Brown (1907) and subsequently became known as the Hell Creek Member of the Lance Formation. From its inception the term Lance was equivalent in part to Laramie; but, due to the confusion attendant with the use of Laramie, the term Lance was retained and the use of Laramie has been largely restricted to the Denver Basin. In Montana and the Dakotas, additional stratigraphic units such as the Lebo, Ludlow, Tullock, Cannonball, Tongue River, and Sentinel Butte were differentiated and variously considered as members of the Lance, Fort Union, or even the Wasatch.

From the beginning, differences of opinion existed as to the age of the Laramie and Fort Union. King asserted a Cretaceous age for his Laramie, and Hayden insisted that the Fort Union was early Tertiary ("Eocene" as then defined). Their greatest error was probably their failure to recognize that they were both largely correct. The mixed state of opinion was aggravated by the work of paleontologists such as Lesquereaux, C. A. White, Newberry, Ward, and others. As a result of the absence of an adequate American standard to cover the floras in question, elements of both the Cretaceous and Tertiary were badly mixed in collections. The opinion prevailed that the "Great Lignite" was transitional between the Cretaceous and the Tertiary. Although Newberry (1888) apparently recognized a marked difference between the floras of the upper and lower parts of the "Great Lignite," it remained for Dorf (1940, 1942) to explicitly define these differences in his comparison of the Lance and Fort Union floras.

Were it not for the fact that the lignite strata of the northern plains contained the Cretaceous-Tertiary boundary, the debate concerning their stratigraphy could never have become so heated and intense. Brown (1962, p. 3-8) presents an interesting account of the evolution of the facts, fancy, and opinion involved in this debate. As it is not my purpose to pursue this topic in detail, I refer interested readers to his account.

The discovery of mammals in Fort Union strata shortly after 1900 contributed significantly to placement of the boundary in Montana, and discovery of Cannonball marine strata aided in clarifying the age of Fort Union strata in the Dakotas. Despite the fact that many principal subdivisions are now recognized, the term Fort Union continues to be used by many in a sense synonymous with Paleocene Series. To paraphrase Jepsen and Woodburn (1969, p. 543), the common practice is simply to assign all Paleocene Rocks to the Fort Union Formation. This designation continues the archaic practice of using the term Fort Union as a verbal receptacle for any somber-colored rocks of Paleocene (or near Paleocene) age. This usage, repeatedly rejected, is inaccurate and confusing, and it violates the rules and concepts of good stratigraphic studies, but it has been defended because it simplifies nomenclature. Simplification is achieved by ignoring, and thus avoiding, some difficult lithologic and cartographic problems and by indicating correlations that are, in part at least, recognized as erroneous. I agree with Jepsen that "Fort Union" has become a stratigraphic wastebasket. The term should probably be confined to the Williston basin and proximal areas of Montana and relegated to no lower rank than that of group. The use of local terminology will contribute more to deciphering this complex stratigraphy than will shrouding significant variations with a "Fort-Union cloak."

STRUCTURE AND STRATIGRAPHY

Within the Williston Basin of western North Dakota, the Paleocene Series conformably overlies the Hell Creek Formation and is overlain conformably by the Golden Valley Formation (Paleocene-Eocene) or disconformably by the White River (Oligocene) Formation and assorted Pleistocene deposits. Major outcrops are largely restricted to sparsely glaciated areas south and west of the Missouri River, although significant exposures are also present along the scarp of the Missouri Coteau and in the Turtle Mountains north of the Missouri (Fig. 1).

The Tongue River and Sentinel Butte Formations constitute the greatest Paleocene outcrop area within the Williston Basin. The base of the Tongue River is conformable upon the Ludlow Formation in the southern portion of the Little Missouri badlands (in northern Slope County) and upon the Cannonball Formation to the east in Morton and Grant Counties. Throughout the greatest portion of its area of outcrop, the basal contact of the Tongue River lies in the subsurface or is concealed by glacial drift. The Tongue River-Sentinel Butte contact is a distinctive and widely exposed horizon. It is distinguished by a marked change in gross color from buff yellow below to somber gray above the

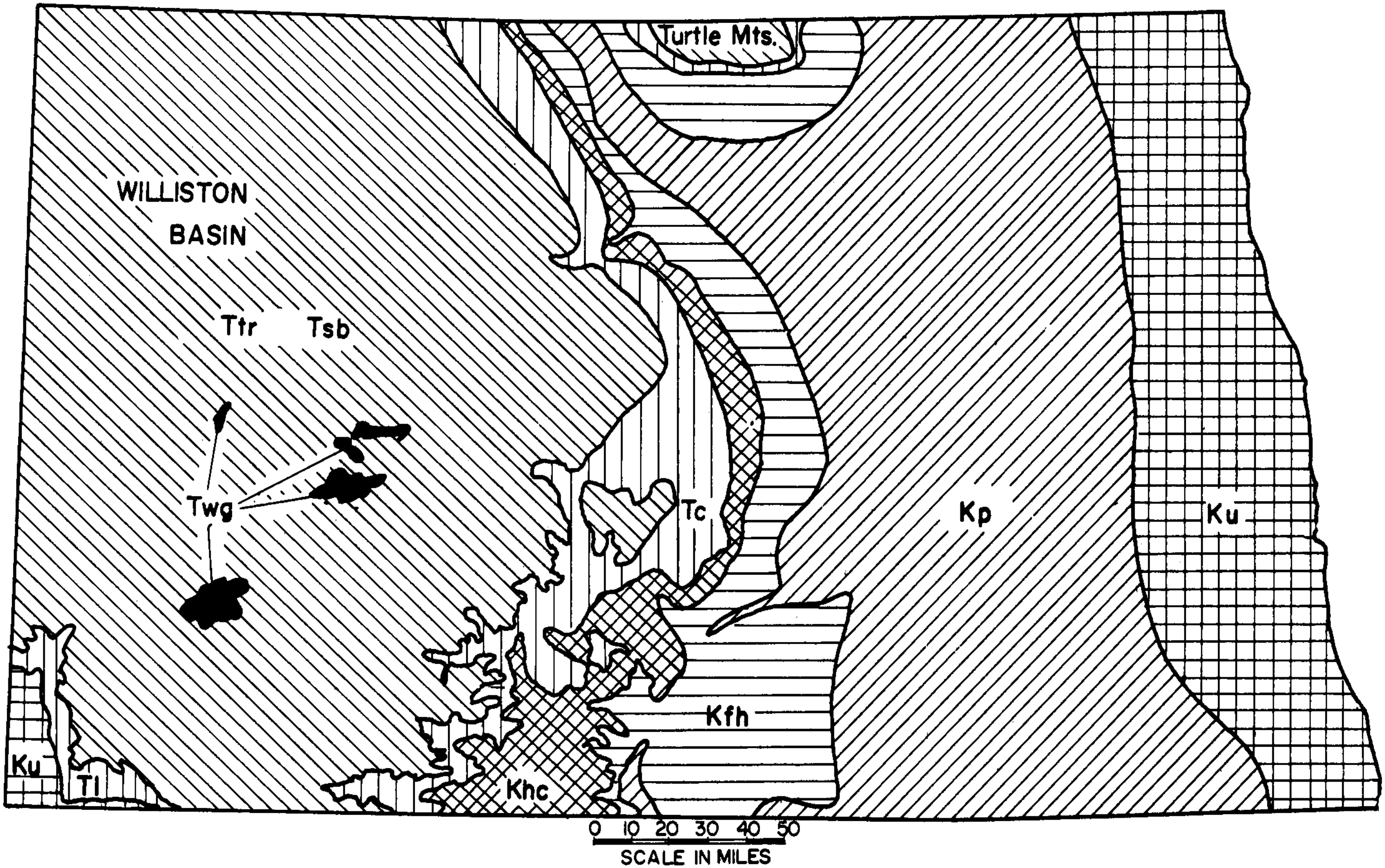

Figure 1. Generalized geologic map of North Dakota (after N. Dakota Geol. Survey., Misc. Map 8). Twg = White River and Golden Valley; Ttr Tsb = Tongue River and Sentinel Butte; Tl = Ludlow; Tc = Cannonball; Khc = Hell Creek; Kfh = Fox Hills; Kp = Pierre Shale; and Ku = undifferentiated Cretaceous formations (from Royse, 1970).

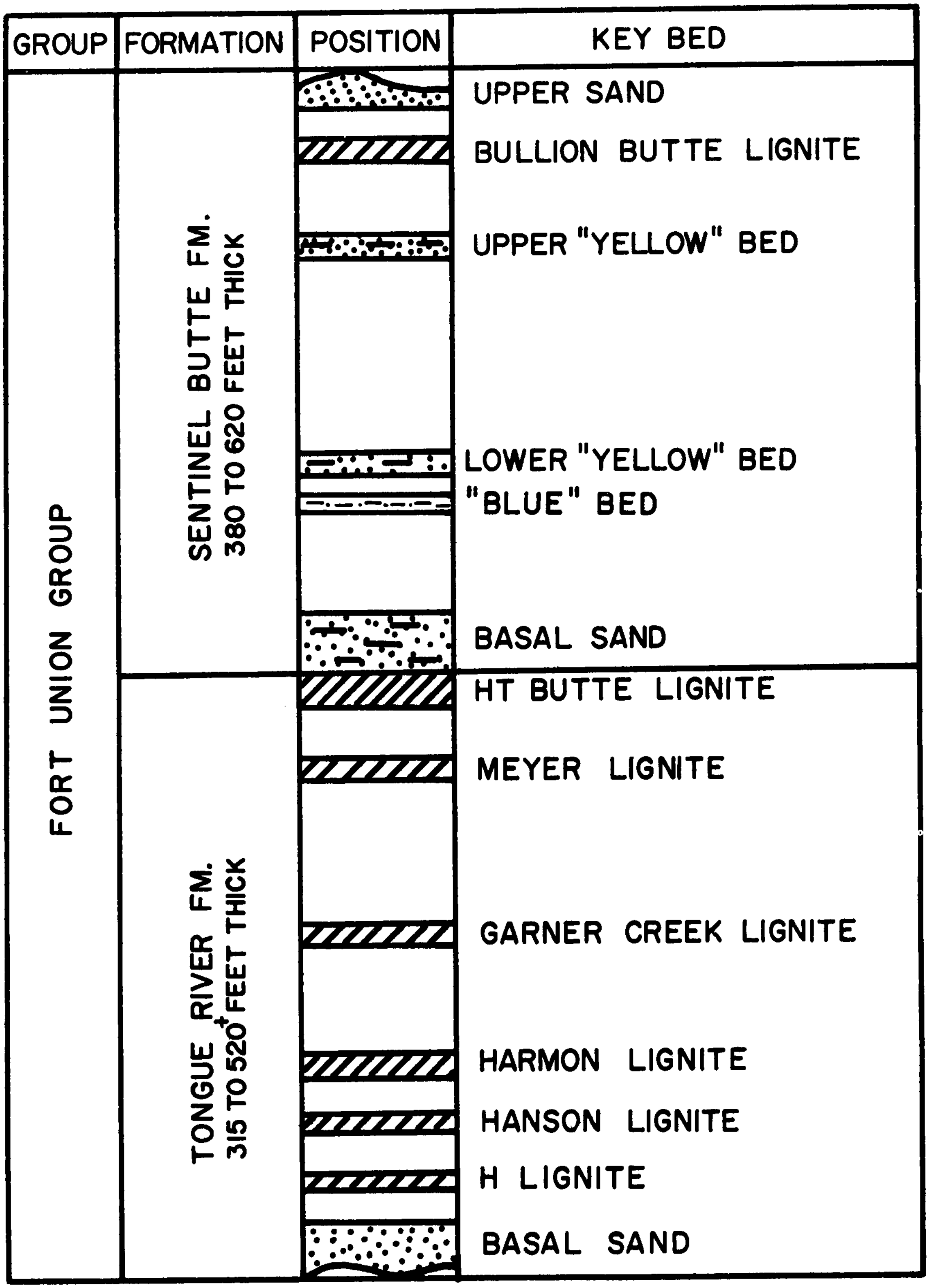

Figure 2. Generalized stratigraphic column of the Tongue River-Sentinel Butte interval in western North Dakota (from Royse, 1970).

contact, the presence of a lignite (the HT Butte bed) at the top of the Tongue River and the presence of a basal sand in the Sentinel Butte Formation. Royse (1967) has discussed the significance and persistence of these and other criteria in mapping the contact.

Lignite beds are good marker horizons in the Tongue River, but their usefulness is limited because most occur low in the section and are exposed in outcrop only in the southern portion of the badlands. They are persistent within the Marmarth coal field (Hares, 1928) but, northward, the regional dip carries them into the subsurface. Lignites are less well developed in the Sentinel Butte Formation, and none are recognized as useful in correlation (Royse, 1970, p. 25). The Bullion Butte lignite, in the upper Sentinel Butte, may have considerable persistence; but, because upper Sentinel Butte strata have been widely removed by erosion, outcrops are scattered and correlations are uncertain. Unlike the Tongue River Formation, several persistent non-lignitic beds are present in the Sentinel Butte which permit limited correlation. These consist of a basal sand, a "blue" bed, a lower "yellow" bed, an upper "yellow" bed and an upper sand. The relative positions of these beds, along with principal lignites, are indicated in Figure 2.

The upper contact of the Sentinel Butte is not widely exposed, but it can be seen at a number of localities. At Sentinel Butte, Bullion and HT Buttes, beds of the White River Formation (Oligocene) rest disconformably on upper Sentinel Butte strata. In the axial portions of the Williston Basin the Sentinel Butte is conformably overlain by the Golden Valley Formation, the lower member of which is also Paleocene (Hickey, 1969). The Sentinel Butte-White River contact is a marked unconformity which, in places such as at Sentinel Butte and Bullion Butte, indicates a long period of weathering and development of a paleosol prior to deposition of the White River beds (Pettyjohn, 1966; Royse, 1970). The Sentinel Butte-Golden Valley contact is gradational and not well defined. Neither the top of the Sentinel Butte nor the base of the Golden Valley has been explicitly and consistently defined. Royse (1970) considered the top of the Sentinel Butte to occur slightly above the "upper" sand, but it was not precisely defined. Likewise, Freas (1962) placed the lower contact of the Golden Valley at the base of a "lower-most light-gray or purplish silt bed which occurs about 10-15 feet below the kaolinitic beds of the basal unit." This is slightly lower than the same contact as defined by Benson (1952). It appears that neither the top of the Sentinel Butte nor the base of the Golden Valley has been mutually considered in any definition of their contact. As noted by Royse (1970, p. 78), the upper Sentinel Butte sand is dissimilar in texture (and possibly in composition) to other sands in the formation and appears to represent a significant rejuvenation of the source area to the west. It may be that, in a genetic sense, this sand unit is more closely related to the Golden Valley depositional episode, than to that of the Sentinel Butte (i.e., that it is a basal Golden Valley sand) and that the contact between the two should be placed at its base. Additional observations are needed to confirm this suggestion.

The basic structural element in western North Dakota is the Williston Basin; minor positive structures that are defined by Paleocene strata within the basin include the Nesson anticline, Poplar Dome, and Cedar Creek anticline. The basinal structure is clearly evident from the regional extent of the Tongue River-Sentinel Butte contact as mapped by Royse (1967, Fig. 1). West of the Little Missouri River the contact is discontinuous and occurs in divides and buttes which rise above the regional level. East of the river, the contact is essentially continuous in outcrop, below the regional level, throughout the badlands from northern Slope to southern McKenzie County. The terrain for many miles east of the "breaks" of the badlands is developed on strata of Sentinel Butte and younger age, but within and west of the badlands Tongue River strata predominate. Both the Tongue River and Sentinel Butte Formations appear to be thin (200-300 feet) along the southern and southwestern flanks of the basin and thicken (600 feet) toward its center, a relationship that suggests that the total accumulated thickness of both units was controlled by Williston Basin subsidence during Paleocene time.

Local variations, and even reversals, of dip define minor structures in Tongue River and Sentinel Butte strata. Some of these have proven to be surface manifestations of deeper structures capable of trapping petroleum. Erickson (1970) utilized surface lineaments and minor structures defined by the Tongue River-Sentinel Butte contact to aid in interpretation of basement structure.

SEDIMENTOLOGY

Texturally, all Tongue River and Sentinel Butte sediments are relatively fine-grained and most are only poorly consolidated. Lithologies range from mudstone and siltstone to sandstone with pods and lentils of impure limestone and beds of lignite. Carbonate is the principal cementing agent, although locally iron oxides form concretionary beds, and iron sulfide (marcasite) forms concretions.

Based on analysis of about 350 sediment samples from 11 stratigraphic sections, Royse (1970, p. 27-34) reported that Tongue River samples have mean diameters that range from 2 to 10 phi and average about 6.6 phi. Sentinel Butte samples are slightly coarser, ranging from about 2.5 to 9.5 phi with an average mean of about 5.9 phi. Sentinel Butte strata are slightly better sorted than those of the Tongue River although both units are poorly sorted in general. Both units are also predominantly positively skewed, but a slight tendency for higher skewness values exists in Tongue River sediments; most are very-fine to fine skewed according to the definition of Folk and Ward (1957). Comparison shows that the range of sediment types is similar for the two formations; but Tongue River sediments have a strong mode in the silty-clay and clayey silt classes, whereas Sentinel Butte sediments are dominantly silts and clayey silts.

A variety of sedimentary structures, both large- and small-scale and primary and secondary, occur in these formations. The bounding surfaces of major lithologic units are usually planar; discordance is prominent only in small-scale features. Laminations in silt, silty clay, and clayey silt beds are nearly ubiquitous in outcrops of both the Tongue River and Sentinel Butte; these vary in thickness but seldom exceed 0.5 cm. Most large sandstone bodies are massive near the base and become both finer grained and more thinly bedded upward; laminations commonly occur in their upper portions. Sandstone bodies in general and flat-bedding in particular is more abundant in the Tongue River Formation.

In terms of volume, cross-stratified sands are not abundant; but, because they are commonly well lithified, they are prominent. Large-scale cross-beds consist primarily of lithologically homogenous wedge-shaped cosets with erosional, planar lower boundaries which rest discordantly on underlyings sets (xi-cross-stratification of Allen, 1963); occasionally wedges elongate to form more tabular sets (omikron-cross-stratification). Large-scale trough sets (pi-cross-stratification) is absent or rare. Small-scale cross beds are lithologically homogenous cosets bounded by erosional or gradational surfaces. The lower bounding surfaces are predominantly curved (kappa-cross-stratification) but planar contacts (lambda-cross-stratification) also occur. Small-scale festoon bedding (nu-cross-stratification) is also present.

Inclined strata of large magnitude occur at a number of localities in the basal Sentinel Butte sand which have been interpreted as delta fore-set beds. Occasionally channel-fill deposits can be identified, but major channeling and other evidences of erosion are uncommon. Convolute bedding is rare but does occur. Likewise, mud-cracks and other subaerial dessication features occur locally. These and other structures have been illustrated by Royse (1967, 1970).

On the basis of textures, structures, and, to a minor extent, the mode of occurrence and distribution of fossils, three fundamental fluvial facies can be defined: backswamp, floodplain, and channel. The attributes of each of these deposits have been discussed in detail (Royse, 1970, p. 51-53) and need not be reiterated here. It is significant, however, that the relative abundance of these facies differs between the Tongue River and Sentinel Butte Formations. The Tongue River contains relatively greater proportions of backswamp and less floodplain material than does the Sentinel Butte.

Although detailed petrographic study of the Tongue River-Sentinel Butte interval is currently in progress, only the gross lithologic relationships will be reviewed here to facilitate paleogeographic and fluvial reconstruction. As noted, both the Tongue River and Sentinel Butte are lignitic, but the thickest and most persistent lignites occur in the Tongue River. Pods, lenses, lentils, and discontinuous beds of argillaceous, dolomitic limestone also occur in both formations but are more abundant in Tongue River strata. Likewise, the average carbonate content (weight percent CO_3) of Tongue River sediments is about 12.1%, whereas Sentinel Butte sediment averages only about 6.5%.

The fauna and flora of the Tongue River-Sentinel Butte interval reflect a fluvial origin of these strata. Mollusks are the predominant faunal component, are most common in finer-grained sediments, and are far more abundant in Tongue River than in Sentinel Butte strata.

The results of textural analyses (Royse, 1970, p. 27-34) used in conjunction with empirical curves for sediment transport (Sundborg, 1956, p. 177 and 218) and the considerations of Jopling (1966, p. 6-12) suggest that minimum competent flow velocities of Tongue River and Sentinel Butte streams were of the order of 47 and 55 cm/sec., respectively. Evaluation of CM diagrams indicates that these streams transported no material exclusively as bed-load; all sediment was subject to suspended transport. Because suspended transport becomes moderately well developed only at velocities 2-2.5 times the competent velocities, actual transport velocities (10 m above the bottom) of the Paleocene streams which coursed eastward across the Williston Basin were probably on the order of 94-118 and 110-138 cm/sec. Because most coarse sediment is transported and deposited by streams during flood stage, these values can be assummed to represent minimum flood velocities. Such values are less than mid-channel velocities of the modern Mississippi River (183 cm/sec, 10 m above the bottom) near Mayersville, Mississippi (Passega, 1957, Fig. 3); and, by comparison, the Paleocene streams must have been somewhat sluggish.

Facies analysis indicates that channel-type deposits comprise nearly 50% of the strata in both the Tongue River and Sentinel Butte Formations, but backswamp deposits are more abundant in Tongue River strata. A necessary requisite for backswamp (floodbasin) development is channel stability; channels must be confined to well-established belts (alluvial ridges) from which sediment escapes to protected backwater areas only during periodic episodes of flood. The lower Mississippi River, where it approaches its deltaic plain, is an example of such a system (Fisk, 1947). By contrast, the Sentinel Butte streams were less stable waterways and backswamp deposits are a minor facies component. Because backswamps usually increase in both area and thickness, relative to levees and channels, in a downstream direction (Fisk, 1947, p. 45-46; Allen, 1965, p. 124), the abundance of backswamp deposits also indicates a near-terminal fluvial environment of deposition for Tongue River sediments.

Both the type and relative abundance of sedimentary structures are useful in paleoenvironmental reconstruction. Small-scale structures predominate over large-scale in both Tongue River and Sentinel Butte strata, but the latter are more abundant in Tongue River strata. Large-scale structures (xi- and omikron-cross-stratification) indicate point-bar and sand-wave origin. Consideration of the criteria for sediment supply involved in forming these structures (Allen, 1963) indicates that the erosional energies of the Sentinel Butte streams were greater than those which deposited Tongue River sediments. Consideration of the origin and abundance of small-scale structures (kappa-, lambda- and nu-cross-stratification) suggests that both Tongue River and Sentinel Butte streams had high suspended-load concentrations and that erosion, even on the scale of small ripples, was not prevalent. All structures observed are products of the lower (tranquil) flow regime.

The greater limestone and interstitial carbonate content of Tongue River sediments, as compared with those of the Sentinel Butte, can also be explained in terms of fluvial regime. Abundant carbonate in vertical accretion deposits of Lower Devonian deposits of Great Britain (Allen, 1963, p. 360) has been interpreted as evidence of subaerial exposure. The high carbonate content of Tongue River floodplain facies is also assumed to be the product of enrichment as a result of groundwater evaporation. The stability of Tongue River streams and a slow rate of topstratum (overbank) deposition would allow more time for carbonate accumulation. A somewhat greater vertical accretion rate for Sentinel Butte streams might result in lower carbonate concentrations in these deposits.

The magnitude of large-scale cross stratification affords additional qualitative data on paleostream depth. Under steady-flow conditions, the height of large-scale ripples ranges from 10 to 20% of the water depth (Allen, 1965, p. 110). Individual sets of large structures in the Tongue River Formation have maximum exposed thicknesses averaging about 2 feet; true maximum thicknesses should be greater. Thus, if at least a portion of the structures studied are bedforms, minimum water depths of 20-40 feet are indicated. Maximum depths were probably much greater. The paucity of large-scale cross-stratification in the Sentinel Butte sequence suggests shoal, perhaps more diffuse channel systems.

Vectoral data for large-scale cross-beds indicate that Tongue River sediments entered the Williston Basin from the west and were dispersed uniformly in an eastward direction. Sentinel Butte deposition was heralded by an influx of "basal" sand which spread southeastward across the basin. This dispersal pattern was maintained until near the close of Sentinel Butte time when the "upper" sand was distributed from west to east in much the same pattern as the Tongue River sediments. The low standard deviation (71°) of vectoral data suggest that the Tongue River paleoslope was stable, a factor which would promote development of a mature (stable) fluvial system. Directional data for Sentinel Butte strata have a greater deviation (91°) which suggests changes in paleoslope during this depositional episode. Because the streams transporting and depositing the prograding Tongue River sediments must have followed the path of the receding Cannonball sea, the directional data suggest that this path lay to the southeast. This is in accord with the suggestion of Waage (Dunbar, 1965, p. 321) that the latest Cretaceous (and hence perhaps earliest Palocene) marine connection with the continental interior was by way of the Mississippi Embayment. The recent discovery of marine beds in the lower portion (47-50 feet above the base) of the Tongue River section in the Cave Hills area of South Dakota (Leffingwell, 1971, Fig. 5) might suggest that the Cannonball Sea lingered longer in this southern area. The precise chronostratigraphic relations of these tongues are, however, as yet unknown. According to Leffingwell (1972, written comm.) they contain marine dinoflagellates and a pollen flora "typical of the oldest Fort Union (i.e. Cannonball) time." Thus, if these beds are actually of Cannonball age (as defined farther northeast), it might be suggested that Tongue River strata began to prograde eastward earlier in the Cave Hills area than in the type area of the Cannonball. Additional study will be required before a satisfactory explanation can be offered.

SUMMARY

Tongue River deposition began with an influx of basal sand over continental sediments of the Ludlow and marine sediments of the Cannonball Formations. The source of sediment lay to the west, but cannot be specifically identified. The relatively mature character of Tongue River sediments (compared with those of the Sentinel Butte) suggests that the source area may have been a low arch of older sedimentary rocks, and that little extrusive volcanism (such as the Crazy Mountain-Livingston event) accompanied deformation of the sedimentary provenance. Dispersion across the basin was eastward, and the low variance of paleocurrent data indicates constancy of the paleoslope, of the source of sediments, and the system of streams which transported them seaward.

Depositional equilibrium was achieved early in Tongue River time through aggradation of a basal sand, and the remainder of the episode was characterized by a stable fluvial system. The streams of this system were confined to relatively deep channels with low gradients, and extensive floodbasin swamps formed in which thick deposits of plant debris accumulated. Subaerial exposure of the floodplain deposits, coupled with capillary rise of ground water and evaporation, resulted in carbonate enrichment. In isolated floodplain depressions carbonate accumulated and subsequently lithified to limestone. The greater development of backswamps may account for the greater abundance of mollusks in Tongue River strata.

The fine texture and relative abundance of the various sediment facies suggest that western North Dakota was near the terminus of a regional drainage system during Tongue River time, but the character of the baselevel is problematical. It is presumed that the paleoslope was continuous across the Williston Basin and that streams continued in a general eastward and southeastward direction. Discharge into a remnant of the Cannonball sea during a significant portion of Tongue River time is possible, but poorly documented.

The accumulation of sediments waned near the close of the Tongue River episode, stream drainages deteriorated, and a vast swamp formed in response to continued basinal subsidence within which organic debris of the HT Butte bed accumulated. Thus, final Tongue River time was a period of widespread quiescence. Deposition of the Sentinel Butte sequence began abruptly with transgression of a sandy basal unit across the HT Butte swamps. Streams of greater competence than those of the Tongue River episode carried sediment in from the northwest and dispersed it in deltaic fashion across the swamp.

A change in sedimentary provenance is suggested by cross-bed measurements from the basal Sentinel Butte. The source area of Sentinel Butte deposits lay northwest of western North Dakota, and extrusive volcanism probably accompanied tectonism. The low degree of dispersion of directional measurements in the basal sand indicates that a single, dominant sediment source and a stable paleoslope direction prevailed during the initial phase of Sentinel Butte deposition; deposition of subsequent strata was more variable. The great variance and polymodality of cross-bed measurements suggest shifting river courses and possibly changing or multiple areas of sediment supply. The drainage pattern was generally much less stable than that of Tongue River time. Stream channels were probably shoal and diffuse but no direct evidence is available to indicate they were braided. The terminus of the fluvial system appears to have shifted eastward during Sentinel Butte time, but streams still transported sediment across the Williston Basin primarily as suspended load. Frequent overbank deposition can be postulated on the basis of sparse backswamps deposits and low carbonate content of topstratum sediments. This system created a habitat less favorable to freshwater mollusks than that of the preceding Tongue River episode.

Late in Sentinel Butte time, increase of the paleoslope caused deposition of an upper sand throughout much of the basin. This sand is cleaner and coarser than any sediment previously introduced into the basin and appears to represent a significant rejuvenation to the west. The maximum extent of this unit has not been defined, but it is believed to have been widespread and may mark the initial phase of Golden Valley deposition.

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DEPOSITIONAL ENVIRONMENTS OF PARTS OF THE TONGUE RIVER FORMATION, WESTERN NORTH DAKOTA

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INTRODUCTION

The Tongue River Formation is a lignite-bearing, non-marine, Paleocene formation present in the western half of North Dakota. Excellent exposures are present in the Little Missouri Badlands and in scattered areas along the eastern and western flanks of the Williston Basin. These exposures provide an excellent opportunity for sedimentologic studies. Until now the only published sedimentologic work concerned specifically with the origin of the Tongue River Formation has been that of Royse (1970).

The present report is based on field work completed during the summer of 1970 and 1971 mostly in Billings, Slope, and Adams Counties (Fig. 1). Its purpose is to present criteria for recognizing the depositional environments of the Tongue River Formation. These criteria were developed through a study of sedimentary structures, lithologic associations, vertical sequences, mapping of sand bodies and their paleocurrent indicators, and construction of detailed cross sections (stratigraphic diagrams) based on closely-spaced measured sections.

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LITHOLOGIC ASSOCIATIONS

General

Four basic lithologic types are present in the Tongue River Formation. These are (1) gray clay and silt that is commonly lignitic, (2) lignite, (3) yellow silt and sand that may be clayey, and (4) sand. Lithification is very poor, except in some places where there are various types of large concretions.

Gray Clay and Silt

Units consisting of beds of gray clay and silt in the Tongue River Formation range from a fraction of a foot to more than thirty feet thick. Colors are light to medium gray on weathered surfaces, although some light yellow-brown is also present, especially where these units overlie lignite.

These units become finer upward, especially where they underlie lignite, probably because the plants increasingly acted as baffles as the swamps became established. Sand may be present, but it is very rare.

Stratification in these units is generally rather regular and laterally continuous when viewed from a distance (Fig. 2). When viewed at close range, however, contorted and disturbed stratification is conspicuous (Fig. 3). The distortion probably results from scour, differential compaction, and bioturbation. Small-scale ripple cross-stratification is present in the silt beds. Shallow channel fillings occur in places (Fig. 2).

Leaves, leaf prints, and other broken plant fragments are common in these units. Tree trunks and other wood fragments probably served as nuclei for precipitation of iron oxide to form iron-stained nodules, as evidenced by the shape of the nodules and the woody texture present in some nodules.

Thick lignite beds occur commonly at the tops of these units, although they may also occur within the units or at their bases. Lignitic clay and thin lignite beds are common throughout these units. Sediment overlying the lignite may be finely laminated clay deposited in lakes that formed as the swamp foundered. Finely laminated lake clay also may be present in other parts of these units, but on the whole it is not common.

Fossils appear to be most abundant in the yellow-brown parts of these units. Various species of gastropods are most abundant, but some pelecypods are present.

These gray clay-and-silt units probably were deposited in floodbasins on a floodplain (Fig. 4). The abundant lignite, lignitic clay, and plant debris, the fine grain size, the high fossil content (compared to surrounding units), the disturbed stratification and scoured channel fillings, and the association with thick channel sands (Fig. 5) all indicate a floodbasin environment (Allen, 1965a).

It is possible that the gray clay-and-silt units are pro-delta deposits, but this is not likely. As a result of progradation in deltaic sequences, pro-delta clay and silt is overlain by delta-front silty sand that is overlain by marsh or swamp deposits (Donaldson, 1966; Frazier and Osanik, 1969). The gray clay-and-silt units of the Tongue River Formation generally are overlain by lignite, not sand. They also commonly have interstratified lignites, suggesting that they had a marsh or swamp origin.

The marshes and swamps may have had a lagoonal origin, but this does not seem likely. No barrier or shoreline sands could be identified in the Tongue River Formation, as will be shown below, so there was no ready means to create the lagoons. Association of the gray clay-and-silt units with deeply channeled sand bodies (Fig. 5) suggests that the marshes and lagoons probably originated in floodbasins that were parts of an alluvial-plain complex. This complex may be part of a large-scale deltaic or coastal-plain sequence, but more work is necessary to determine this.

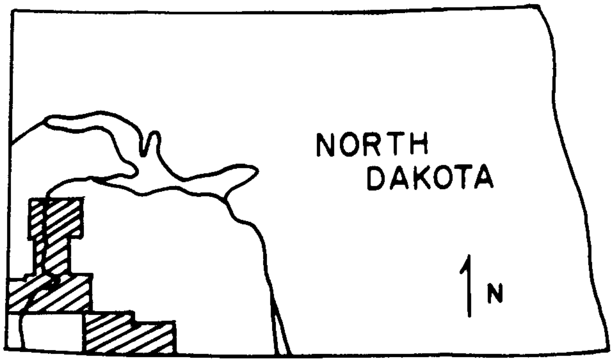

Figure 1. Index map of the study area.

Figure 2. Gray clay and silt, Tongue River Formation, east side of East River Road SE¼, NW¼, sec. 2, T. 136 N., R. 102 W., Slope County. Pick is at the base of a small channel. "Scoria" resulting from burned lignite is at the top of the exposure. The stratification looks regular when viewed from a distance. These sediments are interpreted to be a floodbasin deposit.

Figure 3. Close-up view of Figure 2. The stratification looks irregular when viewed at close range. Clay is dark colored, silt is light. Pen is 6 cm in length.

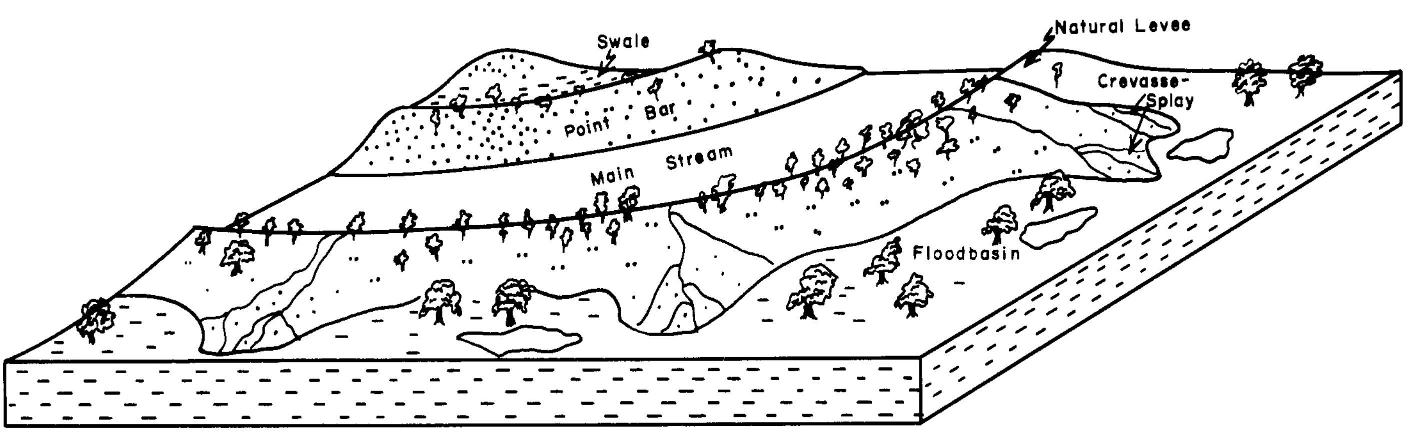

Figure 4. Depositional environments of the alluvial plain. The floodbasin is a subenvironment of the floodplain. Modified from Fisk (1960).

The gray clay-and-silt units weather to a gray color probably because they are poor in iron, due to deposition in a swampy, reducing environment in which iron was leached away. The light yellow-brown parts of these units probably result from a high iron content due to deposition in an oxidizing environment in the upper parts of the floodbasin.

Lignite

Thicknesses of exposed lignite beds in the Tongue River Formation vary from a fraction of an inch to about 40 feet, but most exposed beds do not exceed about 20 feet. Some of the thicker beds have been mapped over large areas (Hares, 1928).

Some lignite beds observed by the writer are quite continuous, but their elevations and thicknesses were found to change within short distances laterally (Fig. 5). This was determined through very careful, detailed tracing of individual beds in areas of excellent exposures. It is only with great difficulty that an individual bed could be traced over large distances with any certainty.

Lignite beds more than a few inches thick occur either at the top of, within, or occasionally at the bottom of gray clay-and-silt units. Thick lignites have never been observed in yellow silt-and-sand units. So the depositional environment of the lignite is closely related to that of the gray clay-and-silt units, which have been interpreted as floodbasin deposits. Association of the lignite beds with channel sands (Fig. 5) supports this conclusion.

The lignite probably was not deposited in lagoons behind barrier islands. As already mentioned, barrier-island sands could not be identified in the Tongue River Formation. This is not surprising in view of the absence of extensive barrier islands in all modern lakes (the Tongue River Formation is non-marine, as mentioned). Lagoonal lignites should be thin, discontinuous and poorly developed (Fisher, 1968). Although lignite beds matching this description are present in the Tongue River, many are present that are thick and continuous.

Fisher (1968), in discussing the Wilcox Group in Texas, distinguished between the "thick swamp peats flanking the main channel of the upper delta plain" and "the more nearly tabular, blanket marsh peats found in the lower parts of the delta plain." Of the two descriptions, the latter describes the lignites of the Tongue River Formation most accurately. This suggests that much of the Tongue River Formation may have originated on a lower deltaic plain. The characteristics of the sand bodies in the formation, discussed below, support this suggestion.

Yellow Silt and Sand

Units consisting of beds of yellow silt and sand in the Tongue River Formation range from about a foot to more than 50 feet in thickness. Fine sand may be present as lenses 1 or 2 feet thick that may extend hundreds of feet laterally. Clay, which is present in many places, usually is dark yellow-brown.

Ripple stratification and horizontal lamination are widespread in these units, and climbing ripple stratification is particularly characteristic (Fig. 6). Allen (1970a) showed that climbing ripples results from a high rate of sedimentation from suspension. So the yellow silt-and-sand units formed in areas of high sedimentation rates. Sedimentary structures may be difficult to observe, possibly due to floral bioturbation as suggested by abundant roots and rootlets.

Iron-stained concretions are present that are cylindrical, vertical, less than a foot in diameter, and contain woody remains at their centers in many places. These vertical concretions appear to be restricted to yellow silt-and-sand units; they were never observed in gray clay-and-silt units. This probably reflects high rates of deposition and burial of trees in growth position. The wood then may have served as nuclei for the precipitation of iron compounds. Roots probably also served as nuclei for iron-rich concretions. Woody matter also accumulated in places in these units to form lignite beds that are a few inches thick and are crumbly and discontinuous. Isolated plant fragments are also present in many places.

Limestone (micrite) lenses, up to about 100 feet across, are present in these units, but are rare in most gray clay-and-silt units. They are laminated, silty, and contain plant fragments. The presence of one lens in a scoured depression in at least one place suggests an origin in small isolated pools, perhaps by evaporation assisted by photosynthetic activity. The Tongue River Formation generally is very calcareous, and the sand in the formation contains large amounts of primary clastic carbonate grains. So at the time of deposition the ground water probably was very calcareous and could have precipitated the limestone.

Invertebrate fossils, consisting mostly of gastropods and pelecypods, occur in these units, but they are not as common as in the gray clay-and-silt units.

The units of yellow silt and sand probably originated as natural levees and crevasse splays (Fig. 4). This is where depositional rates on the floodplain are highest (Allen, 1965a), accounting for the climbing ripples. As mentioned, ripple stratification and horizontal lamination is common in these units, and is typical of natural levees (Allen, 1965b).

The high sedimentation rates can explain the burial of trees in growth position to cause the vertical, cylindrical concretions. Natural levees form the highest elevations of the floodplain, so they occur in a highly oxidizing environment that would favor precipitation of iron to form the concretions and also to form the yellow color of these units.

Allen (1965a) noted that an important characteristic of natural levee sediment is a rapid vertical alteration of coarse and fine sediments. This alteration is present in these yellow silt-and-sand units and results in overall poorer sorting than in the gray clay-and-silt units.

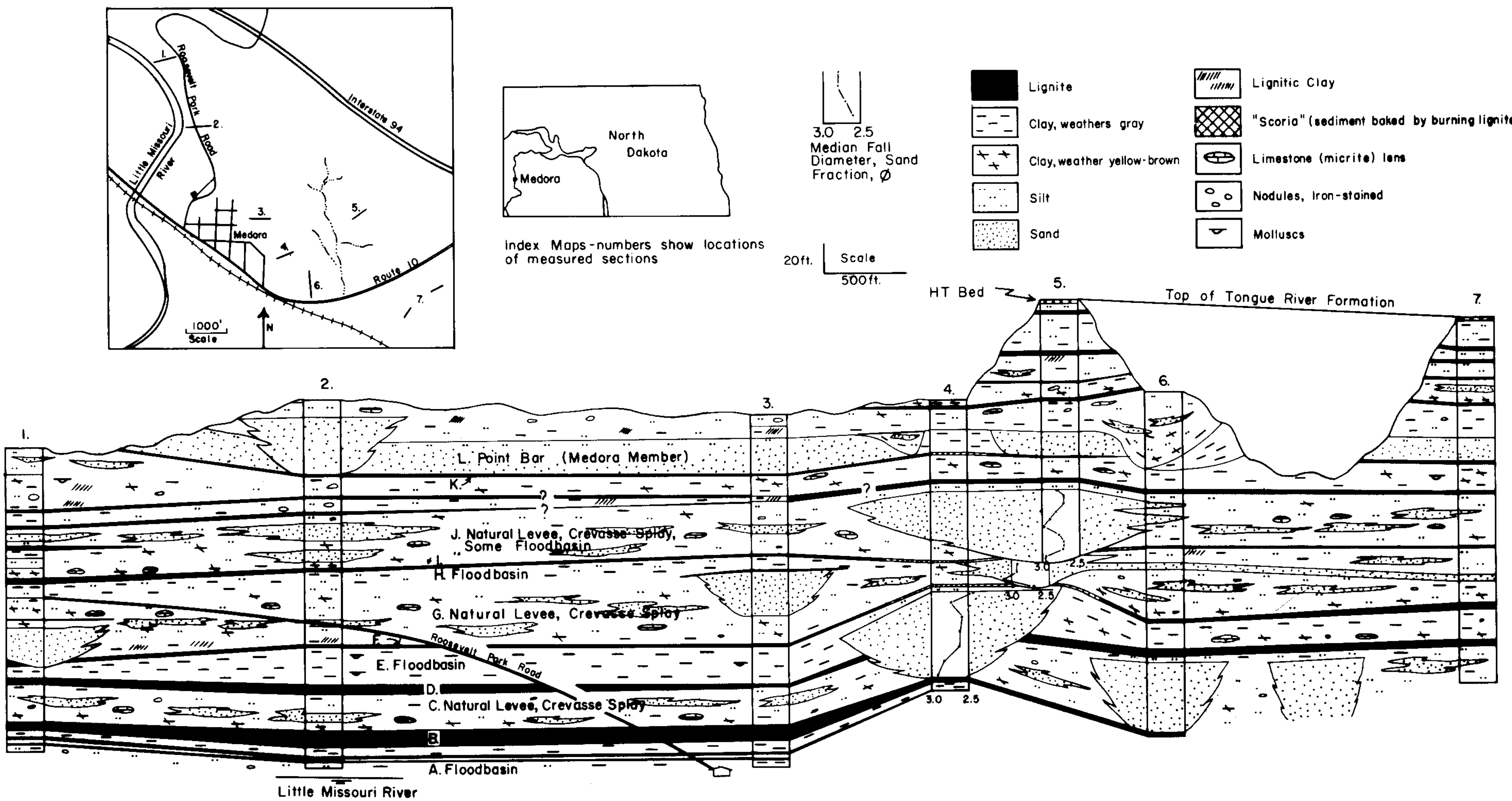

Figure 5. Stratigraphic diagram of part of the Tongue River Formation at Medora, North Dakota. Horizontal scale distorted between measured sections 4 and 6. All units were mapped in the field. There are no hypothetical correlations between measured sections.

Figure 6. Horizontal lamination and climbing-ripple stratification in clayey, yellow silt and sand that overlies lignitic gray clay. The texture, structures and stratigraphic position indicate that the sediment probably is a natural-levee deposit.

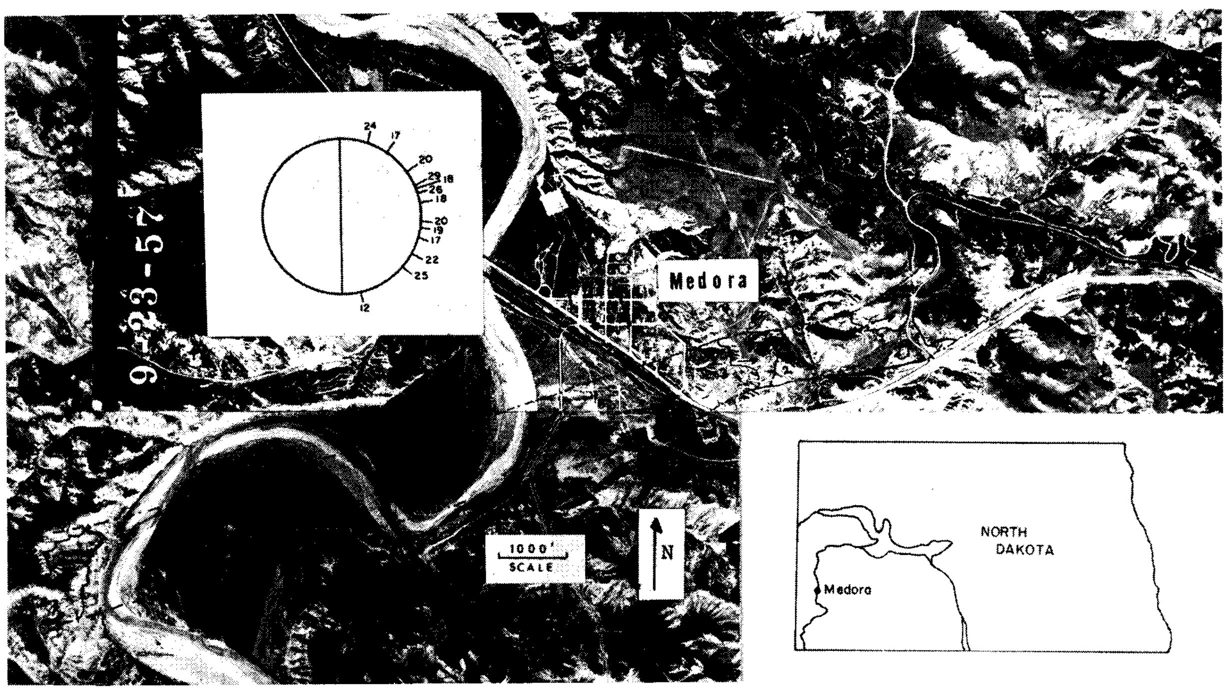

Figure 7. Map of the channel sand at the base of measured section 5, Figure 5. The solid line indicates the sand outcrop; the dotted line is the projection of the channel edge where it is eroded or buried. The circular diagram shows the direction and dip in degrees of foresets of omikron cross-strata at location 1. The arrows show the average trends of elongate concretions.

Some yellow silt-and-sand units may have originated as interdistributary trough fills (Fisk and others, 1954), which are deposits that fill depressions that occur between distributaries on the seaward (or lakeward) edges of deltaic plains. In these cases the yellow silt-and-sand units would comprise part of the delta-front facies in a deltaic sequence. They should overlie sediment that could be interpreted as pro-delta clay and silt, and they should be overlain by lignite formed in marshes or swamps of the delta plain (Donaldson, 1966; Frazier and Osanik, 1969). This sequence occurs in places, and may have resulted from delta progradation, but it is not common.

Most commonly the yellow silt-and-sand units overlie lignite beds (Fig. 5). In these cases they probably formed as natural levees and crevasse splay deposits. Crevassing, and expansion of the levees across the floodbasins would suffocate the swamps previously formed in the floodbasins and would result in the yellow silt-and-sand units over the lignite beds (Fig. 13).

Sand

General

Sand makes up about 10% of the Tongue River Formation. It is almost entirely fine- or very-fine-grained, but medium-grained sand is present in some places near the top and bottom of the formation. The sand is quite silty. Fifty-six analyses show that the content of silt and clay ranges from 1.4% to 89.8%, and averages 22.4%. On fresh surfaces the sand may be light gray to light yellow brown, and on weathered surfaces it is usually light yellow brown.

The sand is very calcareous. Examination of thin sections shows that it consists of up to about 40% primary clastic limestone fragments. This indicates the presence of limestone in the source area, and is consistent with the presence of sand fragments of other supracrustal rocks such as chert and fine-grained volcanic rock.

Linear Sand Bodies

Two main types of sand bodies occur in the Tongue River Formation. The first type is narrow (up to about 1,000 feet wide) and straight, with paleocurrent indicators paralleling the axis of the sand body (Fig. 7). This type of sand channels deeply into the surrounding sediment (Fig. 5), commonly extending downward to a lignite bed that served in most cases, apparently, as a resistant bed below which the channel could not erode. In some cases a thin lignite caps the sand.

In some places sand bodies of this type are stacked on top of each other, and the total stratigraphic section thins in these places (Fig. 5). Stacking of distributary sands in deltaic sequences has previously been described (Fisher and McGowen, 1969), and thinning of the total stratigraphic section has been found to occur along with stacking of distributary sands in lacustrine delta sediments (Jacob, 1969). The cause of the stacking is uncertain.

If the Tongue River Formation has a deltaic origin, the delta was lacustrine because the Tongue River Formation is non-marine. A lacustrine delta would most likely be a high-constructive type because energy input from the lake probably would be low, compared to the rate of sediment influx. Such a delta consists chiefly of fluvial facies with a large amount of fine sediment (Fisher and others, 1969), and the distributaries on the lower subaerial parts of such deltas are quite straight (for example, the Lafourche or the modern Mississippi). These characteristics are present in the Tongue River Formation, suggesting that the formation may have originated on the lower subaerial part of a high-constructive delta.

Vertical changes in grain size in these linear sand bodies show no definite, widespread pattern. A reversed "C" shape of the pattern is present in some sand bodies, indicating a coarsening of the sand just above the base, and a fining upward at the top. The sand body at the base of measured section 5 of Figure 5 shows two such patterns, suggesting that it may consist of two stacked channel sands, rather than one.

Sedimentary structures in this type of sand body are about 15% small-scale ripple cross-stratification, 25% horizontal lamination (plane bed), and 60% planar cross-stratification (McKee and Weir, 1953). Generally plane bed and small-scale ripple cross-stratification occur near the top of the body, and planar cross-stratification occurs throughout the rest of the body. Trough cross-stratification is very rare.

The planar cross-stratification probably originated on transverse bars (lateral bars). Transverse bars occur either in braided streams or in non-braided, low-sinuosity streams (Allen, 1968). The streams depositing the sand in the Tongue River Formation probably were not braided. Braided-stream deposits should be more blanket-like, coarser-grained, and should be associated with much less lignite than are the sand bodies of the Tongue River Formation. Figure 8 shows how the planar cross-stratification in the linear sand bodies of the Tongue River Formation probably originated.

Elongate concretions occur near the tops of sand bodies of this type, and are oriented parallel to the axes of the bodies (Fig. 7). This relationship has been observed throughout the study area. The concretions are visible on air photos and can be used to map trends of paleochannels.

Tabular Sand Bodies

The second main type of sand body in the Tongue River Formation is tabular (Fig. 9). It is quite rare, having been observed only in a few places. It is about 8 to 10 feet thick and extends hundreds of feet laterally, with a scoured base and a fairly sharp top.

Figure 10 shows the vertical sequence of sedimentary structures observed in every tabular sand body observed. Horizontal or low angle planar laminae (plane bed) occur in the lower half of the body and small-scale ripple cross-stratification occurs in the upper half. This type of body becomes finer upward. Yellow silt and sand (described above) underlies these bodies and lignitic gray clay and silt (also described above) overlies them.

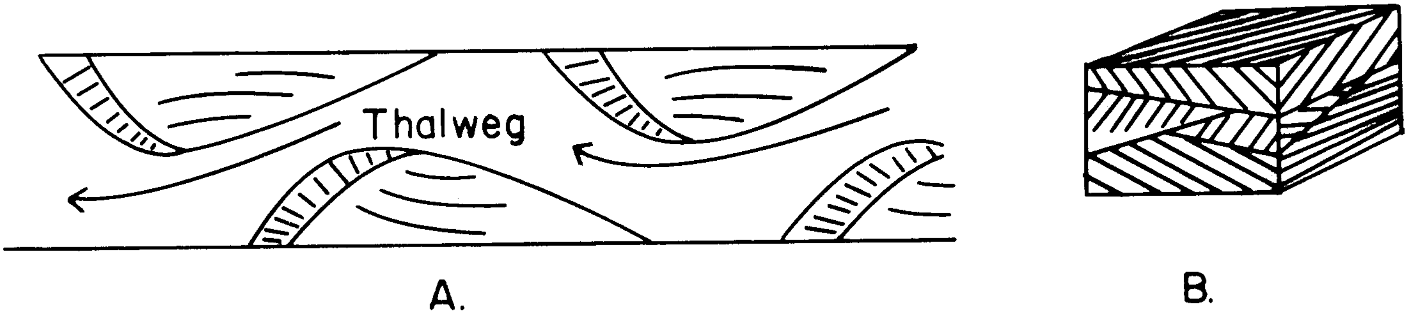

Figure 8. A. Transverse (alternate, or lateral) bars in a low-sinuosity stream. B. Planar cross-stratification resulting from deposition on such bars. Compare with Figure 7. (After Allen, 1966).

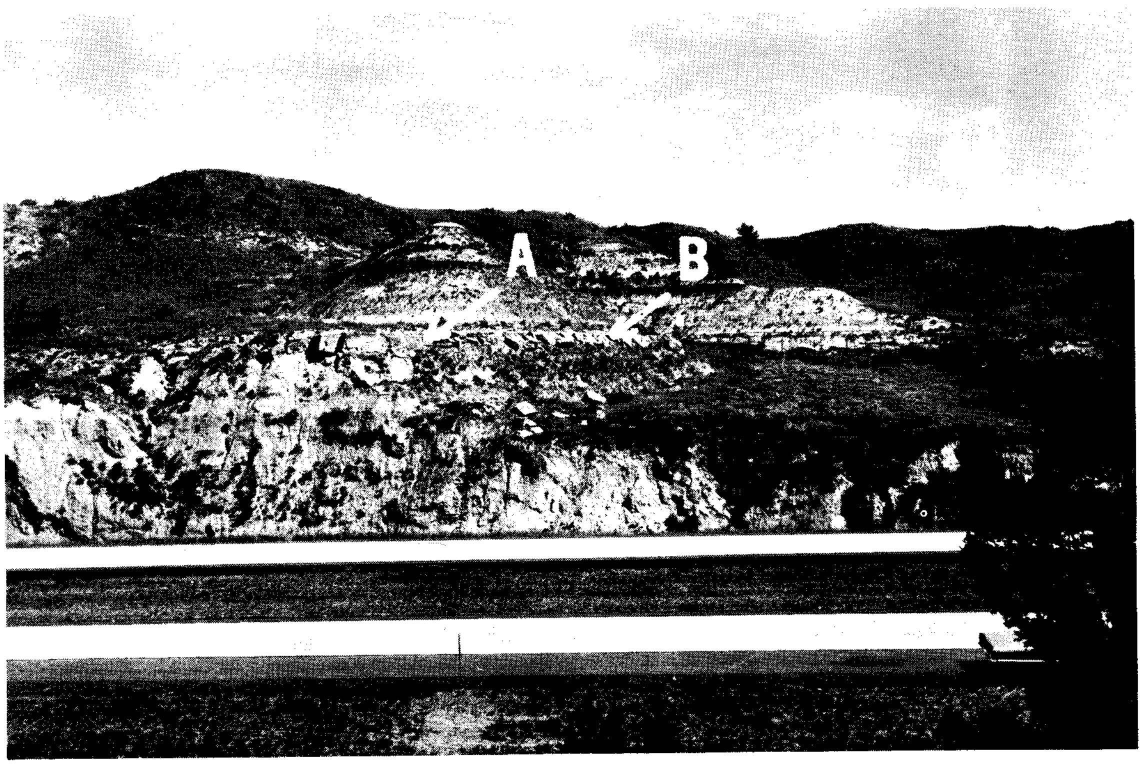

Figure 9. Tabular sand body (arrows) in the Tongue River Formation, NW¼ sec. 30, T. 140 N., R. 101 W., Billings County. View is north across route I-94 just east of exit 7. Photograph of location B is shown in figure 10.

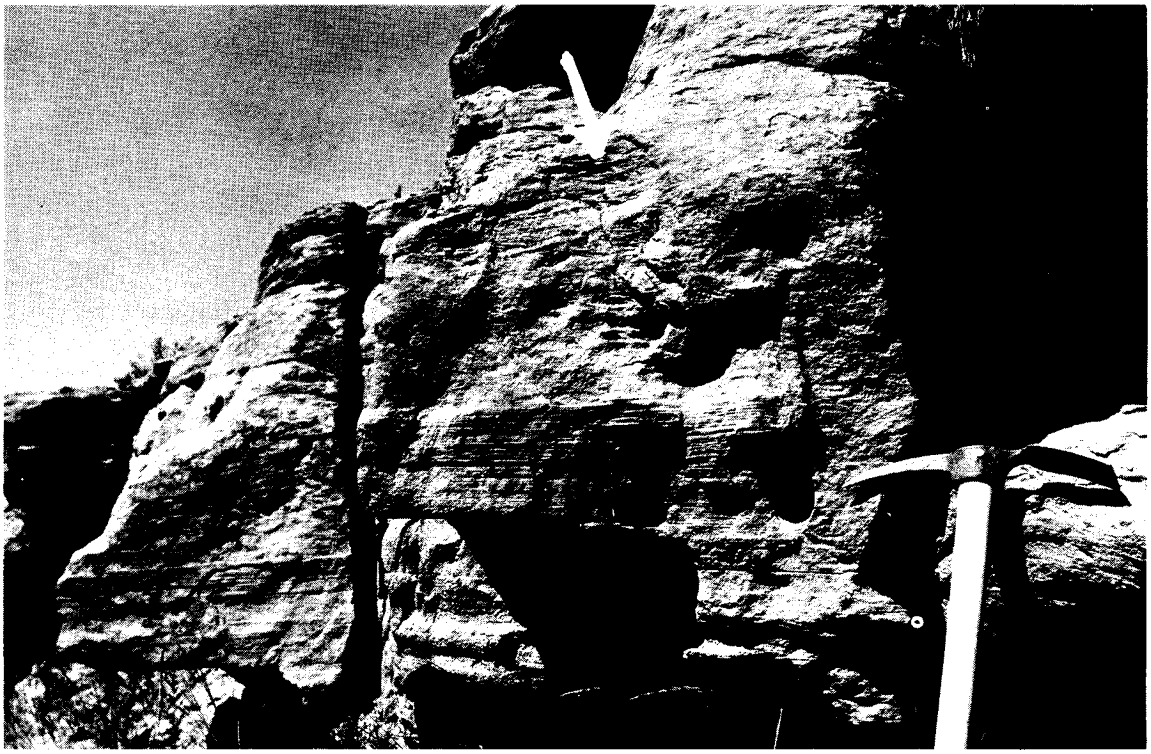

Figure 10. Sedimentary structures in a tabular sand body. Location B, Figure 9. Horizontal laminae (plane bed) at the bottom pass upward into small-scale ripple cross-stratification at the top (arrow).

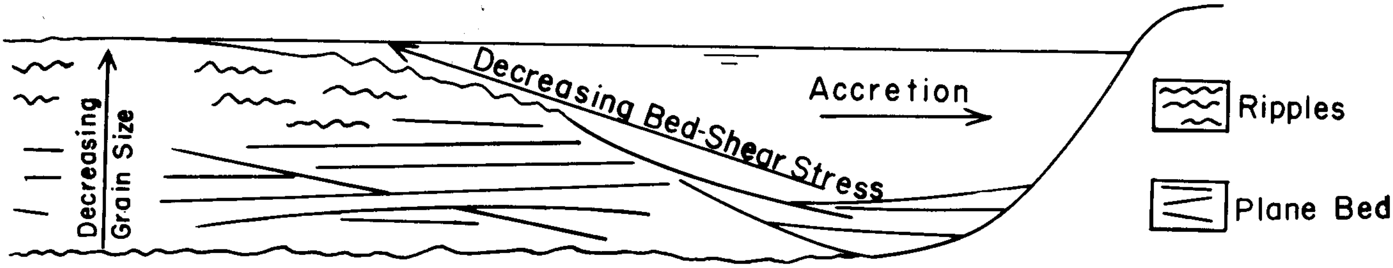

Figure 11. Model for the origin of the tabular sand bodies in the Tongue River Formation. Accretion is taking place toward the concave bank of a stream bend.

These bodies are probably point-bar deposits formed by lateral accretion in high-sinuosity streams. Allen (1970b) showed that such deposits should fine upward and the vertical sequence of sedimentary structures should show a general decrease in the flow regime upward through the deposit. Figure 11 shows how these sand bodies probably originated. The thickness of the sand body is approximately equal to the stream depth.

The absence of trough cross-stratification indicates that dunes did not form in the depositing streams. This may have been due to any number of factors such as small depth, high discharge, low water temperature, high suspended sediment concentration, or fine grain size.

It is possible that this type of sand body had a shoreline origin, but this is unlikely. If it were shoreline sediment, it would be a transgressive lake deposit because it becomes finer upward, and there is a change from plane bed (foreshore) to ripple stratification (offshore) upward. Offshore sediment overlies transgressive shoreline deposits, but the sediment overlying this type of sand body is gray lignitic clay and silt, which is swamp sediment, not off-shore lake sediment.

An eolian origin for this type of sand body also is unlikely. Associated lignite indicates an environment too wet for eolian transport, a silt-clay content of about 30% is too high for an eolian sand, and small-scale ripple cross-stratification is not preserved in eolian deposits.

Medora Member

The Medora Member of the Tongue River Formation is a name informally used here for a tabular sand body 15-25 feet thick that occurs about 80 feet below the top of the Tongue River Formation (Fig. 5). It is typically exposed around Medora, where it gets its name. Its origin is probably the same as that of the tabular sand bodies discussed above.

As is apparent from Figure 5, the entire sand bed is interrupted in places by silt and clay that is fine-grained floodplain sediment incised by the streams that deposited the sand. An excellent example of an abandoned-channel plug occurs between measured sections 3 and 4 in Figure 5.

The Medora Member is different from the other tabular sand bodies of the Tongue River Formation. It has all the characteristics of the sand bodies of the Sentinel Butte Formation. Trough cross-stratification is present, indicating that dunes were present in the depositing streams. It is darker in color than the rest of the Tongue River Formation and is a characteristic somber brownish gray. It is much less friable than all of the other types of sand bodies in the Tongue River Formation and is difficult to disaggregate in the laboratory. Because of this it forms steep cliff faces that show a very characteristic pattern of many closely-spaced vertical rills. The other sand bodies in the formation generally show much smoother, more crumbly surfaces.

Reconnaissance indicates that the Medora Member extends for at least tens of miles north and south of Medora, but it has not yet been mapped.

CYCLIC UNITS

Figure 12 shows the various types of cyclic units in the Tongue River Formation. The basic unit, from bottom to top, is (1) gray clay and silt, (2) lignite, and (3) yellow silt and sand. The lower two members probably are floodbasin deposits, and the upper member probably is natural levee sediment as discussed above. Channel deposits are present in the upper bed or they cut down through one or more entire cyclic units.

The thicknesses of entire cyclic units, or of their individual beds, are extremely diverse, and depend on the rate of deposition and the rate of subsidence. In Figure 13, for example, the overall rate of deposition exceeds the overall rate of subsidence because the floodbasin eventually fills. A thick unit of gray clay and silt results, however, if the short-term rate of subsidence just equals or exceeds the rate of deposition prior to establishment of the swamps.

Once the sedimentation catches up with the subsidence, swamps establish themselves, provided that the sedimentation rate is not too high. If it is too high, plants are smothered, peat is not formed, and the cyclic unit of Figure 12D results. Once the swamps are established, a thick peat bed will form if the rate of deposition and preservation of organic matter just equals the rate of subsidence. A balance between organic productivity, oxidation decomposition, and subsidence is essential to produce thick peat beds. If the rate of subsidence is too high the water table rises, the swamps drown, and increased clastic sedimentation results. If the subsidence rate is too low, the floodbasin fills with overbank sediment and the swamps are destroyed.

The channel shift indicated in Figure 14 is favored by the presence of coarser sediment that has filled the floodbasin. The lower cohesiveness of coarser material allows the channel to change position more easily than if it were flowing in clayey sediment.

In Figure 15 the overall rate of deposition exceeds the rate of subsidence between stages A and C, and during stage C the rates become equal. Between stages C and D the rate of subsidence initially exceeds subsidence and the basin fills. In this way the cyclic unit of Figure 12C is produced. Several lignite beds separated by gray clays may originate by means of multiple alternations between stages C and D.

Figure 5 shows three examples of the basic cyclic unit in the Tongue River Formation. Units A, B, and C form one cyclic unit; units E, F, and G form a second; and units H, I, and J form a third. These cyclic units are readily visible in the cliff face on the east side of the Little Missouri River above Medora.

SUMMARY

The Tongue River Formation, where examined in Billings, Slope, and Adams Counties, appears to be largely an alluvial unit that may have formed on the lower subaerial portion of a high-constructive delta (Fisher and others, 1968a). The various depositional subenvironments of the alluvial plain can be readily identified.

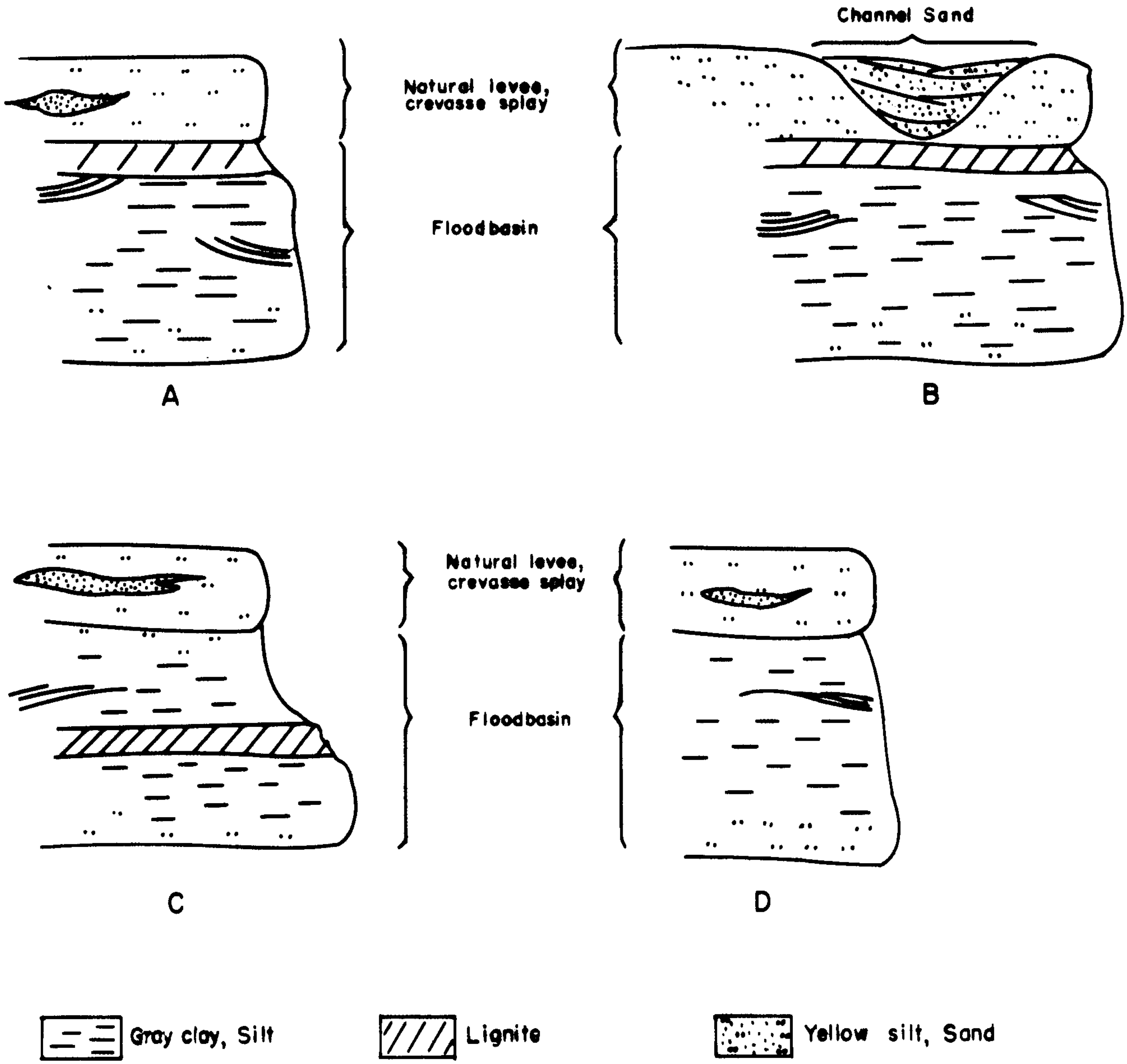

Figure 12. Basic cyclic unit in the Tongue River Formation (A), and variations of it (B-D).

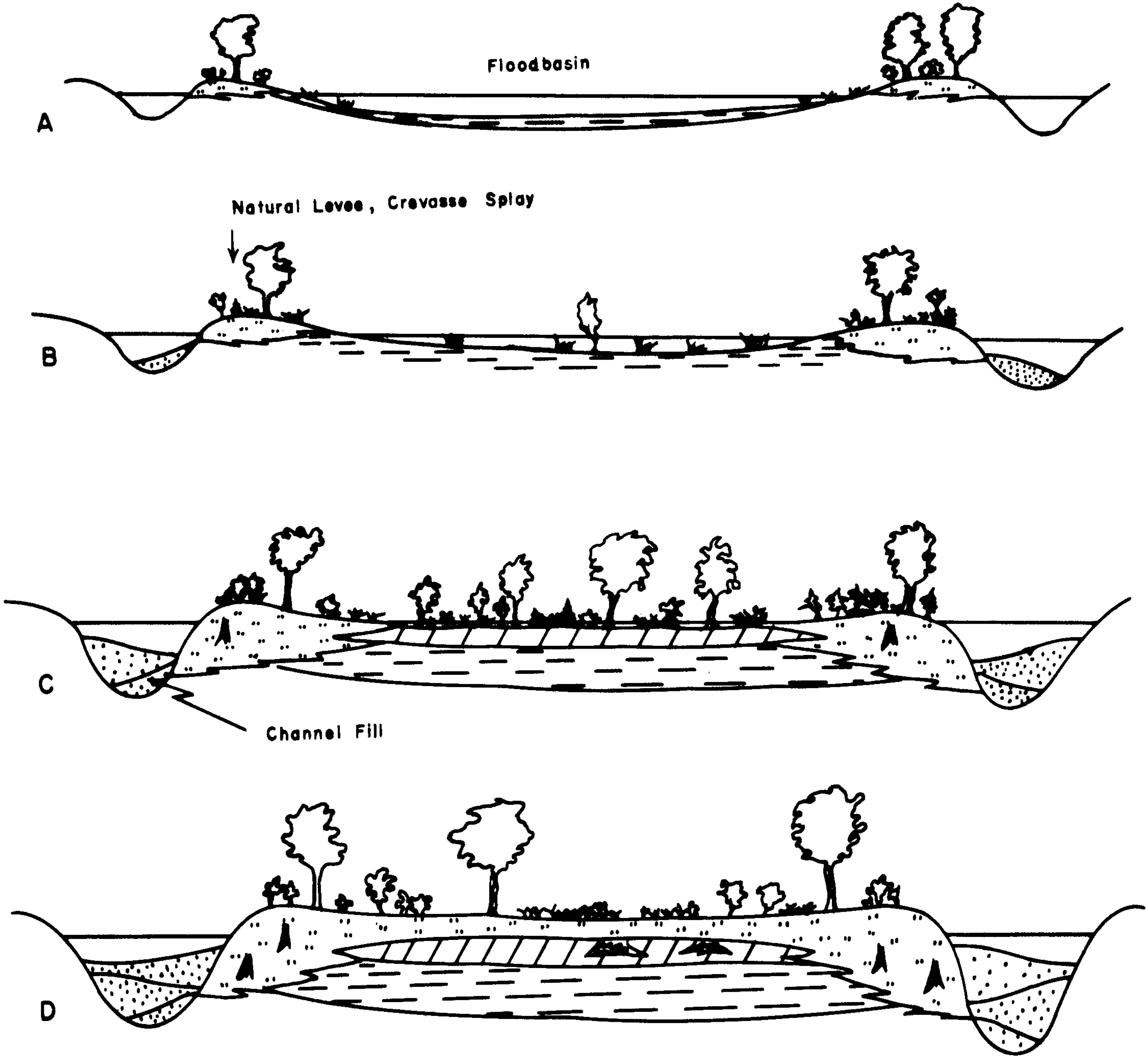

Figure 13. Model for the origin of the cyclic unit shown in Figure 12A. Vertical scale many times horizontal. Legend in Figure 12.

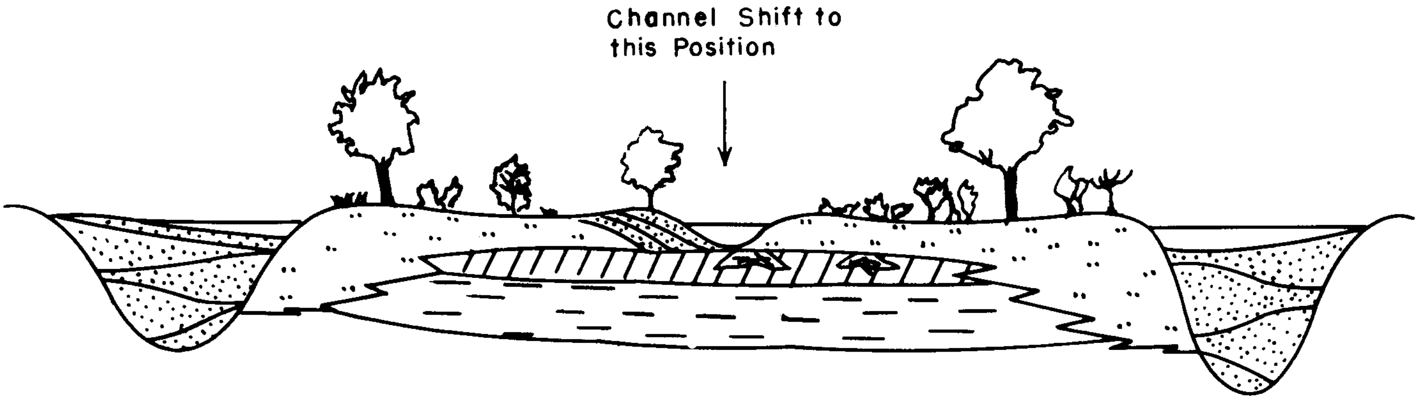

Figure 14. Model for the origin of the cyclic unit shown in Figure 12B. Vertical scale many times horizontal scale. Legend in Figure 12.

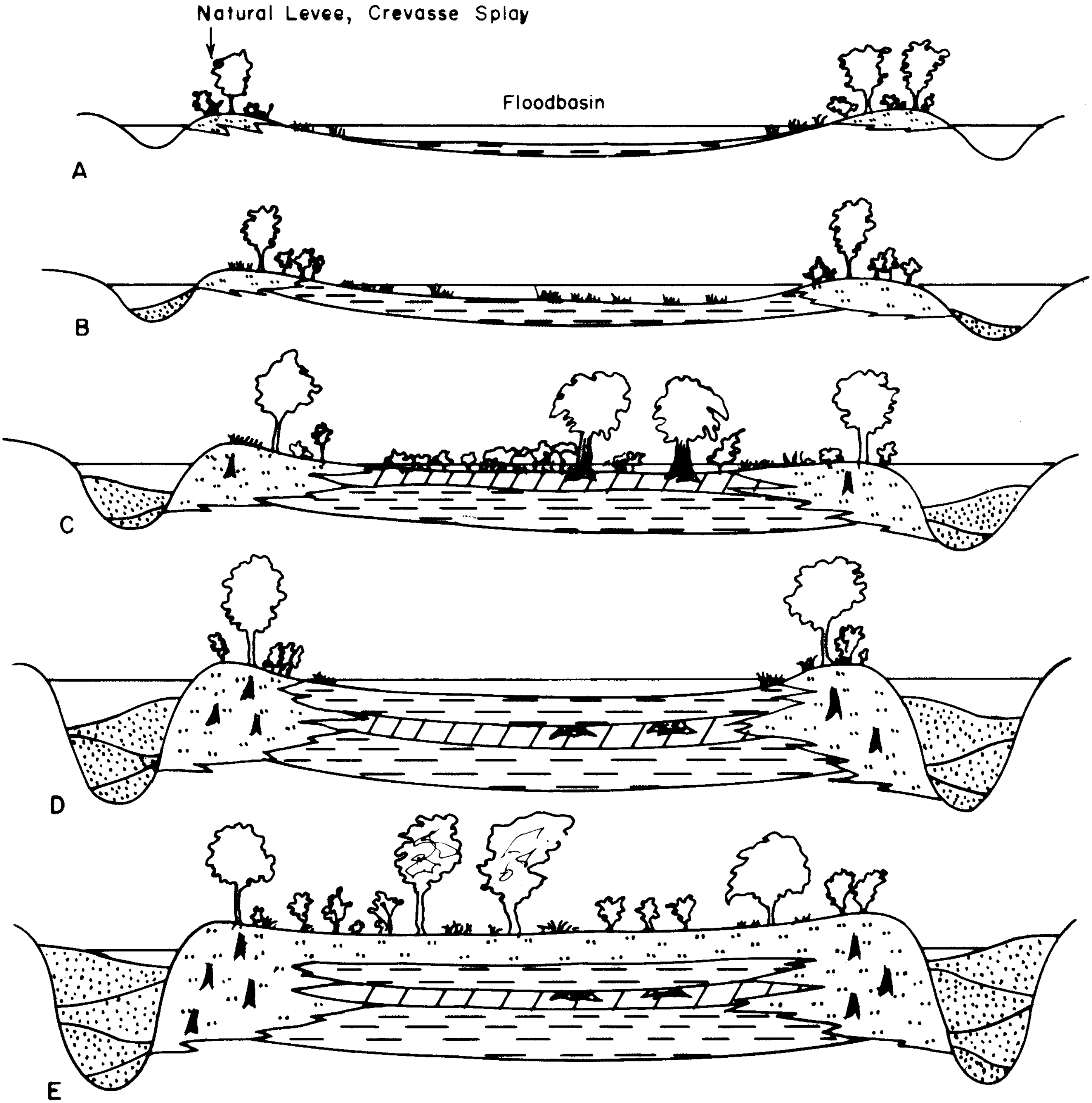

Figure 15. Model for the origin of the cyclic unit shown in Figure 12C. The cyclic unit of Figure 12D may originate if the overall rate of deposition is high enough to prevent development of persistent swamps as the floodbasin fills. Vertical scale many times horizontal scale. Legend in Figure 12.

Units consisting of beds of gray clay and silt that are commonly lignitic probably were deposited in floodbasins. The main lignite beds probably were deposited in floodbasin swamps. Yellow silt and sand, which may be clayey, probably was deposited on natural levees and crevasse-splays. Most of the sand was deposited in deeply eroded straight channels up to about 1,000 feet wide.

These deposits are arranged in a basic cyclic unit that consists (proceeding upward) of (1) gray clay and silt (0.5 to 30 feet thick), (2) lignite (0.5 to 40 feet thick), and (3) yellow silt and sand that may be clayey (1 to 50 feet thick). This unit can be best explained as the result of the formation and filling of a floodbasin. Variations in depositional history from place to place and through time resulted in variations of the basic unit.

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PETROGRAPHIC AND CHEMICAL PROPERTIES

OF SELECTED NORTH DAKOTA LIGNITE

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The Paleocene lignite deposits in the Williston Basin constitute the largest reserve in the United States. A concerted effort is being carried out at the University of North Dakota to investigate this vast natural resource--its mode of occurrence, composition, potential uses, and environmental impact. The following discussion is a preliminary report of part of this comprehensive study.

The lignite is characterized by the presence of abundant lignitized conifer wood (vitrain, xylain, or anthraxylon). Thick vitrain bands (½ inch or more thick) constitute more than 15% of two core samples obtained near Underwood, McLean County, North Dakota. Total vitrinite (huminite) contents account for more than 80% of the cores. The presence of large vitrain lenses is more obvious at the working faces in the strip mines. They occur as slightly compressed logs or stumps up to several feet in length and in diameter.

There are significant variations in the elemental composition of the macerals in lignite (Table 1). Resinites always have the highest hydrogen and carbon content, which helps to explain the extremely high heat value of resinite. Resinite is also low in oxygen content. Vitrinite has moderate hydrogen content, low carbon content, and high oxygen content. Fusinite has the least hydrogen, but is intermediate in carbon and oxygen content.

Table 1. Analyses of macerals of lignite (dry, ash-free basis)

	Percentage (%)				
Sample	H	C	N	O	S
1. Resinite	10.1	79.7	0.3	9.9	0.1
2. Vitrinite	5.1	69.5	0.7	24.4	0.4
3. Fusinite	2.3	75.8	0.7	17.9	3.5

Samples 1 and 2 are from Baukol-Noonan Coal Company Mine, Larson, Burke County, North Dakota.

Sample 3 is from the Hagel Seam, Baukol-Noonan Coal Company Mine, Center, Oliver County, North Dakota.

The lignite in North Dakota is generally low in sulfur content. Published data show that the sulfur contents range from 0.1% to 1.9%, averaging about 0.6% (Sondreal and others, 1968). Iron sulfides and organic sulfur are the most common forms of sulfur in lignite. Iron sulfides occur as nodules, joint fillings, and irregular bodies scattered in the coal seams. Microscopically some of them seem to be associated closely with medullary ray cells and late (summer) wood (Fig. 1 A and 1 B) of conifer stumps. Ray cells are generally the last cells to mature and die. The infiltration of ray cells by pyrite may have a significant relation to the content of pyrite in lignite and other coals.

One of the major concerns in the utilization of lignite is the heat value of the coal. Literature survey and tests conducted in our laboratory indicate that the most significant single factor that contributes to the variations of heat value is the moisture content of the coal. The moisture content of lignite is between 35% and 40%. Any significant decrease in reported moisture content (which results in an increase of heat value on as-received basis) is probably caused by sampling of partially dried samples or results from improper handling of the sample. Oxidized lignite (leonardite) generally has high moisture content, but the heat value is relatively low even if calculated on a moisture, ash-free basis. Moisture content probably differs among the different petrographic components of the lignite. Careful sampling and petrographic analyses are required to determine the effect of petrographic composition on the moisture content. Further, a study is underway to determine the moisture content of individual petrographic components and their mixtures. An additional factor is the inherent heat value of the individual petrographic components. Preliminary studies indicate that resinite (which is extremely low in moisture and ash and often occurs as large globules) has the highest heat value, whereas other components are lower by several thousand btu/lb. (Table 2).

Table 2. Heat Content of Principal Petrographic Components of Lignite

			Btu/lb	
Component*	Moisture	Ash	As Rec'd	DAF***
1. Resinite	1.0	0.2	16,240	16,440
2. Vitrinite (huminite)	39.1	1.5	7,520	12,660
3. Fusinite	12.7**	4.1	10,320	12,400

*Sample 1, Larson, North Dakota; Sample 2, Center, North Dakota; and sample 3, Velva, North Dakota.

**The fusinite is an air dried sample.

***Dry, ash-free basis.

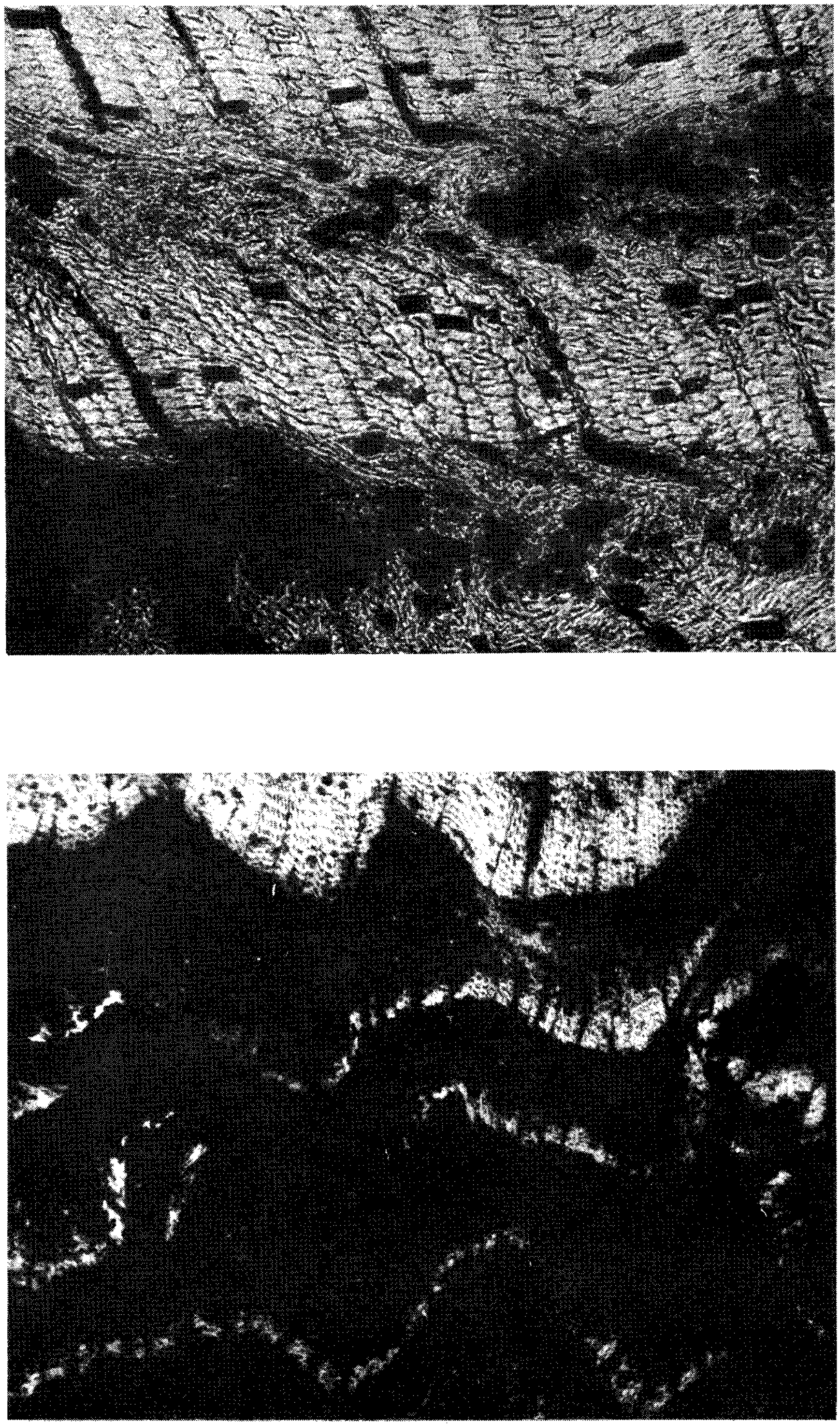

Figure 1. Photomicrograph of traverse sections of lignitized conifer wood showing the prefered occurrence of pyrite in ray cells and late wood. Magnifications of A 140X, B 50X.

Table 3. Composition of Lignite Ash

Sample	Ash % (H_2O Free)	Ash analysis, percent Fe_2O	TiO	CaO	K_2O	SO_3	P_2O_5	SiO_2	Al_2O_3	MgO	Na_2O
Glenharold Mine Stanton, N. D.											
Vitrain (7122)	3.5	13.1	0.0	26.4	0.4	27.3	0.1	4.2	8.7	5.5	10.3
Vitrain (7123)	2.6	11.6	0.0	25.9	0.5	34.3	0.2	0.6	5.7	3.6	14.8
Durain (7119)	6.7	8.1	0.3	40.2	0.3	14.5	0.0	11.4	4.1	8.7	7.4
Durain (7120)	7.1	7.6	0.4	39.4	0.3	13.2	0.0	14.9	3.9	8.3	7.4
Fusain (7124)	7.2	5.1	0.3	24.7	0.3	9.5	0.0	31.8	14.2	5.7	5.0
Baukol-Noonan Mine Center, N. D.											
Vitrain (7102)	2.5	3.4	0.0	36.9	0.6	22.4	0.3	3.3	13.9	10.2	3.9
Durain* (7103)	7.5	4.2	0.2	36.0	0.2	13.4	0.1	18.7	10.5	10.9	1.5

* Fusain-rich

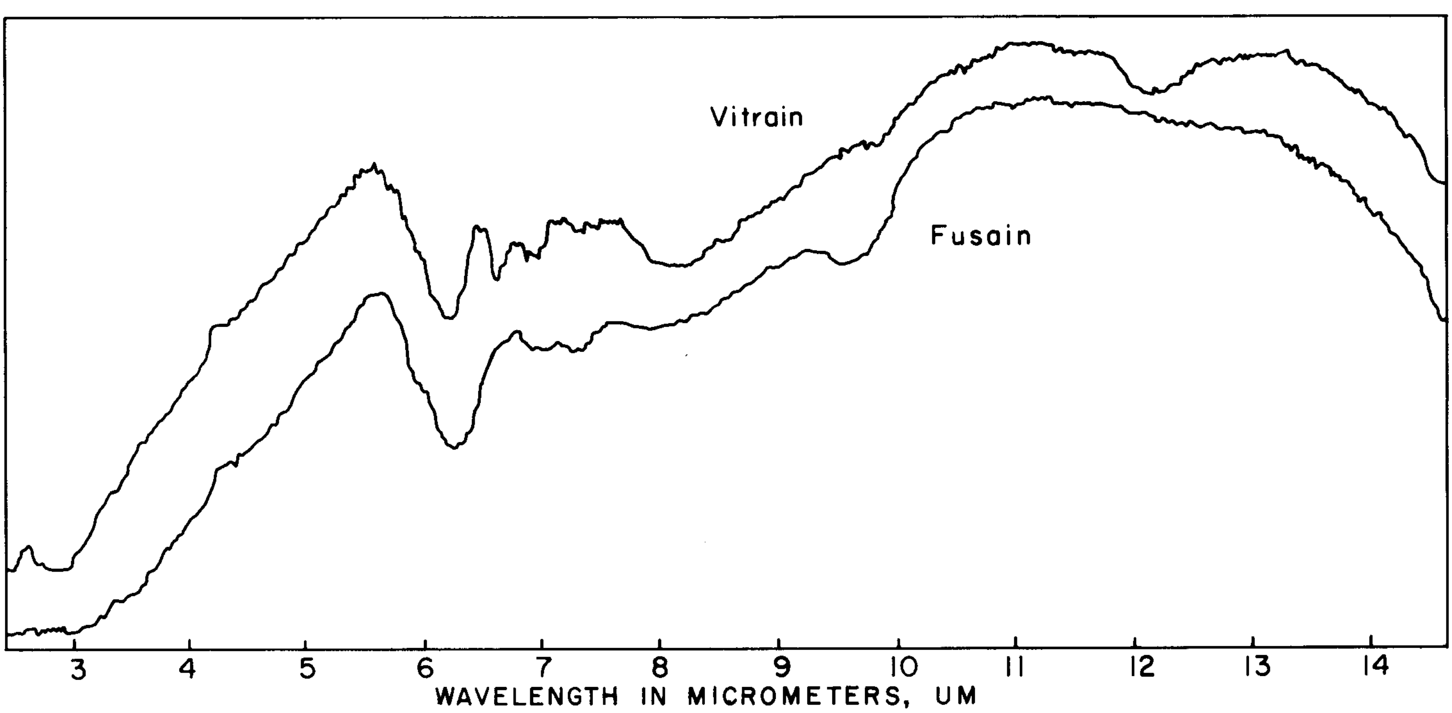

Figure 2. Infrared spectra of a high sodium vitrain sample and a low sodium fusain sample from western North Dakota.

Aside from the heating values, another major concern in the utilization of lignite is the excessive accumulation of lignite ash on the boiler tubes. This unwanted property has been attributed to the high sodium content in the lignite (Gronhovd and others, 1968). High sodium content generally correlates well with excessive accumulation of ash on the boiler tubes. Our recent study indicates that sodium tends to be differentially associated with different petrographic components of lignite. Table 3 illustrates this relationship. At a given sampling locality the ash of vitrain tends to contain more sodium than those of durain and fusain. The ash content of vitrain is generally much lower than that of durain and fusain.

The exact mode of occurrence of sodium in lignite is not well known. Extensive work has been conducted at the U. S. Bureau of Mines, Grand Forks Laboratory. In the absence of any known sodium minerals, and the fact that the sodium ions can be exchanged by calcium ions after washing with $Ca\ Cl_2$ solution, the sodium was considered to be organically attached to the acid groups in the lignite as organic salts (Paulson and Fowkes, 1968, Beckering and others, 1970). Recent x-ray studies of low-temperature ash of a high-sodium lignite failed to show the presence of any sodium minerals.

As mentioned earlier, sodium tends to concentrate in the low-ash vitrain components in lignite. The fact that sodium is concentrated in low-ash components is strong evidence of the organically-attached occurrence of sodium. Infrared absorption spectra of a high-sodium vitrain and a low-sodium fusain were made and are given in Figure 2. Regardless of the compositional differences from the point of view of petrography and chemistry, the two spectra are essentially similar except that the vitrain sample has additional bands at 6.9 um (1450 cm^{-1}), at 6.6 um (1520 cm^{-1}), and at 12.1 um (825 cm^{-1}). The two peaks at 6.9 um and 6.6 um are indicative of the ionized carboxylic acid group and represent the symmetrical and asymmetrical vibration of the COO^- group. This probably indicates larger amounts of salts of carboxylic acids in the vitrain material compared to the fusain (W. Beckering, personal communication). Coupled with the removal of sodium by ion exchange, this suggests that sodium occurs as organic salts in the lignite.

Our recent study indicates that there is a strong correlation between the sodium content and the rock type of the immediate overburden of the lignite. The sodium content of the lignite is usually low when the immediate overburden is a sandstone. The sodium is high when the immediate overburden is a shale. The sandstone is usually rich in carbonates and is loosely consolidated and permeable, whereas the shale is low in carbonates and impermeable. Ion exchange between sodium and calcium and other metallic ions is more likely in a situation where the lignite is overlain by a permeable, carbonate-rich sandstone.

Lignite is generally considered nonagglomerate according to the ASTM standard. When testing of volatile matter content in our laboratory, we found that the residue of vitrain (lignitized wood) caked and exhibited slight porous structure. Additional tests have indicated that nearly all the vitrain samples collected from five different lignite mines in western North Dakota show agglomeration. Nomura (1971) has found independently and earlier that certain Japanese woody lignite also exhibit agglomeration phenomemon. By treating powdered lignite wood with 5% hydrochloric acid for 5 minutes and subsequently carbonized, they have obtained a coke button with a free swelling index of 5, approaching that of a coking bituminous coal. Similar tests were then conducted on the North Dakota lignite, and we obtained coke buttons with free swelling index up to 4. We also observed that if the vitrain sample is rich in pyrite, it will not cake during the normal agglomeration test.

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SUMMARY OF THE CANNONBALL FORMATION

(PALEOCENE) IN NORTH DAKOTA

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INTRODUCTION

The Cannonball Formation and its marine biota has attracted the attention of many geologists, largely because of its restricted occurrence. This Early Tertiary unit is known only from the center of the continent; it has been recognized only in western North Dakota and northwestern South Dakota, and its source still remains unknown. The nearest other, truly marine, Paleocene strata occur in southern Illinois, about 875 miles to the southeast.

This summary of Cannonball stratigraphy and paleontology is based on my studies and those published by others. Unpublished data, particularly from oil and water wells, have not been utilized. All subsurface data will be reevaluated after in-progress micropaleontological studies are completed.

STRATIGRAPHY

The Cannonball Formation and its continental equivalent, the Ludlow, constitute the base of the Fort Union Group. Overlying formations of this group are the Tongue River and Sentinel Butte. Underlying the Cannonball-Ludlow strata is the Hell Creek Formation of Late Cretaceous age.

Naming and areal extent.--Lloyd (1914) named the Cannonball Formation after the Cannonball River for exposures along the bluffs of this river in Tps. 132 and 133 N., R. 88 W., southern Grant County, North Dakota; later he (1915) added R. 87 W. to the type area.

In North Dakota the Cannonball crops out mainly in the south-central part of the state in the drainage of the Missouri River, primarily along its western tributaries, the Heart and Cannonball Rivers, and Cedar Creek. Cannonball outcrops in southwestern North Dakota are sparse; the unit extends to the Little Missouri River valley as thin, brackish tongues. Small, scattered outcrops occur along the Souris River in the Velva area and on the west flank of the Turtle Mountains (Lemke, 1960). Elsewhere, the outcrop area (Fig. R-1) is largely mantled by glacial drift. In the subsurface, the Cannonball probably occurs over most of western North Dakota; specific subsurface localities are discussed under _Thickness_.

Lithology and sedimentary structures.--Two principal types of lithology occur--poorly consolidated sandstone and mudstone (Fig. R-11). The sandstone is grayish green when moist and fresh and weathers light to medium brownish yellow when dry. It contains negligible to appreciable clay and forms steeper slopes where the clay content is higher. This sandstone is very fine- to fine-grained, largely of quartz and micaceous; generally about 1-2% glauconite is present. Cross-bedding is relatively common, in sets of a few inches to a maximum of about 10 inches. Gypsum fills fractures, which are parallel, oblique or normal to the bedding, or occurs as scattered selenite crystals. Small marcasite nodules are common.

Within the poorly consolidated sandstone are lenticular and concretionary beds and concretions that are the carbonate-cemented equivalent of this rock type (Fig. R-11). The indurated sandstone is usually light to medium bluish green to greenish gray when fresh and weathers light to medium brownish yellow. Small, brown and black plant fragments are generally present. The lenticular and concretionary beds are usually 2-2½ feet thick but may be up to 6 feet thick. I have observed oscillation and interference ripples in these beds at three localities in Grant County. Larger sandstone concretions are generally flattened-subspherical (nearly spherical types are rare), of a composition similar to that of the lenticular beds, and less than 2½ feet in the shortest dimension; fossils are uncommon to rare. Cone-in-cone structure rarely forms a peripheral layer surrounding these concretions. Smaller sandstone concretions, subspherical (mean diameter of 2½ inches) to fusiform, are phosphatic, medium grayish brown on fresh surfaces and weather light yellowish gray to light grayish yellow. Crabs are most conspicuous in these concretions, but mollusks, vertebrae, shark teeth, and wood fragments also occur. "Crabiferous" concretions are common east of Flasher in southern Morton County. Indurated claystone also occurs in the poorly consolidated sandstone, as small (few inches in smallest dimension) nodules and lenticular beds, up to half a foot thick (Fig. R-11). As the claystone beds weather, they form a characteristic rubble of yellowish to dark orange yellow "chips" on the surface of exposures.

Mudstone is the other major lithology; it has been called shale by most workers, but I prefer mudstone because the rock is nearly always blocky and lacks fissility. This mudstone is usually medium to very dark gray when moist, and weathers light gray when dry. It is generally sandy and micaceous, and commonly thinly interbedded with lenticular beds of silt or very fine- to fine-grained, commonly cross-bedded sandstone. The contact of this rock with the poorly consolidated sandstone is usually gradational and interbedding occurs in places. Selenite crystals and small marcasite nodules are common. Mudstone concretions, the carbonate-cemented equivalent of this rock type, are common. They are usually flattened and of a size similar to that of sandstone concretions; light to medium gray to medium bluish gray on fresh surfaces, they weather light gray to medium brownish-yellow. Small, black and brown plant fragments are common but other fossils occur sparingly. Limestone concretions, up to 2 feet "thick," also occur in the mudstone; they are dark bluish gray to nearly black when fresh and weather light whitish gray. Fossils, mainly mollusks, occur more commonly in these limestone concretions than in any other type. A decrease in the carbonate content results in a mudstone rather than a limestone concretion. Presumed clastic dikes and sills occur in the upper part of a mudstone at a south-facing bluff exposure in southern Grant County (NW¼ sec. 11, T. 132 N., R. 88 W.). These structures are about 1 foot thick (or wide), occur parallel and oblique to the bedding, and are of fine-grained sandstone similar to that of the overlying unit.

Considerable variation occurs within the two basic lithologic types of the Cannonball. The sandstone may be very clayey or strikingly green so as to be termed a "greensand"; the "greensand," however, is usually relatively thin and less persistent than characteristically grayish-green sandstone. The mudstone may be mottled, a combination of light to medium grayish tan or grayish green and medium gray when moist, and weathers light or light grayish, brownish yellow when dry. Mottling seems to be accompanied by more silt than sand in the non-clay fraction. Sandstone and mudstone may be combined in varying proportions; this results in a gradual change from one rock type to the other or in interbedding, whereby each bed may be less than 1 inch thick, or greater than several feet thick.

Relationship with adjacent units.--The Ludlow Formation, of yellowish-weathering, poorly consolidated sandstone and gray to brown shale with lignite, conformably underlies the Cannonball Formation in most of western North Dakota. The Cannonball-Ludlow contact is usually placed above the highest lignite or lignitic shale. Along the Little Missouri River valley the Ludlow interfingers with the Cannonball.

Both disconformable and conformable relationships appear to occur at the top of the Cannonball where it is overlain by the Tongue River Formation. Thinly interbedded mudstones and sandstones of the Cannonball disconformably overlain by a "basal," massive Tongue River sandstone occur in Burleigh (Kume and Hanson, 1965, p. 47), Mercer and Oliver (Carlson, 1972), McLean (Bluemle, 1971, p. 12), and Ward and McHenry Counties (Lemke, 1960, p. 11, 29). A different, disconformable relationship exists just above the mouth of Heart Butte Creek (SE¼ sec. 16, T. 136 N., R. 88 W.) in northern Grant County. Here, a basal, poorly consolidated conglomerate within a poorly consolidated sandstone of the Tongue River Formation overlies a poorly consolidated, Cannonball sandy mudstone with a sharp and irregular contact. Presumed conformable contacts occur in southern (NW¼ sec. 2, T. 133 N., R. 89 W.) and northern Grant County (SW¼ sec. 17, T. 136 N., R. 86 W.); at both localities Cannonball sandstone passes gradually into overlying Tongue River sandstone. Little difference is apparent between the two sandstones except that of the Tongue River appears less well sorted and slightly coarser.

Thickness.--The thickest, well-exposed (but incomplete) Cannonball is about 300 feet (Cannonball River cutbank exposure in northeastern Morton County; SE¼ sec. 10, T. 138 N., R. 83 W.). Over most of the outcrop area sections are incomplete. Westward, the Cannonball thins as the Ludlow thickens; at least two, thin (few tens of feet thick), brackish tongues represent the Cannonball in the Little Missouri River valley (Brown, 1962, Fig. 1). Contacts are somewhat difficult to place in the subsurface so thicknesses of Cannonball from subsurface data are generally provisional. The thickest subsurface Cannonball known is 395 feet at Garrison Dam, west-central North Dakota (Fox and Olsson, 1969, p. 1397). Other values are about 340 feet in northwestern Burleigh County (Kume and Hansen, 1965, p. 46), 180-340 feet (thinning northwestward) across Oliver and Mercer Counties (Carlson, 1972), and up to 300 feet in southern McLean County (Bluemle, 1971, p. 12). Thicknesses for undifferentiated Cannonball-Ludlow are 360 feet for one well in northwestern Ward County (Lemke, 1960, p. 11, 29), 250-350 feet for two wells in north-central Mountrail and southern Burke Counties (Armstrong, 1971, p. 21-22), and 210-370 feet for north-central to western Divide County (Hansen, 1967, p. 21). Armstrong (1969, p. 23) has reported 130 feet of Cannonball from a well in southern Williams County, but his mention of lignite in the section suggests he has also included Ludlow in this thickness.

PALEONTOLOGY

Fossil groups.--The Cannonball biota consists of foraminifers (Fox and Ross, 1942; Fox and Olsson, 1969), corals (Vaughan, 1920; Wilson, 1957), bryozoans (Cvancara, 1965), mollusks (Stanton, 1920; Cvancara, 1966, 1970a), ostracods (Swain, 1949), crabs (Holland and Cvancara, 1958), lobsters Feldmann and Holland, 1971), the crustacean burrow *Ophiomorpha* (Cvancara, 1965), sharks (Stanton, 1920; Leriche, 1942), skates, rays, turtles, and crocodiles or alligators (Cvancara, 1965), dinoflagellates and hystrichosphaerids (Stanley, 1965), spores and pollen (Stanley, 1965), and driftwood (Cvancara, 1970b). Mollusks, mainly bivalves and gastropods in about equal numbers and relatively fewer scaphopods, are the most frequently found macro-organisms.

Occurrence of fossils.--Fossils are generally not abundant within the Cannonball but may be so locally. Macrofossils occur throughout the formation and are more common in sandstones than in mudstones. Concretions, especially of limestone, contain fossils but do not represent such concentrations as do concretions of the Late Cretaceous Pierre and Fox Hills Formations. Most abundant macrofossils have been collected from poorly consolidated, dark grayish green to greenish gray, clayey, glauconitic sandstone. Generally, fossils are fewer or absent in thinly interbedded (beds few inches or less thick) sandstone and mudstone.

A generalized macrofossil zonation of the formation appears to be present. Most macrofossils occur in two main units or "zones," each of mainly poorly consolidated sandstone with well indurated, lenticular sandstone beds or concretions. Both zones occur in about the middle of the formation. The lower zone is in the lower middle or lower part of the formation and contains most of the mollusks; crabs are rare. The upper zone occurs in the upper middle or upper part of the formation and contains fewer mollusks; crabs appear to be more frequent than in the lower zone. Other fossil groups appear to be equally distributed in both zones. The identities of these zones are not maintained everywhere. Further macro- and microfossil studies are necessary to determine whether a detailed biozonation of the Cannonball exists.

AGE

A Paleocene age has been assigned to the Cannonball since Dorf (1940, p. 231) said the Ludlow Formation was Paleocene on the basis of plants, and Fox and Ross (1942) showed strong relationships of Cannonball foraminifers with those of Paleocene (Midway) species of the U. S. Gulf Coast. Stanley (1965, p. 208) corroborated a Paleocene age for the Cannonball in South Dakota with dinoflagellates and hystrichosphaerids, and suggested (p. 206) an early Paleocene age with spores and pollen. Cvancara (1966, p. 281) indicated that the bivalves suggested Thanetian (middle Paleocene) affinities. Fox and Olsson (1969), using planktonic foraminifers, assigned a Danian (earliest Paleocene) age to the Cannonball. Sloan (1970, p. 441), on the basis of mammals in nonmarine equivalents, gave an age of Puercan and Torrejonian (early to middle Paleocene) for the Cannonball.

DEPOSITIONAL ENVIRONMENTS

The dominantly fine grain size of both major types of Cannonball lithology--very fine- to fine-grained sandstone and sandy mudstone--suggests deposition adjacent to a lowland, similar to a present, low-sloping coastal plain. I envisage a setting somewhat similar to that of the coastal area of the Netherlands and part of northern Germany adjacent to the southeastern part of the North Sea. Here, a lagoon (Wadden Sea) separates a chain of barrier islands (Frisian Islands) from the mainland. A complex of sedimentary environments, including salt marshes, tidal flats, tidal channels, beaches, and shelf bottoms, is present. (Klein, 1967; Reineck, 1967).

Much of the Cannonball sandstone, commonly cross-bedded and well sorted, was probably deposited in a bar, barrier island, or near-beach environment. Mollusks are most commonly found in this lithology and crabs are apparently restricted to it. Ophiomorpha, the crustacean burrow, is almost restricted to well-sorted sandstone in the Cannonball and suggests deposition in the littoral or shallow sublittoral zone (Hoyt and Weimer, 1964). Less well-sorted sandstone may have been deposited in "high tidal flats" (Klein, 1967, p. 208-209).

The mudstone, poorly sorted and dark-colored, was deposited within a protected or semi-protected environment, probably a tidal flat, estuary, or shallow shelf. The presence of lenticular interbedding, of thin beds of mudstone and very fine- to fine-grained sandstone, and small-scale cross-bedding, seem to be particularly indicative of the tidal flat environment (Reineck, 1967, p. 193-197). A general scarcity of detailed stratification, in the mudstone as well as in the sandstone, is attributed to the reworking of sediment by burrowing organisms. Lateral and down-current shifting of streams on the tidal flats must have also reworked the sediment considerably. An abandoned tidal channel may be represented in the lower part of the Fort Lincoln section (Fig. R-11).

Preserved Cannonball may not represent any deep, open-water environments. Planktonic foraminifers, from near the eastern eroded edge of the Cannonball, are scarce and smaller than those expected from more open water. Associated benthonic foraminifers generally suggest deposition in shallow, inner sublittoral depths (Fox and Olsson, 1969, p. 1400).

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THE TONGUE RIVER AND SENTINEL BUTTE MEMBERS OF THE FORT UNION FORMATION NEAR GLEN ULLIN, MORTON COUNTY, NORTH DAKOTA

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INTRODUCTION

The purpose of this report is to describe lower Tertiary rocks and lignite beds of the Fort Union Formation near Glen Ullin, southwestern North Dakota. Glen Ullin, a small town in western Morton County on U. S. Highway 10 about 52 miles west of Bismarck, N. Dak. (Fig. 1), is near the center of the Glen Ullin quadrangle, one of several adjoining 7½-minute quadrangles that are being mapped by the U. S. Geological Survey to furnish a basis for classification for coal and to contribute to the geologic map atlas of the United States. Results of some of the mapping have been released in reports by Smith (1966), Stephens (1970a, b), and Barclay (1970, 1971, 1973). In addition to field mapping, the U. S. Geological Survey conducted a drilling program in the region (Smith, 1970) to gather information on the existence, thickness, and depth of lignite beds in withdrawn Federal lands.

STRATIGRAPHY

The Glen Ullin and Dengate quadrangles are near the outer limit of Wisconsin Glaciation (Fig. 1) in a region characterized by rolling prairies, low hills, and steep-sided buttes. The Tongue River and Sentinel Butte Members of the Fort Union Formation[2] of Paleocene age underlie most of the surface of the area. The Fort Union is locally covered by Pleistocene glacial drift or Holocene alluvium. Outcrops of the Fort Union are poorly exposed except in a few places where erosion of clayey parts of the Fort Union has produced badland topography. Generalized stratigraphic sections of that part of the Fort Union exposed in the area are presented as Figure 2.

The Paleocene Fort Union Formation in North Dakota consists of the Ludlow, Cannonball, Tongue River, and Sentinel Butte Members (Brown, 1962, p. 11). The Ludlow Member, a continental deposit, is the basal unit of the Fort Union in southwestern North Dakota where it overlies the upper Cretaceous Hell Creek

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[1]Publication authorized by the Director, U. S. Geological Survey.

[2]The Fort Union Formation has been elevated to group rank and the Ludlow, Cannonball, and Tongue River and Sentinel Butte Members have each been elevated to formation rank by the North Dakota Geological Survey (Royse, 1967).

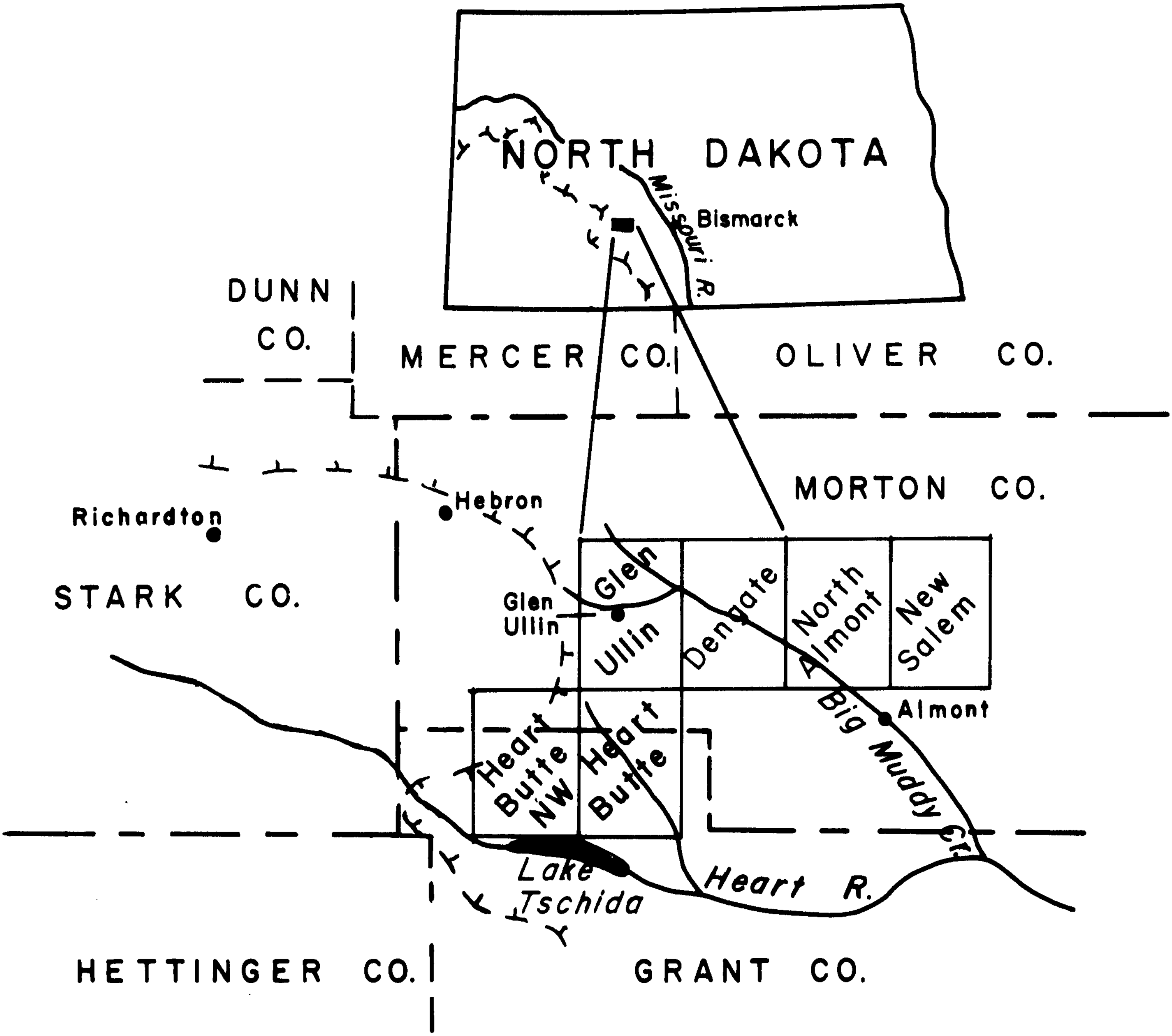


Figure 1. Index map showing the locations of the Glen Ullin, Dengate, and other nearby 7½-minute quadrangles in North Dakota being mapped by the U. S. Geological Survey. Hachured dashed lines show the outermost drift border of Wisconsin age as mapped by Colton, Lemke, and Lindvall (1963).

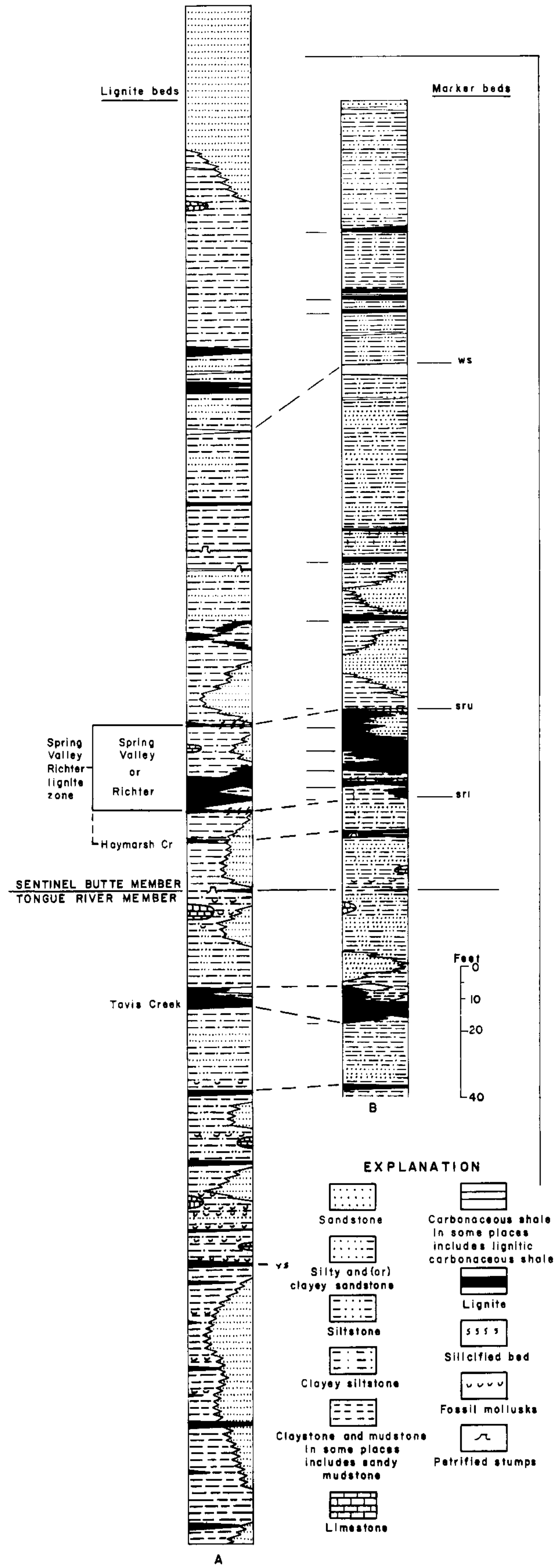


Figure 2. Generalized stratigraphic sections of the part of the Fort Union Formation exposed in (A) the Dengate quadrangle and (B) the Glen Ullin quadrangle, North Dakota.

Formation; it intertongues with the marine Cannonball Member (Brown, Fig. 1). The Tongue River and the overlying Sentinel Butte are continental deposits and are exposed over most of western North Dakota (Carlson, 1969). In southwestern North Dakota the Sentinel Butte Member locally is overlain by the Golden Valley Formation of late Paleocene and early Eocene age (Hickey, 1969), by the Oligocene White River Formation, or by Quaternary deposits.

About 265-305 feet of the Tongue River and Sentinel Butte Members is exposed in the Glen Ullin quadrangle, and about 445-495 feet is exposed in the Dengate quadrangle.

The lower and upper contacts of the Fort Union cannot be seen near Glen Ullin. The nearest locality to Glen Ullin where the base of the Fort Union can be seen is about 35 miles southeast in southeastern Morton County (Laird and Mitchell, 1942, pl. I; Carlson, 1969). The nearest exposures of the contact between the Sentinel Butte and the overlying Golden Valley Formation are about 10 miles north of Glen Ullin (Carlson, 1969).

That part of the Fort Union exposed in the Dengate and Glen Ullin quadrangles is composed of weakly indurated very thinly to thickly interbedded sandstone, siltstone, mudstone, and claystone, numerous beds of carbonaceous shale and of lignite, and a small amount of limestone. Sandstone also occurs in very thick lenticular beds that locally cut out thick sections of the other rock types. The colors of most rocks in the formation range from light shades of gray, yellow, and olive to darker shades of gray, olive gray, and greenish gray. The sandstone is generally light colored, silty, very fine grained, and friable. Sandstone in thick lenticular channel-filling deposits is mostly fine grained and locally has thin conglomeratic lenses containing rounded pebbles of claystone or siltstone and angular fragments of ferruginous nodules. The siltstone is generally clayey and is light or moderately dark colored, depending on the clay content. The claystone is commonly dark and silty. Silty claystone and clayey siltstone are the most abundant rock types in the formation. Many of the rocks in the formation are most conveniently classified as mudstone, a massive rock that contains at least 50 percent clay and silt but in which the relative amounts of silt and clay are unknown. Thin beds of brownish-gray to dark-grayish-brown carbonaceous shale are common, and carbonaceous claystone, mudstone, and (or) shale are generally associated with lignite beds.

The limestone in the formation is dense and brownish gray weathering to yellowish orange. It occurs exclusively in discoidal pods that are commonly 1-3 feet thick and 3-8 feet in diameter. Lines of limestone pods crop out at several stratigraphic horizons in the Tongue River but are rare in the Sentinel Butte. In gross aspect the limestone pods appear to be concretions, but they could be primary deposits (Royse, 1970, p. 55). Samples from four limestone pods (three in the Tongue River and one in the Sentinel Butte) from the Dengate quadrangle were studied in thin section and analyzed by chemical and X-ray diffractometer methods and found to consist of 54-75 percent carbonate of which most was calcite. All samples analyzed are dolomitic, and one sample from the Tongue River contains at least 10 percent dolomite.

Carbonate and clay minerals are the predominant cementing materials in most rocks of the formation. Insoluble-residue analyses of 181 samples (54 from that part of the Tongue River above the ys marker (Fig. 2) and 127 from the Sentinel Butte) from outcrops of clastic rocks in the Glen Ullin and Dengate quadrangles were made by R. F. Gantnier, U. S. Geological Survey. The results of these determinations show that material soluble in about 4N HCl ranges from 3 to 30 percent in about 90 percent of the samples and 30 to 76 percent in 10 percent of the samples. Samples containing more than 50 percent acid-soluble material are from resistant limy lenses in sandstone beds. Thin sections of several such samples show extensive replacement of matrix material of a sandstone by calcite.

Siliceous cement, commonly opal, was found by diffractometer and (or) thin-section studies in samples from beds of various types of resistant carbonaceous rocks in the Sentinel Butte Member in the Dengate and Glen Ullin quadrangles. In one sample--a silty sandstone or siltstone containing rootlet or stem molds--the matrix consisted of heulandite-clinoptilolite (?) in addition to opal, quartz, and clay minerals (Barclay, 1973). Thin sections of silicified carbonaceous shale, a locally abundant rock of the Sentinel Butte Member, show replacement of most of the original material of the rock by very fine grained chalcedonic quartz and opal.

Pyrite is commonly found as monomineralic nodules and in concretions in many rocks of the formation, and it also occurs as grains and irregularly shaped masses replacing matrix material in some sandstone and siltstone. Locally resistant limonitic layers generally about 1 inch thick form dark-yellowish-orange bands in some exposures of claystone-siltstone and, less commonly, in clayey laminae in sandstone. Before oxidation most of these layers were probably thin beds and lenticles of very limy, pyritic claystone and (or) of nodular pyritic limestone which were seen in core samples from Geological Survey drill holes in the area. Crystals of gypsum and, in a drill core from the Dengate quadrangle, barite were found in some rocks of the formation. At least some of the gypsum was probably derived from the oxidation of iron-sulfide nodules.

Tongue River Member

About 60-75 feet of the upper part of the Tongue River is exposed in the Glen Ullin quadrangle and about 180-220 feet is exposed in the Dengate quadrangle. Along part of the Heart River valley in northern Grant County 15-20 miles south of Glen Ullin, Tisdale (1941, p. 10-11 and Pl. 1) mapped the contact between the Cannonball and Tongue River Members of the Fort Union and reported that the Tongue River commonly has a basal sandstone as much as 100 feet thick. Using Tisdale's thickness for the basal sandstone and using the stratigraphic interval between the top of the basal sandstone and various Fort Union marker beds which also crop out in the Dengate quadrangle, the total thickness of the Tongue River is estimated to be at least 260-320 feet in the Glen Ullin quadrangle and 295-325 feet in the Dengate quadrangle.

Reconnaissance indicates that in the region between the southern part of the Dengate quadrangle and the Heart River and between the town of Almont and Lake Tschida (Fig. 1) the Tongue River Member can locally be divided into two parts informally designated as units A and B. The lower part, unit A, is estimated to be at least 150-210 feet thick regionally and 150-180 feet thick in most places in the Dengate quadrangle. None of unit A is exposed in the Glen Ullin quadrangle, and only a portion of the upper part is exposed in the Dengate quadrangle. Unit A consists of thick light-colored lenticular sandstone beds, an interval of dark-colored mudstone and claystone, and a few lignite beds, some of which are several feet thick. The dark-colored beds, which occur in the upper part, are the most distinctive part of the unit. The best exposures of these drab beds are south of Almont in those parts of T. 137 N., Rs. 85 and 86 W., that are west of Big Muddy Creek and at altitudes between 1,900 and 2,100 feet.

Some of the fine-grained rocks in the upper part of unit A are fossiliferous. Fossils collected 15-30 feet below the top of unit A in the Dengate and Heart Butte NW quadrangles and identified by D. W. Taylor and N. F. Sohl of the U. S. Geological Survey are the snails *Campeloma nebrascensis* (Meek and Hayden), *Lioplacodes nebrascensis* (Meek and Hayden), and *Cleopatra tenuicarinata* (Meek and Hayden) and the clam "*Corbula*" *mactriformis* Meek and Hayden.

A persistent, thin lignite or carbonaceous shale bed that commonly has a thin locally pyritic coquina of snail and small clam shells in the roof claystone generally occurs at the top of unit A in the Dengate quadrangle where it was informally named the ys marker bed for the yellow siltstone of the basal beds of the overlying unit B. The ys marker was traced into the North Almont quadrangle and was found near Sims Creek in the southwestern part of the New Salem quadrangle and south of Almont in T. 137 N., Rs. 85 and 86 W. At the Sims Creek locality and in the area south of Almont the ys marker seems to be what Hancock (1921, p. 32 and 35, pl. V) mapped as the B bed. Hancock (p. 13) put his B bed about 100 feet above the Cannonball, but in the area that he mapped south of Almont he may have included some sandstone near the base of the Tongue River in the Cannonball. On the north side of Lake Tschida a lignite bed subjacent to rocks typical of the basal beds of unit B of the Tongue River and believed to be equivalent to the ys marker crops out 70-90 feet above Tisdale's (1941, p. 11-13) basal sandstone and was mapped by Stephens (1970a, b) as the Koehler lignite bed. Identification of the ys marker is difficult in the subsurface. The ys marker was intersected about 96.5 and 145 feet below the top of the Tongue River in two drill holes in the Dengate quadrangle. In a deep drill hole in the Glen Ullin quadrangle lithologies characteristic of unit A of the Tongue River occur about 163 feet below the top of the Tongue River, but the ys marker could not be definitely identified. In a drill hole in the northern part of the Heart Butte quadrangle (Stephens, 1970b) a lignite bed about 165 feet below the top of the Tongue River and about 60 feet above a possible correlative of Tisdale's basal sandstone may be equivalent to the ys marker bed.

Unit B of the Tongue River Member is about 95-160 feet thick in the Dengate quadrangle and consists of a lower sequence of clayey siltstone, mudstone, and subordinate sandstone and an upper sequence of siltstone and sandstone. The lower part of unit B is commonly about 80 feet thick, although it ranges in thickness from about 45 to 115 feet. It is marked at the base by a pale-yellow or golden interval, commonly 20-30 feet thick, of locally fossiliferous clayey siltstone that contains thin ripple-marked sandstone beds and limestone pods. Fossils are snails, small clams, and plant remains (mostly leaves). Fossils collected in the Dengate quadrangle from pale-yellow-weathering clayey siltstone beds near the base of unit B and identified by D. W. Taylor are the snails Bellamya leai (Meek and Hayden) and Campeloma nebrascensis (Meek and Hayden) and the clam Corbula cf. C. Crassatelliformis Meek. The distinctive pale-yellow basal interval is conspicuous on some of the buttes south of Almont in T. 137 N., Rs. 85 and 86 W., where it is in sharp color contrast to the drab beds of the underlying unit A (Fig. 3).

The Tavis Creek lignite bed, a locally thick lignite bed which seems to split into two beds as much as 20 feet apart in some places, occurs at the top of the lower part of unit B. The interval between the pale-yellow strata at the base of unit B and the Tavis Creek bed consists generally of olive-gray to pale-olive clayey siltstone and mudstone, some light-olive-gray to yellowish-gray sandstone, at least one conspicuous level of limestone pods, and a few thin lignite beds. Thick, lenticular, channel-filling sandstone beds locally are present in the lower part of unit B. Thick sandstone beds that appear to be of this type and at this stratigraphic level crop out in the southeastern part of the Dengate quadrangle and in other areas within the region studied.

The upper part of unit B ranges in thickness from 10 to 40 feet but is generally about 20-30 feet thick. It is locally well exposed and is composed predominantly of dusky-yellow clayey siltstone and yellowish-gray sandstone. Limestone pods crop out in the upper part. The basal beds are composed mostly of olive-gray to pale-olive silty claystone; similar beds at the top generally contain one or two very thin (1-2 in.) lignite or carbonaceous shale seams. In some places in the Dengate quadrangle a lignite bed 4-8 inches thick that contains white-weathering silicified wood slabs and large tree stumps crops out at the top of unit B. In parts of western North Dakota a thick lignite bed referred to as the HT Butte lignite (Royse, 1967, p. 5) also occurs at the top of the Tongue River.

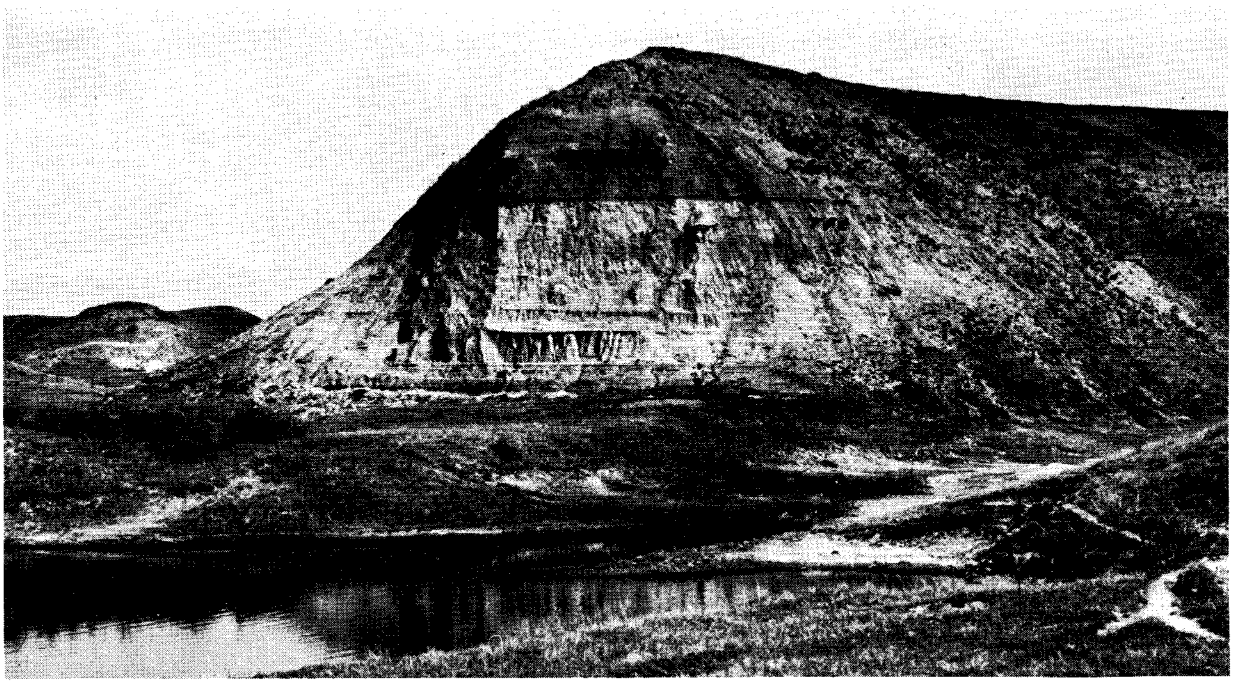
Palynological studies by E. B. Leopold and R. H. Tschudy of the U. S. Geological Survey of outcrop and drill core samples from the Glen Ullin and Dengate quadrangles suggest that most of the Tongue River in that area ranges in age from early (but not earliest) or middle Paleocene, equivalent to a Lebo (but not Tullock) age, to late Paleocene.

Sentinel Butte Member

The Sentinel Butte Member, which is about 265-285 feet thick in the Dengate quadrangle and 200-240 feet in the Glen Ullin quadrangle, is lithologically similar to the Tongue River Member. Separation of the two members in the field, based primarily on a change from light outcrop colors below to dark outcrop colors above, is difficult except in well-exposed areas. The color separation and other features that may be used to distinguish between the two members in western North Dakota were discussed ably by Royse (1967, 1970).

In the Glen Ullin and Dengate quadrangles the Sentinel Butte Member is characterized by drab-colored bentonitic mudstone and clayey siltstone beds, locally abundant white-weathering silicified carbonaceous shale, stumps, and logs, and the "mud butte" topography described by Seager and others (1942, p. 1417). These features are most conspicuous in the basal 40-70 feet and may be mainly confined to the lower 140-170 feet of the Sentinel Butte.

Figure 3. Views of the pale-yellow beds at the base of unit B and the drab beds of the upper part of unit A of the Tongue River Member, Fort Union Formation, south of Almont, N. Dak. The ys marker at the top of unit A in this area is a thin lignite bed commonly overlain by a very thin mollusk shell hash. A, view in the SW¼ sec. 14, T. 137 N., R. 86 W.; B, view in the SW¼ sec. 19, T. 137 N., R. 85 W.



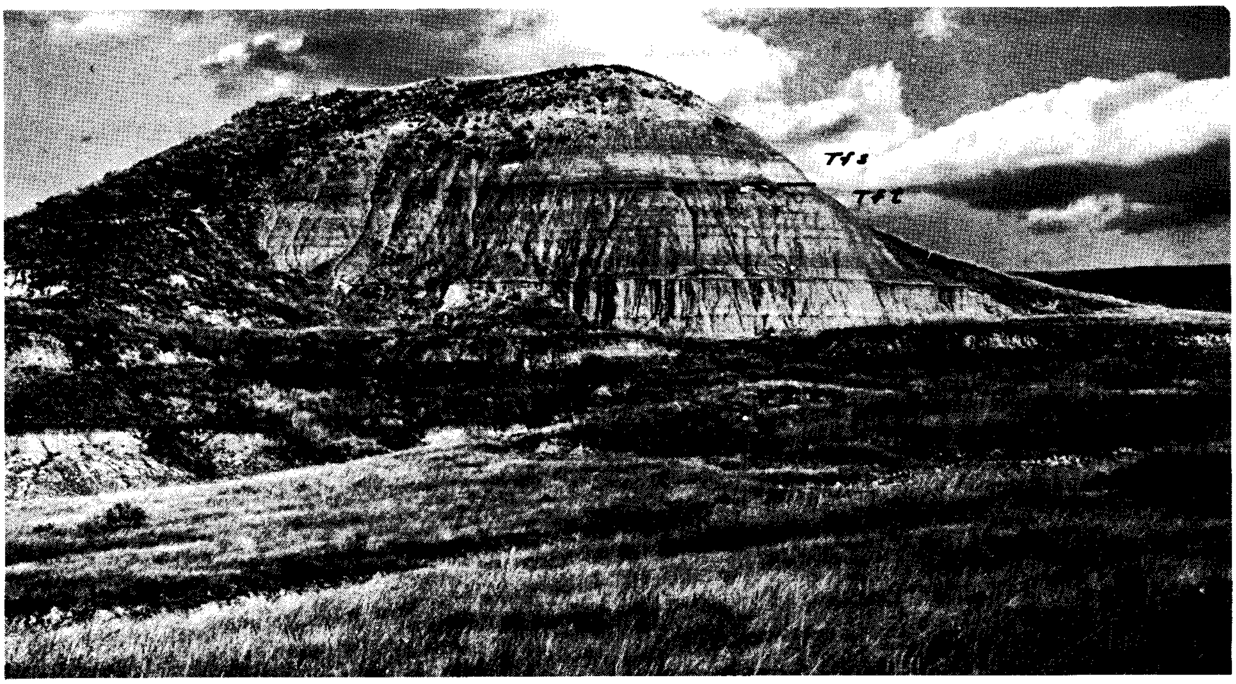


Figure 4. Views of the contact between the Sentinel Butte (Tfs) and Tongue River (Tft) Members of the Fort Union Formation in the Dengate quadrangle, North Dakota. A, an outcrop in the NE¼NW¼ sec. 30, T. 139 N., R. 87 W. The dark bed at about the level of the man's feet is a thin upper bench of the Tavis Creek lignite bed. Bushes in the left foreground grow on clinker derived from the burning of the Tavis Creek bed. The tops of the buttes are capped by clinker derived from the burning of the Richter lignite bed. B, an outcrop in the NE¼SE¼ sec. 34, T. 139 N., R. 87 W. The contact between the Sentinel Butte and the Tongue River in this area is commonly marked by a thin lignite bed containing white silicified wood slabs (shown) and tree stumps. The Tavis Creek bed is partly exposed in a shallow trench in the middle ground. The top of the butte is capped by clinker derived from the burning of lignite beds in the Spring Valley-Richter lignite zone.

For purposes of discussion the Sentinel Butte Member can be divided into three units, A, B, and C, of which only unit A is well exposed. Unit A is that part of the Sentinel Butte below the top of the Spring Valley-Richter lignite zone. Unit A, which is approximately 40-70 feet thick, is composed of interbedded light- and yellowish-gray sandstone and sandy siltstone, light-olive-gray and pale-olive clayey siltstone, and dark-olive and greenish-gray bentonitic mudstone and small amounts of brownish-gray carbonaceous mudstone or claystone, grayish-brown carbonaceous shale, lignite, and rare limestone pods. Thin beds of white-weathering silicified carbonaceous shale are fairly common and form locally mappable marker beds. Large, white-weathering, silicified tree stumps, logs, and wood slabs occur in some lignite and carbonaceous shale beds. The Spring Valley-Richter lignite zone at the top of unit A is a zone of locally thick and persistent mappable lignite beds.

A badland, or "mud butte," topography, characterized by small round, nearly conical, and flat-topped bare buttes, is locally formed on the strata of unit A. Profiles of the buttes typically display reentrant slopes and benches at stratigraphic intervals that contain large amounts of swelling clays. The dark mudstone at the base of the Sentinel Butte commonly forms a bench that has a thick, hummocky, clay crust above 20-40 feet of light-colored Tongue River sandstone and siltstone which stands in fluted near-vertical walls.

Unit B is that part of the Sentinel Butte between the Spring Valley-Richter lignite zone and the ws marker bed. Unit B is about 90-115 feet thick, is poorly exposed, and in general appears to consist primarily of a sequence of light- and dark-colored beds similar to strata in unit A, a few thin lignite beds, and locally thick channel-filling sandstone beds.

Unit C is that part of the Sentinel Butte above the base of the ws marker bed. Unit C is about 120-130 feet thick at Twin Buttes in the northwestern part of the Dengate quadrangle. At this locality unit C has a basal sequence of about 40 feet consisting mostly of pale-yellow clayey siltstone, yellowish-gray to nearly white weathering, coarse-grained siltstone and silty sandstone containing some thin interbeds of lignite and carbonaceous shale, and near the top yellowish-brown siltstone (-mudstone) and thin lignite beds. A bed of brownish-black carbonaceous shale or lignite that generally occurs at the base of unit C is informally named the ws marker bed for the white sandstone or siltstone beds of the overlying rocks. The interval of light-colored siltstone (-sandstone) beds near the base of unit C is an areally persistent lithologic unit that was seen on some high hills and buttes in the northern part of the Dengate quadrangle, in the Glen Ullin quadrangle, and farther westward. A lignite bed at the top of the light-colored siltstone (-sandstone) sequence in the Twin Buttes area is believed to be equivalent to the beds that are burned near the top of Rocky Ridge in the southern part of the Glen Ullin quadrangle. On the northwest butte of Twin Buttes the lignite bed is overlain by 40 feet of olive-gray to dusky-yellow clayey siltstone and mudstone containing a limestone pod horizon and a thin carbonaceous shale at the top. Above the carbonaceous shale is 50 feet of yellowish-gray to pale-brown massive fine-grained sandstone that forms the cap rock of the buttes.

The contact between the Sentinel Butte and Tongue River Members in the area is at the base of the lowest bed of a sequence of alternating thick dark bentonitic mudstone or claystone beds and light-colored siltstone or sandstone beds. The dark color of the basal mudstone contrasts sharply with the uniformly light colored interval of siltstone and sandstone typical of the uppermost part of the Tongue River. The contact is exposed at many localities in the southern parts of both the Dengate (Fig. 4) and Glen Ullin quadrangles.

The outcrop appearance of the Sentinel Butte-Tongue River contact in the area is strikingly similar to its appearance in the Twin Buttes area north of the town of Sentinel Butte (Fig. 5A) and near the north edge of the South Unit of Theodore Roosevelt National Park (Fig. 5B) in western North Dakota. The contact in those areas was described by Royse (1967, p. 12 and 22, Figs. 4C-D and 5A-C). In many other areas of western North Dakota the contact is drawn between a locally thick lignite, the HT Butte lignite bed of the Tongue River, and a silty sandstone which is commonly several tens of feet to more than 100 feet thick (Royse, 1967, p. 5, 7).

Three samples collected from the interval 9-22 feet above the base of unit C of the Sentinel Butte Member on Rocky Ridge in the southern part of the Glen Ullin quadrangle yielded a late Paleocene pollen assemblage (E. B. Leopold, written commun., April 10, 1972).

LIGNITE DEPOSITS

Lignite Beds and Zones

Lignite beds 1-13 feet thick occur in many parts of the Fort Union Formation exposed in the Glen Ullin and Dengate quadrangles. Individual lignite beds are generally lenticular, but lignite zones tend to be areally persistent. During mapping of the two quadrangles, a few lignite beds and one lignite zone were given informal names which are shown in the generalized stratigraphic sections (Fig. 2). The thickest and probably the most persistent lignite beds in the area are the Tavis Creek bed in the upper part of the Tongue River Member and some of the beds of the Spring Valley-Richter lignite zone in the Sentinel Butte Member.

The Tavis Creek lignite bed is commonly 20-40 feet below the top of the Tongue River Member. The thickest outcrops of this bed are west and south of Big Muddy Creek where a thickness of 4-7 feet in a single bed was found at several localities, and a thickness of 11.5 feet was measured at one place in the Glen Ullin quadrangle. Locally, the Tavis Creek bed seems to split, and two beds, the lower of which is generally the thicker, crop out near the normal stratigraphic position of the Tavis Creek bed. The Tavis Creek bed was mined, generally by open-pit methods, at several localities in the area. The Tavis Creek bed is approximately equivalent to Stephens' (1970a, b) Beaver Creek bed and to Hancock's (1921, p. 13) C bed, and it correlates well with a lignite bed that occurs 20-25 feet below the top of the Tongue River at Klondike Butte in the New Salem quadrangle.

The Spring Valley-Richter lignite zone is in the lower part of the Sentinel Butte Member. Lignite beds in the zone were mapped in the Glen Ullin and Dengate quadrangles, and the zone was recognized in parts of the Heart Butte, North Almont, and New Salem quadrangles. The thickest beds of the zone in the area are the Spring Valley and Richter beds after which the zone is named. The Spring

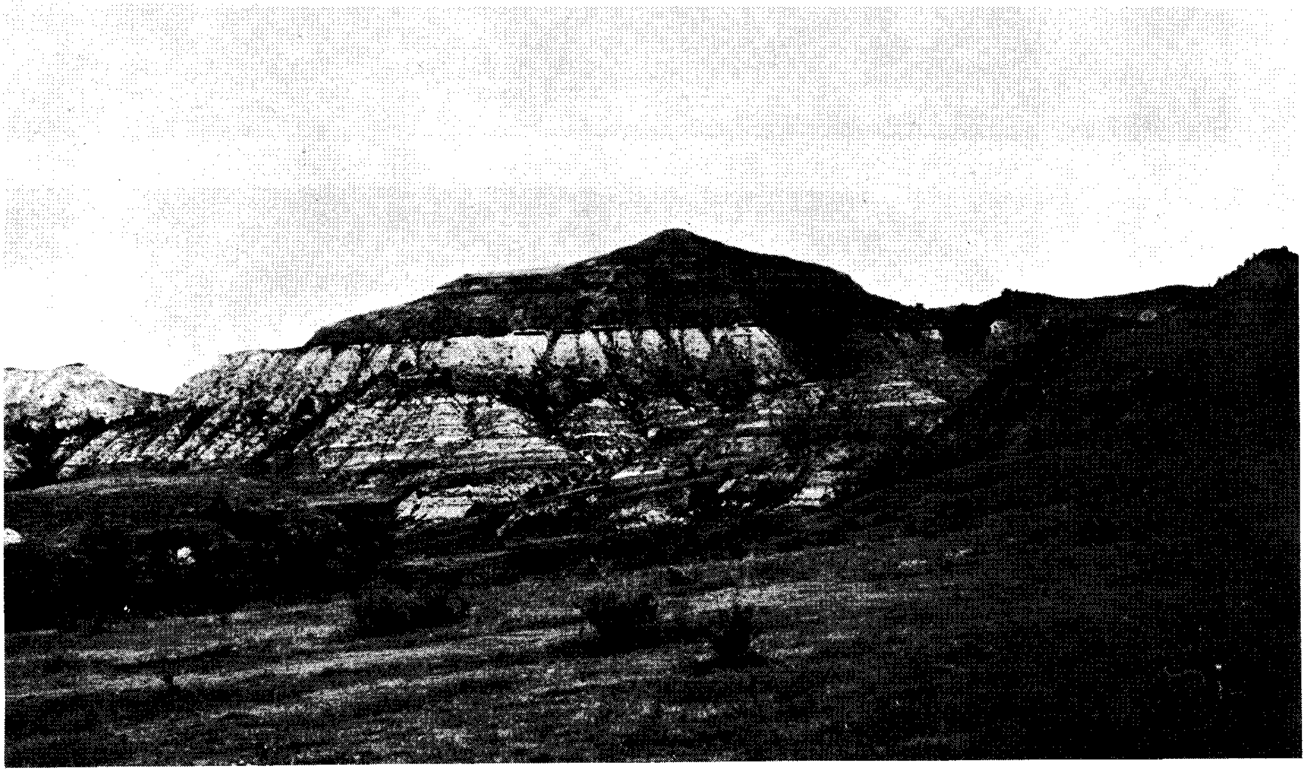
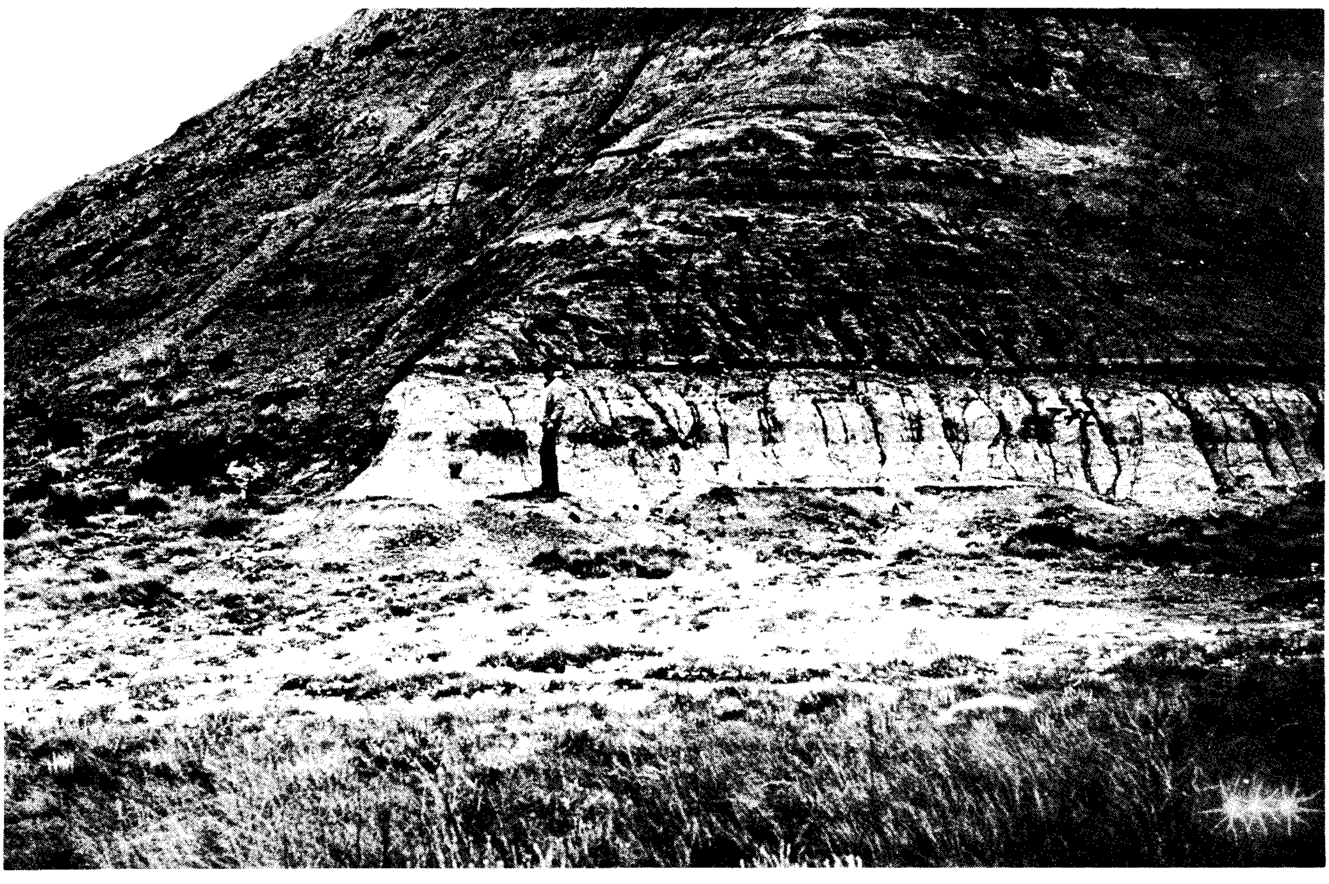


Figure 5. Views of the contact between the Sentinel Butte (Tfs) and Tongue River (Tft) Members of the Fort Union Formation in western North Dakota. A and B, views in secs. 8 and 9, respectively, T. 141 N., R. 101 W.; C, outcrop north of the town of Sentinel Butte in sec. 17, T. 141 N., R. 103 W. The contact is marked by about 4-6 inches of lignite that may be equivalent to the HT Butte lignite of the Sentinel Butte area. C. F. Royse, Jr. (1967), photographed in C, described the contact between the Sentinel Butte and Tongue River in this area.



Valley bed was mined at the Spring Valley mine, an underground mine in sec. 22, T. 138 N., R. 88 W., in the southeastern part of the Glen Ullin quadrangle where it is commonly 8-10 feet thick and locally as much as 12 feet thick. The Spring Valley bed was mapped extensively in the Glen Ullin quadrangle but was mapped at only a few places near the west edge of the Dengate quadrangle. The Richter bed was mined at the Richter mine, an open-pit mine in sec. 13, T. 139 N., R. 88 W., in the northwestern part of the Dengate quadrangle where it is commonly 7-9 feet thick. The Richter bed, or clinker from its in situ combustion, occurs in most areas of the Dengate quadrangle except in the southeast corner. The Spring Valley and Richter beds are at least partly equivalent to and are approximately correlative with Hancock's (1921, p. 13)D bed. The Spring Valley and Richter beds mapped in the Heart Butte area by Stephens (1970a, b) are in the Spring Valley-Richter zone, although they may not be exactly equivalent to beds of the same names in the Glen Ullin and Dengate quadrangles.

In many parts of the area the Spring Valley-Richter zone does not contain a single thick bed but has one to four lignite beds, 1-6 feet thick, none of which seems to be areally extensive. In those areas in the Dengate quadrangle where a single Richter or Spring Valley bed was difficult to trace, a thin bed of silicified carbonaceous shale or, less commonly, of carbonaceous shale or lignite, which locally seems to merge with the Richter bed, was mapped as the srl marker bed for the approximate position of the base of the Spring Valley-Richter zone. A bed of similar lithology, the sru marker bed, near the top of the Spring Valley-Richter zone was locally mapped in both the Dengate and Glen Ullin quadrangles.

In addition to the Tavis Creek, Spring Valley, and Richter beds and the local beds associated with them, several very lenticular lignite beds, 1-4 feet thick, were mapped in the Dengate and Glen Ullin quadrangles. Among these are a local bed generally about 20-30 feet below the Tavis Creek bed, the Haymarsh Creek bed(s) near the base of the Sentinel Butte in the Glen Ullin quadrangle, local beds between the Spring Valley-Richter zone and the ws marker bed, and local beds 5-35 feet above the ws marker. Of these, the local beds above the ws marker, which occur only on a few of the highest buttes of the area, and the local bed below the Tavis Creek bed appear to be the most areally persistent.

Lignite beds 2.5-4 feet thick that do not crop out in the area were intersected 152-190 feet below the top of the Tongue River Member in Geological Survey drill holes in the area. These beds, Hancock's (1921, Pl. V) A bed, and Stephens' (1970a, b) Shell lignite bed are believed to belong to a persistent lignite zone in the upper part of unit A of the Tongue River.

The total lignite resources 2.5-10.0+ feet thick within 0-450 feet of the surface in the Glen Ullin and Dengate quadrangles are estimated to be 866.25 million short tons, of which 521.27 million short tons is measured and indicated resources and 344.98 million short tons is inferred resources. A table showing the lignite resources in the Tongue River and Sentinel Butte Members is presented below.

Lignite resources in the Glen Ullin and Dengate quadrangles, Morton County, N. Dak.

(In millions of short tons in beds of thickness indicated)

Member	Name and (or) stratigraphic position of lignite bed(s)	Measured and indicated resources			Inferred resources			Total
		2.5-5 ft.	5-10 ft.	10 ft.	2.5-5 ft.	5-10 ft.	10 ft.	
Sentinel Butte Member	Beds above the Spring Valley-Richter lignite zone.	1.22	---------	---------	6.80	---------	---------	8.02
Sentinel Butte Member	Beds in the Spring Valley-Richter lignite zone.	31.40	94.64	1.09	1.77	---------	---------	128.90
Tongue River Member	Tavis Creek lignite bed(s).	140.61	114.54	0.82	4.96	19.41	-------	280.34
Tongue River Member	Beds below the Tavis Creek lignite bed(s).	123.31	1.71	11.93	232.05	38.16	41.83	448.99
	Total---------	296.54	210.89	13.84	245.58	57.57	41.83	866.25

Physical and Chemical Characteristics

The lignite in the Fort Union Formation in the Glen Ullin and Dengate quadrangles is commonly blackish brown, hard, and woody and is slabby when freshly dug. It characteristically slacks rapidly when exposed to the atmosphere.

Samples of lignite and various kinds of rocks containing carbonaceous material or plant impressions were obtained from Geological Survey drill holes and from outcrops in the area. Results of the analyses of these samples by the Geological Survey and the U. S. Bureau of Mines laboratories were reported by Barclay (1971, Tables 2-5; 1973, Tables 1,2). Results of the lignite analyses are summarized in part below.

Nineteen core samples and 12 outcrop samples of lignite were analyzed by semiquantitative spectrographic methods. The compositions of the minor elements in the ash of both the lignite core samples and the lignite outcrop samples are similar to compositions reported for Fort Union lignite ash of North Dakota and the east edge of Montana (Zubovic and others, 1961, Tables 3, 4; Sondreal and others, 1968, Tables 3, 12).

Nine core samples of lignite, analyzed (on an as-received basis) by the U. S. Bureau of Mines, gave the following results:

	Moisture (percent)	Volatile matter (percent)	Fixed carbon (percent)	Ash (percent)	Sulfur (percent)	Heating value (Btu)
Average-	38.6	25.7	26.1	10.2	0.7	6,242
Range---	36.3-42.7	23.7-26.1	24.6-27.2	6.3-13.6	0.2-1.2	5,900-6,640

The percentage of sodium in ash has been cited by U. S. Bureau of Mines researchers at Grand Forks, N. Dak., as a useful index of the fouling potential of Fort Union lignite beds that is used in many of the large power generating facilities of the Northern Great Plains-Great Lakes region (Gronhovd, 1968, p. 4-5). According to Gronhovd, Harak, and Paulson (1968, p. 77-80), fouling of convection surfaces and the rate of formation of slag deposits on boiler walls are excessive for lignite with 9 percent Na_2O in ash. Fifteen lignite core samples were analyzed for Na, K, Ca, and Mg by atomic absorption methods. The calculated percentage of sodium oxide in lignite ash ranges from 1.8 to 16.5 percent and is more than 9 percent in six samples. The sodium content of each of these samples may not be representative of the beds sampled; Gronhovd, Harak, and Paulson (1968, p. 77) reported that sodium content varies markedly from place to place in a single mine.

A portion of each of the lignite core samples used in the chemical analyses was studied by X-ray diffractometer methods. Both raw lignite and ash produced by low-temperature oxidation of the lignite after the method of Gluskoter (1965) were used in the study. Quartz, pyrite, calcite, siderite(?), and clay minerals were the principal minerals detected in most samples. Gypsum, anhydrite(?), albite(?), and orthoclase(?) occur in very small amounts in some samples, and heulandite-clinoptilolite(?) was found in one sample from the Dengate quadrangle in which it is the most abundant mineral present. No mineral containing sufficient sodium to account for the amounts that were detected in the ash could be found in any sample except the sample containing zeolite, and that sample contained only 2.4 percent Na in ash. Researchers at the Bureau of Mines, Grand Forks, N. Dak., who have done considerable work on the composition of Fort Union lignites have not found any sodium-rich minerals in the North Dakota lignite (Spencer, 1969, p. 50) and suggest that the sodium is "probably attached to the coal molecule" (Gronhovd, 1968, p. 5).

In view of the current interest in determining and evaluating possible sources of mercury contamination of the environment, 11 lignite core samples from the area were analyzed by using a stannous chloride flameless atomic-absorption method. In nine of the samples Hg content ranged from 0.05 to 0.18 ppm and averaged 0.12 ppm; the two remaining samples contained 0.26 and 0.43 ppm Hg. Ruch, Gluskoter, and Kennedy (1971) reported that in the Illinois coals they sampled a significant amount of mercury is associated with iron-sulfide minerals. Diffractometer studies of raw and low-temperature ash samples of the 11 lignite core samples showed a good correlation between the pyrite and the mercury content of lignite. The sample that contains 0.26 ppm Hg and the one that contains 0.43 ppm Hg give very strong pyrite lines on diffractograms. The remaining nine samples for which Hg content averaged 0.12 ppm have only small to possibly trace amounts of pyrite.

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STRATIGRAPHIC POSITION OF LIGNITE BEDS IN THE

TERTIARY ROCKS OF MERCER AND OLIVER COUNTIES

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INTRODUCTION

Mercer and Oliver Counties are located in west-central North Dakota near the eastern margin of the lignite bearing Tertiary Formations. This geographic advantage plus the easy accessibility and thickness of some of the lignite beds led to early and continued exploitation. Surface mapping led to the naming of twenty-four lignite beds in Mercer and Oliver Counties, and many unnamed local beds have been mapped. Since 1932 Mercer County has been the leading county for lignite production in North Dakota with the exception of 1944, when it was second to Ward County. Oliver County was a minor producing area until the Minnkota plant began operations in 1970; now it is the second leading county. The bulk of the production in Mercer County has been from the Beulah-Zap bed while the Hagel bed is supplying the Minnkota plant.

The stratigraphic position of the lignite beds in this area and their relationship to lignite beds in other areas of the state have been continuing problems. The main problems of correlation and stratigraphic placement of the lignite beds are:

1) The variability in thickness of lignite beds. This is known from areas where continuous exposures or closely spaced drill hole information is available;

2) The lateral variability of lithology and thickness of the section between lignite beds;

3) Areas of drift covered bedrock or poor bedrock exposures;

4) Uncertainties about the thickness of the Sentinel Butte and Tongue River Formations; and

5) Uncertainties about the Sentinel Butte-Tongue River contact in areas other than along the Little Missouri River.

PREVIOUS STUDIES

Most previous studies of the Tertiary rocks in Mercer and Oliver Counties have been primarily concerned with determination of the presence and thickness of the lignite beds. The general approach was usually to measure the thicknesses of lignite beds, name the beds, relate the lignite beds to each other by the stratigraphic interval between the beds or the interval above or below key "persistent" lignite beds using lithology and thickness of beds as tools of correlation. Recognizing the difficulties of correlation, most workers were content to apply local names when mapping in the different geographic areas, sometimes suggesting correlations to other areas in their summaries. Using this approach Bauer and Herald (1925) mapped the lignite beds of the Fort Berthold Indian Reservation in northwestern Mercer County and adjacent areas and Andrews (1939) mapped the lignite beds of northeastern Mercer County and adjacent areas. Hancock (1926) mapped the lignite beds using letter designations in the New Salem lignite field, located just south of Oliver County. Benson (1952) mapped most of the lignite beds exposed in Mercer County, named some of the previously unnamed beds, arranged the lignite beds stratigraphically in the different geographic areas of his study (Table I), and suggested some correlations of beds to previous studies to the north and east. Johnson and Kunkel (1952) mapped the lignite beds of Oliver County, arranged them stratigraphically for the different geographic areas (Table II), and suggested correlations within these areas and with adjacent areas.

The uncertainty of extension of the Sentinel Butte-Tongue River contact into this area led Benson (1952, p. 42) to refer all of the strata between the Golden Valley and Cannonball Formations to the Tongue River Member of the Fort Union Formation, while Johnson and Kunkel (1959, p. 11) referred these strata to the Fort Union Formation. The key beds which they used for constructing stratigraphic sections were the Beulah-Zap, Stanton, Garrison Creek, Hagel, and Otter Creek beds. They then related their other named beds to these key beds by the stratigraphic interval above or below the key beds. Based on this approach Johnson and Kunkel (1959, p. 13) estimated a total thickness of the Fort Union (Sentinel Butte and Tongue River Formations of this study) Formation to be about 520 feet in Oliver County. In Mercer County, Benson (1952, p. 65) noted that based on piecing together his measured surface sections he had an estimated thickness of 550 to 575 feet for his Tongue River Member, but based on a few deep wells he estimated the thickness to be 750 to 800 feet.

Recognition of the Sentinel Butte and Tongue River Formations in western North Dakota has been based largely on color differences which are easily recognizable where good exposures are present along the Little Missouri River, although Royse (1967) used three criteria in his studies of that area. These were color differences, a lignite bed at the top of the Tongue River Formation, and a basal sandstone bed in the Sentinel Butte Formation. In Morton County, about 12 miles south of the southwest corner of Oliver County, the Sentinel Butte-Tongue River contact has also been mapped on the basis of color differences (Barclay, 1970, 1971) where there are good exposures in the Glen Ullin area. In that area there is no lignite bed nor basal sandstone bed present at the color contact, but his placement of the contact fits within the regional framework.

Sentinel Butte and Tongue River Formations

Recognition of similar Sentinel Butte-Tongue River contacts in the Mercer-Oliver area is further complicated by glacial drift (Figs. 1 and 2) which obscures the contact in many areas, rates of erosion in some areas of good exposure which eliminates color differences, and a lack of color differences in test hole cuttings of these formations. In the Square Butte Creek drainage, where post-glacial drainage follows the preglacial drainage, exposures of the Tongue River Formation have weathered to light yellow and buff colors typical of the Tongue River Formation in the Little Missouri valley area. These colors

TABLE 1.-Named lignite beds and their relationship to "key beds" according to Benson (1952).

WESTERN AREA

Golden Valley Formation

Shaffner bed
30 feet above Alamo Bluff bed

Alamo Bluff bed
at base of upper member

Fort Union Formation

Twin Buttes Bed
130 to 150 feet above Beulah-Zap bed

Schoolhouse bed
45 to 50 feet above Beulah-Zap bed; increasing westward to 80 to 100 feet

Beulah-Zap bed
60 feet below Beulah-Zap bed

Spaer bed
110 to 115 feet below Beulah-Zap bed

Hazen "B" bed

HAZEN AREA

Beulah-Zap bed
75 to 95 feet below Beulah-Zap bed

Star bed
25 to 40 feet below Star bed

Hazen "B" bed
155 to 160 feet below Beulah-Zap bed

Hazen "A" bed

GARRISON AREA

Kruckenberg bed
50 feet above Garrison Creek bed

Garrison Creek bed
(?) position

Wolf Creek bed

STANTON AREA

Local bed
50 feet above Stanton bed

Stanton bed
35 to 40 feet below Stanton bed

Coal Creek bed
85 to 95 feet below Stanton bed

Knoop bed
150 to 160 feet below Stanton bed

Hancock bed

BLACKWATER-EMMET AREA

Beulah-Zap bed
160 to 165 feet below Beulah-Zap bed

Garrison Creek bed

TABLE 2.-Named lignite beds and their relationship to "key beds" according to Johnson and Kunkel (1959).

NORTHWEST AREA

Byer bed
65 feet above Otter Creek bed

Otter Creek bed
135 to 145 feet above Beulah-Zap bed

Herman bed
25 to 30 feet above Buckman bed

Buckman bed
65 to 75 feet above Beulah-Zap bed

Schoolhouse bed
30 to 45 feet above Beulah-Zap bed

Beulah-Zap bed
45 feet below Beulah-Zap bed

Spaer bed

CENTRAL AND NORTH-CENTRAL AREA

Red Butte bed
100 feet above Keuther bed

Keuther bed
35 to 45 feet above Hagel bed

Hagel bed
25 to 40 feet below Hagel bed

Yeagher bed
30 feet above Berg bed

Berg bed
40 feet above Stanton bed

Stanton bed
20 to 45 feet below Stanton bed

Brahzda bed

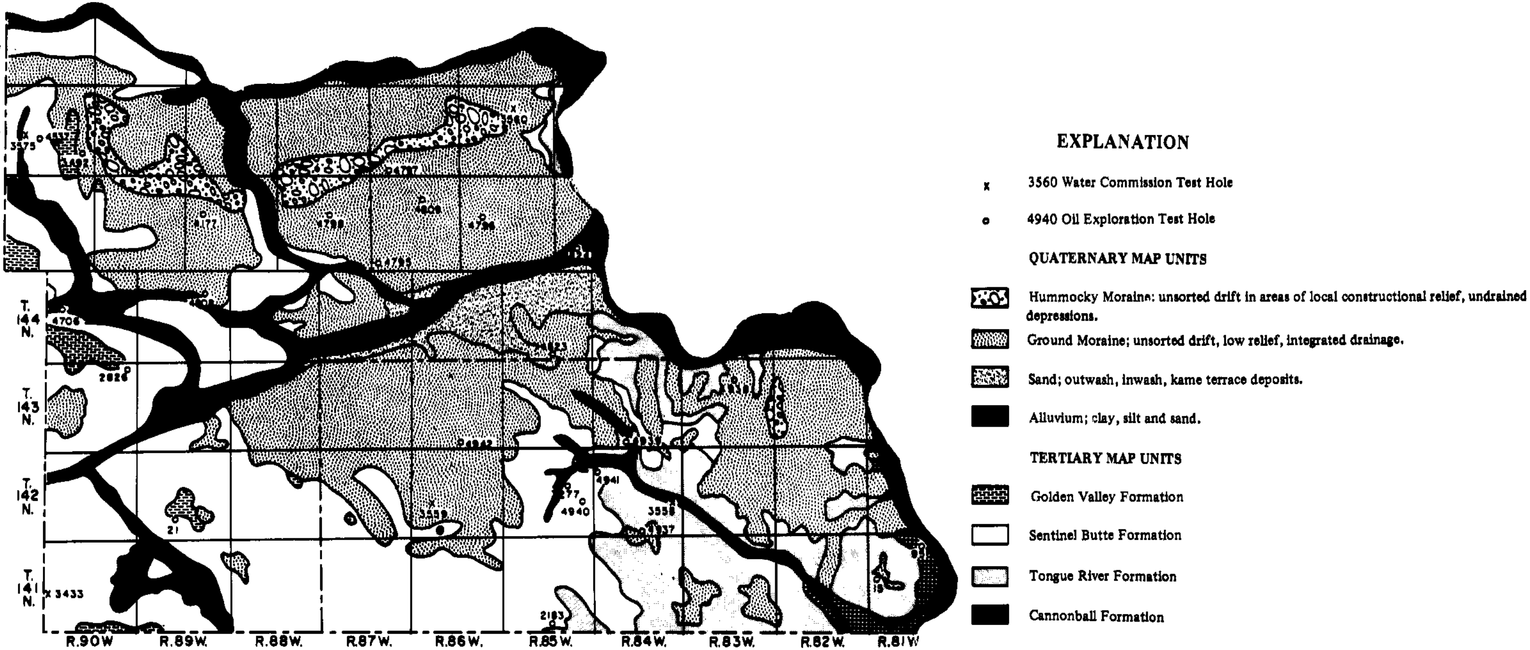


Figure 1. Geologic map of Mercer and Oliver Counties.

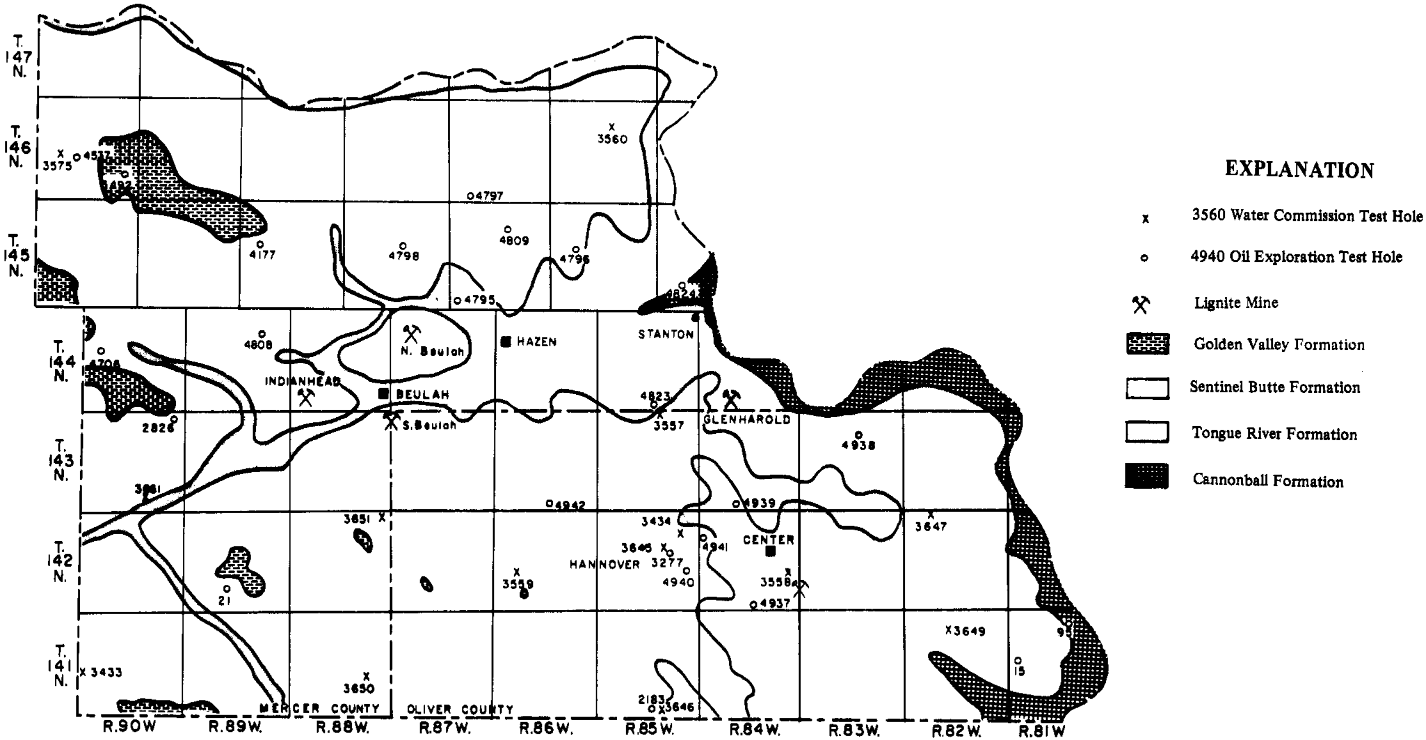
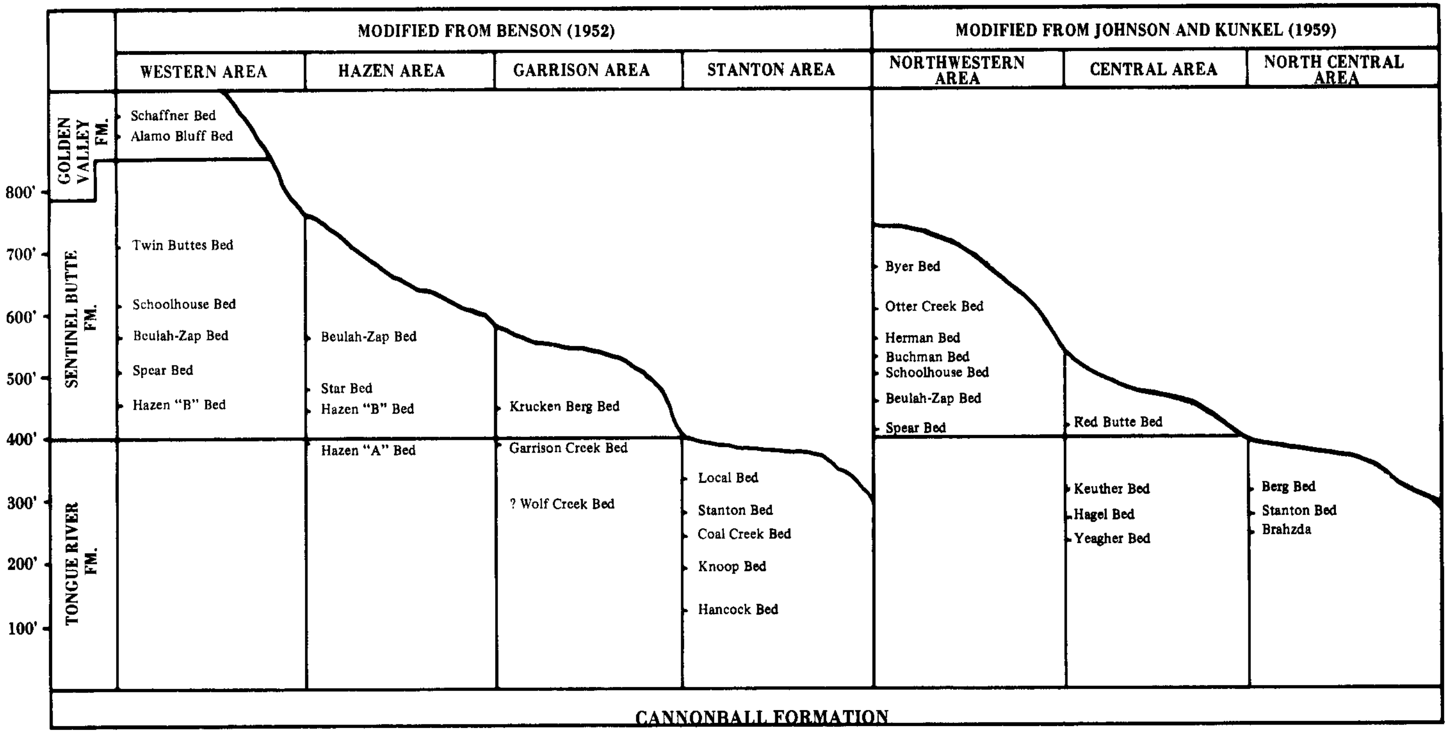


Figure 2. Bedrock geologic map of Mercer and Oliver Counties.


MODIFIED FROM BENSON (1952)
MODIFIED FROM JOHNSON AND KUNKEL (1959)
WESTERN AREA
HAZEN AREA
GARRISON AREA
STANTON AREA
NORTHWESTERN AREA
CENTRAL AREA
NORTH CENTRAL AREA
GOLDEN VALLEY FM.
SENTINEL BUTTE FM.
TONGUE RIVER FM.
800'
700'
600'
500'
400'
300'
200'
100'
Schaffner Bed
Alamo Bluff Bed
Twin Buttes Bed
Schoolhouse Bed
Beulah-Zap Bed
Spear Bed
Hazen "B" Bed
Beulah-Zap Bed
Star Bed
Hazen "B" Bed
Hazen "A" Bed
Krucken Berg Bed
Garrison Creek Bed
? Wolf Creek Bed
Local Bed
Stanton Bed
Coal Creek Bed
Knoop Bed
Hancock Bed
Byer Bed
Otter Creek Bed
Herman Bed
Buchman Bed
Schoolhouse Bed
Beulah-Zap Bed
Spear Bed
Red Butte Bed
Keuther Bed
Hagel Bed
Yeagher Bed
Berg Bed
Stanton Bed
Brahzda
CANNONBALL FORMATION

extend up to and above the Hagel bed in the area near Center. However, in the short drainages along the Missouri River trench from Hensler to Garrison Dam only a few of the exposed beds are of the typical Tongue River colors, although the Tongue River-Cannonball contact is present at the upper terrace level of the Missouri River just east of Hensler. Hence, the short drainages between Hensler and Stanton are eroding the same stratigraphic interval as that of the Square Butte creek drainage southeast of Center. The explanation for the lack of light colors in this area seems to be that these drainages are adjusting to the new base level, and the rate of erosion exceeds the rate of weathering so that the weathering effects (i.e., the light colors) are not present in this area.

Groundwater test holes (Croft, 1970), oil exploration test holes, and topographic mapping in Mercer and Oliver Counties now provide a framework for determining the thickness of the Sentinel Butte and Tongue River Formations. They also provide a means for relating the measured surface sections of the different geographic areas and placing the lignite beds in their proper stratigraphic position. Lacking the clear cut color differences of the Little Missouri area, the Sentinel Butte-Tongue River contact is somewhat subjective, so for mapping purposes it was placed at the base of sandstone beds which are present at many localities in about the right stratigraphic position to be at the contact based on subsurface information and topographic control.

A test hole in northwestern Mercer County (3575, 90-146-20 ccc) started in sand of the Sentinel Butte Formation at a surface elevation of 2,120 feet. The Golden Valley Formation crops out about one mile east of this test hole at only a slightly higher elevation, so a nearly complete Sentinel Butte-Tongue River section was present at this site. The Cannonball Formation was penetrated at a depth of 960 feet, so a maximum thickness for the Sentinel Butte-Tongue River interval in this area is about 1,000 feet. Part of the nonmarine section above the Cannonball may belong in the Ludlow Formation which would then thin the Sentinel Butte-Tongue River interval by perhaps as much as 100 to 150 feet. Samples from this test hole show 15 separate lignite beds above the Cannonball of which 4 appear to be more than 5 feet thick based on logs and samples. Correlations of these lignite beds to named beds of surface studies is uncertain because of distances to areas of mapped beds with topographic control, but based on regional dip the lignite bed at about 240 feet may be equivalent to the Beulah-Zap bed. If this correlation is correct, the Beulah-Zap bed is about 275 feet below the top of the Sentinel Butte Formation.

A test hole south of Beulah (3651, 88-142-1 cdc) was drilled from a surface elevation of 2,075 feet to a depth of 640 feet with the lower 30 feet logged as Cannonball Formation. The base of the Golden Valley Formation is present at elevations of 2,110 feet in Sections 10 and 11, T. 142 N., R. 88 W, where it lies on silts and clays of the Sentinel Butte Formation. It is difficult to be certain of the Tongue River-Cannonball contact when so short a section of Cannonball is cut, but if the call is correct, then the total Sentinel Butte-Tongue River section has thinned to about 700 feet. It seems likely that it is thicker and that the test hole did not penetrate Cannonball. A 20-foot thick lignite is present at a depth of 250 to 270 feet, and a 10-foot thick lignite bed is present at a depth of 95 to 105 feet. Based on elevation and thickness the 10-foot thick bed is the Beulah-Zap bed of the South Beulah mine area (test holes are about 2.5 miles away). This places the Beulah-Zap bed about 130 feet below the top of the Sentinel Butte Formation in this area.

A test hole (3557, 85-143-3 dad) was drilled about 3.5 miles west of the Glenharold mine where the Hagel bed is being mined. Glacial drift is present at the surface here and overlies the lower 357 feet of the Tongue River Formation. This test hole penetrated a 5-foot thick lignite bed 170 feet above the base of the Tongue River Formation and a 6-foot thick lignite bed 245 feet above the base of the Formation. The base of the Hagel bed was 275 feet above the base of the Tongue River Formation at an elevation of 1,850 feet. These were the only significant lignite beds penetrated in this test hole. Surface elevations of bedrock on the drainage divide about three miles south of this test hole are as high as 2,330 feet with no Golden Valley Formation present. Therefore, the total thickness of the Sentinel Butte and Tongue River Formations in this area was at least 750 feet thick and the Hagel bed is about 480 feet below an eroded top of the Sentinel Butte Formation.

A test hole (3646, 85-141-27 ddd) was drilled about ten miles north of New Salem. Bedrock is present at the surface at this location, and the Tongue River-Cannonball contact was penetrated at a depth of 404 feet. A 3-foot thick lignite bed (the Hagel ? bed) was present 270 feet above the base of the Tongue River Formation and a 12-foot thick lignite bed was present 80 feet above the base of the Tongue River Formation. No other lignite beds exceeding 2.5 feet in thickness were present in this test hole.

CONCLUSIONS

This information leads to the conclusion that surface mapping studies might be misleading in terms of the number of lignite beds expected to be present at any one locality. It also indicates that the estimated thickness for the Sentinel Butte-Tongue River interval based on surface exposures were generally thinner than those present in the test holes.

In northwestern Mercer County the Sentinel Butte-Tongue River interval is at least 850 feet thick, and may be as much as 1,000 feet thick; eastward it thins to about 750 feet in the Beulah-Hannover area where the Golden Valley Formation is present. Where the Golden Valley Formation is absent the thickness varies with most of the thinning accounted for by erosion of the Sentinel Butte Formation until the erosional edge is reached in central Oliver County, and then the Tongue River Formation thins eastward due to erosion.

Benson (Table I) did not attempt to correlate between the Hazen-western area where he used the Beulah-Zap bed as his key bed and the eastern area where he used the Stanton bed as his key bed. Johnson and Kunkel (Table II) also used different key beds in the different areas of their study, but they (1959, p. 35) then attempted to correlate key beds between these areas. They correlated the Hagel bed of the Square Butte drainage with Bed D of the New Salem study and to the Otter Creek bed of their northwestern area. Based on test hole data and topographic control some adjustments of these correlations now seem probable. Table III is my interpretation of the stratigraphic position of the previously named beds in Mercer and Oliver Counties.

In the Square Butte creek drainage there are nearly continuous bedrock exposures from the Cannonball-Tongue River contact to the area northwest of Center, so the position of the Hagel "key" bed was given as about 240 feet above the base of the Tongue River Formation based on surface mapping. Test hole 3558 (142-84-24 bba) penetrated the Cannonball Formation at a depth of 305 feet from a surface elevation of 2006 feet, so the base of the Tongue River Formation is at an elevation of about 1700 feet. Test holes 1 to 1.5 miles south and west of this test have the base of the Hagel bed at elevations of about 1,985 feet, or about 285 feet above the base of the Tongue River Formation.

Glacial drift caps the drainage divide between Square Butte Creek and the short drainages cutting back from the Missouri River trench, so direct correlations across this divide are not possible; and correlation between exposures in each of the drainages is difficult because of the lateral variability. In this area topographic maps furnish elevations of the exposures as well as the Tongue River-Cannonball contact. This information combined with test hole data furnishes the regional dip of the Tongue River-Cannonball contact and provides a means of placing the lignite beds in their proper stratigraphic position. The lignite bed which is being mined at the Glenharold mine was mapped as the Stanton bed by Benson (1952) as well as Johnson and Kunkel. Based on test hole 3557 this bed is about 275 feet above the base of the Tongue River Formation and is in the stratigraphic position if not a physical equivalent of the Hagel bed of the Center area (Table III).

In the western area (Otter Creek drainage) another problem in correlation arises from the naming of the Herman bed. This bed was mapped only on the west side of Otter Creek and the exposure at locality 21 (Johnson and Kunkel, 1959, p. 44) is equivalent to the Beulah-Zap bed of the south Beulah mine based on topographic control and drill hole information now available. This introduces some confusion in Johnson and Kunkel's western area as either their sections based on key beds (i.e., Otter Creek and Beulah-Zap) are in error or there are errors in correlation to Benson's Knife River beds. Recognizing the difficulties of correlations based on lithology and thickness of beds, it seems best to use their names and measured sections for the Otter Creek drainage and adjust the stratigraphic position of the beds based on Herman bed = Beulah-Zap of Benson (Table III, western area).

In the Beulah area the Beulah-Zap bed is about 130 feet below the top of the Sentinel Butte Formation. The Herman bed (Beulah-Zap of Benson) then is about 130 feet below the top of the Sentinel Butte Formation, and the Otter Creek bed is about 80 feet below the top of the Sentinel Butte Formation. Since the Hagel bed is at least 480 feet below the top of the Sentinel Butte Formation, then the Otter Creek bed is actually about 400 feet higher stratigraphically than the Hagel bed rather than a lateral equivalent as suggested by Johnson and Kunkel. This miscorrelation would also account for much of the discrepancy in thickness between their estimated thickness of about 520 feet and the actual thickness of 750 to 800 feet for the Sentinel Butte and Tongue River Formations in this area.

The test hole information indicates that most of the lignite beds do not extend over wide areas and that correlations based on matching of measured surface sections is difficult. The practice of naming beds in different geographic areas without regard to correlation to adjacent areas has the advantage of not having the same name applied to different beds because of miscorrelations. When subsurface information permits reliable correlations it may be advantageous to recognize where the same bed has received different names (e.g., Hagel = Stanton, Herman = Beulah-Zap of Benson, ?Hazen B = Beulah-Zap of Johnson and Kunkel). However, the arrangement of the named beds in Table III is not intended to suggest that named beds present in different areas at about the same stratigraphic horizon should be correlated as one and the same bed. Rather, it is only intended to show the approximate position of these beds with respect to their position within the Sentinel Butte and Tongue River Formations.

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STRATIGRAPHIC SUMMARY OF THE GOLDEN VALLEY FORMATION (PALEOCENE-EOCENE) OF WESTERN NORTH DAKOTA

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INTRODUCTION

In the Williston Basin the Golden Valley Formation is the youngest unit in a sequence of somber-colored, carbonaceous strata ranging in age from Late Cretaceous to Early Tertiary and once termed the "Lignitic group" by early workers in the area. The present article is intended to present a brief summary of the stratigraphic relationships of this formation in advance of a more detailed treatment forming part of a monograph on the Golden Valley Formation and its fossil flora (Hickey, In press).

Implicit recognition of the Golden Valley Formation was made by Leonard (1906), the first North Dakota State Geologist, over sixty-five years ago, when he referred to "white fire clays" and "high grade refactory clays" in his report on the stratigraphy of North Dakota clays. Although the concept of these white clays as developed in studies by Leonard and by Babcock and Clapp (1906) included lenses of kaolinitic clay in the upper Fort Union Formation, the map in the latter report shows much of the Golden Valley outcrop as presently recognized. In addition, Leonard accurately characterized the remarkable lateral persistence of the lower member of the formation, its striking coloration, and the rarity of lignites in it. He also described the unit as present only on higher elevations, realized its former more widespread extent, and postulated a lacustrine origin for it. Subsequently, because these higher beds were regarded as Eocene, the term "unnamed member of the Wasatch Formation" was applied to them (Fig. 1).

Recognition of the Golden Valley Formation as a distinct lithologic unit finally occurred with the formal proposal of its name by Benson and Laird (1947). They designated its type area as lying in the hills three miles south of the town of Golden Valley in Mercer County. Based on the presence of the distinctive floating fern, Salvinia preauriculata, Benson and Laird considered the new formation to be "definitely Eocene."

GENERAL FEATURES

The Golden Valley Formation occurs only within the confines of the Williston Basin of western North Dakota. Because of its stratigraphic position close to the top of the depositional sequence there, erosion has destroyed most of the formation except in a few areas near the axis of the basin or in shallow synclinal troughs (Fig. 2). The extent of erosional removal is emphasized by the fact that, although the formation is distributed within a 13,000 square mile area covering ten counties, the actual area of Golden Valley sediments remaining is only about 350 square miles or 2.5% of the area. Significant expanses of Golden Valley sediment remain in

Stark County around Dickinson, in Mercer and Dunn Counties in the area of Golden Valley, in the Hebron area of Morton County, and in northwest Hettinger County.

The formation consists of claystones, mudstones, lignites, and micaceous sandstones ranging to a maximum preserved thickness of 180 feet. It overlies the Fort Union Formation conformably and is in turn separated from the overlying White River Group by an angular unconformity (See Table 1). Stratigraphic relationships within the formation are complex and subject to rapid lateral change as a result of its terrestrial environment of deposition.

Table 1. Time-Stratigraphic relationships of the Early Tertiary formations of North Dakota as used in this report.

Oligocene series:
- White River Group

Eocene series:
- Golden Valley Formation
  - Upper member

Paleocene series:
- Golden Valley Formation
  - Lower member
- Fort Union Formation
  - Sentinel Butte Member
  - Tongue River Member

The Golden Valley Formation is divided into two members of sharply differing aspect (Fig. 3). The lower member (0 to 65 feet) is a predominantly tough, kaolinitic claystone or mudstone with interbeds of sandstone and rare lignite, forming bare slopes weathering to bright yellow, orange, or ash grey. The upper member (0 to 150 feet) is relatively soft and usually poorly exposed, weathering to shades of buff or tan. It consists of lenses of micaceous sandstone, frequently carbonate-cemented and cross-bedded, separated by finer grained, characteristically parallel-bedded sediment. Its dominant clay minerals are illite and montmorillonite.

Benson and Laird (1947) and subsequent authors (Benson, 1949, 1952, 1954; Freas, 1962; Jepsen, 1963) assigned the entire Golden Valley Formation to the Eocene Epoch based on the occurrence of Eocene fossils in its upper member. However, the presence of a Paleocene mega- and microflora, as well as invertebrates in the lower member, to be detailed in a forthcoming monograph (Hickey, In press), have led me to revise the age determination of this member to latest Paleocene.

Diagnostic features of the Golden Valley Formation are:

1) the kaolinitic composition, brilliant weathering colors, and lateral persistence of its lower member,

2) the mica content of its sands and silts in contrast to the general lack of mica in comparable beds of adjacent formations,

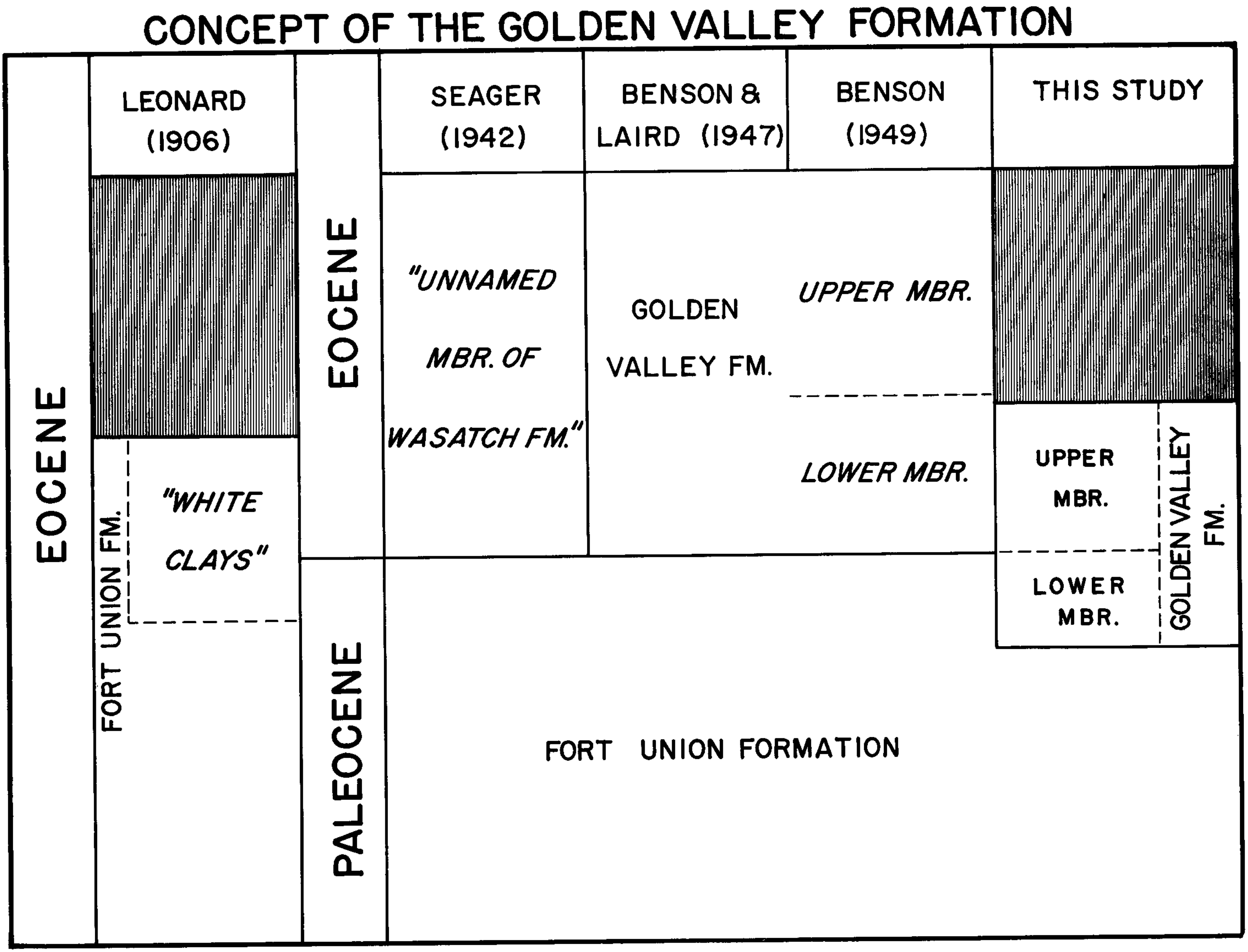

Figure 1. Development of the concept of the Golden Valley Formation.

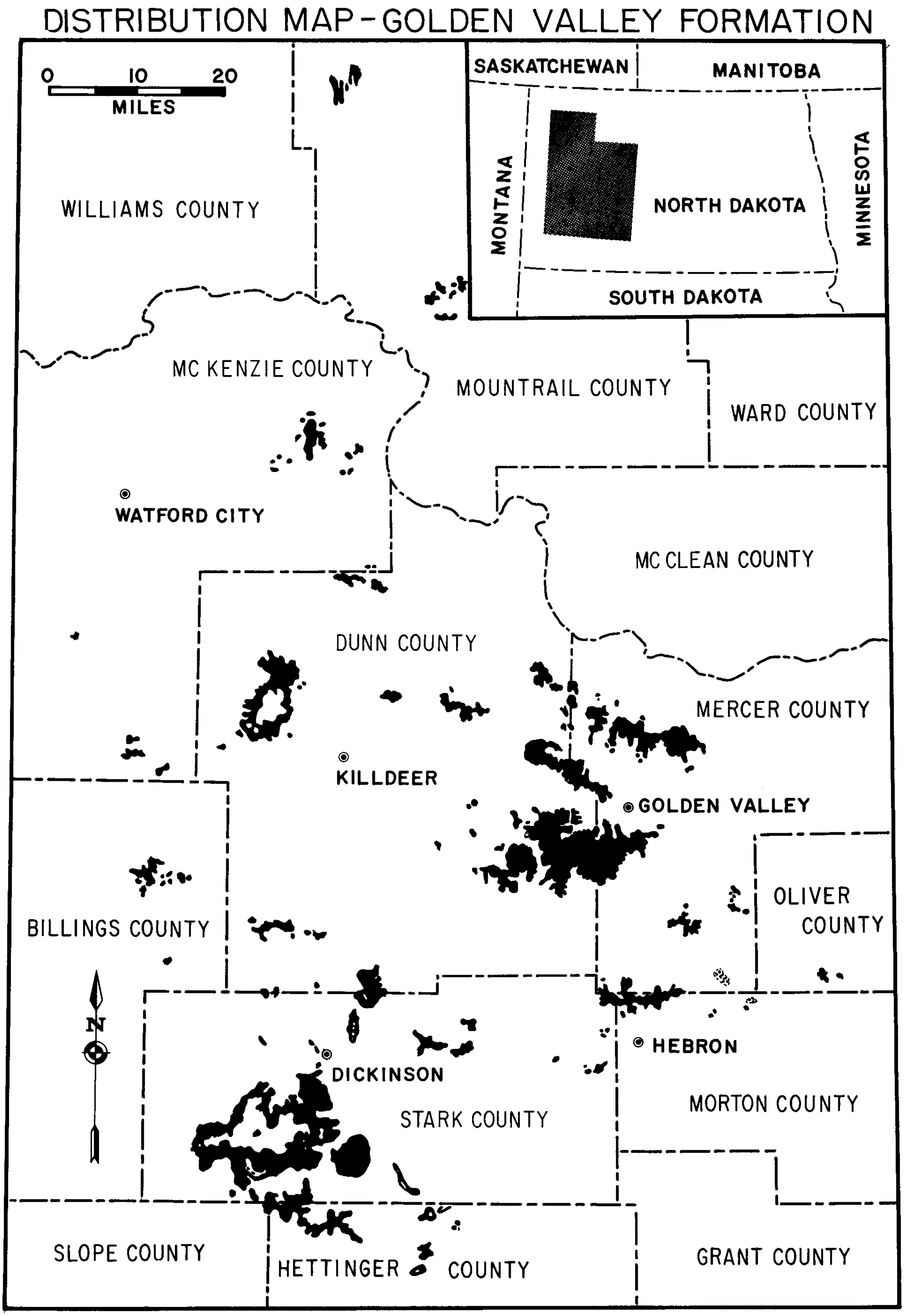

Figure 2. Distribution of the Golden Valley Formation. Outcrop is shown in black with areas of residual chert boulders in Mercer and Morton Counties indicated by stipples.

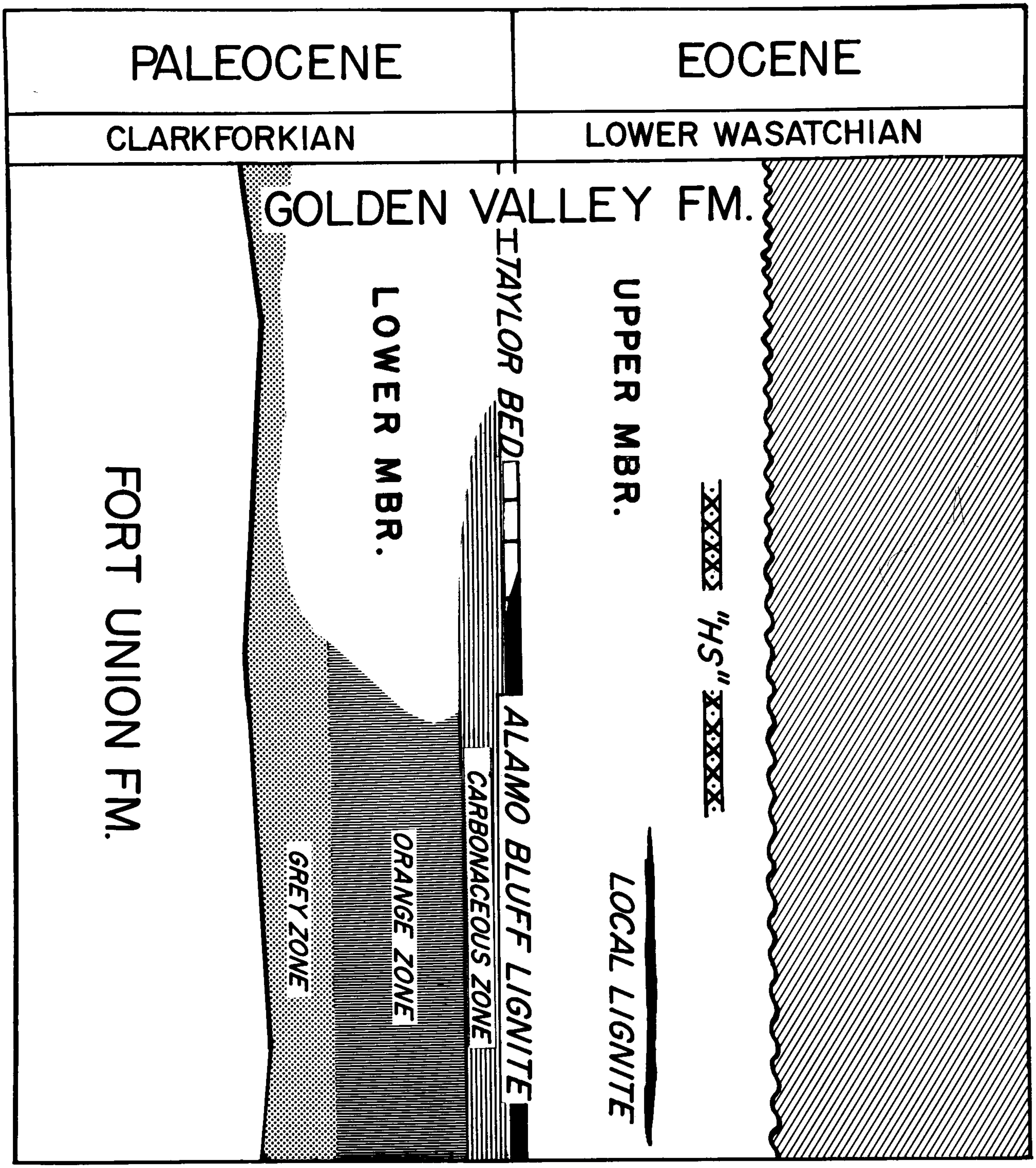

Figure 3. Units of the Golden Valley Formation, including the color-zoned and unzoned portions of the lower member.

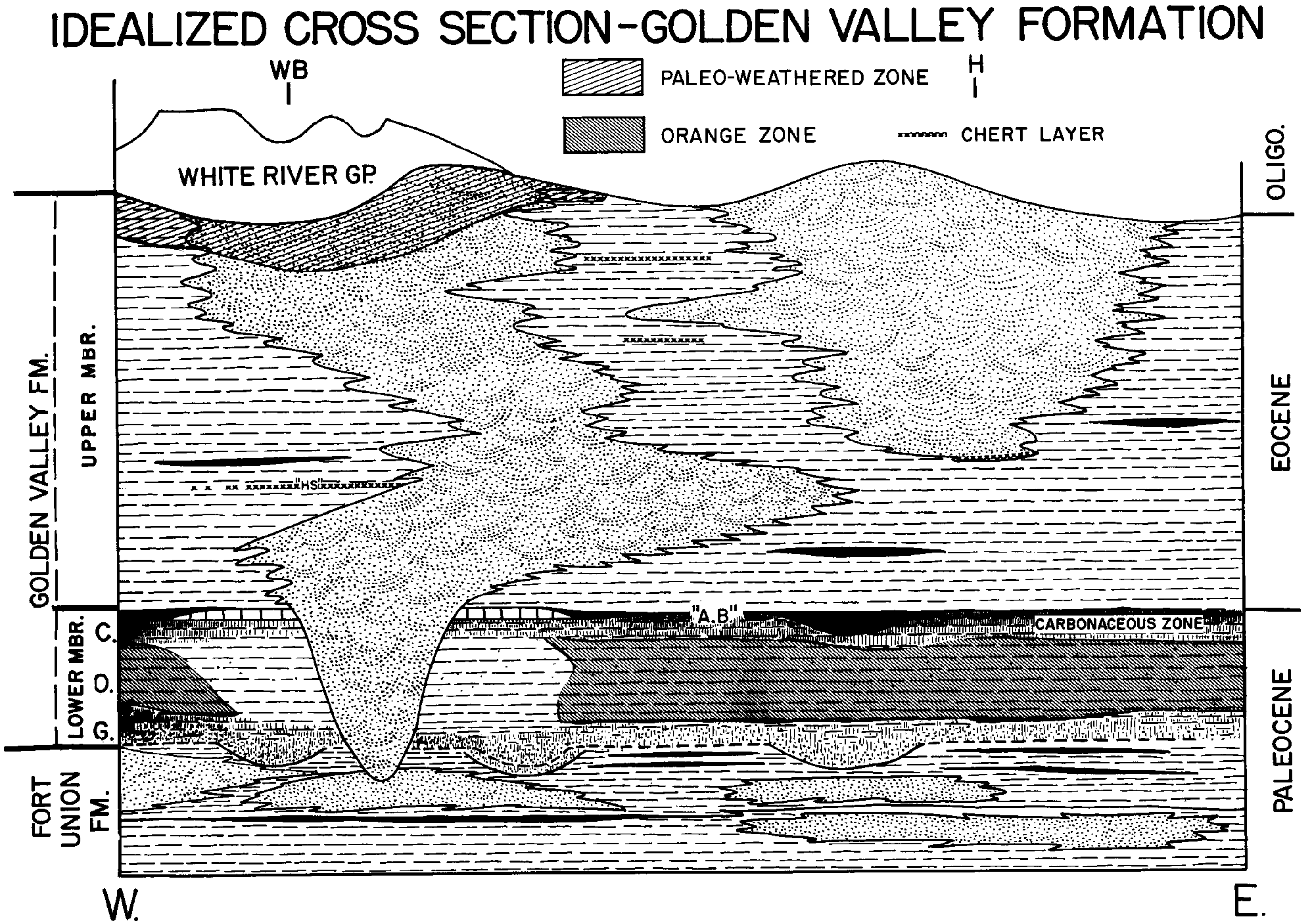

Figure 4. Idealized cross section of the Golden Valley Formation. Although this section does not represent any one traverse line it runs east-west with the approximate locations of Hebron (H) and White Butte (WB) indicated. The carbonaceous, orange, and grey zones of the lower member are represented by the letters C, O, and G respectively. Stippled areas represent the channel lithofacies with dashed areas indicating interchannel sediements. Lignites are black and the lower contact of the formation is indicated with a dashed line except where it coincides with the base of a channel.

3) the presence of Salvinia in the upper member of the formation,

4) and the general scarcity, and mostly local distribution, of lignite in the formation.

GOLDEN VALLEY - FORT UNION CONTACT

Over 70 stratigraphic sections made during my study of the formation, as well as Benson's work (1952), and structural contour maps (Meldahl, 1956) clearly demonstrate that the Golden Valley Formation is regionally conformable on the Sentinel Butte Member of the Fort Union Formation. In general, the contact is placed at a lithologic change from plastic clays of brownish to olive hue, dominated by illite or montmorillonite, or generally non-micaceous sandstones to tough, non-plastic, blocky, kaolinitic clays of grey color or kaolinitic sandstones where mica is a conspicuous constituent (3/4 to 5%).

Generally the lower contact occurs in a sequence of conformable horizontal beds with no sign of a hiatus. Although sharp changes in lithology are sometimes found at the boundary, in most cases, Fort Union sediments simply grade upward into those of Golden Valley aspect through a zone of transition, making its exact placement impossible (Fig. 4).

Such a contact occurs on the eastern side of the Farmers Buttes, in Morton County, where there is a gradual upward change in color and clay composition above the fissile shales interbedded with the Harnisch lignite (Benson, 1952) which marks the approximate upper limit of the Fort Union Formation. Northwest of Taylor in Stark County, non-micaceous sandstones with a gradually increasing content of kaolin grade upward into grey kaolinitic siltstones and shales of the Golden Valley Formation. Throughout most of southern Dunn County, the Fairfield area of Billings County, and the Grassy Butte area of McKenzie County the lower contact of the Golden Valley Formation is a transition from a dark yellowish-grey, non-micaceous siltstone with siderite concretions in the Fort Union Formation which gradually becomes grey, contains less concretions and has an increase in kaolin content upward.

Gradational contacts are also found within lenticular bodies of cross-bedded sandstone at the formational boundary. The lower portion of one such lens on the Heart River Bluffs, one mile south of Dickinson, is a typical Fort Union, buff, carbonate-cemented sandstone lacking mica or kaolin. A gradual upward increase in both of these latter constituents, however, results in its transition into a typical Golden Valley sandstone 60 feet above the base of the lens. This same relationship seems to occur in the poorly exposed area west of Lefor, southeast of Dickinson.

More rarely, the contact may occur at an easily recognized break in color and composition in a sequence. Such is the case at the Dennis Ranch, northeast of Hebron, at localities along the Crooked Creek Escarpment in southern Dunn County, and in the southern Blue Buttes of McKenzie County. The predominance of conformable contacts demonstrating these relationships indicates that the onset of Golden Valley deposition does not mark a break in sedimentation but only a change in sediment input.

Unconformable contacts between the formations are strictly limited in extent and are mainly the product of local channel scour. The type most frequently seen involves lenses of light-grey or white kaolinitic sandstone at the base of the Golden Valley Formation which appear to cut only a few feet into the underlying Fort Union Formation, as in the central portion of the Farmers Buttes (Fig. 4). Large sandstone lenses incised more than 35 feet into the lower formation, as well as occupying much of the thickness of the Golden Valley lower member, are also common. Examples of these occur at the head of Big Muddy Creek, northeast of Hebron, and in the central portion of the Fairy Dells in south-central Dunn County. Occasionally, as at localities east of Schaffner Creek in Dunn County, nine miles north of Zap in Mercer County, and in a channel exposed in a brick pit five miles north of Hebron, a lignite, inferred to be reworked, will occur at the base of the lens.

Finally, two examples were found where channels of sandstone of the upper member of the Golden Valley Formation have cut through the lower member into the Fort Union Formation. These occur three miles east of Fairfield and on Ash Coulee southwest of Dickinson. Only their content of mica and the gradual rise of their lower contacts into the upper member of the Golden Valley Formation betrays their true formational identity where they rest directly on Fort Union beds. Since the extent of downcutting in both of these cases exceeds 100 feet, its cause is inferred to have been basin movement during deposition rather than simple channel scour.

Lower Member, Golden Valley Formation

The lower member of the Golden Valley Formation is unique among the sedimentary units of North Dakota in that its dominant clay mineral is kaolinite. Local lenses of kaolinitic sediment are present in the upper portion of the Fort Union Formation (e.g., along Deep Creek in Slope County and in Tps. 141 and 142 N., Rs. 94 and 95 W. in southern Dunn County) but the Golden Valley lower member is a contiguous unit of kaolinitic sediment averaging 25 feet thick, whose original volume over the area of the formation must have exceeded 60 cubic miles. In addition to its uniformly high kaolin content, the member displays considerable uniformity in its tripartite color zonation and in a tendency to become finer grained upward. Sandstones of the member differ markedly from those of adjacent units in being very light grey, lithic subgreywackes (Pettijohn, 1957) with a kaolin matrix and no carbonate cement.

However, the lower member of the formation is far from homogeneous and displays rapid lateral and vertical changes in thickness and lithology. Within the extremes of zero to 65 feet no consistent pattern of thickness change is evident across the basin of deposition. Locally, large variations in thickness are common and occur within short distances. For example, variations of fifteen feet in the lower member Golden Valley section in less than one-quarter mile are common north of Hebron, and a thickness increase of fifteen feet occurs within a mile in sections measured nine miles north of Zap.

Within the member, individual beds usually prove to be of strictly local extent, often showing rapid thickness or lithologic changes. When traced laterally a bed of pure clay will include gradually increasing amounts of coarser material until it becomes a mudstone or clayey sandstone. Contacts are mainly lenticular and are only occasionally sharply defined; in most cases one lithology simply grades imperceptibly into another both laterally and vertically.

Of great value in correlation is the fact that over most of its outcrop the member shows a characteristic division into three color zones which are independent of individual beds (Fig. 3). The lowest of these, termed the grey zone, ranges from ash white to light grey. Above this a zone of yellow- to orange-stained beds, called the orange zone is followed by the carbonaceous zone, so named because of a gradually increasing carbon content which causes a darkening of its grey color. Although the colors of these zones are produced by surficial weathering, they provide reliable markers and are generally associated with a particular lithology. Thus the grey zone is dominated by sands and silts; mudstones, siltstones, and pure clays are most important in the orange zone; while shales and claystones predominate in the carbonaceous zone.

The orange zone frequently makes up over half the thickness of the Golden Valley lower member and the brilliant coloration of this "orange marker bed" allows the recognition of the formation even at great distances. Oxidation of ferrous iron compounds near the face of the outcrop appears to be responsible for the bright yellow to orange staining of the zone and for its gypsum content. The limonite occurs either disseminated within the beds, or as spherules 0.4 to 0.8 mm in diameter, or as concretionary aggregations of spherules. Gypsum occurs in large crystals, as sugary coatings or crusts on bedding planes, and mixed with limonite in joint cracks. Although the sediments of this zone generally contain the highest percentage of kaolin, the presence of limonite and gypsum constitutes an important disadvantage to its use in better grade clay products.

The average thickness of the carbonaceous zone is three feet, and although variations are known, both its thickness and lithology remain consistent over wide areas, in contrast to those of the lower zones. The dark colors of this zone, ranging from brownish and olive grey to dark grey, are due to carbonaceous matter. These colors deepen upward as the carbon content increases and there is a concomitant decrease in grain size of the sediments. Characteristic rock-types of the zone are shales, mudstones, and siltstones, all of which are commonly parallel-bedded and laminated. Paper shales with abundant remains of emergent aquatic plants are frequently encountered.

The upper boundary of the lower member of the Golden Valley Formation is marked by the Alamo Bluff lignite (Benson, 1952) or by its equivalent which I have called the Taylor bed (Figs. 3 and 4). Although the thickness of the lignite is generally only one-half to three inches, except for rare local increases to as much as four to six feet at Alamo Bluff, eight miles south of Golden Valley, and at localities one to two miles west of Taylor, the remarkable persistence and continuity of this unit at the top of the distinctive lower member of the formation make it a marker bed of considerable potential value for the study of Williston Basin structural trends.

In local areas where the Alamo Bluff lignite is absent, a layer of carbon debris or carbonaceous paper shale marks the contact between the lower and upper members of the formation. In the rare sections where even this is lacking, the contrast between the carboncaeous zone and the yellow to buff weathering, micaceous, illitic to montmorillonitic sediments of the upper member allows ready recognition of the contact.

The Taylor bed, named for exposures west of that town, is a bed of silicified siltstone or rarely marlstone, ranging from six inches to two feet in thickness and forms the lateral equivalent of the Alamo Bluff lignite over limited areas at the lower-upper member contact. It is a massive unit, breaking into blocks riddled with plant stem moulds and weathering light brownish grey. The erosional resistance of the layer frequently causes it to form flat-topped upland surfaces with abrupt, clay slopes at their margins such as those found south of Dickinson and from that town east to Taylor.

The original distribution of the Taylor bed is inferred to have been patchy and discontinuous. One to two miles west of Taylor the unit was observed to wedge in beneath the Alamo Bluff lignite, replacing it completely in another mile westward. A similar relationship is found in southern Dunn County. The largest area where the Taylor bed forms the top of the lower member of the Golden Valley Formation centers around Dickinson, in central Stark County, with other areas found on the Knife River-Spring Creek Divide in eastern Dunn County, around Stoney Butte in northwest Hettinger County, south of Fairfield in Billings County, and in the Achenback Hills in the North Unit of Roosevelt Park in McKenzie County. In these areas the usually strongly developed color-zonation of the lower member of the formation is faded or nearly absent. Although the colors of the orange and carbonaceous zones generally show only faint development here, they retain the same sequence of lithologies found in color-zoned areas. The much reduced content of limonite staining, spherules, and gypsum in the faded areas probably gives more value to the clays there than in the portions of the lower member where zonation is more intense.

In other more local areas, the color zonation of the relatively fine-grained lower member Golden Valley sediment is interrupted by laterally gradational, lenticular bodies of cross-bedded to massive, grey kaolinitic sandstone. These lenses, interpreted as channels, may occupy a small portion or the entire thickness of the member and occasionally cut deeply into the underlying Fort Union beds. In most cases the sediments of the carbonaceous zone extend over these channels without interruption. Good examples of these coarse grained lenses can be seen at Long Butte west of Lefor in southeast Stark County; in the central part of the Fairy Dells, about 14 miles northeast of Dickinson and in the eastern pits of the Hebron Brick Company, seven miles northeast of that town.

Upper Member, Golden Valley Formation

The lower-upper member contact is generally sharply marked and easily recognized. In the space of only a few inches, the tough, dark grey kaolinitic clays of the lower member of the Golden Valley Formation are succeeded by a sequence of soft, yellow to tan, fissile, montmorillonitic or illitic clays or parallel-bedded silts of the upper member. Only in rare cases, as in the Grassy Butte area of southeastern McKenzie County, is this contact difficult to recognize. Paleontologic evidence from several sources indicates that this lithologic change also coincides with the Paleocene-Eocene boundary.

The upper member of the Golden Valley Formation is composed predominantly of claystones, siltstones, and sandstones. Mica, frequently in large flakes 1-2 mm across, is a prominent constituent of sandstones and siltstones in this member. Lignites, sometimes ranging up to six feet in thickness, are present in the sequence; but they are uncommon and never more than a few miles in extent.

The almost invariable yellow-grey to yellowish-orange weathering color of the unit is a marked contrast to those of the lower member of the formation. Even on recently exposed faces, shades of yellowish brown, yellowish grey, or dark yellowish orange predominate. Another contrast of the member is the occurrence, immediately above the steep barren slopes of the lower member, of its mostly low vegetated weathering profile, broken by indurated sandstone ledges.

Lack of reliable stratigraphic markers in the upper member of the formation necessitate its stratigraphic description in terms of its two contrasting lithofacies; i.e., cross-bedded sandstone lenses inferred to represent channels and the intervening, mostly finer grained sediment, probably representing the interchannel areas.

Compositionally the sandstones of the channels are fine to medium grained subgreywackes (Pettijohn, 1957) with a montmorillonite clay matrix. Calcite-cemented portions of this facies commonly form the caprocks of buttes and stream divides underlain by the Golden Valley Formation. Bases of lenses generally truncate underlying units and are occasionally sheathed with silicified peat, as at the locality nine miles north of Zap in Mercer County, or impregnated with limonite.

Toward the bases of some of the larger sandstone bodies, their cross-bedding is contorted into isoclinal and diapiric folds as a result of soft-sediment deformation. The sand below these disturbed beds characteristically lacks any trace of bedding, probably as the result of excessive movement. Examples of this deformation occur on Medicine Butte in southern Mercer County, on Grassy Butte, and at a locality two miles east of Fairfield in Billings County.

Intraformational conglomerates occasionally occur in the channel lithofacies particularly in the upper portion of the member. Clasts may range up to 2 1/2 feet in diameter and invariably seem to have been derived from the interchannel silts of the upper member of the formation. An excellent example of this conglomerate is found on Camels Butte and a number of adjacent buttes in the vicinity of New Hradec in southern Dunn and northwest Stark Counties. Cases of upper member Golden Valley channels cutting through the lower member of the formation into Fort Union beds have been cited above. Apparently channel sediments become increasingly widespread at higher levels in the upper member. In the few places where extensive areas of Golden Valley strata remain, cross-bedded sandstone units in the upper part of the upper member seem to have coalesced into a nearly continuous sheet. Deep channel cutting, intraformational conglomerates, and disharmonically folded sandstones all appear to have been initiated during deposition of the upper portion of the Golden Valley upper member.

Interchannel facies rock-types include montmorillonitic to illitic shales and siltstones, lignites, and sandstones with parallel-bedding or oscillation ripple marks. Diffusion-banded, limonite-cemented concretions with hollow cores filled with loose gypsum crystals are a highly characteristic component of the siltstones. Other types of concretions found in this lithofacies include limestone nodules and rare zones of siderite concretions.

Boundaries between the channel and interchannel lithofacies in the upper member are usually indefinite. Channels lens out into adjacent areas of fine grained, parallel-bedded sediment. Small, cross-bedded sand channels are common in interchannel areas, while some sharply lenticular bodies may be filled with fine grained, parallel-bedded sediment typical of the interchannel-facies, probably as the result of deposition in a cut-off meander.

Massive, blocky, tan-weathering chert beds from three inches to over one foot in thickness occur sporadically at a number of localities throughout the Golden Valley upper member. Plant stem impressions and moulds are conspicuous in the chert as are sugary coatings of quartz crystals lining joint cracks and voids. The undulatory upper and lower surfaces of these beds cause them to thicken and thin irregularly, often disappearing and reappearing over short distances. A common setting for the cherts is the base of a sandstone lens. The presence of appreciable carbon in these cherts gives them a dark-brown to brownish-black color when fresh, but this weathers rapidly to a yellowish grey. In thin section the cherts appear as a mosaic of minute interlocking quartz crystals with large amounts of carbon specks and blebs and the "ghost" outlines of plant cell walls.

The texture, scarcity of detrital grains, and high carbon content of these cherts, together with their associated cell walls, occasionally inclusions of lignified wood, and the observation of the lenticular replacement of a lignite by one of these cherts, point to their origin as post-diagenetic replacements of lignites.

One such chert layer, occurring 40 feet above the base of the upper member, is a conspicuous and reliable marker bed southwest of Dickinson and has been named the "hard siliceous" or "HS layer" by Jepsen (1963) (Figs. 3 and 4). Jepsen's experience in this area of the Golden Valley Formation led him to believe that this chert was unique to one level throughout the upper member of the formation. Actually, however, identical silicified beds occur at a number of different stratigraphic levels and settings in numerous upper member sections (Fig. 4). Although silicified layers are also found in the upper Fort Union Formation, all of those observed were thin, breaking into plates and weathering to a light grey or white.

Loose residual boulders of chert, probably derived from the upper member of the Golden Valley Formation, cap low hills 10 to 12 miles north of Glen Ullin in Morton County (stippled areas of Figure 2) and are inferred to have been erosionally down-dropped to their present position on upper Fort Union sediments. Residual deposits of Golden Valley cherts appear to have been an important source of "flint" for the Indians of the Knife River area (Clayton, Bickley, and Stone, 1970).

Paleo-weathered zone of the Golden Valley Formation

Extant portions of the upper member of the Golden Valley Formation which lie close to the unconformable upper boundary of that unit with the White River Group have been leached and oxidized to depths of 25 to 100 feet below this hiatus during an episode of intensive weathering prior to the initiation of Oligocene deposition. Formations ranging from the Early Cretaceous Skull Creek Shale to the Golden Valley Formation have been similarly altered beneath this unconformity over a wide area of eastern Montana and Wyoming, northwestern Nebraska, and western North and South Dakota (Pettyjohn, 1966). I have termed this ancient episode of penetrative alteration "paleo-weathering" in order to distinguish its effects from those of recent surficial weathering of the Golden Valley deposits.

The brilliant coloration of the paleo-weathered beds in shades of yellow and orange with white and light grey interbeds contrasts strongly with the typical buff and dull yellowish-brown hues of the upper member resulting from modern surficial weathering. Because of their bright colors, paleo-weathered sequences have been mistaken for color-zoned lower member Golden Valley outcrops. However, the paleo-weathered zone occurs high in the Golden Valley section, lacks the sequence of color zonation found in the lower member, and penetrates through the sequence, rather than being confined to surface portions of the unit.

Leaching of the carbonate cement of the sandstones in the upper member of the formation, together with the oxidation of the iron minerals originally present yields a relatively soft rock with homogeneous weathering properties which forms local areas of brilliantly colored badland topography, as in the Little Badlands area southwest of Dickinson. Such exposures are completely atypical of the upper member where it has not undergone paleo-weathering. In addition to the Little Badlands, other areas of paleo-weathered upper member are found on Lone Butte, in eastern Stark County; on the southwest side of the Killdeer Mountains in Dunn County; on the Davis Buttes east of Dickinson; and from Lefor in south central Stark County to Black Butte in Hettinger County.

The Golden Valley-White River unconformity displays readily observable local relief which may range up to 150 feet (Denson and Gill, 1965). Often the exact position of this contact is easily recognized because of the marked lithologic differences between the units. At White Butte, southwest of Dickinson, for example, white channels of the White River Group with an appreciable content of volcanic material cut into a brightly colored sequence of paleo-weathered strata belonging to the upper member of the Golden Valley Formation. Farther to the southwest, in the Little Badlands south of South Heart, large quantities of reworked Golden Valley material in the basal White River sequence make it difficult to draw the boundary between that unit and the *in situ* sediments of the Golden Valley Formation below the unconformity. Even in areas of clear demarcation between formations, the lower 20-30 feet of White River beds frequently carry weathered mica and clinker granules derived from the Golden Valley and underlying formations after an interval of erosion and paleo-weathering.

Marginal Facies

Although my investigations covered the entire area of the formation with over 70 measured sections, I failed to discern any depositional thinning or development of a marginal facies outward from the center of its distribution. Lack of such features are inferred to mean that the present limits of the Golden Valley Formation stand well inside its original depositional limits.

Denson's (1969) studies of heavy mineral suites led him to suggest that the butte-capping sandstone on Sentinel Butte, west of our mapped area, constituted such a marginal equivalent. However, the obvious lithologic differences of this sandstone from any found in the Golden Valley Formation, lying only twenty miles to the east, including its analcite rather than carbonate cement, the absence of kaolin or mica, and its stratigraphic position above an angular unconformity on a Sentinel Butte Member sequence showing some evidence of paleo-weathering, are strong indications that this unit represents another episode of deposition from that in which Golden Valley sedimentation occurred.

Fossils

Well preserved plant and animal remains occur in the Golden Valley Formation and are abundant at several localities. Megafossil plants are fairly common in the lower two-thirds of the formation and will be described in a forthcoming monograph (Hickey, In press). The lower member of the formation contains a Late Paleocene representative of the Fort Union flora consisting of 41 species of megafossils (of which 9 are new) and at least 22 forms of pollen and spores (Leopold, written communication, 1970). The common megafossil plants include: *Metasequoia occidentalis* (Newberry) Chaney, *Corylus sp.*, *Meliosma sp.*, *Cocculus flabella* (Ward) Wolfe, and *Cercidiphyllum sp.* *Pinus*, *Picea*, *Abies*, *Corylus*, and *Pterocarya* occur in the pollen record as well as grains assignable to the Ulmaceae, Anacradiaceae, Myrtaceae, and Platanaceae.

A typical Late Paleocene assemblage of mollusks (Yen, written communication, 1966) is found mainly at channel bases and in inferred cut-off meanders in the lower member of the formation. Forms present include *Viviparus* cf. *reynoldsianus* Meek and Hayden, *V.* cf. *retusus* (Meek and Hayden), *Unio* cf. *priscus* Meek and Hayden, and *U.* cf. *silberlingi* Russell.

Fossil plants inferred to represent a humid climate, warm temperate lowland forest are commonest and most widespread in the grey zone of the lower member of the Golden Valley Formation, whereas swamp and aquatic vegetation increases in abundance upward into the carbonaceous zone of the member.

A number of Eocene plant species, among them, *Salvinia preauriculata* Berry, *Lygodium kaulfussi* Heer, *Hemitelia sp.*, *Platycarya sp.* and *Dombeya sp.* among the megafossils and *Tilia*, *Eucommia*, *Platycarya* and chenopodiaceous types of pollen first appear at the level of the Alamo Bluff lignite and gradually replace the Paleocene species of the flora. Many of the 37 megafossil species of the upper member are new, giving it an aspect unlike that of any previously described Eocene flora. Its numerically dominant species are *Lamanonia sp.*, *Meliosma sp.*, *Salvinia* and *Ternstroemites sp.* and appear to indicate sub-tropical conditions.

Early Eocene invertebrates occur immediately above the Alamo Bluff lignite. Among forms identified by Yen (written communication, 1966) are *Viviparus* cf. *trochiformis* (Meek and Hayden), *Hydrobia recta* White, *H. utahensis* White, *Goniobasis tenera* (Hall), *Lioplacodes tenuicarinata* (Meek and Hayden) and *Planorbis*. A rich vertebrate fauna from White Butte, southwest of Dickinson, consists of 39 species representing fish; frogs; reptiles, including four genera of crocodilians; a small bird; and mammals, including rodents, carnivores, pantodonts, perissodactyls (*Hyracotherium* and *Homogalax*), and artiodactyls. Not only does this assemblage corroborate the very early Eocene date assigned to the upper member, but it adds additional evidence to the paleoecological picture of a lush, humid, swampy lowland setting, deduced from the fossil plants.

Depositional Setting and History of the Formation

Deposition of the Golden Valley Formation took place within a broad, shallow, gradually subsiding tectonic basin east and northeast of the areas of mountain building activity in the Rocky Mountains.

Previous investigators have proposed a lacustrine origin for the widespread, kaolinitic lower member of the formation (Benson, 1952; 1954; Freas, 1962). My research, however, suggests a fluvial environment to explain features of this unit such as random thickness changes, rapid lateral changes in lithology, lenticularity of beds, numerous small breaks in sedimentation, and the common occurrence of cross-bedded units. The uniformly high kaolin content of the lower member is believed due to protracted and intensive weathering of the source area which supplied the Golden Valley basin with kaolinitic detritus. In-place origin of the lower member kaolin is precluded by the detrital features of the grains (Freas, 1962), lack of a leaching profile, occurrence beneath an illitic and montmorillonitic mantle in unbroken depositional sequence above it, and associated fossil plants in well preserved condition. Origin of the color zonation in the lower member is perhaps due to the effect of climatic or tectonic events which overprinted the effects of local depositional settings. An inferred sequence of events in the depositional history of the formation begins with mild uplift in a kaolinitic source area at the beginning of lower member time initiating the relatively coarse deposition of the grey zone. Following this, tectonic stability coupled with continued subsidence of the basin resulted in finer grained, eventually paludal and lacustrine sediments at the top of the lower member. The renewal and steady increase of instability in the source area is believed to have produced the change in clay mineralogy at the base of the upper member, then resulted in progressive increase in the volume of channel facies sediments, and finally terminated deposition of the Golden Valley Formation as the orogenic movement reached the basin.

Mild climates with adequate, non-seasonal rainfall prevailing over the Williston Basin during Golden Valley time allowed the development of lowland forest vegetation. During the increasingly paludal and lacustrine phases of the orange and carbonaceous zones swamp vegetation became more widespread. Gradual climatic warming from warm-temperate, during deposition of the lower member of the formation, to sub-tropical, during upper member time, rather than evolution, appears to account for the floristic change between these units.

SUMMARY

The Golden Valley Formation, whose maximum preserved thickness is 180 feet, is a sequence of claystones, mudstones, lignites, and micaceous sandstones deposited during the Late Paleocene and Early Eocene in the Williston Basin of western North Dakota. The lower member of the formation is dominated by kaolin and appears to represent a shift from illitic and montmorillonitic source terraines to ones having a residual mantle developed under conditions of long-term tectonic stability and protracted leaching. Lenticularity and lateral inhomogeneity indicate a fluvial origin for the lower member, with the three color zones of the unit, which serve as stratigraphic markers, probably resulting from climatic or tectonic influences on the basin of sedimentation. Decrease in grain size and increase in carbonaceous content in the unit are inferred to be the result of tectonic influences and culminate in a basin-wide episode of organic and chemical sedimentation at the level of the Alamo Bluff lignite and Taylor bed.

A sharp return to illitic and montmorillonitic sedimentation in the upper member of the Golden Valley Formation, immediately above the lignite, is believed to represent a new period of instability in the source area whose effects gradually increase upward. Deep channel cutting and intraformational conglomerates found in the upper portion of the member are inferred to record the onset of basin movement whose gradual intensification caused the cessation of Golden Valley deposition and the initiation of a major period of erosion and paleo-weathering prior to deposition of the Oligocene White River Group.

In addition to allowing the boundary between the Paleocene and Eocene series to be set at the lower-upper member contact in the Golden Valley Formation, its excellently preserved plant and animal fossils indicate that the climate of the area changed from warm-temperate to sub-tropical during the course of its deposition. Due to its distance from the masking effects of local tectonic events in areas of mountain building, the Golden Valley Formation provides a sensitive record of sedimentational, tectonic, and paleoenvironmental events over a broad region of the northern Great Plains across an important epochal boundary.

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MIDDLE CENOZOIC STRATIGRAPHY OF NORTH DAKOTA

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INTRODUCTION

The North Dakota bedrock section is capped by about 425 feet of Oligocene and Miocene deposits. The middle Cenozoic deposits are exposed in widely separated butte clusters and scattered isolated buttes in the unglaciated southwestern part of North Dakota (Fig. 1). Major outcrop areas include the following: the Killdeer Mountains (Dunn County), the Little Badlands (Stark County), and the Chalky Buttes (Slope County). There are also minor exposures in several buttes in the Lefor area (northern Hettinger and southern Stark Counties) and small outlying buttes in Adams, Bowman, Golden Valley, and Grant Counties.

Oligocene deposits have been known to occur in North Dakota since 1883 (Cope, 1883). The Oligocene record in the state is represented by the White River Group which consists of the Chadron Formation below and the Brule Formation above. The White River Group rests unconformably on the Interior Formation (a lateritic paleosol according to Pettyjohn, 1966, p. C65) which overlies the Eocene Golden Valley Formation in North Dakota.

Strata of Miocene age have only recently been recognized in North Dakota (Denson and Gill, 1965, p. 13, 14). The youngest 25 to 200 feet of strata of the middle Cenozoic section in North Dakota are quite variable in lithology but differ markedly from the Chadron and Brule Formations of the White River Group below. Denson and Gill (1965, p. 13, 14) referred this section to the "Arikaree Formation." More recent work has shown that although this sequence does contain early Miocene fossils, it is not lithologically referrable to any part of the traditional Arikaree Group of South Dakota or Nebraska; the sequence is informally referred to as the Killdeer Formation.

The general lithology and most recent nomenclature for the middle Cenozoic deposits in North Dakota are given in Figure 2. The nomenclature for the middle Cenozoic deposits of North Dakota is compared to that of South Dakota and Nebraska in Figure 3. The member names for the Chadron and Brule Formations of the White River Group and that for the Miocene section, as given in Figures 2 and 3, are new and have been cleared and reserved for my use by the Geologic Names Committee, United States Geological Survey. These new names, used informally here, will be formally defined in a forthcoming publication of the North Dakota Geological Survey.

WHITE RIVER GROUP (OLIGOCENE)

Chadron Formation

The Chadron Formation in North Dakota includes 27 to 146 feet of silty bentonitic claystone, cobbly arkose and bentonite and can be subdivided into three easily recognizable members on the basis of lithology. The lower member is the Amidon, the middle is the Chalky Buttes, and the upper member is the South Heart (Fig. 2).

The Amidon Member consists of 7 to 16 feet of bentonite and silty, bentonitic claystone unconformably overlying the Interior and Golden Valley Formations in North Dakota. The strata of the Amidon Member weather to very pale orange (10 YR 8/2) or light brown (5 YR 6/4) but are very pale orange to grayish orange (10 YR 7/4) where fresh. This unit is not everywhere present but occurs in the Chalky Buttes (Slope County) and the Little Badlands (Stark County). No fossils have as yet been found in the Amidon Member and its specific age is uncertain. The stratigraphic position of the Amidon Member is similar to that of the Ahearn Member of the Chadron Formation in the South Dakota Badlands as described by Clark and others (1967, p. 22,23) and member "A" of the Chadron of Nebraska as defined by Schultz and Stout (1955, p. 31-34). The Amidon Member is also lithologically and stratigraphically similar to the "Golden Brown" Member of the Chadron at Slim Buttes, northwestern South Dakota, informally described by Lillegraven (1970, p. 832).

The Chalky Buttes Member unconformably overlies the Amidon Member. This unit consists of 8 to 75 feet of "dazzling white," fine to coarse-grained, cross-bedded, cobbly arkose (Fig. 4). The sandstone is not everywhere white (N 9) but in places is very pale orange (10 YR 8/2), dark yellowish orange (10 YR 6/6) or light brown (5 YR 5/6) where weathered and very pale orange to pinkish gray (5 YR 8/1) where fresh. The cobbles are generally of felsic to intermediate, fine-grained and porphyritic igneous lithologies and are believed to have been derived from the northern Black Hills (Stone, 1970b). This unit is present at all of the major exposures (Killdeer Mountains, Little Badlands and Chalky Buttes) and constitutes the most striking lithology of the Chadron Formation in North Dakota. Leonard (1922, p. 220) collected lower jaw fragments of titanotheres from strata now assigned to this unit, 20 miles southwest of the Chalky Buttes (near the town of Rhame, Bowman County), permitting its general correlation with the Chadron of South Dakota and Nebraska. More specifically, the Chalky Buttes Member is lithologically and stratigraphically comparable to a thin, unnamed, white, pebbly sandstone which locally underlies the typical Chadron bentonite in the Big Badlands of South Dakota. The Chalky Buttes Member also corresponds lithologically and stratigraphically to what Lillegraven (1970, p. 832) informally named the "Dazzling White" Member of the Chadron at the Slim Buttes, northwestern South Dakota.

Conformably overlying the Chalky Buttes Member is the South Heart Member, which constitutes the uppermost Chadron in North Dakota. This unit consists of 8 to 55 feet of green bentonite. The clay is pale greenish yellow (10 YR 8/2) where weathered and yellowish gray (5Y 7/2) to pale olive (10 Y 8/2) where fresh.

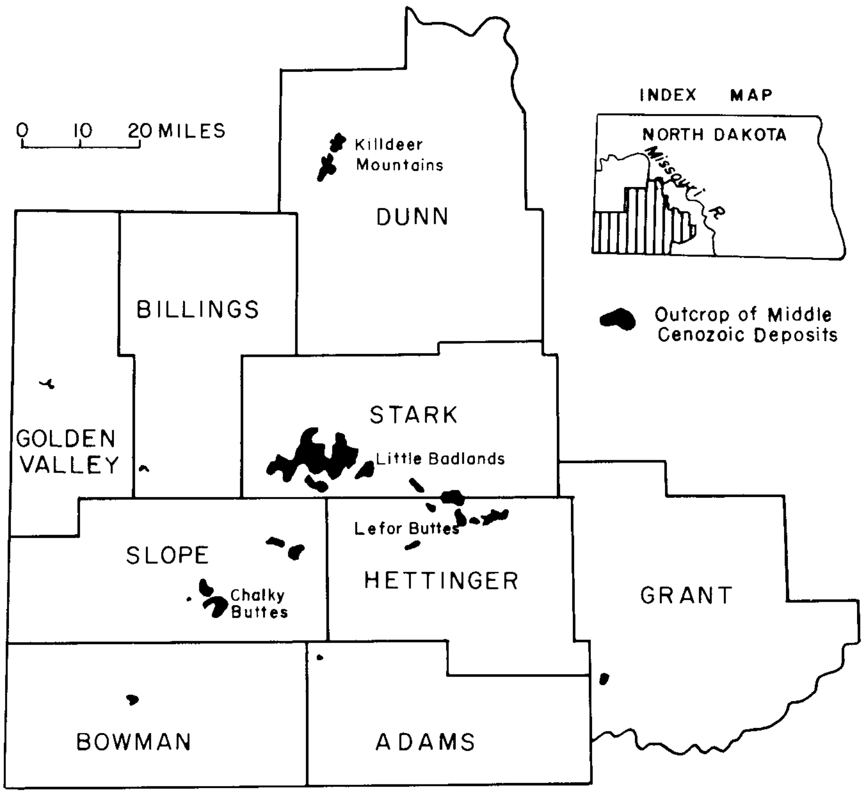

Figure 1. Location of Middle Cenozoic deposits in North Dakota.

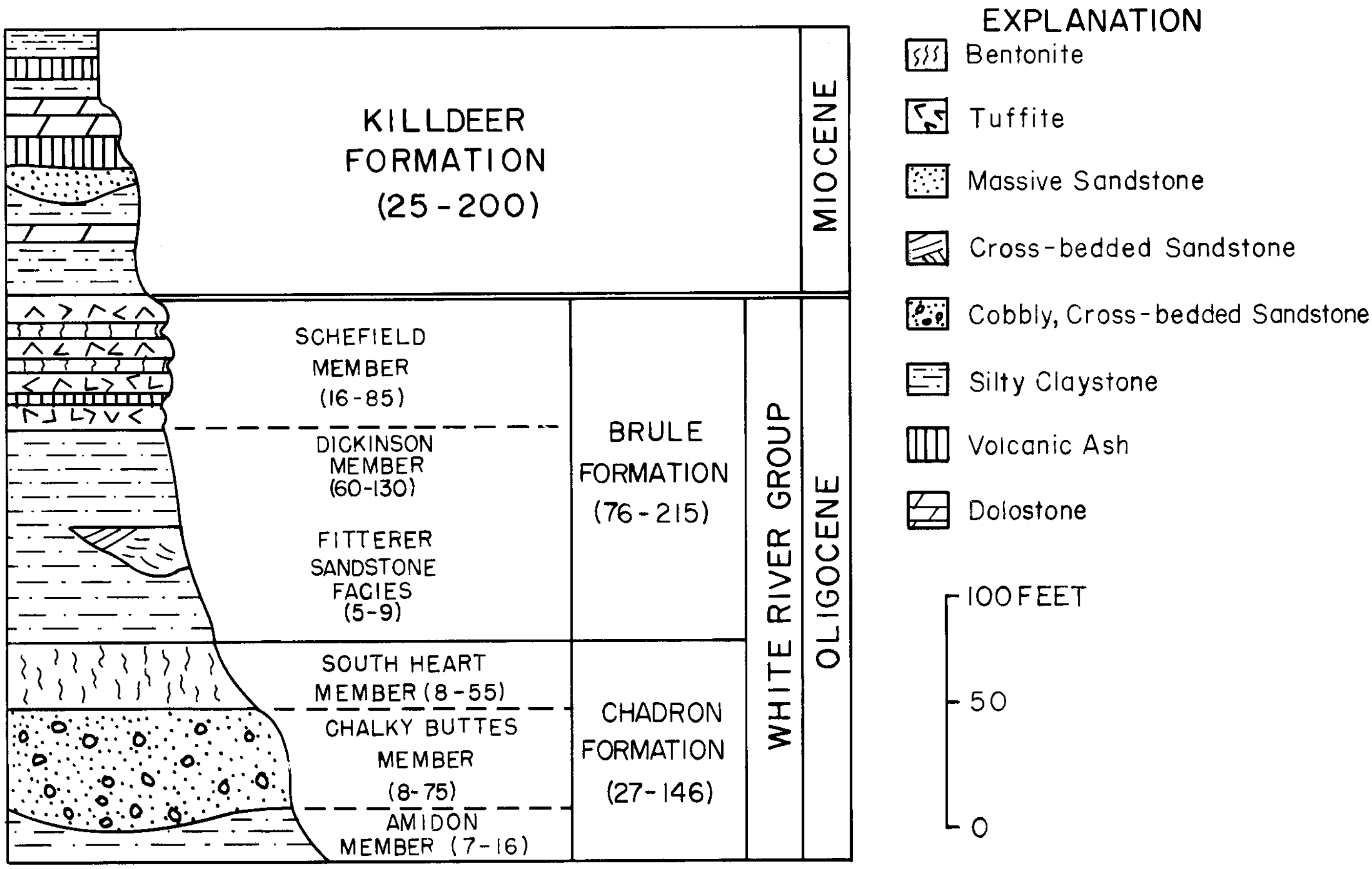

Figure 2. Generalized composite column and nomenclature for Middle Cenozoic deposits in North Dakota.

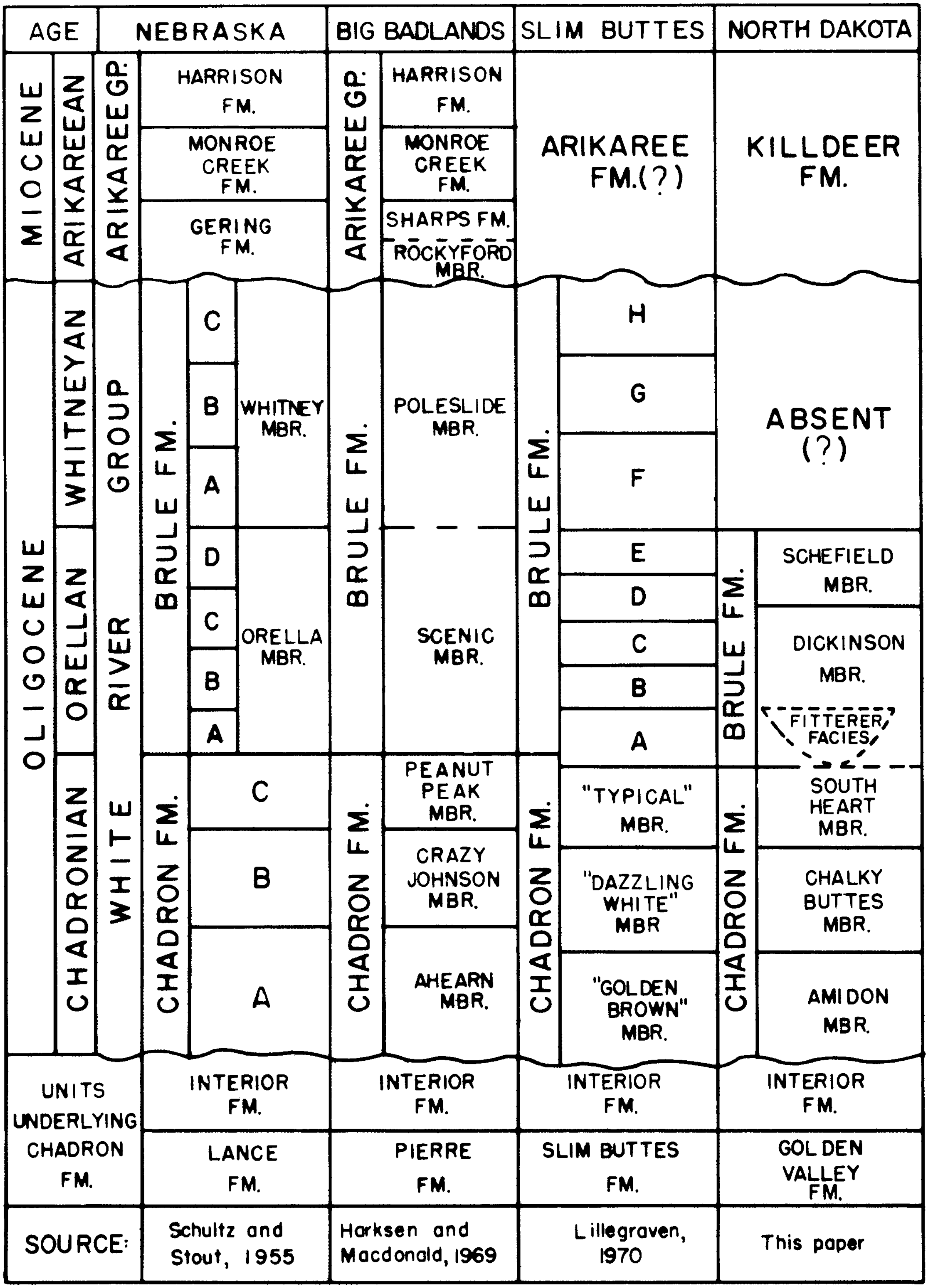

Figure 3. Middle Cenozoic Nomenclature, Midcontinent Region.

Upon erosion this unit forms the distinctive low rounded hills or "haystacks" covering a large area south of the town of South Heart, Stark County. The lower part of the South Heart Member is silty and gradational with the Chalky Buttes Member below. In places, an unusual and erosion-resistant lithology called "silicified silty bentonite" by Denson and Gill (1965, Plate 1) is present at the base of the South Heart Member (Fig. 4). The silica may have been derived from the conversion of the original volcanic ash deposit to bentonite. The top of the South Heart Member is characterized by thin marl and limestone beds, caliche zones, and calcareous nodules, often occurring in great abundance. These nodules occur as mushroom-shaped, fibrous growths up to 6 inches in maximum diameter. The outside of the nodules is irregular and light brown (5YR 6/4); on the inside, the nodules are fibrous and very pale orange (10 YR 8/2) to white (N 9). X-ray diffraction analysis showed that the nodules were originally aragonite but have since been converted to the more stable carbonate. No fossils were collected from the South Heart clay, but Hansen (1953, p. 12) reported Oligocene gastropods from the limestone beds at the top of this unit at Cogrove Butte, Hettinger County. I found traces of ostracodes and algal crusts in the limestone from that area as well. In addition to these meager fossil remains, the South Heart Member may also be correlated on the basis of lithology and stratigraphic position with the green bentonite which constitutes the bulk of the Chadron of South Dakota and members "B" and "C" of the Chadron Formation of Nebraska as described by Schultz and Stout (1955, p. 34-38). It also corresponds to what Lillegraven (1970, p. 832) referred to as "typical Chadron" at Slim Buttes, northwestern South Dakota.

Brule Formation

The Brule Formation in North Dakota includes 75 to 215 feet of mudstone, tuffite, and bentonite and has been subdivided into two distinct members: the Dickinson Member below and the Schefield Member above (Fig. 5). The name "Fitterer," suggested by Skinner (1951, p. 54) for the green, cross-bedded sandstone of the lower Brule in North Dakota (Fig. 5), is retained for the sandstone facies of the Dickinson Member.

The Dickinson Member unconformably overlies the South Heart Member of the Chadron Formation below and makes up the fluted slopes of the lower Brule section in North Dakota (Fig. 5). The Dickinson Member consists of 60 to 130 feet of pitted-weathering, silty claystone and bentonite. The claystone is very pale orange (10 YR 8/2) where weathered and yellowish gray (5 Y 7/2) where fresh. The bentonite is yellowish gray where weathered and pale olive (10 Y 6/2) to light olive gray (5 Y 7/2) where fresh. The pitting is caused by the weathering out of clay clasts generally up to 1 inch in diameter. However, locally these clasts reach a foot or so in diameter. At such places the clasts form a jigsaw puzzle-like framework and are surrounded by a matrix of calcite, suggesting a possible pedogenic origin. Near the middle of the Dickinson Member in the Little Badlands area is a 2 foot-thick, calcareous, somewhat silty, impure, white ash bed. This bed makes a good stratigraphic marker for local correlations as pointed out by Skinner (1951, p. 54, 57). It has not been recognized outside the Little Badlands area, however. Locally in the Little Badlands a 5 to 9 foot-thick,green, very fossiliferous, cross-bedded sandstone, the Fitterer sandstone facies, occurs at various horizons within the Dickinson Member (Fig. 6). This sandstone is moderately sorted, fine to medium-grained arkose, consisting of subrounded grains of quartz, feldspar, fine-grained igneous rock fragments and clasts up to 1 inch in maximum diameter of green bentonite, similar to that of the South Heart Member of the Chadron Formation below. Clear, acicular crystals of zeolite occur in the pores and weathering voids of the sandstone. X-ray diffraction analysis of the sandstone, as well as the claystone, revealed the presence of the zeolites clinoptilite, erionite, and heulandite. The sandstone is further characterized by large-scale trough or pi cross-bedding (Fig. 6) (Allen, 1963, p. 110, 112). Orellan or middle Oligocene fossils have been reported from both the claystone (Skinner, 1951, p. 58 and Estes, 1970, p. 329) and the Fitterer sandstone facies (Chinburg and Holland, 1965). The Dickinson Member, therefore, correlates with some part of the Scenic Member of the Brule Formation in the Big Badlands of South Dakota, as described by Harksen and Macdonald (1969, Figs. 6 and 7) and the Orella Member of the Brule of Nebraska, as described by Schultz and Stout (1955, p. 41-44). The Fitterer facies may correspond to the "Metamynodon channel sandstones" of older terminology for the sandstones in the Scenic Member of the Brule Formation of South Dakota and similar sandstones in the Orella Member of the Nebraska Brule. The Dickinson Member also corresponds both lithologically and stratigraphically to the transitional "Brule Unit A" which Lillegraven (1970, p. 835, 842) informally defined in the Slim Buttes of northwestern South Dakota.

The Schefield Member conformably overlies the Dickinson Member and forms the steep vertical cliffs characterizing the upper Brule in North Dakota (Fig. 5). This unit consists of 16 to 85 feet of interbedded tuffite and bentonite. The tuffite occurs in beds up to 1 foot thick and is very pale orange (5 YR 8/2) where weathered and grayish orange pink (5YR 7/2) to yellowish gray (5 Y 7/2) where fresh. The bentonite occurs in single, massive beds up to 6 inches thick and is moderate reddish orange (10 R 6/6) where weathered and pale reddish brown (19 R 5/4) where fresh. The alternation of the erosion-resistant tuffite and the soft bentonite gives this unit a banded or "washboard" appearance (Fig. 7). Some of the Schefield strata have a pitted-weathering habit similar to that of the Dickinson Member mudstones. In addition to being pitted, the Schefield tuffites contain vertically oriented, calcareous concretions, ½ to 1 inch in diameter and up to 5 inches long and spherical to horizontally oriented, irregular, oblong, calcareous concretions, up to 2 inches in diameter and up to 4 inches long. The latter may be mammalian coprolites. Orellan mammalian fossils were reported from this unit by Skinner (1951, p. 58) permitting correlation with the Scenic Member of the Brule Formation in South Dakota and the Orella Member of the Brule in Nebraska. Lithologically and stratigraphically, the Schefield Member corresponds to Lillegraven's (1970, p. 835, 842) "Brule Unit B" at Slim Buttes, northwestern South Dakota.

No Whitneyan-aged Brule occurs in North Dakota. Strata originally referred to the Whitney by Wood and others (1941, p. 36) are now recognized to be part of the Miocene section.

Figure 4 Chadron Formation at White Butte (sec. 32, T. 139 N., R. 97 W.), Stark County, looking southeast; CB = Chalky Buttes Member, SH = South Heart Member, ssb = silicified silty bentonite.

Figure 5 Brule Formation at Fitterer Ranch (sec. 7, T. 137 N., R. 97 W.), Stark County looking northwest; D = Dickinson Member, S = Schefield Member.

Figure 6 Fitterer Sandstone Facies of the Dickinson Member of the Brule Formation, overlying South Heart Member of Chadron Formation, Fitterer Ranch (sec. 7, T. 137 N., R. 97 W.), Stark County.

Figure 7 Close-up of Schefield Member of the Brule Formation at the Fitterer Ranch (sec. 7, T. 137 N., R. 97 W.), Stark County, to show banded appearance caused by alternating hard layers of tuffite and soft layers of bentonite.

KILLDEER FORMATION (MIOCENE)

This formation consists of 25 to 200 feet of calcareous, concretionary sandstone, mudstone, impure volcanic ash and dolostone. In places, the sandstone contains small-scale ripple bedding and large-scale trough or pi cross-bedding (Allen, 1963, p. 110, 112). The concretions range up to 2 inches in diameter, are mainly tubular, vertically oriented and hollow, as if formed around plant stems or roots. The impure ash beds often contain green siliceous nodules up to 6 inches in diameter. Early Miocene fossils collected from the sandstone of the Killdeer Formation include the skull of a beaver, *Paleocastor* sp. (Stout and Stone, 1971), and a primitive peccary mandible, similar to that of *Hypertragulus minor*. Both of these specimens are comparable to forms from the early Miocene Gering Formation of Nebraska. A complete rhinoceros mandible recovered from the sandstone caprock of the Chalky Buttes (Slope County) was referred to the late Oligocene to Miocene genus *Amphicaenopus* by Stone (1970a).

Further collection and study of vertebrate fossils from the middle Cenozoic deposits of North Dakota would permit more precise correlation of the North Dakota section with that of Nebraska and South Dakota. Various detailed petrographic, mineralogic, radio-metric studies of the middle Cenozoic deposits of North Dakota are also desirable. It is hoped that the new stratigraphic framework for these deposits in North Dakota will provide a solid basis for such further work.

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METALLIFEROUS LIGNITE IN NORTH DAKOTA

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Lignite beds in certain areas in southwestern North Dakota and adjacent parts of South Dakota are enriched in uranium, molybdenum, and arsenic. More than a half million pounds of U_3O_8 ("yellow cake") have been produced from North Dakota alone, and a large amount of uraniferous lignite remains unmined. The uranium was recovered from thin, impure ("dirty") lignite beds assaying on the order of 0.25% U_3O_8, or 5 pounds of U_3O_8 per ton of lignite. A roughly equal amount of molybdenum was recovered from much of the uraniferous lignite that was mined.

The mineable concentrations of metals in lignite are probably the result of a favorable combination of (1) available source rocks that included volcanic ash with anomalously high metal content, (2) leaching of these rocks by groundwater, and (3) passage of this metal-bearing groundwater through sandstone aquifers adjacent to, or partially comprised of, lignite beds. As the water passed through these lignite beds, the metals were apparently precipitated by sorption and by formation of metallo-organic compounds or complexes. Concentrations of metals in lignite are generally found only within a few inches or feet of a sandstone-lignite contact, suggesting that the sandstone functioned as an aquifer transmitting relatively large amounts of metal-bearing water. Further, practically all significant metalliferous lignites are in the upper part of the Paleocene Sentinel Butte Formation, close to its contact with the overlying ash-bearing White River Formation (Oligocene) that has been largely removed by erosion.

When plotted on a map, the major known deposits of metalliferous lignite are seen to fall in an imaginary belt extending several miles north and south of Belfield, a town at the junction of Interstate Highway 94 and U. S. Highway 85. This belt also coincides roughly with a major surface-drainage divide, which probably also represents a major groundwater divide. It seems likely, then, that the metalliferous lignites are associated with zones of infiltration or recharge by groundwater that moved generally downward and laterally through the ash-bearing Oligocene rocks, into the lignite-bearing Sentinel Butte Formation, where the metals were extracted. Locally, concentrations of calcite- and analcime-cemented sandstone and siltstone are found in association with the metalliferous lignites, further indicating the effectiveness of groundwater as an agent in dissolution, transportation, and deposition. Conceivably, patterns of concentrations of extrinsic elements in lignites can be used to decipher details of paleohydrology, which in turn may be helpful in predicting or explaining patterns of concentration of deleterious elements in lignite deposits, as well as indicate potential mineral deposits.

Future exploitation of metalliferous lignites, such as for the uranium market, will require methods of greater sophistication than those practiced during the 1960's, when uranium and molybdenum were extracted and sold. Extensive spoil-banks reclamation will be required, and the practice of open burning of metalliferous lignite for the purpose of upgrading it and making it more amenable to milling will have to be modified or abandoned. Unless the price of uranium increases markedly, therefore, it is unlikely that North Dakota lignites will again be mined as ores of metals.