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PRELIMINARY REPORT ON STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS OF THE LIGNITES IN THE FORT UNION FORMATION, WEST-CENTRAL NORTH DAKOTA

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(plates in pocket)

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Introduction

North Dakota ranks first among the states in identified coal resources because of the enormous tonnage of lignite in the Fort Union Formation (Brant, 1953, p. 2; Averitt, 1975, p. 22). The present report summarizes the stratigraphy and structure of the Fort Union Formation in part of western North Dakota (fig. 1). The effects of sedimentary environment and basin subsidence on lignite deposition are emphasized. Analysis of the depositional patterns is largely based on subsurface interpretations of well-log correlation diagrams and structure and isopach maps. Interpretations of this report are compared to those of previous surface mapping and sedimentological studies of the Fort Union Formation. Analogous depositional patterns in other sedimentary basins are discussed.

This study provides a better understanding of the variations in lignite thickness and lateral continuity.

Previous Work

During the early 1900's several studies of the lignite-bearing strata of western North Dakota were published by the U.S. Geological Survey (Leonard and Smith, 1909; Lloyd, 1914; Hares, 1928) and by

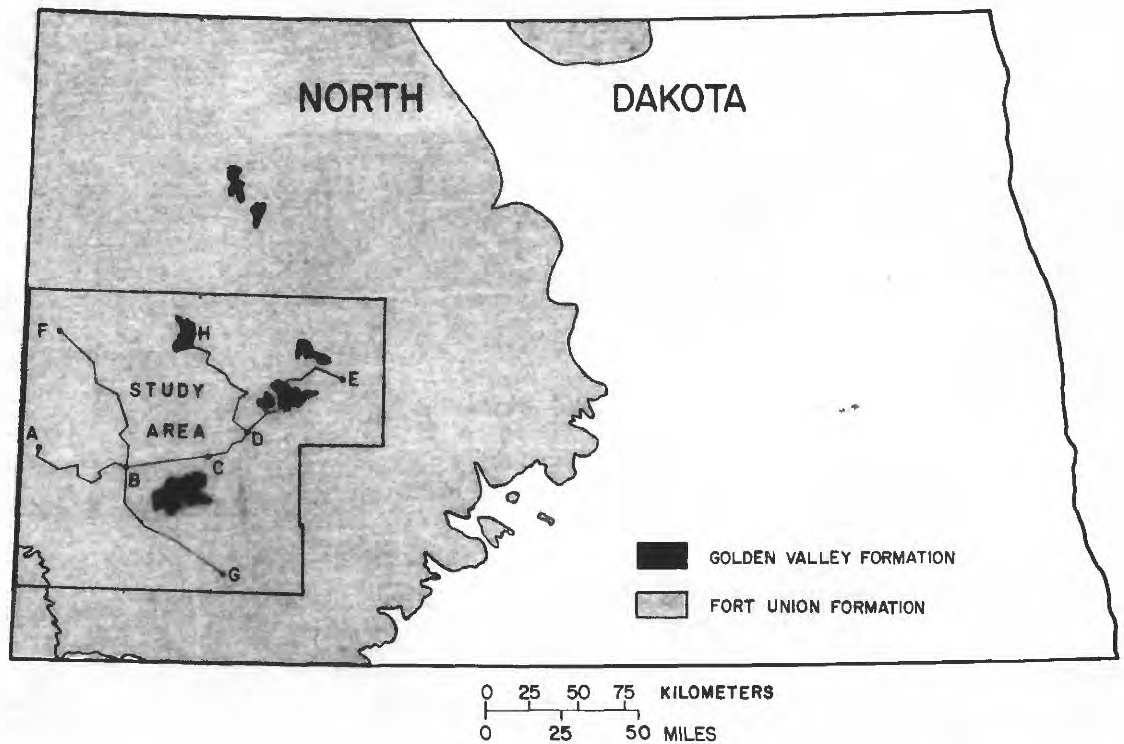

Figure I. Location of study area, correlation diagrams, and extent of the Fort Union and Golden Valley Formations in North Dakota the North Dakota Geological Survey (Leonard, 1908: Leonard and others, 1925). These reports were surface studies that compiled basic data concerning the thickness and location of outcropping lignite beds. Stratigraphic units were recognized and described, and local names were given to lignite beds.

Later work by the U.S. Geological Survey dealt with the uranium and lignite resources of the Fort Union Formation (Benson, 1951; Brant, 1953; May, 1954; Kepferle and Culbertson, 1955; Moore and others, 1959; Denson and Gill, 1965). Royse (1967) defined stratigraphic units in the upper Fort Union Formation and mapped them over a large area in western North Dakota. Royse (1970) and Jacob (1973) studied the rocks and drew conclusions about their depositional environments.

Method of Study

Geophysical logs from more than 300 oil wells and deep water wells were the basic data for this study. Wells without geophysical logs or with logs of poor quality were not used. A preliminary examination of the logs within the area showed gamma-ray logs to be the most useful because they: (1) readily show lignite beds, (2) commonly were run in wells within the study area, and (3) clearly indicate the lignite beds through surface casing; this last feature enabled near-surface lignite beds to be identified and supplied a lithologic record of all of the Fort Union Formation at the well location.

Where available, acoustic density, neutron, and induction electric logs were used in conjunction with gamma-ray logs for correlation and more positive identification of lignite beds.

Induction logs alone are inadequate for identifying lignite beds and were not used. Kaiser (1974, p. 32) reported difficulties in recognizing Texas lignites using only induction logs.

The gamma-ray logs of selected wells were used to construct stratigraphic correlation diagrams, and the most laterally continuous lignite bed was used as a datum. These diagrams illustrate the stratigraphic relationships of the lignite beds to other lithologic units in the Fort Union Formation and to the rocks above the marine Pierre Shale (Cretaceous).

Isopach maps, correlation diagrams, and well-log patterns were used to interpret depositional environments. Analysis of well-log patterns was based on work by Fisher and others (1969, fig. 60, 68, and 98), Galloway (1968, p. 283), and Kaiser (1974, p. 8, 13, 20, and 34). The configurations of the isopach and structure maps were also used to determine relationships between basin subsidence and lignite deposition.

Regional Structure

The Williston basin is the major structural feature of western North Dakota. Surface rocks, including the Fort Union Formation, generally dip about 20 ft/mi (3.8 m/km) toward the basin center. Surface dips increase slightly near large folds such as the Cedar Creek anticline and Nesson anticline, but the dips rarely exceed 1°. Faults in the Fort Union Formation are rare, although some of of relatively small displacement were observed by Townsend (1950, p. 1558).

General Stratigraphy

The Fort Union Formation consists of more than 1,500 ft (457 m) of interbedded sandstone, siltstone, shale, and lignite, and covers an area of about 32,000 mi^2 (82,880 km^2) in North Dakota (fig. 1). It conformably overlies nonmarine beds of the Hell Creek Formation (Upper Cretaceous) and is conformably overlain by the nonmarine Golden Valley Formation (upper Paleocene-lower Eocene) (Hickey, 1972, p. 106). At scattered localities in the southwestern part of the State, the Fort Union is unconformably overlain by the White River Group (Oligocene).

The Fort Union Formation consists of four members, in ascending order, the Cannonball, Ludlow, Tongue River, and Sentinel Butte. The marine Cannonball intertongues with the time-equivalent, nonmarine Ludlow. About 350 ft (107 m) of marine sandstone and shale of the Cannonball Member comprise the eastern part of the outcrop area. To the west and south the Cannonball Member laterally intertongues with lignite-bearing strata of the Ludlow Member.

The Tongue River Member is 350-900 ft (107-274 m) thick within the study area and consists of nonmarine sandstone, shale, and lignite beds. It conformably overlies the Cannonball and Ludlow Members except in isolated small areas, where the basal Tongue River sandstone fills channels cut into the underlying rocks (Hares, 1928, p. 37). The basal Tongue River sandstone has been recognized in outcrops over a large area (Lloyd, 1914, p. 250; Hares, 1928, p. 24; Tisdale, 1941, p. 10) and is usually easy to identify in well logs.

The Sentinel Butte Member averages 500 ft (152 m) in thickness throughout the study area and is lithologically very similar to the underlying Tongue River. The contact between the two is generally conformably and is arbitrarily placed at the top of the HT Butte lignite bed. The HT Butte bed was identified on well logs near Sentinel Butte, the type area of the Sentinel Butte Member. From Sentinel Butte, the contact was extended throughout the study area by subsurface well-log correlations.

Where the HT Butte bed is absent, owing to nondeposition or penecontemporaneous erosion, the contact can be projected to the equivalent stratigraphic horizon by careful correlation of underlying and overlying stratigraphic units. The contact in these areas is generally at the base of a well-developed channel sandstone or arbitrarily placed within a fluvial sandstone-siltstone-shale sequence. These rock types at the horizon of the Tongue River-Sentinel Butte contact represent point bar, levee, and crevasse splay sediments deposited contemporaneously with the HT Butte lignite, or channel-fill deposits in penecontemporaneously eroded channels.

The lignite beds of the Tongue River and Sentinel Butte Members are generally under less than 1,000 ft (305 m) of overburden. The beds range in thickness from 0 to 40 ft (0 to 12.2 m) but are usually less than 5 ft (1.5 m) thick. The average analyses (as-received) of 212 lignite samples from 10 mines in Fort Union coals is: moisture, 37.8 percent; volatile matter, 26.0 percent;

fixed carbon, 29.9 percent; ash, 6.3 percent; sulfur, 0.62 percent; and Btu/lb 6,750 (Sondreal and others, 1968, p. 8).

The correlation diagrams (pls. 1, 2, and 3) also show the Upper Cretaceous Fox Hills Formation and Pierre Shale beneath the Hell Creek Formation. The contact between the marine shale of the Pierre Shale and marine sandstone of the Fox Hills Formation is readily identified on most induction logs or laterologs. This contact is a good datum for correlation of overlying stratigraphic units.

Stratigraphy of the Cannonball and Ludlow Members

Stratigraphic relationships.--Hares (1928, p. 24-25) described the Cannonball and Ludlow Members as intertonguing, marine and nonmarine facies; this stratigraphic relationship resulted from gradual westward transgression of the sea, with some oscillations, to an area that is now near the western boundary of North Dakota. An east-west correlation diagram illustrates this relationship (pl. 1).

At point E (pl. 1), 200-250 ft (61.0-76.2 m) of marine shale and siltstone of the Cannonball Member overlie the Cannonball lignite bed of the Ludlow Member. Westward the Cannonball rocks become gradually coarser grained. Between points C and B (pl. 1) the lower part of the Cannonball and Ludlow interval is characterized by "carrot-shaped" gamma-ray log patterns, indicating upward-coarsening, progradational sequences of marine sandstone, which are capped by thin, continuous lignite beds. (The well-log pattern shown in figure 2 is typical.) The upper part of the interval is predominantly marine and contains similar, repeating, upward-coarsening units. The uppermost marine sandstone unit is capped by nonmarine lignite-bearing Ludlow strata.

Westward from point B lignite beds occur at progressively higher levels in the stratigraphic section as the Cannonball Member thins and intertongues with the Ludlow Member. The lignites of the Ludlow Member become thicker and more numerous. The gamma-ray log patterns of the Ludlow sandstones are more "blocky" indicating sharp basal and upper contacts characteristic of distributary channel sandstones. At point A, near the State border, little or none of the Cannonball Member remains.

Correlation diagrams HD and FBG (pls. 2 and 3) roughly parallel depositional trends. Prograding marine sandstone units characterize the Cannonball and Ludlow intervals shown on correlation diagram HD, and lignite-bearing strata intertongue with marine rocks shown in correlation diagram FBG.

Depositional environments.--The facies changes of the Cannonball and Ludlow interval, and particularly the lateral variations in lignite deposition, indicate deposition during this interval resulted from a series of high-constructive, lobate deltas prograding into shallow marine water. In this deltaic

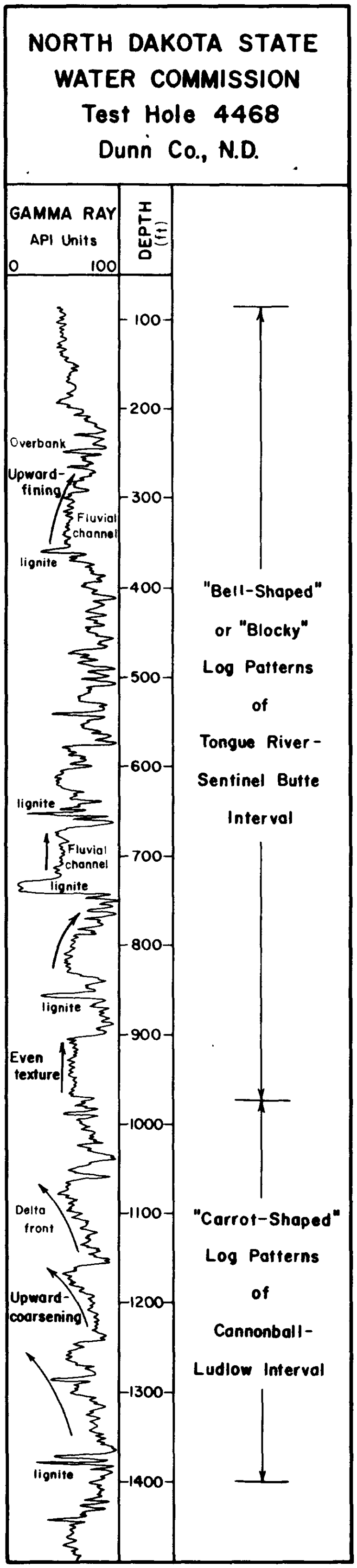

Figure 2. Representative gamma-ray log contrasting log patterns of the Cannonball and Ludlow interval with those of the Tongue River and Sentinel Butte interval

setting, the upward-coarsening sandstone units of the Cannonball Member represent a delta-front sand facies. The delta-front facies grades laterally to the east into a prodelta facies and to the west into the distributary channel-marsh-swamp facies of a delta plain which represents the Ludlow Member.

Lignite deposition in the Ludlow Member.--The delta-plain origin of the lignite beds of the Ludlow Member is evident. Fisher and McGowen (1967, p. 112) found that two kinds of lignite occur typically in the delta-plain facies of the lower Wilcox Group of Texas. One type is lenticular, thin, and local in extent and probably formed in interdistributary areas of actively prograding deltas. Many of the lignites of the Ludlow Member (pls. 1 and 3) display this lenticularity and small extent; in addition, they are interbedded with distributary channels, as shown by a typical gamma-ray log pattern (fig. 3).

The second type of deltaic lignite in the Wilcox Group, tabular and more areally extensive, formed on the plains of abandoned delta lobes. This type of lignite is well illustrated in the Ludlow Member by the thin, laterally continuous lignites from points B to C and B to G (pls. 1 and 3). Hares (1928, p. 48) also noticed two types of lignite beds in the Ludlow Member which, when he wrote his report, were considered to be part of the Lance Formation. He observed that "the thicker beds of Lance lignite are associated with many lesser and lenticular beds."

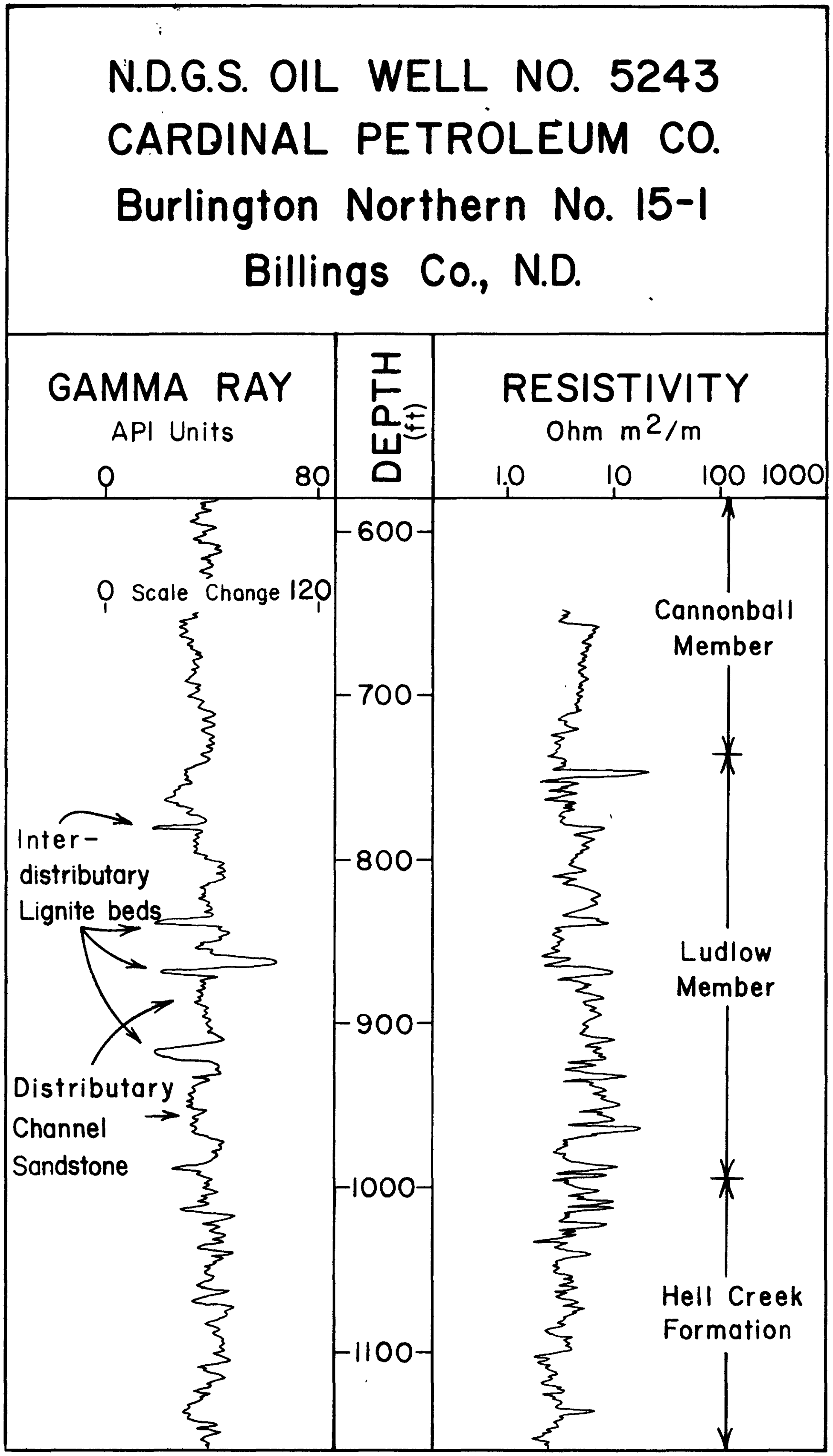

Figure 3. Representative gamma-ray and resistivity well logs showing interdistributary lignite beds and distributary channel sandstone beds of the Ludlow Member

Other depositional environments.--From outcrop studies, Cvancara (1972, p. 73) suggested a barrier bar and lagoon-bay setting for deposition of the Cannonball Member. Some of the lagoon-bay environments Cvancara noticed may have existed marginally to prograding delta lobes; however, the percentage of lagoonal lignite in the Ludlow Member is probably small. Fisher and McGowen (1967, p. 18) reported that lagoonal lignite is less continuous in lateral extent and higher in ash content than deltaic lignite. The average ash content of Ludlow lignites, which is about 10 percent (Winchester and others, 1916, p. 42), is typical of deltaic lignite. By comparison, the ash content of lagoonal lignite in the Gulf Coast basin varies from 16 to 40 percent (Kaiser, 1974, p. 12) and in the San Juan basin varies from 10 to 30 percent (Fassett and Hinds, 1971, p. 1). The lignites of the Ludlow Member are also more extensive than the lagoonal lignites of either the Gulf Coast or San Juan basins.

Stratigraphy of the Tongue River Member

Areal extent of lignite beds.--The lignite beds of the Tongue River Member are unlike those of the Ludlow Member, especially in their exceptional lateral continuity. As illustrated in the correlation diagrams, the Harmon and Hansen beds extend for at least 100 mi (160 km) north-south and east-west. These two beds are identifiable, except in the channel areas, over the 6,600 mi^2 (17,094 km^2) of the study area and are known to continue much farther.

Though partially removed by erosion, at one time the HT Butte bed was probably as continuous as the Harmon and Hansen beds. Other lignite beds between the Harmon and the HT Butte are less continuous but nevertheless can be traced over thousands of square miles.

The lateral extent of the Tongue River lignites was noticed, to a degree, in surface-mapping studies. Leonard and Smith (1909, p. 23) recognized that the lignite beds were not necessarily lenticular and could be traced continuously for many miles. Hares (1928, p. 30) noticed that compared to the underlying lignites of the Ludlow Member, the Tongue River contained "thicker, more persistent beds of lignite." In particular, he calculated that the Harmon bed extended for at least 5,500 mi^2 (14,245 km^2) and compared it in areal extent to the Pittsburgh bed of Pennsylvania, Ohio, and West Virginia (Hares, 1928, p. 50).

The wide extent of the lignite beds of the Tongue River Member has led to use of different names in separately mapped areas; therefore, the literature contains many more names for lignite beds than there are beds (see also Carlson, 1972, p. 102). The Harmon bed, for example, has received the following names: A bed (Leonard and Smith, 1909, p. 24), Bowman, Scranton, and I beds (Leonard and others, 1925, p. 63), C bed (May, 1954, p. 271), and Burkey bed (Hares, 1928, p. 64). Similarly, the Hansen bed has been called the Haynes bed (Lloyd, 1914, p. 252) and the Shell bed (Stephens, 1970).

Depositional environments.--In contrast to the deltaic origin of the Ludlow lignites, the lignite beds of the Tongue River Member accumulated within a fluvial depositional system. This difference in sedimentary environment is illustrated by differing well-log patterns for the Cannonball and Ludlow interval and for the Tongue River and Sentinel Butte interval (fig. 2). Upward-coarsening sandstone beds of the Cannonball Member form "carrot-shaped" log patterns which differ significantly from the "bell-shaped" or "blocky" log patterns produced by upward-fining or evenly textured Tongue River sandstone beds.

The log patterns of the Tongue River Member closely resemble those of the fluvial channel-overbank facies of Fisher and others (1969, fig. 60) and Kaiser (1974, p. 8). Fluvial channel sandstones of the Tongue River Member have sharp basal contacts and either grade upward into finer-grained, point-bar deposits or are immediately overlain by overbank deposits. Lignites are commonly interbedded with overbank deposits and formed in large swamps adjacent to the fluvial channels.

In a sedimentological study of the Tongue River and Sentinel Butte interval, Royse (1970, p. 54) also concluded that the lignite beds of this interval were deposited within a fluvial depositional system. His analysis showed that the Tongue River Member consists primarily of fluvial channel and backswamp deposits with minor flood-plain deposits. Using the dip direction of crossbed measurements, he demonstrated that sediment transport was, on the average, from west to east during Tongue River time (Royse, 1970, p. 74).

Jacob (1973, p. 1038) reported that the Tongue River sediments were deposited on an alluvial plain. In the field he observed the upward-fining sandstone bodies that are typically shown by the "bell-shaped" log patterns of the Tongue River Member.

Lignite deposition.--The main features of lignite deposition during Tongue River time are illustrated by the isopach maps of the Harmon and Hansen beds (pls. 4 and 5). During the deposition of the Harmon bed a stabilized meander belt 4-14 mi (6.4-22.5 km) wide crossed the middle of the study area while another, parallel, meander belt existed to the northeast. Peat was deposited in large, elongate swamps roughly parallel to the meander belts. Occasional deposition of overbank sediments onto flood-plain areas adjacent to the meander belts interrupted peat deposition. As a result, accumulated peats were thicker away from the meander belts and thinner or with partings near them (fig. 4).

The Hansen bed was deposited in similar manner except that the distributary aspect of the drainage system (pl. 5) suggests deposition near or on a delta plain. A "near-terminal" fluvial environment of deposition in the Tongue River Member was suggested by Royse (1970, p. 70).

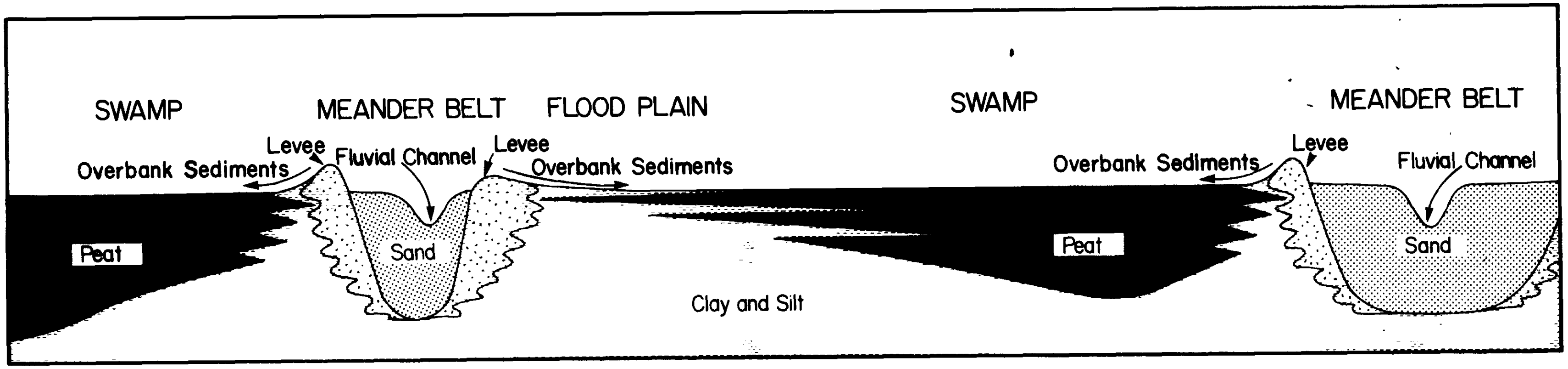

FIGURE 4. SCHEMATIC CROSS SECTION SHOWING SEDIMENTARY ENVIRONMENTS DURING DEPOSITION OF THE HARMON AND HANSEN BEDS

Stratigraphy of the Sentinel Butte Member

Depositional environment.--The depositional environment of the Sentinel Butte Member is very similar to that of the Tongue River. Log patterns of Sentinel Butte rocks show the same fluvial channel-overbank facies and correlation diagrams show little difference. The Sentinel Butte lignites are almost as continuous but possibly fewer in number. Several names have probably also been given to the same lignite bed in the Sentinel Butte Member. For example, the Dunn Center, Beulah-Zap, and Fryburg beds appear to be equivalent.

Lignite deposition.--Data are insufficient to construct an isopach map of a single lignite bed in the Sentinel Butte Member in the study area. Coal isopach maps of small areas based on closely spaced drilling of near-surface lignite deposits, however, exhibit the same basic characteristics as the Harmon and Hansen beds of the Tongue River Member. The lignite bodies are elongate and on the average trend northwest. This orientation parallels the direction of sediment dispersal during Sentinel Butte time (Royse, 1970, p. 74). Apparently, peats during Sentinel Butte time were also deposited in elongate swamps roughly parallel to the major meander belts.

From slight, but significant, differences in the sedimentary composition of the Tongue River and Sentinel Butte Members, Royse (1970, p. 67-78) concluded that there was more extensive and frequent deposition of sand during Sentinel Butte time. Consequently, detailed studies of the Sentinel Butte Member will probably show non-coal intervals in the Sentinel Butte to be more variable in thickness than such intervals in the Tongue River. Lignites of the Sentinel Butte will probably be shown to be more lenticular and have a greater tendency to split, or develop partings.

Structural Features of the Fort Union Formation

A contour map drawn on the top of the Hansen lignite bed or its time-equivalent horizon illustrates the major structural features of the area (pl. 6). The largest structure shown is the southwest flank of the Williston structural basin. From the southwest and south, strata dip about 20 ft/mi (3.8 m/km) toward the basin center. Dips of this magnitude and direction have been observed by many in the field (Leonard and Smith, 1909, p. 22; Lloyd, 1914, p. 251; Hares, 1928, p. 45; Roe, 1950, p. 435).

A few northeast-trending folds cross the major structural trend of the Williston basin. The most noticeable is the syncline that extends from southwest of Dickinson, North Dakota, to northwest of the town of Golden Valley. Caldwell (1954, pl. II) and Denson and Gill (1965, pl. 10) recognized the southernmost part of this syncline, by means of field mapping. The depression probably contributed to the preservation of the Golden Valley Formation at its type locality near the town of Golden Valley and in the Little Badlands area southwest of Dickinson.

Minor, undulating folds (not shown on plate 6) with less than 100 ft (30.5 m) of relief are superimposed on the larger, regional trends. These smaller folds were revealed by closely spaced, shallow drilling within small parts of the study area.

Effect of Basin Subsidence on Fort Union Deposition

The sedimentary environments during Fort Union time were not the only factors influencing deposition. Equally significant is the effect of basin subsidence and stability. The isopachs of the Tongue River Member (pl. 7) conform roughly to the general configuration of the structure map of the Hansen bed (pl. 6). The Tongue River Member thickens toward the center of the Williston basin and along the syncline mentioned before. Apparently, the total thickness of the Tongue River Member was controlled by the slow subsidence of the Williston basin.

No such correlation exists between the configuration of the Williston basin and the deposition of the lignite beds. Correlation diagrams and lignite thickness maps show no obvious relation to the Tongue River Member isopach map or the Hansen structure map. Basin subsidence apparently had little effect on the areal distribution of the lignite beds.

The relative stability of the Williston basin, however, probably contributed to the remarkable lateral continuity of the Tongue River and Sentinel Butte lignites. The depositional environment of fluvial systems alone cannot adequately account for the areal extent of the lignite beds. Coals associated with fluvial systems of the

Appalachian basin in southern West Virginia are extremely lenticular (Winger and Rehbein, 1975, p. 8). Abrupt lateral facies changes are common in rapidly subsiding, unstable basins such as the Gulf Coast (Fisher and McGowen, 1967, p. 122). Lateral persistence of lithologies, including coal, are more typical of stable, intracratonic basins such as the Pennsylvania Eastern Interior basin (Wanless and others, 1963). By analogy, it seems reasonable to infer that slow subsidence of the Williston basin, alternating with long periods of stability, promoted the vast areal extent of the Tongue River and Sentinel Butte lignites.

In contrast, the Cannonball and Ludlow Members record several oscillations of base level and greater lateral facies changes. This implies less stability during the Cannonball and Ludlow interval which, together with the prograding delta system, probably contributed to the lenticularity of the lignite beds of this interval.

To summarize, it appears that relative stability of the Williston basin during the Tongue River and Sentinel Butte interval controlled the areal extent of the lignite beds, and the geographic location of major fluvial channels affected the configuration and thickness of the lignites.

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