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Depositional environments of the lower Tullock Formation (Paleocene), Slope County, southwestern North Dakota

William K. Hickey
University of North Dakota

DEPOSITIONAL ENVIRONMENTS OF THE LOWER TULLOCK FORMATION (PALEOCENE), SLOPE COUNTY, SOUTHWESTERN NORTH DAKOTA

by

William K. Hickey

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This thesis submitted by William K. Hickey in partial fulfillment of the requirements for the Degree of Master of Arts from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

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Title DEPOSITIONAL ENVIRONMENTS OF THE LOWER TULLOCK FORMATION (PALEOCENE), SLOPE COUNTY, SOUTHWESTERN NORTH DAKOTA

Department Geology

Degree Master of Arts

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ABSTRACT

The lower Tullock Formation (Paleocene), which consists of a section 5 to 30 feet thick, was studied in Slope County, southwestern North Dakota to determine its depositional environments. The lithologies present are sand, silt, clay and lignite. A bed of lignite or yellow silt marks the base of the Tullock Formation throughout the study area.

The silt beds are interpreted as having been deposited as natural levees because they are wedge-shaped and contain climbing-ripple cross-stratification, interbedded sand lenses and lignitized paleo-root systems. Well-drained swamp deposits are difficult to distinguish, but are probably located in the silt beds.

There are two types of clay beds which were deposited in different environments. The first type of clay bed is dark-colored, rich in organic matter, silty and shaly. It is interpreted as having been deposited in a poorly-drained swamp in a fluvial floodbasin because of its organic content and interbedded relationships with lignite beds. The other type of clay bed is light-colored and contains less organic material and silt than the first type. It is interpreted as having been deposited in small lakes within a floodbasin because of its low organic content, massively bedded clay and stratigraphic position above lignite beds.

Lignite beds are interpreted as having been deposited in poorly-drained swamps in fluvial floodbasins because of their wood content,

lateral persistence, thickness and interbedded relationships with dark-colored clay beds.

The sand beds of the lower Tullock Formation are interpreted as having been deposited as crevasse-splays because their grain size (very fine- to medium-grained) is coarser than levee deposits, and they show lateral thinning, scoured bases and small-scale ripple cross-stratification. The sand beds are underlain by lignite and overlain by dark-colored clay indicating the sand was rapidly dispersed into poorly-drained swamps.

Prodelta and near- and off-shore lacustrine environments of deposition are rejected because of incorrect vertical successions of beds. Commonly clay beds rich in organic matter are overlain by lignite beds, which, in turn, are overlain by silt beds. Lacustrine deposits would show clay beds overlain by silt and sand beds, in turn overlain by lignite beds. The succession present is what would be expected for a fluvial environment.

INTRODUCTION

Purpose and Location of Study

The Tullock Formation, of Paleocene age, is the lowest formation of the Fort Union Group (Figure 1). The purpose of this study is to determine the environments of deposition of the lower part of the Tullock Formation in Slope County, southwestern North Dakota.

The study section is at the base of the Tullock Formation and is between 5 and 30 feet thick. It is underlain by the Pretty Butte Member of the Hell Creek Formation (Upper Cretaceous). It is overlain by a bed which is recognizable throughout the study area due to its distinctive alternating light and dark coloration and nearly vertical weathered slopes.

The study section is dominated by silt but also contains clay, lignite and sand.

Field Methods

Field work consisted of measuring sections, collecting sedimentological samples and tracing persistent beds. Sections were measured to the closest quarter of a foot. Approximately sixty sections were measured in the study area (Figure 2). Such a high density of measured sections within the field area gives good control for the determination of the three dimensional shape of beds that is essential in determining depositional environments. Detailed descriptions of the measured sections are given in Appendix A.

Fig. 1.--Upper Cretaceous and Paleocene rock units in southwestern North Dakota. Dotted area is the study section. Not drawn to scale.

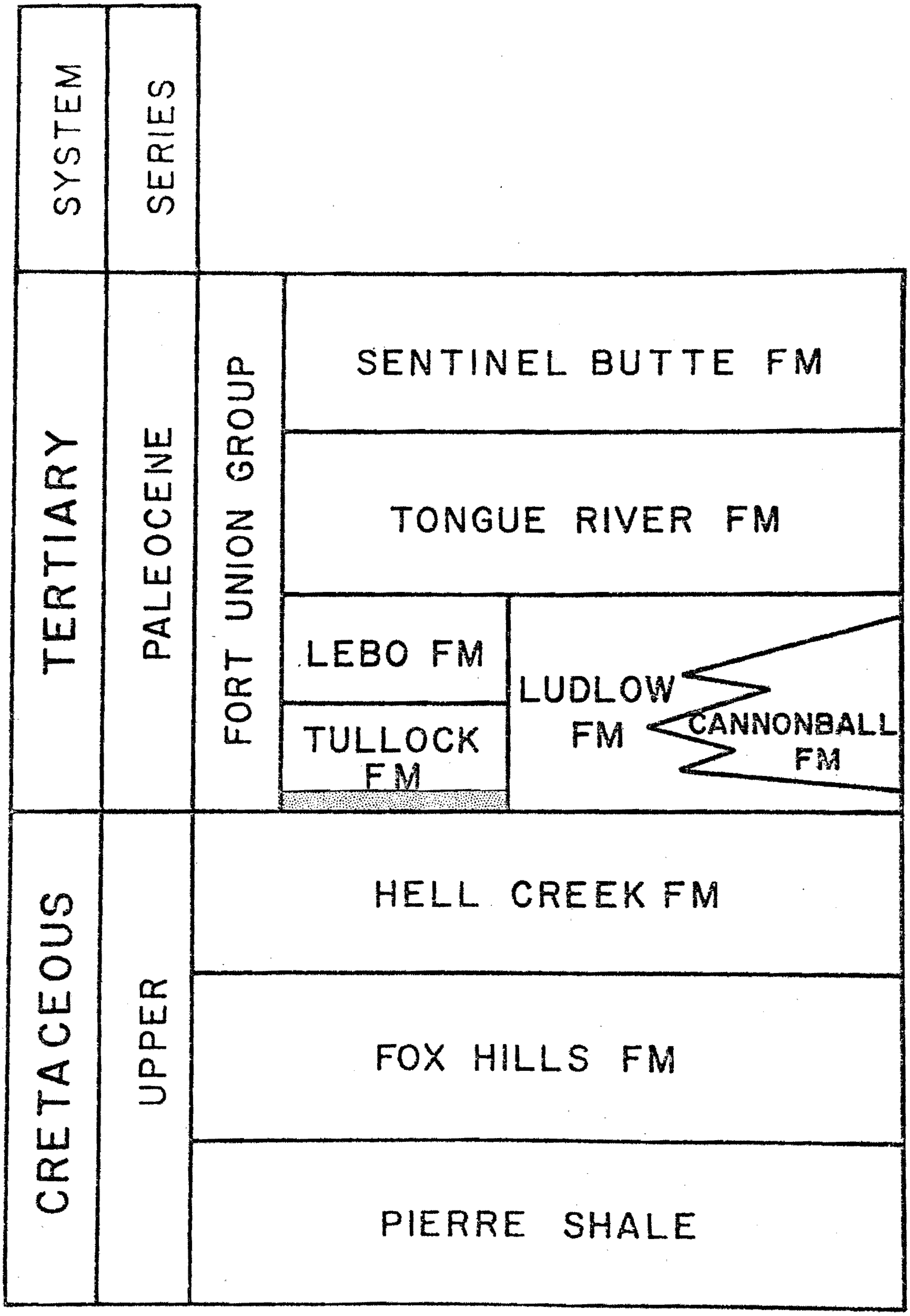
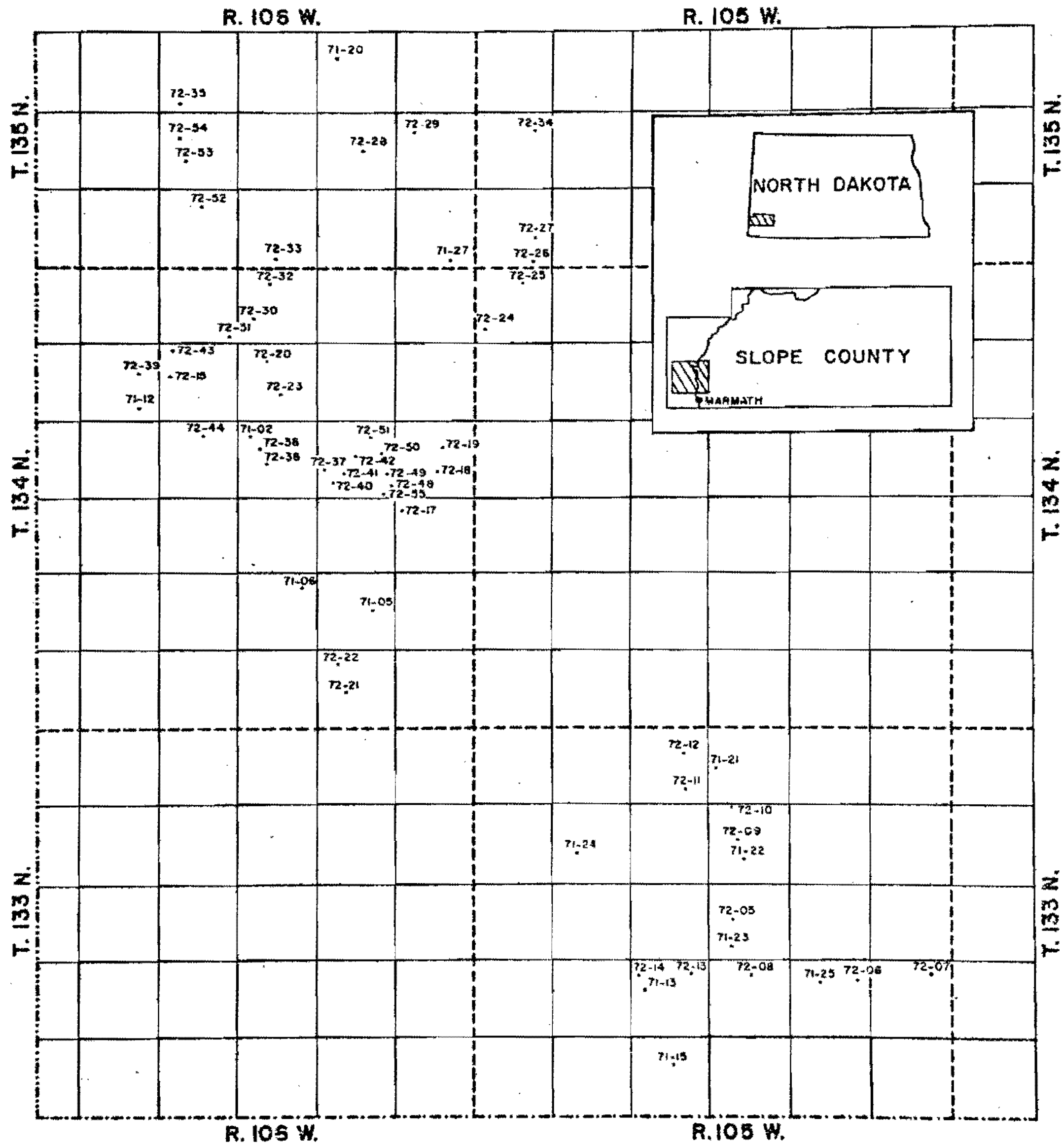

SYSTEM
SERIES
TERTIARY
PALEOCENE
FORT UNION GROUP
SENTINEL BUTTE FM
TONGUE RIVER FM
LEBO FM
TULLOCK FM
LUDLOW FM
CANNONBALL FM
CRETACEOUS
UPPER
HELL CREEK FM
FOX HILLS FM
PIERRE SHALE

Fig. 2.--Index map showing the location of measured sections.


R. 106 W.
R. 105 W.
T. 135 N.
T. 134 N.
T. 133 N.
NORTH DAKOTA
SLOPE COUNTY
MARMATH
71-20
72-35
72-54
72-53
72-29
72-28
72-34
72-52
72-27
72-33
71-27
72-26
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71-12
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71-02
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72-50
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72-18
72-40
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72-12
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72-09
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72-05
71-23
72-14
72-13
72-08
71-25
72-06
72-07
71-13
71-15

Samples were collected as the sections were measured to demonstrate grain size characteristics that were noted in the field and that could be diagnostic of depositional environments. A grain-size-analysis approach to environmental interpretation has proven unsuccessful and is used here only to support field observations.

Laboratory Procedures

Sedimentologic samples were analyzed to determine the vertical and lateral distribution of grain sizes. Samples were disaggregated, wet sieved through a 4 phi sieve, and the sand fraction analyzed in a weight accumulation settling tube described by Felix (1969).

STRATIGRAPHY

History of Nomenclature

Both Brown (1962) and Frye (1969) presented extensive accounts of the history of the Upper Cretaceous and Paleocene nomenclature in the Dakotas, Montana and Wyoming. Only a brief review will be given here.

The original geological investigations into the western interior region began in the 1850s with F. V. Hayden's expeditions. Hayden and his co-workers applied the term "Great Lignite group"to the lignite-bearing strata of the Rocky Mountains and Great Plains. In the following years, several different names were applied to various parts of the "Great Lignite." In addition, names applied to rock units in different areas were equated with the "Great Lignite." Meek and Hayden (1862, p. 433) applied the term "Fort Union" for the original, less specific "Great Lignite." In 1876, King introduced the term "Laramie" for lignite-bearing strata in Wyoming. This term soon became equated with the "Great Lignite." The term "Lance" was introduced by Stanton in 1910. Other terms that were used for various parts of the "Great Lignite" included "Ceratops Beds," "Lower Fort Union," and the "somber beds." Because of the large number of terms, many of them incorrectly applied, the "Great Lignite" and its related strata became one of the major nomenclatural problems in American stratigraphy.

Paleontological data did not help the situation. There were a number of problems involved in both the collection and identification of specimens. Incorrect stratigraphic location of the samples resulted in the lumping together of Cretaceous and Paleocene fossils, especially plants. It eventually became evident, however, that Upper Cretaceous dinosaurs were found in the lower part of the "Great Lignite" and that mammals dominated the upper parts of the strata. In addition, distinctive Cretaceous and Tertiary plant floras were recognized. The Cretaceous-Tertiary boundary, therefore, was located somewhere within the "Great Lignite group."

The true age relationships of the "Great Lignite" strata did not become evident until well into the 1900s. The first attempts at subdivision were based on light and dark colored zones. At this point the "Great Lignite group" included both Cretaceous and Tertiary strata. Brown (1907) named the Hell Creek Formation and correlated it with the Lance Formation of eastern Wyoming.

Rogers and Lee (1923, p. 19 and 29) defined the Tullock Member of the Lance Formation in the Tullock Creek area of southwestern Montana. The Tullock Member was distinguishable from the lower Lance by its yellowish sandstones and shales and the presence of numerous coal beds. A persistent coal marked the base of the member (Rogers and Lee, 1923, p. 31). In 1935 the Tullock was raised to formational rank by the U.S. Geological Survey (Wilmarth, 1938, p. 2196), and its age was given as Upper Cretaceous or Eocene.

The Lebo was first defined as the basal member of the Fort Union Formation by Stone and Calvert (1910, p. 746) in the Crazy Mountain area of Montana. In its type area it is an andesitic sandstone with interbedded shale but it becomes dominantly a shale to the east (Frye, 1969, p. 5). When the Fort Union Formation was raised to group status, the Lebo was elevated to formational rank (Simpson, 1937, p. 15).

Dorf (1940, 1942) concluded that the Lance and Hell Creek floras were similar and were Upper Cretaceous. The flora of the Tullock Formation was Paleocene in character and should, therefore, be placed in the Fort Union. The floras from the rest of the Fort Union were definitely Tertiary in age. Figure 1 shows the Upper Cretaceous and Paleocene rock units recognized in western North Dakota. The usage of the terminology of the Tullock and Lebo interval is still uncertain in North Dakota.

General Stratigraphy

The Upper Cretaceous and Paleocene formations in the western part of North Dakota form a complex succession of strata involving various marine transgressions and regressions. The marine, Upper Cretaceous Pierre Shale is the oldest formation cropping out in the western part of the state. Overlying the Pierre is the Fox Hills Formation which is dominantly sandy and contains a shallow-water, marine fauna. The Fox Hills is overlain by the Hell Creek Formation which marks the top of the Cretaceous in western North Dakota. The Hell Creek consists of poorly consolidated sandstone, silstone, and claystone that were deposited in lagoons on the flood plains (Frye, 1967, p. 27). This entire Upper Cretaceous Series indicates a marine regression. Such a regressive series is seen not only in North Dakota but throughout the entire western interior region.

In the south-central part of North Dakota, the Cannonball Formation at the base of the Paleocene Series represents a marine transgression. In the western part of the state, continued continental conditions are indicated by the lignite bearing Tullock and Lebo Formations.

In extreme western North Dakota, the presence of brackish tongues of the Cannonball Formation interfingering with the Lebo Formation indicates a westward marine transgression (Brown, 1962, Figure 1). The upper parts of the Lebo Formation were deposited under exclusively continental conditions indicating that the sea had withdrawn from the state. The overlying Tongue River and Sentinel Butte Formations are composed of sand, silt, clay and lignite and represent continued continental conditions.

The Tullock Formation is the lowest Paleocene formation in North Dakota known mainly from Slope and Bowman counties. It is largely a poorly consolidated, fine- to medium-grained clastic formation that contains beds of clay, silt, sandy silt, and fine- to medium-grained sand. Coarser sediment is also present but is a minor constituent. Significant amounts of lignite are also present. The Tullock is characterized as being evenly bedded with many of the beds showing remarkable lateral persistence. Thicknesses of individual beds seldom exceed 25 feet with the exception of sand beds, which may exceed 50 feet in thickness. Several of the sand beds show lateral thickness changes. Concretions are common throughout the formation though they occur almost exclusively in beds of sand and silt. They range in shape from elongate or "log-like" (up to several 10s of feet in length) in the thick sands, to small (up to a foot in diameter) irregular to spherical shape in the silt beds. The larger,elongate concretions have proven useful in other areas as indicators of trends of sand bodies (Jacob, 1972, p. 50).

The sediments in the Tullock Formation are generally various shades of brown and gray with distinctive yellow beds at several horizons. The yellow beds are good markers because of their distinct color and lateral persistence. One of these yellow beds is located at or near the base of the Tullock. Most of the sand and silt beds examined are cross-bedded though the degree of consolidation effects the ease with which the structures can be observed. The thicker sand beds contain large-scale, epsilon cross-stratification (Allen, 1963, p. 102) as well as smaller scale cross-stratification. The yellow beds, which are mainly silt, contain small-scale, ripple cross-stratification. Many of the larger concretions and concretionary lenses also contain cross-stratification.

The Tullock Formation contains a fairly extensive flora (Frye, 1967, p. 192). All lithologies except lignite contain recognizable leaf impressions although they are not abundant. One of the sandy concretionary layers contains abundant, well-preserved leaves; however, similar layers at other locations are barren. Virtually all lithologies contain plant fragments in all outcrops. Fragments range from lignitized organic material in sand to plant fragments in clay to paleo-root systems in silt. The Tullock Formation contains a sparse vertebrate and invertebrate fauna (Frye, 1967, p. 207-210).

Study Interval

Lower Contact

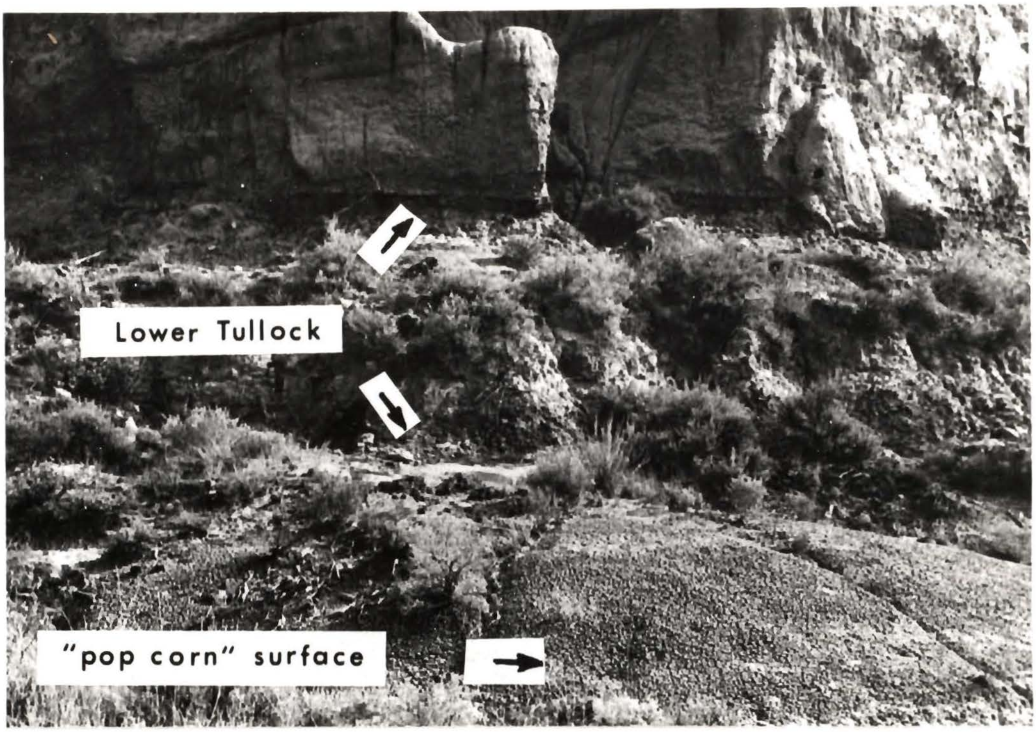
Several criteria are useful in the recognition of the Hell Creek-Tullock contact. Frye (1969, p. 25) noted the occurrence of a "yellow marker" bed at or near the contact throughout most of western North Dakota. This bed marks the base of the Tullock Formation except where it is underlain by a lignite ("lowest persistent bed of lignite" of Calvert, 1912, p. 196) in which case the lignite is considered the base. At several locations the "yellow marker" bed loses its distinctive color and is replaced by various shades of brown or gray. There are other yellow beds higher in the section that can be mistaken for the true "yellow marker."

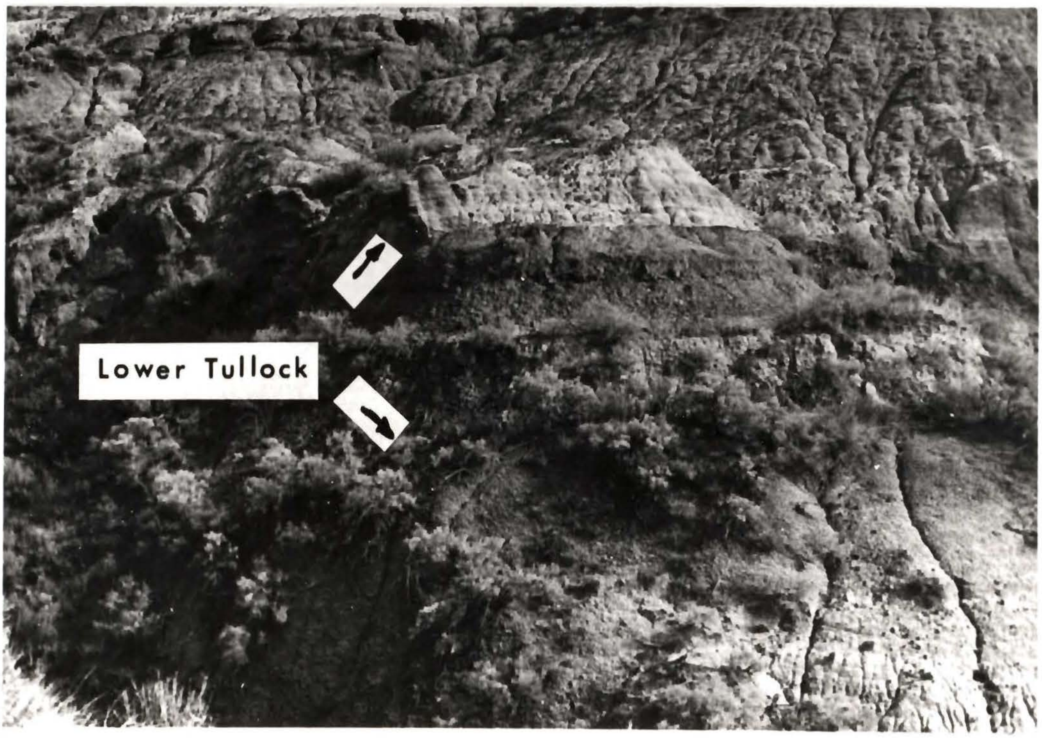
The overall bedding characteristics are also useful in identifying the contact. The Hell Creek bedding tends to be discontinuous and has a "dumped" or slumped appearance (Frye, 1969, p. 25). The bedding in the Tullock Formation tends to be flat and persistent. Care must be exercised as there are exceptions to these generalizations in both formations.

The Pretty Butte Member of the Hell Creek Formation, which underlies the Tullock everywhere in the study area, forms slopes that are generally distinctive. The slopes are broadly convex upward (Figures 3 and 4). They tend to have a distinctive "pop corn" surface where the clay content is high. The "pop corn" surface becomes smoother with an increase in the silt content. In many places a lignite bed directly overlies the Pretty Butte Member. In such cases, the lignite bed forms a vegetated bench which can be seen for some distance.

Fig. 3.--Lower Tullock Formation underlain by the Pretty Butte Member of the Hell Creek Formation and overlain by a bed showing a distinctive alternation of light and dark layers. Note convex upward slopes of the Pretty Butte Member with characteristic "pop corn" surface and the near vertical weathered slopes of the overlying bed. Arrows indicate upper and lower contact of study section. Located near section 72-50 (Appendix A).

Fig. 4.--Lower Tullock Formation underlain by the Pretty Butte Member of the Hell Creek Formation and overlain by a bed showing a distinctive alternation of light and dark layers. Arrows indicate upper and lower contact of study section. Located near section 72-50 (Appendix A).


Lower Tullock
"pop corn" surface


Lower Tullock

In many cases there is a tendency to place the contact between the Hell Creek and Tullock Formations too high. Brown (1962, Plate I, Figure 2) placed the contact at Pretty Butte approximately 100 feet higher than it should be. It is necessary to keep this tendency to place the contact too high in mind and to always look lower than the section being measured for beds which satisfactorily locate the base of the Tullock Formation.

Upper Contact

The study section is overlain by a bed which shows a distinctive alternation of light and dark layers (Figure 4). The layers are only a few inches thick and are composed of sand, silt and clay. The bed is between 15 and 50 feet thick but averages 25 feet. The bed also has a near vertical weathered surface at most locations (Figure 3).

At most measured sections the top of the study interval is marked by either lignite or dark, shaly, silty bentonite.

LITHOLOGY

Sand

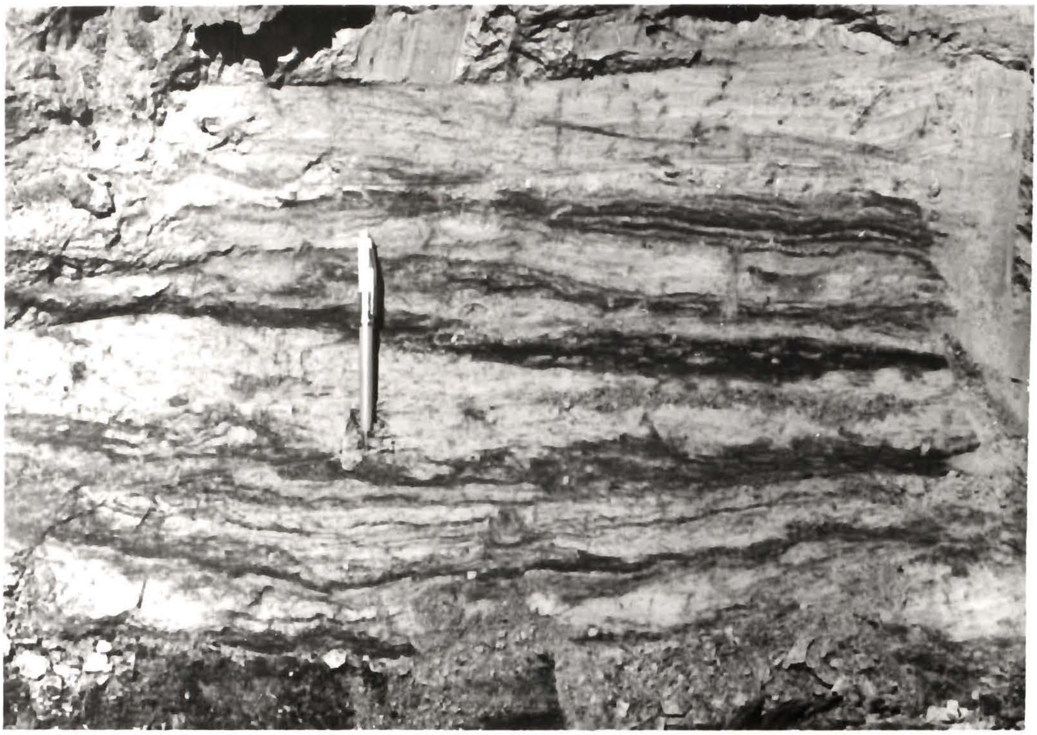
Sand occurs in beds that range from approximately one-half to five feet thick. Grain size ranges from very fine- to medium-grained sand with the thicker, more laterally persistent beds coarser than thin beds. Consolidation of the sand beds varies with thickness. The thicker, coarser beds are less consolidated than the thinner, finer-grained beds. Consolidation directly effects the ease with which primary sedimentary structures can be seen. Thick sand beds (illustrated on Plate III) show no observable primary sedimentary structures. Thin sand beds (Plate I, between sections 72-50 and 72-51) show small-scale ripple cross-stratification (Figure 5).

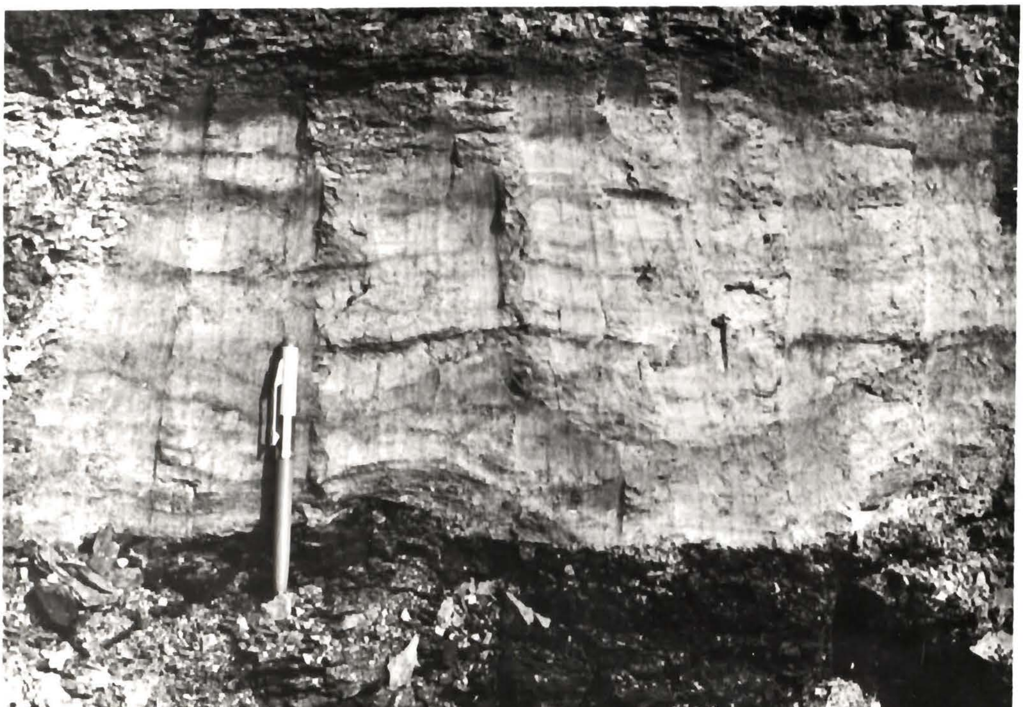
All sand beds in the lower Tullock Formation possess an eroded base. In the thick sand beds the eroded base is indicated by a thin lignite (an inch to almost a foot thick) and the inclusion of lignite fragments within the sand. The thin sand beds also show an eroded base (Figure 6). All sand beds contain concretions but they are more numerous in the fine-grained sand beds.

Thin, fine-grained sand beds crop out over limited distances (not more than a mile) and show lateral decreases in thickness. Thick, medium-grained sand beds crop out over much larger distances (up to four miles) and a definite thinning trend could not be distinguished. The less laterally persistent sand beds grade into silt in one direction and lignite in the opposite direction.

Fig. 5.--Small-scale cross-stratification in thin, very fine-grained sand bed in lower Tullock Formation. Section 72-37, unit 2 (Appendix A).

Fig. 6.--Lower contact of a thin, very fine-grained sand bed in the lower Tullock Formation. Section 72-51, unit 2 (Appendix A).





Silt

Silt makes up the bulk of the lower Tullock Formation. Gener-
lly the thickest lithologic unit at any given locality is composed of
ilt. At many of the measured sections, the silt beds contain thin
andy lenses (Figure 7). Generally the silt beds become finer upwards.
he color of the silt ranges from light yellowish brown to light gray
gray indicating increased clay content). Because of the yellowish
olor and great lateral persistence, silt is the most noticeable lith-
logy in the Tullock and makes the best marker beds. The lower part
f the Tullock is marked by a very persistent yellow silt bed known
nformally as the "yellow bed" (Frye, 1969, p. 25).

Silt commonly contains limonite concretions of various size
nd shape, calcareous concretionary lenses and organic material.
imonite concretions, the most common concretion in the lower Tullock,
re rarely larger than six inches in diameter and range in shape from
pherical to irregular. They are composed of jarosite, marcasite and
iderite which weather to limonite (Frye, 1967, p. 157). They are
istributed throughout the vertical extent of most silt outcrops;
owever, at several locations they seem to be restricted to certain
orizons. Calcareous concretionary lenses were observed at a limited
umber of outcrops. The lenses are up to approximately ten feet in
iameter and are composed of calcite-cemented sand. They contain
mall-scale ripple cross-stratification. Abundant leaf impressions
ere found at one locality (section 71-15, unit 2). The concretions
re sand lenses that have been cemented. Most of the silt outcrops

Fig. 7.--Thin (less than 1 foot), very fine-grained sand lens in a silt bed in the lower Tullock Formation. Section 72-55, unit 2 (Appendix A).

contained lignitized organic material on bedding planes and lignitized plant roots in growth position.

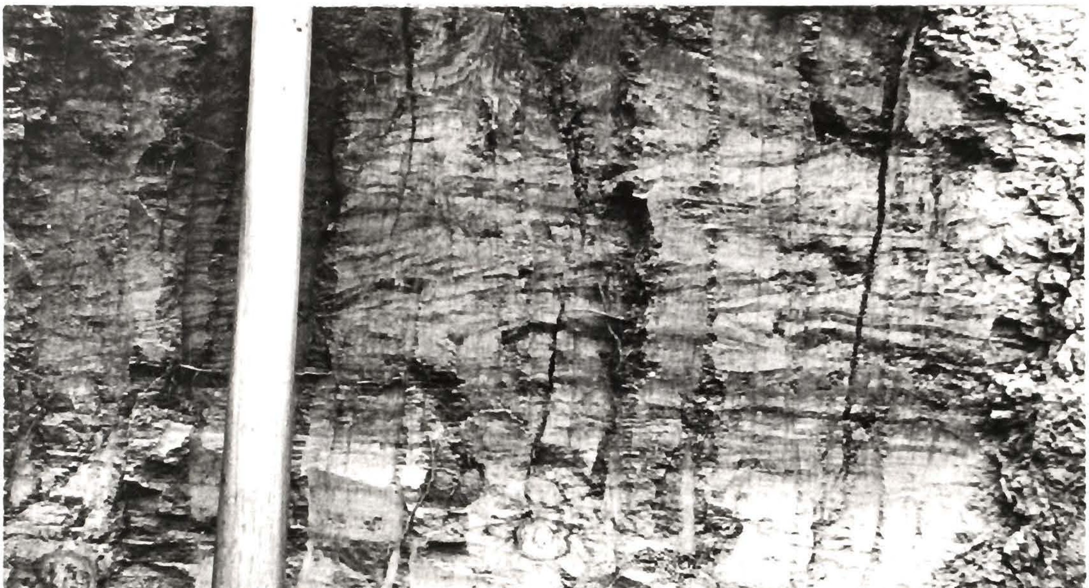
At most of the sections the sedimentary structures are poorly preserved and difficult to see. The poor preservation can be explained, in part, as the result of bioturbation during and shortly after deposition. Climbing-ripple cross-stratification (Figure 8) is the most diagnostic sedimentary structure in the silt; however, preservation is usually poor. Flat bedding is rare in the silt beds of the lower Tullock. Another type of sedimentary structure that occurs at several localities is wavy lamination. The term "wavy lamination" was used (Coleman and others, 1964) to describe a type of lamination caused by deposition due to the interference of plant roots on sediment-laden floodwaters.

The silt is in beds that are wedge-shaped and vary from a few feet to 10 to 15 feet thick within less than a mile. Plate I shows such a relationship between sections 72-48 and 72-51. Between sections 72-49 and 72-51 the lithology changes from sandy silt to fine sand.

Clay

Clay is fairly abundant in the lower Tullock Formation, but not as common as silt. It is almost always associated with lignite but a few measured sections consist almost entirely of clay with no lignite (Plate II, sections 72-52 through 72-54). The clay of the lower Tullock Formation occurs in beds which are either light- or dark-colored.

Fig. 8.--Climbing-ripple cross-stratification in a silt bed in the lower Tullock Formation. Note the lignitized paleo-root system and small, limonite concretions. Located near section 72-55 (Appendix A).



The light-colored type is light to medium gray. Organic material is present in all clay beds of the lower Tullock Formation but is least abundant in the light clay beds. At several localities complete leaf impressions were found in the light-colored clay. Light-colored clay beds contain relatively little silt and tend to be massively bedded. The light-colored clay is above lignite in more places than it is below lignite.

The dark-colored type is reddish brown to black clay to silty clay. Organic material is abundant, generally in the form of plant fragments not over six inches in length. The dark clay beds contain silt and exhibit varying degrees of fissility. The dark-colored clay is the most abundant type of clay in the lower Tullock Formation and occurs either below lignite or interbedded with lignite. At several localities dark clay makes up the entire lower Tullock Formation and here it is generally fissile and up to six feet thick. Very rarely does dark clay occur above a lignite. In places dark clay grades upward into light clay but the reverse does not occur.

Lignite

Lignite occurs at almost all measured sections in the lower Tullock Formation. Throughout most of the study area, the base of the Tullock is marked by a persistent lignite. It ranges in thickness from one inch (Plate III, section 72-10) to more than five feet (Plate II, sections 72-28 and 72-29). Lignite occurs also at other horizons within the study section as beds that are neither as thick (usually less than 2 feet) nor as laterally persistent as the lower lignite.

The lignite is dominantly black but may grade into various shades of dark brown. Most beds of lignite within the study area contain compressed wood fragments up to several feet in length. This indicates that the coal swamps were dominated by woody vegetation. Detailed petrography of the coal would be helpful in determining the characteristics of the coal-forming swamps. Where beds of lignite are more than 5 feet thick, it is not uncommon for the coal to be burned out, forming "scoria." "Scoria" is a local term applied to the sediments baked during burning of the lignite.

DEPOSITIONAL ENVIRONMENTS OF THE TULLOCK FORMATION

General

It has been determined that the Tullock Formation is non-marine in origin (Frye, 1967, Brown, 1962) mainly on the basis of its flora and fauna. Therefore, depositional environments involving marine processes cannot be considered. It is doubtful that eolian processes could have been important in the deposition of the lower Tullock Formation because the climate, based on the flora, was warm temperate, moist-summer (Frye, 1967, p. 218). Abundant moisture is also indicated by the presence of many lignite deposits throughout the Tullock Formation. It will be shown that exclusive lacustrine deposits are not present in the lower Tullock Formation.

A fluvial depositional environment is considered to be the best explanation for the deposits of the lower Tullock Formation. There is a marked lack of channel deposits in the study section. However, there are abundant channel deposits throughout the rest of the Tullock Formation. The deposits of the lower Tullock Formation are, therefore, natural levee and floodbasin in origin.

Depositional Environment of Silt

The silt beds of the lower Tullock Formation are interpreted to be natural levee deposits. Natural levees have been described in modern fluvial-deltaic systems (Allen, 1965; Coleman, 1966, 1969;

Coleman and Gagliano, 1965; McKee, 1966; and Welder, 1959) but relatively little has been published about ancient levee. It appears that many of the characteristics of modern natural levee environments can be applied to ancient deposits.

Natural-levee deposits are wedge-shaped in cross-section and form ridges bordering river channels in plan view (Figure 9). The concave side of meandering streams and straight reaches provide the best areas for the formation of natural levees (Allen, 1965, p. 121).

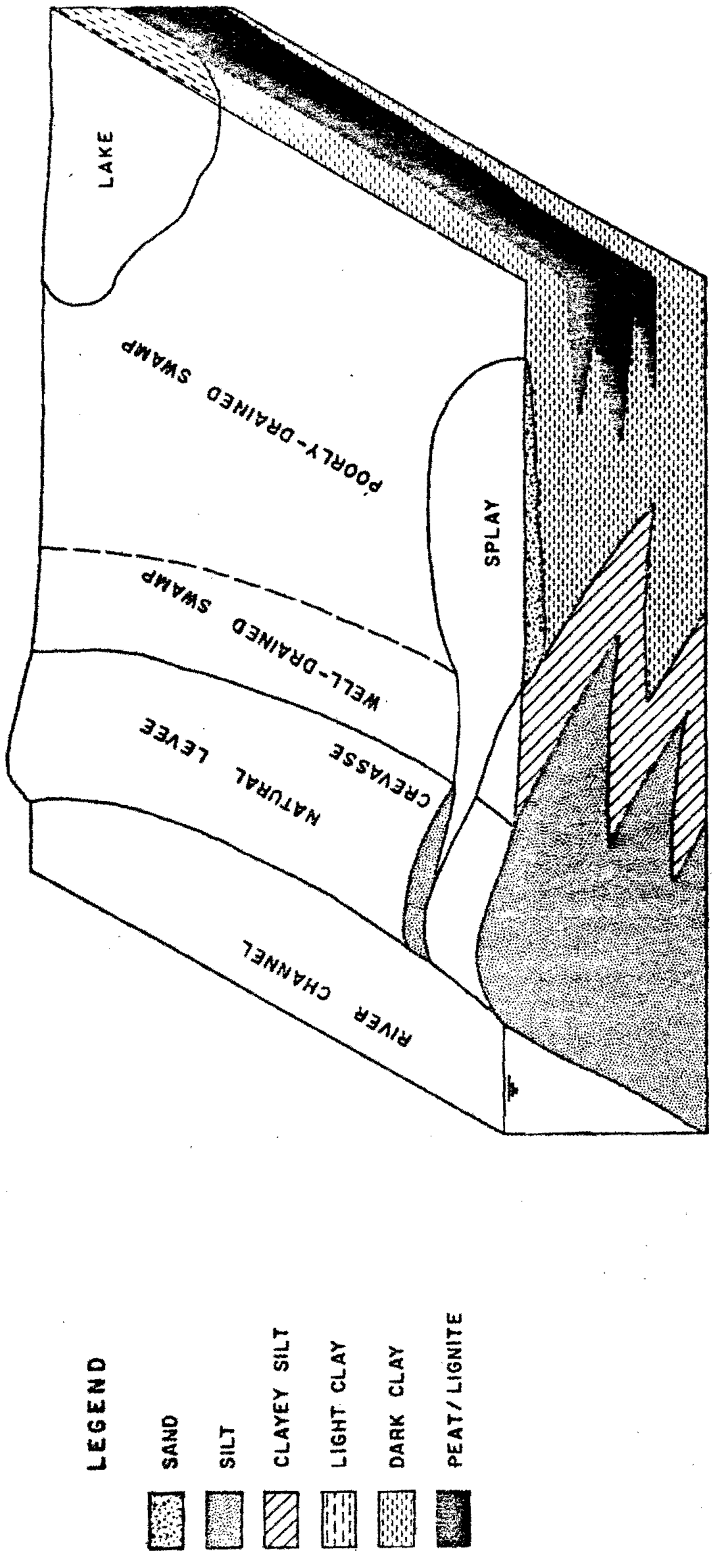
Natural levees of the Mississippi River attain a maximum elevation of 15 to 25 feet and a maximum width of 1 mile. The Sacramento River, which is considerably smaller than the Mississippi River, has levees with a maximum elevation of 10 to 15 feet and a maximum width of up to 1.5 miles (Allen, 1965, p. 122).

The silt beds of the lower Tullock Formation are wedge-shaped (Plate I, sections 72-48 through 72-51) and reach a maximum thickness of 12 feet (Plate I, section 72-48). Several of the silt beds in the upper Tullock Formation are approximately 20 to 25 feet thick.

Climbing-ripple cross-stratification is a type of primary sedimentary structure which is characteristic of natural levees (McKee, 1966). Other types of structures which occur in levees but are not as indicative of depositional environment include planar cross-stratification and wavy lamination (Coleman and Gagliano, 1965).

Deposition on natural levees occurs during floods from suspended load of rivers. When the river tops its banks the velocity of the flowing water is checked; as the velocity decreases, its ability to carry sediment also decreases and sediment is deposited. Most

Fig. 9.--Environments of an alluvial plain. Modified from Fisk (1960) with terminology of Allen (1965) and Coleman (1966).


LAKE
POORLY-DRAINED SWAMP
SPLAY
WELL-DRAINED SWAMP
CREVASSE
NATURAL LEVEE
RIVER CHANNEL
LEGEND
SAND
SILT
CLAYEY SILT
LIGHT CLAY
DARK CLAY
PEAT/LIGNITE

of the deposition occurs adjacent to the river because the greatest decrease in velocity occurs there.

Allen (1970) presented a quantitative model of climbing-ripple cross-stratification. The equations that he derives are geologically significant in that it is possible to make environmental interpretations in hydraulic terms based on the various types and patterns of climbing ripples. From this article as well as McKee (1966) it appears that climbing-ripple cross-stratification is characteristic of fluvial depositional environments, especially natural levees.

The presence of vegetation on natural levees affects the primary sedimentary structures. Wavy lamination is a type of structure caused by the interference of plant roots on sediment-laden floodwaters (Coleman and others, 1964). Plant roots also tend to destroy primary structures by bioturbation.

The primary sedimentary structures of the lower Tullock Formation have been bioturbated and in most places are difficult to see. The silt beds of the lower Tullock Formation contain recognizable climbing-ripple cross-stratification at several locations (Figure 8). Bioturbation is indicated by the presence of lignitized plant roots in growth position (Figure 8). Wavy lamination results from deposition caused by the interference of plant roots and other plant material on sediment-laden floodwaters (Coleman and Gagliano, 1965, p. 146).

Most modern natural levee deposits are fine-grained; the actual grain size is dependent on the stream load and the distance from the source (Allen, 1965, p. 145). Natural levee deposits show a grain-size decrease toward the floodbasin. This would be expected as the coarser material would be deposited close to the channel where the velocity decreases are the greatest. The sediments in modern natural levees tend to be poorly sorted. It was observed that the clay content of the silt beds in the lower Tullock Formation increased toward the top of a given bed. It was not possible either in the field or in the laboratory to demonstrate a floodbasinward decrease in grain-size.

Allen (1965, p. 146) noted that interbedded within many natural levee deposits were sand lenses. Such sand lenses are very diagnostic of natural levee deposits and may actually represent crevasses cut through the levees during floods. Many of the silt beds in the lower Tullock Formation contain sand lenses (Figure 7). The lenses are thin (up to 1 foot thick) and are composed of very fine-grained sand.

It is possible that the silt beds of the lower Tullock Formation could be considered near-shore lacustrine in origin. This interpretation seems unlikely for a number of reasons. It will be demonstrated that off-shore lacustrine deposits are not present in the study area. Therefore, it is highly unlikely that near-shore deposits would be present. Fossil content of the silt beds also argues against a near-shore origin. Many of the measured sections contained silt beds with paleoroot systems in growth position (Figure 8). In addition there is a complete lack of invertebrate fossils which would be expected in lacustrine environments. Such a lack of invertebrates is a characteristic of natural levee environments (Allen, 1965, p. 145).

Depositional Environment of Clay

The clay beds of the lower Tullock Formation can be divided into two types based on color, content of organic material and the content of clay. One type of clay bed is dark, rich in organic matter, silty, and even becomes fissile at many locations. The other type of clay bed is light, contains relatively little organic material and is composed mostly of clay with minor amounts of silt. The differences between these two types of clay beds indicates that they were deposited in different environments.

In modern fluvial systems, clay is deposited in floodbasins (Figure 9). Floodbasin deposits form in shallow areas flanking natural levees. They are the finest-grained fluvial deposits and, generally, contain the highest percentage of organic material (Allen, 1965). Floodbasins may also be areas of formation of significant quantities of peat (Fisk, 1960; Allen, 1965).

A number of different sedimentary environments within the floodbasin have been recognized in modern fluvial systems. Coleman (1966) subdivided the floodbasin into two distinct environments: the poorly-drained swamp and well-drained swamp. Both of these environments of deposition were distinguished during his studies in the Mississippi River delta system.

Poorly-drained swamps possess an ineffective drainage system and, therefore, are covered by stagnant water at a fairly stable level. The deposits consist of highly organic black clay with thin, flood-introduced, laminated silt (Coleman, 1966, p. 163). Sandy, splay deposits may also extend out into the poorly-drained swamp (Figure 9). Woody peat beds are randomly distributed throughout the swamp.

The well-drained swamp environment possesses a better developed drainage system; and is exposed subaerially for much of the year, being inundated only during floods. In effect the well-drained swamp forms transitional deposits between natural levees and poorly-drained swamps.

In the lower Tullock Formation the reddish brown, silty, shaly clay beds that are rich in organic matter represent part of the poorly-drained swamp deposits. Interbedding relationships between dark clay and lignite beds are seen at numerous localities in the study section (best displayed on Plate II, between sections 72-54 and 72-28). The color, content of organic matter, and interbedding relationships with lignite provide evidence that the dark clay beds of the lower Tullock Formation were deposited in poorly-drained swamps in a fluvial flood-basin.

Well-drained swamp deposits are difficult to distinguish from natural levee deposits. Several of the silt beds become grayer upward. In addition lateral changes in color from yellow to grayish-brown are also seen. The color changes represent slight increases in the clay content and content of organic matter of the silt beds. Such deposits represent well-drained swamps.

Lakes of various sizes may form in a fluvial swamp environment. They can result from any process which leaves a low area in which water can accumulate to a depth which prohibits the growth of normal swamp vegetation. Large, inland lakes, such as Lake Pontchartrain, represent the only significant lacustrine deposits in fluvial systems (Kolb and Van Lopik, 1966, p. 47). Most of the lakes in floodbasins are very small and do not form significant deposits.

The sediments in small lakes in floodbasins are characterized by fine-grained clastic sediment (dominantly clay) and smaller amounts of organic material than are found in swamp deposits. The lake deposits are generally thin due to low sedimentation rates. Kolb and Van Lopik reported thicknesses of up to 12 feet for small lakes in southeastern Louisiana.

The light-colored clay beds in the lower Tullock Formation are interpreted as small lake deposits. They are dominantly massive clay with minor silt. The content of organic matter is much less than in the dark-colored beds. The light clay beds generally overlie lignite beds and are never interbedded with them. Grain size, content of organic matter and stratigraphic relationships with lignite indicate that the gray clay beds of the lower Tullock Formation were deposited as small lakes which formed in depressions in poorly-drained swamps. The stratigraphic relationships indicate that the lakes formed by drowning part of an existing swamp.

Both types of clay beds could be interpreted as being prodelta deposits in a large lake (the Tullock Formation is non-marine). The organic-rich clay and silt beds could be proximal prodelta deposits and the organic-rich clay beds could be distal prodelta (Rainwater, 1966, p. 5). A prodelta deposit would require distal, prodelta clay at the base; overlain by proximal, prodelta organic silt and clay; overlain by delta fringe and distributary channel sand; capped by lignite (Rainwater, 1966, p. 5). The vertical succession of beds of the lower Tullock Formation is quite different. Dark, clay beds rich in organic matter usually underlie lignite beds and light clay beds almost always overlie lignite beds. In addition sand beds in the lower Tullock Formation are always underlain by lignite beds. An origin as prodelta deposits has to be rejected for the clay deposits of the lower Tullock Formation.

Depositional Environment of Lignite

In modern fluvial-deltaic systems, peat swamps form in a number of different depositional environments. Different types of vegetation dominate a given area depending on salinity and water depth. Lagoonal and marsh peat deposits dominate the lower portions of marine delta systems (Fisk, 1960). These swamps are dominated by non-woody vegetation. In lacustrine delta woody vegetation may dominate the entire delta.

Poorly-drained swamp deposits in fluvial systems are dominated by woody vegetation (Coleman, 1966, p. 163) which is not salt tolerant and cannot survive in deep water (such as a small lake). The presence of large wood fragments within a lignite bed indicates that at least part of the bed was deposited in a fluvial environment. Petrographic study of the lignite beds would be required to determine the types of plants which formed the coal. Almost all measured sections of the lignite in the Tullock Formation contained large (up to two feet in length) wood fragments. Many of the thinner, less continuous lignite beds near the top of the study section also contained wood fragments. This evidence, plus interbedding of the lignite beds with clay beds interpreted as poorly-drained swamp deposits, support a fluvial backswamp origin for the lower Tullock Formation lignite beds.

Fisher (1968) noted the characteristics of lignite beds formed in various environments. Lagoonal lignite deposits tend to be thin, discontinuous and non-woody. Marsh lignite deposits tend to be thick (up to 30 feet thick in the Wilcox Group of Texas), blanket-like and non-woody. Fluvial lignite deposits are elongate with maximum thickness of about 7 feet and are dominated by woody vegetation. The lignite beds of the lower Tullock Formation seem to be blanket-like indicating they may have been formed in the lower part of a delta system. The lignite beds are woody perhaps because they were deposited on a delta in a lacustrine rather than a marine environment.

Depositional Environment of Sand

Considering silt beds to be natural levee deposits and the clay and lignite beds to be floodbasin deposits, then the sand beds of the lower Tullock Formation may be crevasse-splay deposits. Crevasses form during floods when the natural levees are breached and water flows out onto the floodbasin forming a fan-like splay deposit.

Splay deposits are tongue-like or fan-like deposits which are sinuous to lobate in plan (Allen, 1965, p. 122). Splay deposits could be confused with channel deposits except that they are generally thin (not usually more than a few feet thick) and are much wider than they are thick.

The grain size of splay deposits generally tends to be coarser than adjacent levee deposits. This is because a crevasse taps water much closer to the bottom of the channel than the water which carries levee material. Sediment carried near the bottom of a stream channel tends to be coarser than sediment carried near the surface. In fact, splay deposits are usually the coarsest floodbasin deposits with moderately well sorted, very fine- to medium-grained sand not uncommon (Allen, 1965, p. 48).

Primary sedimentary structures range from low angle planar cross-stratification at the base to small-scale ripple cross-stratification at the top (Allen, 1965). It is not uncommon to find plant or peat material incorporated into the splay deposits.

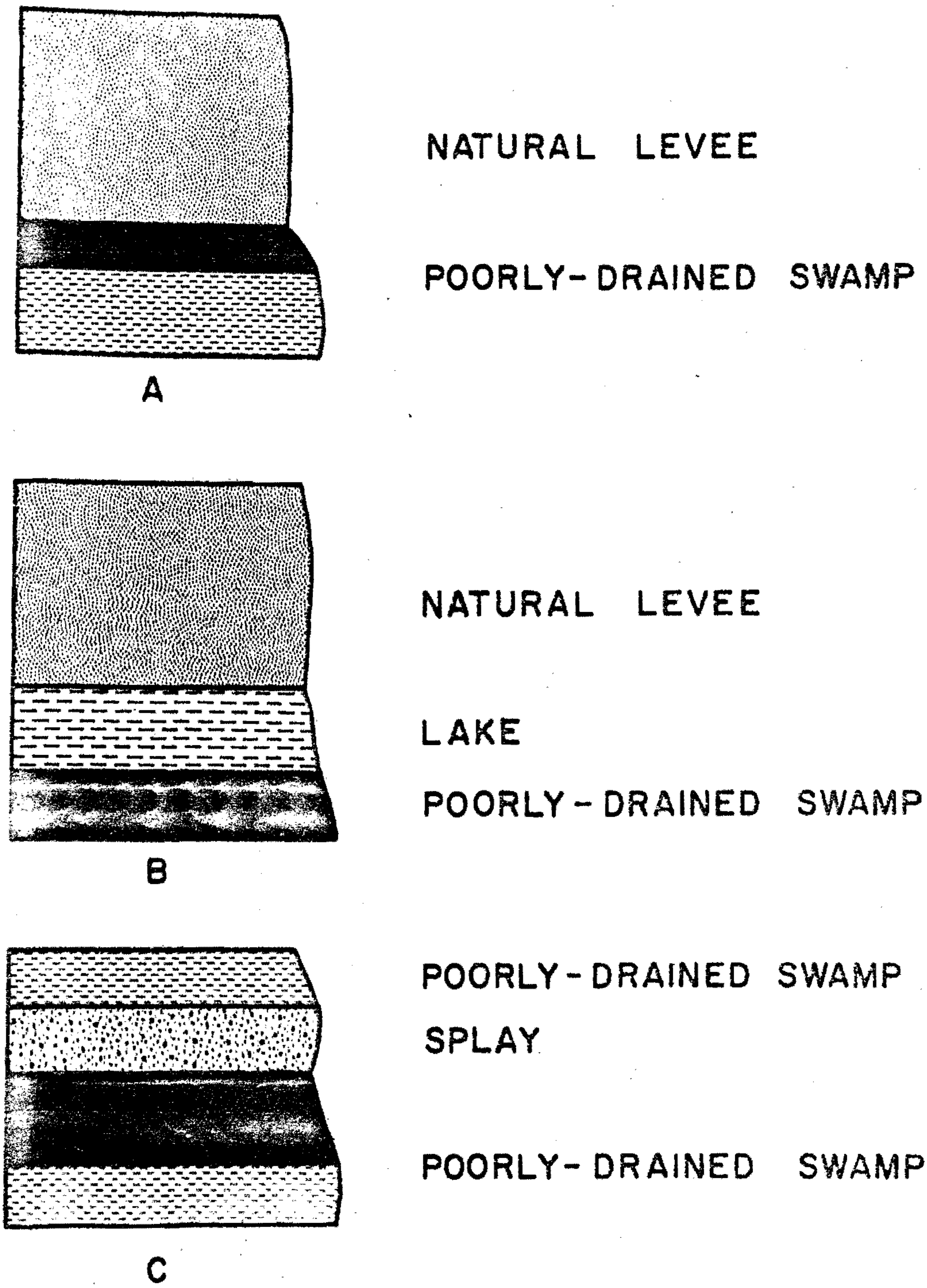
Many of the crevasse-splay deposits of the lower Tullock Formation show lateral thickness changes over short distances (less than a mile). Plate I (sections 72-50 through 72-51) shows a typical splay deposit. Near 72-50 the natural levee deposit becomes thin (3 feet) and is dominated by very fine-grained sand that is coarser than the natural levee deposits. The sand bed can be traced to section 72-51 where it is less than a foot thick. The coarsest and thickest sand bed in the lower Tullock Formation (Plate III) does not show a lateral decrease in thickness even though it crops out over a distance of 4 miles. The sand bed is medium-grained sand while the other sand beds are very fine-grained sand. This could indicate that a much larger crevasse was involved in the formation of the sand bed shown on Plate III than any other sand bed in the lower Tullock Formation.

The sand beds of the lower Tullock Formation possess other features indicating their origin as splay deposits. All of the sand beds are coarser than natural levee deposits. The thinner sand beds have scoured bases and contain small-scale ripple cross-stratification (Figures 5 and 6). Most sand beds in the lower Tullock Formation occur above lignite beds and below either lignite or dark clay indicating that the sand was rapidly dispersed into floodbasins.

Vertical Successions of Beds

Three kinds of cyclic successions of beds are present in the lower Tullock Formation (Figure 10). The succession of beds provide further evidence of a fluvial origin for the deposits of the lower

Fig. 10.--Cyclic successions of beds in the lower Tullock Formation and interpretation of depositional environments. Symbols as in Figure 9. Beds drawn to relative scale. (A) The most common common cycle. Dark, organic-rich clay overlain by lignite capped by silt and sandy silt. (B) Lignite overlain by light-colored clay with low organic content and capped by silt and sandy silt. (C) Dark, organic-rich clay; lignite; thin very fine-grained sand; and dark, organic-rich clay.


NATURAL LEVEE
POORLY-DRAINED SWAMP
A
NATURAL LEVEE
LAKE
POORLY-DRAINED SWAMP
B
POORLY-DRAINED SWAMP
SPLAY
POORLY-DRAINED SWAMP
C

Tullock Formation. In addition it can be demonstrated that lacustrine deposits are not dominant because of incorrect succession of beds.

It has already been demonstrated that the clay beds in the lower Tullock Formation cannot be prodelta deposits due to an incorrect vertical succession of beds. It may be argued that the vertical succession could indicate a lacustrine environment. The clay beds could represent offshore deposits, the lignite beds lagoonal deposits and the sand and silt beds beaches.

Most measured sections show a succession of dark, organic-rich clay beds overlain by lignite beds (Figure 10 [A] and [C]). This would indicate changing from offshore to lagoonal conditions without the presence of a barrier to create a lagoon. The dark clay beds contain much organic material. The organic material is so abundant and the plant fragments are so large (up to six inches in many cases) that it would seem unlikely that these clay beds were deposited in deep water. One would expect finely divided organic material in deep water deposits. These deposits should also be laminated. So the sand and silt beds are probably not beach deposits.

Lagoonal lignite deposits tend to be poorly developed, discontinuous and non-woody (Fisher, 1968). The lower Tullock Formation lignites are remarkably continuous and contain large wood fragments. This is indicative of fluvial/deltaic lignites (Fisher, 1968). A lacustrine origin for the clay and lignite beds of the lower Tullock Formation has to be rejected.

The vertical successions of beds does support fluvial environments of deposition. The most common vertical succession (Figure 10

[A]) is composed of dark, organic-rich clay beds at the base that represent well-drained swamps. They are overlain by lignite beds that were deposited in poorly-drained swamps, which, in turn, are capped by silt beds that were deposited as a natural levee.

A variation of the above succession occurs when a depression allowed water to attain a depth great enough to drown the swamp vegetation and form a small lake deposit that consists of light clay with relatively little organic material (Figure 10 [B]).

A third succession (Figure 10 [C]) was deposited entirely within a floodbasin. The well- and poorly-drained swamp is as above (Figure 10 [A]) with a very fine-grained sand bed overlying the lignite bed. The sand bed was deposited as a splay deposit. The sand bed is overlain by dark, organic-rich clay as swamp conditions resumed.

APPENDIX A

MEASURED SECTIONS OF THE LOWER PART OF THE TULLOCK FORMATION

This appendix lists all measured sections used in this study. Figure 2 shows their locations. Field numbers are used throughout the report. Missing numbers represent unused sections.

All sections were measured to the nearest quarter of a foot. All colors are for unweathered exposures. Weathered exposures are generally lighter than unweathered ones, especially in the light yellowish brown silt beds.

Sections are listed in ascending stratigraphic order from low to high unit numbers.

Section 71-02

NW¼sec.15, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

UNIT	FEET
5. Lignite, black; overlain by bentonite, dark gray, organic-rich, silty	0.75
4. Bentonite, dark gray to black, organic-rich	1.50
3. Lignite, black	1.00
2. Sand, dark to light gray, very fine containing organic material and limonite concretions	3.50
1. Bentonite, black, organic-rich and lignite, black to brown	1.75
Total Thickness . .	8.50

Section 71-05

SW¼NE¼sec.26, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

5. Silt, gray, organic-rich, bentonitic	1.00
4. Shale, dark brown, lignitic	1.00
3. Silt, dark gray, organic-rich, bentonitic	1.25
2. Silt, light yellowish brown, to light brownish gray and sand, very fine containing concretionary zones	10.75
1. Bentonite, black and lignite, black to dark brown	2.25
Total Thickness . .	16.25

UNIT	FEET

Section 71-06

NE¼sec.27, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

3. Shale, dark brown to black, lignitic	0.50
2. Silt to silty bentonite, dark gray to brown containing concretion zones and organic material	12.75
1. Bentonite, black, shaly; lignite, dark brown to black; and silt, dark reddish brown	2.75
Total Thickness . .	16.00

Section 71-08

SW¼sec.14, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

3. Bentonite, dark reddish brown, shaly, organic-rich, silty and lignite, black	1.25
2. Silt, light yellowish brown containing small limonite concretions and organic material becoming more bentonitic and darker in color toward the top	10.75
1. Bentonite, dark brownish gray to black; lignite, dark brown to black; and silt, reddish brown	2.25
Total Thickness . .	14.25

Section 71-09

NE¼sec.23, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

3. Bentonite, dark reddish brown, shaly, organic-rich, silty and lignite, black	1.25
2. Silt, light yellowish brown containing small limonite concretions and organic material, becoming more bentonitic and darker in color toward the top	10.75
1. Bentonite, dark brownish gray to black; lignite, dark brown to black; and silt, reddish brown	2.25
Total Thickness . .	14.25

Section 71-10

.23, T.134N., R.106W., Slope County, North Dakota
.ower Part of the Tullock Formation

UNIT	FEET
ntonite, dark brown to dark gray, shaly, silty; .t, dark reddish brown; and bentonite, reddish own, shaly, organic-rich, silty	2.25
ntonite, reddish brown, shaly, organic-rich, .ty and lignite, dark brown to black	2.50
nd, light gray very fine containing concretions l some organic material	1.00
ntonite, black to dark brown, shale, dark brown gnitic and lignite, dark brown to black	2.75
Total Thickness . .	8.50

Section 71-11

13, T.134N., R.106W., Slope County, North Dakota
.ower Part of the Tullock Formation

.tonite, reddish brown, shaly, organic-rich, .ty and lignite, black	0.75
t, reddish brown to bentonitic silt containing .onite concretions	4.75
.tonite, dark brownish gray, organic-rich and nite, black	2.00
d, yellowish gray very fine and silt, sandy taining concretions and organic material, omes a silt to bentonitic silt near the top	9.25
le, dark brown lignitic, lignite, black, silt, reddish brown	1.75
Total Thickness . .	18.50

UNIT	FEET
Section 71-12	
ec.8, T.134N., R.106W., Slope County, North Dakota Lower Part of the Tullock Formation	
Shale, dark brown, lignitic and lignite, black	0.75
Bentonite, gray, organic-rich, silty	2.25
Bentonite, reddish brown, shaly, organic-rich, silty and lignite, black	2.50
Sand, gray, very fine and silt, sandy containing concretions and organic material	1.50
Bentonite, reddish brown, organic-rich, and lignite, black	0.50
Total Thickness . .	7.50

UNIT	FEET
Section 71-15	
c.28, T.133N., R.105W., Slope County, North Dakota Lower Part of the Tullock Formation	
Lignite, black	0.25
Silt, reddish brown to yellowish brown; sand, buff, organic-rich, very fine to fine; and bentonite, light gray, silty	16.75
Bentonite, black; lignite, black; and bentonite, reddish brown, shaly, organic-rich, silty	3.00
Total Thickness . .	20.00

UNIT	FEET
Section 71-21	
N½sec.23, T.135N., R.106W., Slope County, North Dakota Lower Part of the Tullock Formation	
3. Lignite, black to dark brown, and bentonite, dark gray and reddish brown, shaly, organic-rich, silty	2.25
2. Silt, gray containing limonite concretions and organic material	2.25
1. Lignite, black	1.25
Total Thickness . .	5.75
Section 71-21	
SW¼sec.3, T.133N., R.105W., Slope County, North Dakota Lower Part of the Tullock Formation	
3. Bentonite, light gray to reddish brown, shaly, organic-rich, silty and lignite, black	2.50
2. Sand, gray, medium containing organic material	3.00
1. Lignite, black very thin ("smut line") and bentonite, dark gray, silty	0.25
Total Thickness . .	5.75
Section 71-22	
S½sec.10, T.133N., R.105W., Slope County, North Dakota Lower Part of the Tullock Formation	
3. Bentonite, reddish brown, shaly, organic-rich, silty . . .	2.00
2. Sand, gray, medium containing organic material	4.50
1. Lignite, black, very thin ("smut line") and bentonite, light grayish brown, organic-rich, silty	0.50
Total Thickness . .	7.00

UNIT	FEET

Section 71-23

SW¼sec.15, T.133N., R.105W., Slope County, North Dakota
Lower Part of the Tullock Formation

4. Bentonite, reddish brown, shaly, organic-rich, silty and lignite, black	1.75
3. Sand, gray, medium containing organic material and limonite concretions	4.50
2. Silt, light brown containing some organic material	1.50
1. Lignite, black	0.50
Total Thickness . .	8.25

Section 71-24

W½sec.8, T.133N., R.105W., Slope County, North Dakota
Lower Part of the Tullock Formation

3. Bentonite, dark gray, shaly, organic-rich, silty; lignite, dark brown to black; and silt, reddish brown, organic-rich	4.50
2. Silt, light yellowish brown containing limonite concretions and organic material, grades into a bentonite, gray, silty near the top	18.00
1. Bentonite, reddish brown to black, shaly, organic-rich . .	1.00
Total Thickness . .	23.50

Section 71-25

W½sec.23, T.133N., R.105W., Slope County, North Dakota
Lower Part of the Tullock Formation

4. Lignite, black	0.50
3. Sand, light gray, medium containing limonite concretions .	5.25
2. Silt, medium gray and silt, bentonitic containing organic material	1.25
1. Bentonite, black and lignite, black	1.25
Total Thickness . .	8.25

UNIT	FEET
Section 71-27	
SE¼sec.36, T.135N., R.106W., Slope County, North Dakota Lower Part of the Tullock Formation	
3. Lignite, black to dark brown interbedded with bentonite, reddish brown, shaly, organic-rich, silty . . .	3.25
2. Silt, light yellowish brown to gray and silt, sandy containing organic material and a concretion zone near the base	15.00
1. Bentonite, dark gray to reddish brown, organic-rich and lignite, black	3.00
Total Thickness . .	21.25
Section 72-05	
E½sec.15, T.133N., R.105W., Slope County, North Dakota Lower Part of the Tullock Formation	
4. Lignite, black with a thin bentonite, reddish brown, shaly, organic-rich, silt at the base	1.75
3. Sand, grayish brown, fine	5.50
2. Silt, grayish brown, sandy with a thin lignite bed, black at the base	2.00
1. Sand, light gray, medium containing concretions, small-scale ripple cross-stratification, and lignitized organic material	5.50
Total Thickness . .	14.75
Section 72-06	
N½sec.23, T.133N., R.105W., Slope County, North Dakota Lower Part of the Tullock Formation	
5. Bentonite, reddish brown, shaly, organic-rich, silty containing thin, black lignite zones	0.50
4. Silt, grayish brown, sandy containing ripple cross-stratification and lignitized plant material	3.00
3. Silt, light brownish gray containing small concretions and lignitized plant material	2.50

UNIT	FEET
2. Silt, light gray, bentonite	1.50
1. Lignite, black	1.00
Total Thickness . .	8.50

Section 72-07

N½sec.24, T.133N., R.105W., Slope County, North Dakota
Lower Part of the Tullock Formation

5. Lignite, black	0.50
4. Silt, light brownish gray containing ripple cross-stratification	2.00
3. Lignite, black	0.50
2. Bentonite, light gray, organic-rich silty grading upward into a bentonite, reddish brown, organic-rich, silty	9.50
1. Bentonite, light to dark gray, shaly, silty containing organic material	2.00
Total Thickness . .	14.50

Section 72-08

N½sec.22, T.133N., R.105W., Slope County, North Dakota
Lower Part of the Tullock Formation

4. Bentonite, reddish brown to black, organic-rich, silty .	0.50
3. Sand, light brownish gray, fine, containing organic material	6.50
2. Bentonite, dark gray, silty	2.50
1. Lignite, black	1.00
Total Thickness . .	10.00

UNIT	FEET

Section 72-09

S½sec.10, T.133N., R.105W., Slope County, North Dakota
Lower Part of the Tullock Formation

4. Lignite, black	1.00
3. Bentonite, reddish brown, organic-rich, shaly, silty . . .	1.25
2. Sand, light brown, very fine containing lignitic zones and small concretions	5.50
1. Bentonite, gray, silty with a very thin lignite, black at the base	0.50
Total Thickness . .	8.25

Section 72-10

N½sec.10, T.133N., R.105W., Slope County, North Dakota
Lower Part of the Tullock Formation

2. Lignite, black containing a thin bentonite, reddish brown near base	1.00
1. Sand, light brown, medium containing lignitized organic material. Base is marked by a thin lignite ("smut line")	9.00
Total Thickness . .	10.00

Section 72-11

S½sec.4, T.133N., R.105W., Slope County, North Dakota
Lower Part of the Tullock Formation

4. Bentonite, reddish brown, organic-rich, shaly, silty . . .	0.50
3. Lignite, black	1.00
2. Sand, light brown, medium containing lignitized organic material in upper part	8.50
1. Bentonite, medium gray, silty with a thin lignite ("smut line") at base	1.00
Total Thickness . .	11.00

UNIT	FEET

Section 72-12

N½sec.4, T.133N., R.105W., Slope County, North Dakota
Lower Part of the Tullock Formation

4. Bentonite, reddish brown, shaly, silty and lignite, black, shaly	2.00
3. Bentonite, light brownish gray, silty containing organic material	1.50
2. Sand, light gray containing thin organic-rich shaly zones and ripple cross-stratification	9.00
1. Bentonite, light gray, silty to bentonite with a thin lignite ("smut line") at base	2.50
Total Thickness . . .	15.00

Section 72-13

E½sec.21, T.133N., R.105W., Slope County, North Dakota
Lower Part of the Tullock Formation

3. Bentonite, reddish brown, silty with a thin lignite, shaly	1.50
2. Sand, light brownish gray, fine containing small limonite concretions	10.00
1. Lignite, black, woody	0.75
Total Thickness . .	12.25

Section 72-14

W½sec.21, T.133N., R.105W., Slope County, North Dakota
Lower Part of the Tullock Formation

4. Bentonite, reddish brown, organic-rich, shaly, silty with a thin lignite, black at top	2.00
3. Sand, light brown, fine containing a zone of large concretions near base and small, limonite concretions throughout	7.50
2. Bentonite, brown, silty	2.00
1. Lignite, black, woody	1.00
Total Thickness . .	11.50

UNIT	FEET
Section 72-15	
$N\frac{1}{2}$sec.9, T.134N., R.106W., Slope County, North Dakota Lower Part of the Tullock Formation	
4. Silt, light brown grading upward into bentonite, reddish brown, shaly, organic-rich, silty with a thin lignite at top	3.00
3. Lignite, black	1.00
2. Sand, yellowish brown, very fine containing small concretions and organic material	4.00
1. Bentonite, reddish brown, shaly, organic-rich, silty, thin, overlain by a lignite, black	3.00
Total Thickness	11.00
Section 72-17	
sec.24, T.134N., R.106W., Slope County, North Dakota Lower Part of the Tullock Formation	
3. Bentonite, reddish brown, shaly, organic-rich, silty with thin, interbedded lignite beds	3.00
2. Silt, light brownish yellow ("yellow bed") containing concretions near top (Figure 10)	8.00
1. Lignite, black, woody	2.00
Total Thickness	13.00
Section 72-18	
$S\frac{1}{2}$sec.13, T.134N., R.106W., Slope County, North Dakota Lower Part of the Tullock Formation	
3. Bentonite, reddish brown, shaly, organic-rich, silty, interbedded with lignite, thin, black	1.75
2. Silt, light yellowish brown, sandy grading upward into silt, gray; bentonite, silty and bentonite, organic-rich. Silt contains small concretions	14.50
1. Lignite, black, woody	2.00
Total Thickness	19.25

UNIT	FEET
Section 72-19	
N½sec.13, T.134N., R.106W., Slope County, North Dakota Lower Part of the Tullock Formation	
3. Bentonite, reddish brown, shaly, organic-rich, silty, interbedded with thin black lignite beds	1.50
2. Bentonite, light gray, silty becomes darker toward top . .	6.00
1. Lignite, black, woody	2.00
Total Thickness . . .	9.50
Section 72-20	
NW¼sec.10, T.134N., R.106W., Slope County, North Dakota Lower Part of the Tullock Formation	
3. Bentonite, reddish brown, shaly, organic-rich, silty grading into a lignite, black, shaly and a lignite, black .	2.00
2. Sand, light brown, fine containing organic material, thin lignitic layers and small limonite concretions	11.25
1. Lignite, black, shaly	0.50
Total Thickness . . .	13.75
Section 72-21	
E½sec.35, T.134N., R.106W., Slope County, North Dakota Lower Part of the Tullock Formation	
3. Bentonite, reddish brown, shaly, organic-rich, silty, overlain by a lignite, black, thin	2.25
2. Silt, light yellowish brown to gray, sandy ("yellow bed") containing limonite concretions and laminae or organic material	10.50
1. Lignite, black overlain by a shale, dark gray to black, lignitic	2.50
Total Thickness . . .	15.25

UNIT	FEET

Section 72-22

½sec.35, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

. Bentonite, reddish brown, shaly, organic-rich, silty with interbedded lignitic material	2.50
. Silt, yellowish brown becoming grayer and more bentonitic near the top	10.00
. Lignite, black	2.50
Total Thickness . .	15.00

Section 72-23

½sec.10, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

. Lignite, black	1.00
. Silt, brown to yellowish brown containing thin, lignitized zones and limonite concretions, grades upward into a bentonite, dark gray, silty, organic-rich	11.50
Lignite, black	0.50
Total Thickness . .	13.00

Section 72-24

sec.6, T.134N., R.105W., Slope County, North Dakota
Lower Part of the Tullock Formation

Bentonite, reddish brown to black, shaly, organic-rich, silty with a thin lignite at top	11.00
Total Thickness . .	11.00

Section 72-25

sec.6, T.134N., R.105W., Slope County, North Dakota
Lower Part of the Tullock Formation

Bentonite, reddish brown, shaly, organic-rich, silty with thin, interbedded lignites	2.25
Bentonite, reddish brown, silty	1.50

UNIT	FEET
Silt, gray, sandy, containing limonite concretions and organic material	10.50
Bentonite, reddish brown to black, shaly, organic-rich, silty containing lignitized woody material	5.00
Total Thickness . .	19.25

Section 72-26

sec.31, T.135N., R.105W., Slope County, North Dakota
Lower Part of the Tullock Formation

Bentonite, reddish brown, shaly, organic-rich, silty with a thin lignite, black at top	3.00
Bentonite, reddish brown, silty	2.00
Sand, grayish brown, silty, very fine containing limonite concretions and organic material	10.00
Lignite, black overlain by bentonite, reddish brown, shaly, organic-rich, silty	3.00
Total Thickness . .	18.00

Section 72-27

sec.31, T.135N., R.105W., Slope County, North Dakota
Lower Part of the Tullock Formation

Lignite, black	1.50
Bentonite, reddish brown, silty grading upward into a bentonite, dark gray, shaly, organic-rich, silty	4.50
Silt, light gray to bentonite, silty containing concretions and thin sandy zones	7.00
Bentonite, reddish brown to dark gray, shaly, organic-rich, silty with a thin lignite bed at top	4.50
Total Thickness . .	17.50

UNIT — FEET

Section 72-28

SE¼sec.26, T.135N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

1. Lignite, black to reddish brown and shale, lignitic. "Scoria" occurs lateral to this section 5.25

Total Thickness . . 5.25

Section 72-29

N½sec.25, T.135N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

1. Lignite, black. Laterally a "scoria" 5.50

Total Thickness . . 5.50

Section 72-30

N½SW¼sec.3, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

1. Lignite, black interbedded with shale, lignitic 9.00

Total Thickness . . 9.00

Section 72-31

SW¼SW¼sec.3, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

1. Bentonite, reddish brown to black, shaly, organic-rich, silty with thin interbedded lignite, black 9.00

Total Thickness . . 9.00

Section 72-32

N½sec.3, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

3. Bentonite, reddish brown, shaly, organic-rich, silty and lignite, black grading upward into a bentonite, dark gray, organic-rich with a thin lignite at top 4.00

2. Sand, light gray, fine containing thin concretionary lenses and thin layers of organic material 13.00

UNIT	FEET
Lignite, black with bentonite, reddish brown, thin, shaly, silty in middle	1.75
Silt, light gray, sandy containing an extensive paleo-root system	3.00
Lignite, black, woody	4.00
Total Thickness . .	11.75

Section 72-37

sec.14, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

Lignite, black	0.50
Sand, white, fine containing numerous, small limonite concretions (Figure 5)	3.00
Lignite, black, woody, becomes a scoria laterally	4.00
Total Thickness . .	7.50

Section 72-38

sec.15, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

Bentonite, reddish brown, shaly, silty with thin lignite, black at top	2.00
Sand, light gray, fine containing small limonite concretions	4.00
Bentonite, thin, reddish brown, shaly, silty at base with lignite, black above	3.00
Total Thickness . .	9.00

Section 72-39

sec.8, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

Bentonite, reddish brown, shaly, organic-rich, silty with thin lignite, black at top	1.50
Sand, light to medium brown, fine grading upward into silt	7.00

UNIT	FEET
1. Bentonite, reddish brown, shaly, organic-rich, silty with lignite, black, woody at top	1.50
Total Thickness . . .	10.00

Section 72-40

S½sec.14, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

3. Lignite, black	1.25
2. Sand, gray, fine and silt	0.75
1. Shale, black, lignitic grading into lignite, black	3.00
Total Thickness . . .	5.00

Section 72-41

S½sec.14, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

5. Bentonite, reddish brown, shaly, organic-rich, silty . . .	0.50
4. Bentonite, gray, silty	2.00
3. Bentonite, reddish brown, shaly, organic-rich, silty with thin lignite, black at top	2.75
2. Silt, light gray	1.00
1. Lignite, black	2.00
Total Thickness . . .	8.25

Section 72-42

N½sec.14, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

3. Shale, reddish brown to black, lignitic	2.00
2. Silt, light brownish yellow ("yellow bed" containing accretions	10.00
1. Bentonite, reddish brown, shaly, organic-rich, silty with a lignite, black at top	2.00
Total Thickness . . .	14.00

UNIT	FEET
Section 72-43	
NE¼sec.16, T.134N., R.106W., Slope County, North Dakota Lower Part of the Tullock Formation	
5. Lignite, black	2.00
4. Silt, brown containing small cretions	1.00
3. Lignite, black	1.50
2. Bentonite, reddish brown, shaly, organic-rich, silty . . .	3.00
1. Shale, black, lignitic and lignite, black	2.00
Total Thickness . .	9.50
Section 72-44	
NE¼sec.16, T.134N., R.106W., Slope County, North Dakota Lower Part of the Tullock Formation	
3. Lignite, black with thin shale, reddish brown in middle .	2.00
2. Silt, light reddish brown, sandy containing concretions and organic material	7.25
1. Lignite, black	1.00
Total Thickness . .	10.25
Section 72-48	
SW¼sec.13, T.134N., R.106W., Slope County, North Dakota Lower Part of the Tullock Formation	
3. Lignite, black	1.00
2. Silt, light yellowish brown, sandy containing small-scale cross-stratification and concretions	11.75
1. Lignite, black, woody	2.00
Total Thickness . .	14.75

UNIT	FEET

Section 72-49

SW¼sec.13, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

4. Lignite, black	1.25
3. Bentonite, reddish brown, shaly, organic-rich, silty . . .	3.00
2. Silt, light yellowish brown, sandy containing concretions	3.25
1. Lignite, black	1.50
Total Thickness . .	9.00

Section 72-50 (Figures 3 and 4)

NW¼sec.13, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

4. Lignite, black	0.50
3. Bentonite, reddish brown, shaly, organic-rich, silty . . .	2.50
2. Silt, light yellowish brown, sandy to sand, very fine containing small-scale cross-stratification and small limonite concretions	3.00
1. Lignite, black	1.00
Total Thickness . .	7.00

Section 72-51

NE¼sec.14, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

3. Bentonite, reddish brown, shaly, organic-rich, silty with lignite, black at top	1.75
2. Sand, light yellowish brown, very fine to silt, sandy containing small concretions (Figure 6)	0.50
1. Lignite, black	3.00
Total Thickness . .	5.25

UNIT	FEET

Section 72-52

NE¼sec.33, T.135N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

1. Shale, black, lignitic grading upward into bentonite gray, organic-rich, silty	5.50
Total Thickness . . .	5.50

Section 72-53

SE¼sec.28, T.135N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

1. Shale, black, lignitic grading upward into bentonite, gray, organic-rich, silty	5.75
Total Thickness . . .	5.75

Section 72-54

NW¼sec.28, T.135N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

1. Shale, black, lignitic grading upward into bentonite, gray, shaly, organic-rich, silty	5.75
Total Thickness . . .	5.75

Section 72-55

SW¼sec.14, T.134N., R.106W., Slope County, North Dakota
Lower Part of the Tullock Formation

3. Lignite, black and bentonite, reddish brown, shaly, organic-rich, silty	1.50
2. Sand, light yellowish brown, fine and silt, sandy ("yellow bed") containing concretions (Figure 7)	9.00
1. Lignite, black	1.50
Total Thickness . . .	12.00

REFERENCES CITED

REFERENCES CITED

Allen, J. R. L., 1963, The classification of cross-stratified units with notes on their origin: Sedimentology, v. 2, p. 93-114.

Allen, J. R. L., 1965, A review of the origin and characteristics of recent alluvial sediments: Sedimentology,v. 5, p. 89-191.

Allen, J. R. L., 1970, A quantitative model of climbing ripples and their cross-laminated deposits: Sedimentology, v. 14, p. 5-26.

Brown, B., 1907, The Hell Creek beds of the Upper Cretaceous of Montana; their relation to contiguous deposits with faunal and floral lists, and a discussion of their correlation: Am. Musc. Nat. History Bull., v. 23, p. 823-845.

Brown, R. W., 1962, Paleocene flora of the Rocky Mountains and Great Plains: U. S. Geol. Survey, Prof. Paper 375, 119 p.

Calvert, W. R., 1912, Geology of certain lignite fields in eastern Montana: U. S. Geol. Survey Bull. 471, p. 187-201.

Coleman, J. M., 1966, Ecological changes in a massive freshwater clay sequence: Trans. Gulf Coast Assoc. Geol. Soc., v. 16, p. 159-174.

Coleman, J. M., 1969, Brahmaputra River: Channel processes and sedimentation: Sedimentary Geol., v. 3, p. 129-239.

Coleman, J. M. and Gagliano, S. M., 1965, Sedimentary structures-Mississippi River deltaic plain, in Middleton, G. M., (ed.), Primary sedimentary structures and their hydrodynamic interpretation: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 12, p. 133-148.

Coleman, J. M., Gagliano, S. M., and Webb, J. E., 1964, Minor sedimentary structures in a prograding distributary: Marine Geology, v. 1, no. 3, p. 240-258.

Dorf, E., 1940, Relationship between floras the the type Lance and Fort Union Formations: Geol. Soc. America Bull., v. 51, p. 213-236.

Dorf, E., 1942, Upper Cretaceous floras of the Rocky Mountain region: Carnegie Inst. Wash. Pub. 508, 168 p.

Felix, D. W., 1969, An inexpensive recording settling tube for analysis of sands: Jour. Sed. Petrology, v. 39, p. 777-780.

Fisher, W. L., 1968, Variations in lignites of fluvial, deltaic, and lagoonal systems, Wilcox Group (Eocene), Texas: Geol. Soc. America Annual Meeting, Mexico City, 1968, text of talk, 10 p.

Fisk, H. N., 1960, Recent Mississippi River sedimentation and peat accumulation: Congres pour l'Avancement des Etudes de Stratigraphie et de Geologie du Carbonifere, 4th, Heerlen, 1958, Compte rendu, Maastricht, Netherlands, p. 187-199.

Frye, C. I., 1967, The Hell Creek Formation in North Dakota: Unpublished Ph.D. Dissertation, Univ. of North Dakota, 411 p.

Frye, C. I., 1969, Stratigraphy of the Hell Creek Formation in North Dakota: North Dakota Geol. Survey, Bull. 54, 65 p.

Jacob, A. F., 1972, Depositional environments of parts of the Tongue River Formation, western North Dakota, in F. T. C. Ting (ed.), Depositional environments of the lignite-bearing strata in western North Dakota: North Dakota Geol. Survey Misc. Series no. 50, p. 43-62.

King, C., 1876, Annual report upon the geological exploration of the fortieth parallel from the Sierra Nevada to the eastern slope of the Rocky Mountains: U.S. 44th Cong. 2d sess., H. Exec. Doc. 1, pt. 2, v. 2, pt. 3, App. 2, p. 217-218.

Kolb, C. R., and Von Lopik, J. R., 1966, Depositional environments of the Mississippi River deltaic plain-southern Louisiana, in M. L. Shirley (ed.), Deltas in their geologic framework: Houston Geol. Society, p. 17-61.

McKee, E. D., 1966, Significance of climbing-ripple structure: U.S. Geol. Survey, Prof. Paper 550-D, p. 94-103.

Meek, F. B., and Hayden, F. V., 1862, Descriptions of new lower Silurian (Primordial), Jurassic, Cretaceous, and Tertiary fossils collected in Nebraska . . ., with some remarks on the rocks from which they were obtained: Philadelphia Acad. Nat. Sci. Proc., 1861, v. 13, p. 415-435.

Rainwater, E. H., 1966, Geological importance of deltas, in M. L. Shirley (ed.), Deltas in their geologic framework: Houston Geological Society, p. 1-15.

Rogers, G. S. and Lee, Wallace, 1923, Geology of the Tullock Creek Coal Field: U.S. Geol. Survey, Bull. 749, 181 p.

Simpson, G. G., 1937, The Fort Union of the Crazy Mountain field, Montana and its Mammalian Faunas: U.S. National Museum Bull. 169, 287 p.

Stanton, T. W., 1910, Fox Hills sandstone and Lance formation ("Ceratops Beds") in South Dakota, North Dakota, and eastern Wyoming: Am. Jour. Sci., 4th serv., v. 30, p. 172-188.

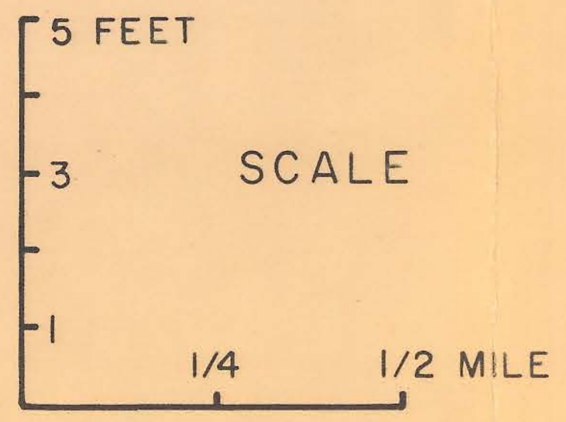
Stone, R. W., and Calvert, W. R., 1910, Stratigraphic relations of the Livingston Formation of Montana: Economic Geology, v. 5, p. 741-764.

Welder, F. A., 1959, Processes of deltaic sedimentation in the lower Mississippi River: Louisiana State Univ., Coastal Studies Inst. Tech. Rept. 12, 90 p.

Wilmarth, M. G., 1938, Lexicon of geologic names of the United States: U.S. Geol. Survey, Bull. 896, 2396 p.

PLATE I CROSS SECTION OF THE LOWER TULLOCK FORMATION IN SOUTHERN PART OF STUDY AREA, SLOPE COUNTY, NORTH DAKOTA

PLATE II CROSS SECTION OF THE LOWER TULLOCK FORMATION IN NORTHERN PART OF STUDY AREA, SLOPE COUNTY, NORTH DAKOTA



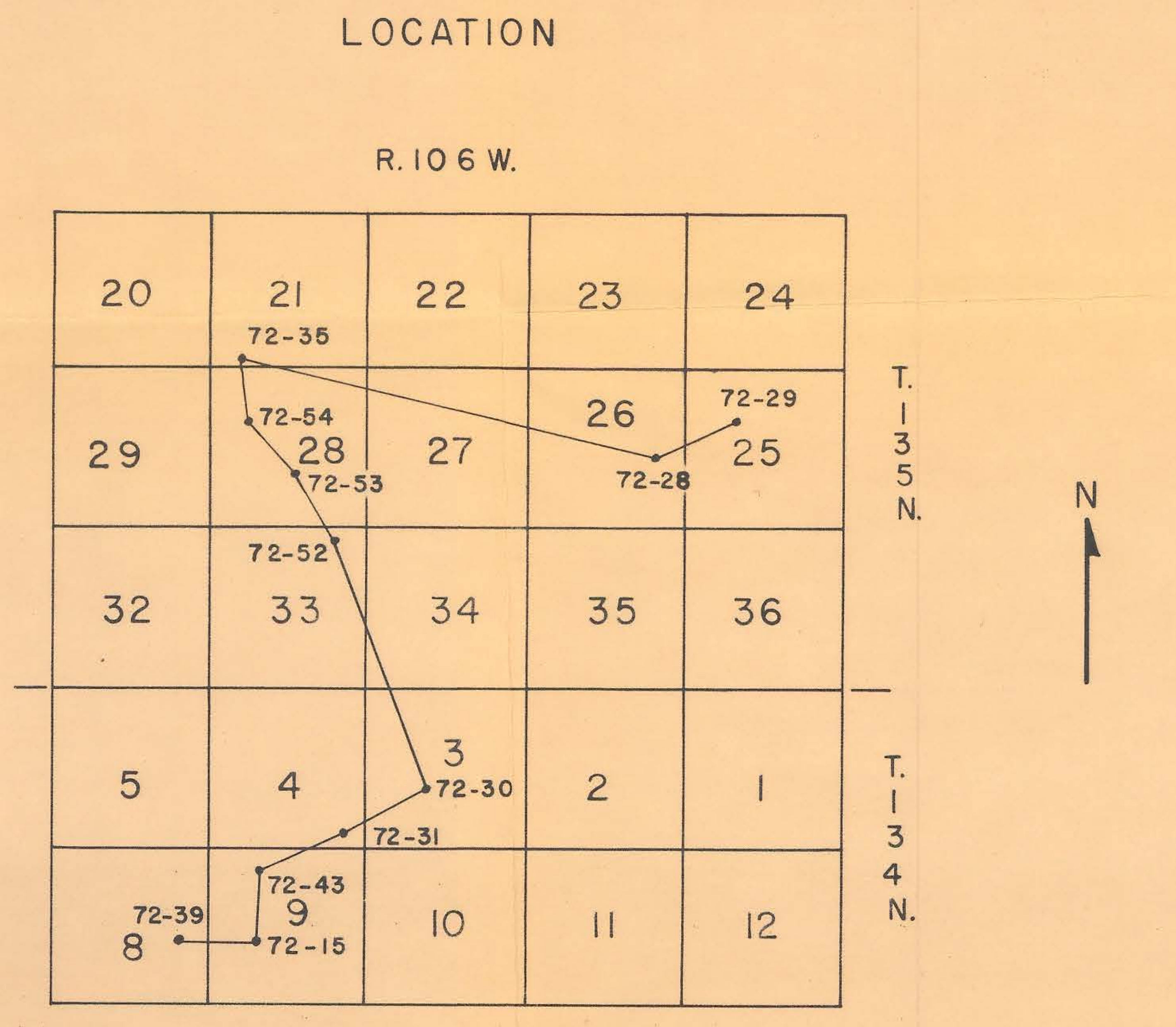


PLATE III CROSS SECTION OF THE LOWER TULLOCK FORMATION IN EASTERN PART OF STUDY AREA, SLOPE COUNTY, NORTH DAKOTA