GEOLOGY OF THE UPPER PART OF THE FORT UNION GROUP (PALEOCENE), WILLISTON BASIN, WITH REFERENCE TO URANIUM

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REPORT OF INVESTIGATION NO. 58

NORTH DAKOTA GEOLOGICAL SURVEY

E. A. Noble, State Geologist

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PREPARED FOR THE U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
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ABSTRACT

Lignite-bearing, sandy, silty, and clayey formations make up the Fort Union Group in the Williston basin, the upper part of which consists of the Tongue River Formation conformably overlain by the Sentinel Butte Formation. Two types of sandstone beds are present in the Tongue River Formation, one of which is elongate in plan view, trough shaped, and as much as about 300 m wide and 20 m thick. This type, which is most common, was deposited in low-sinuosity, non-braided channels typical of the seaward part of a high-constructive delta. The second type of sandstone bed in the Tongue River is elongate in map view (probably), tabular, in most cases about 3 m thick, and as much as several hundred metres wide. This type was deposited as lateral-accretion, point-bar deposits in high-sinuosity streams. Siltstone, claystone, lignite, and a small amount of limestone were deposited on natural levees, crevasse splays, and in flood basins between the distributaries.

Tabular sandstone beds in the Sentinel Butte Formation are thicker (as much as 30 m thick), more laterally extensive (more than 2 km wide in many places), and more abundant than in the Tongue River Formation. This indicates that high-sinuosity streams were more abundant where the Sentinel Butte Formation was deposited, and the streams were deeper and occupied wider meander belts, as would be found on the landward part of the delta plain. Siltstone, claystone, lignite, and a small amount of limestone were deposited on natural levees, crevasse splays, and in flood basins. The vertical arrangement of the two formations (deposits of the landward part of the delta plain—the Sentinel Butte—over deposits of the seaward part—the Tongue River) indicates a progradation of a large deltaic complex into the sea in which the Cannonball Formation was deposited.

Sandstone in the Tongue River Formation classifies mostly as carbonate litharenite, and the fine fraction of the formation consists mostly of mica-group minerals, some kaolinite-group minerals, and a little montmorillonite. Sandstone in the Sentinel Butte Formation classifies mostly as volcanic litharenite, and the fine fraction consists mostly of montmorillonite, some kaolinite-group minerals, and a little of the mica-group minerals.

The highest-grade uranium deposits in North Dakota are in the Sentinel Butte Formation in the area of the Little Missouri River escarpment in eastern Billings and northwestern Stark Counties. Little uranium has been found in the Tongue River Formation. Uranium may be more abundant in the Sentinel Butte Formation because of the abundance of glassy volcanic matter, which has now been largely altered to montmorillonite, and the abundance of fragments of volcanic rock. Weathering of the upper part of the Sentinel Butte Formation during formation of the Eocene paleosol in the northern Great Plains may have mobilized uranium that was deposited in the formation below the paleosol before deposition of the overlying Oligocene and younger sediment. The volcanic debris in the Oligocene, Miocene, and Pliocene formations may have contributed uranium to the deposits.

Other Cretaceous and Paleocene formations that appear to contain significant amounts of volcanic matter, such as the Hell Creek and Ludlow Formations, may contain important uranium deposits that formed probably at the time that the Eocene paleosol developed, or later by derivation from the volcanic matter in the Oligocene, Miocene, and Pliocene formations, or both.

INTRODUCTION

Lignite-bearing, sandy, silty, and clayey formations make up the Fort Union Group in the Williston basin in western North Dakota, western South Dakota, and eastern Montana (figs. 1 and 2). This report is a summary of stratigraphy of the upper part of the Fort Union Group, the Tongue

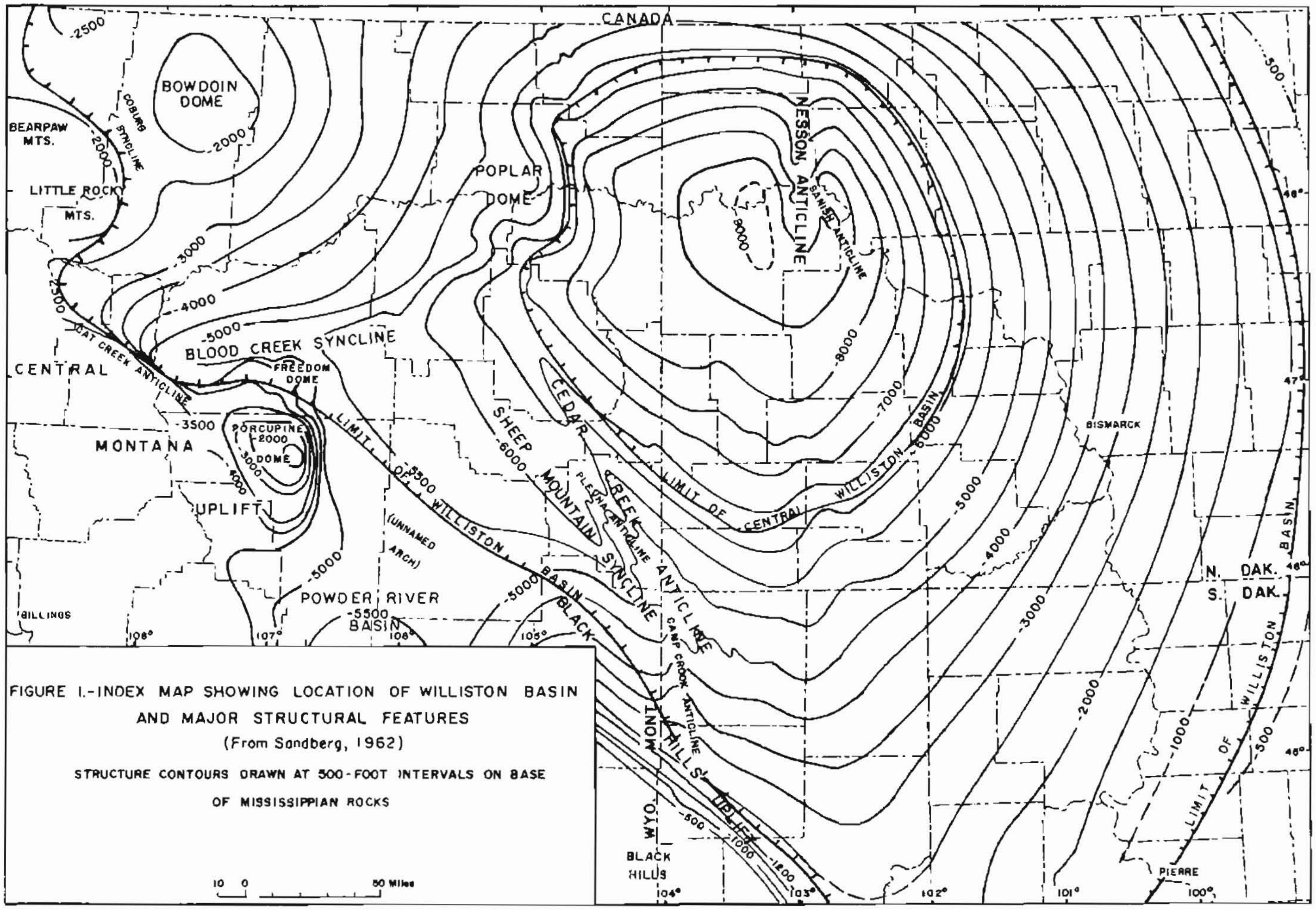

Figure 1. Index map of the Williston basin (from Sandberg, 1962).

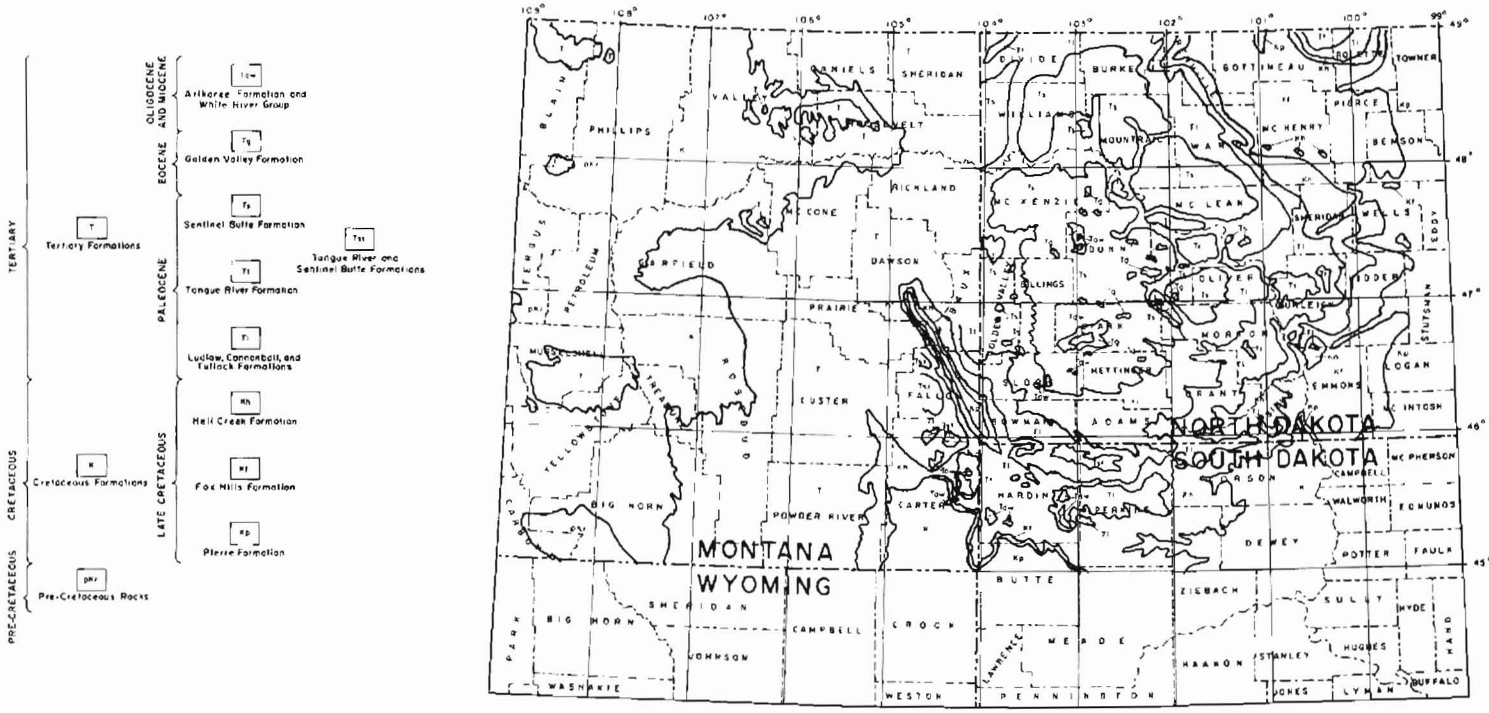

Figure 2. Geologic map of the Williston basin and adjacent areas. Compiled from Carlson (1969), Denson and Gill (1956, fig. 140), and King and Beikman (1974).

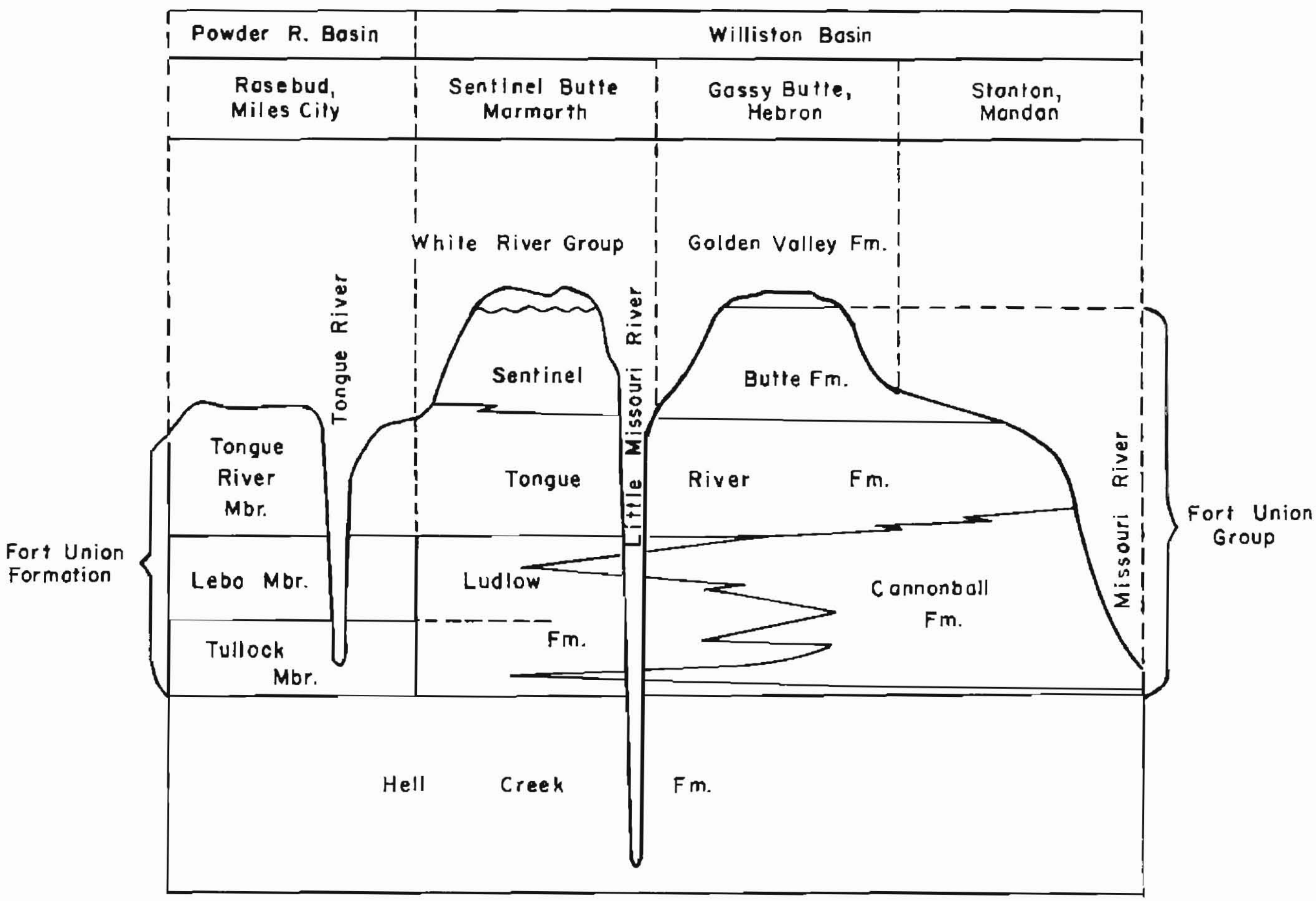

Figure 3. Uppermost Cretaceous and Tertiary lithostratigraphic units of the Williston basin and northeastern edge Powder River Basin (modified from Brown, 1948).

River and Sentinel Butte Formations (fig. 3), particularly as it pertains to the occurrence of uranium. The report suggests general guidelines for the future exploration for uranium in the Williston basin.

Trace amounts of uranium were first discovered in weakly radioactive lignite of the Fort Union Group in the Williston basin in 1948 (Wyant and Beroni, 1950). In the following years, uranium ore was discovered in lignite and lignitic shale in the Ludlow, Tongue River, and Sentinel Butte Formations, and to a lesser extent in some overlying formations. Figure 4 shows the areas in the Williston basin underlain by known uraniferous lignite.

More uranium deposits in lignite are now known in this region than in any other region in the United States, and nearly half of the economically significant uranium deposits that are found in coaly carbonaceous rocks in the United States are found in this region (Vine, 1962). Denson and Gill (1965) estimated more than 1 million tons of inferred reserves of coaly carbonaceous rocks containing more than 0.1 percent uranium in the region.

Some exploration for sandstone-type uranium deposits has been undertaken in the region, but almost no uranium ore has yet been discovered in sandstone in the Williston basin. Some mining of uranium has taken place in Billings County, North Dakota, and in Harding County, South Dakota.

Jacob's (1973b) classification of cross stratification is used throughout this report. Grain size of sand-size sediment was determined with a settling tube method, described by Felix (1969), modified with a shutter-type release mechanism.

ACKNOWLEDGMENTS

Between 1969 and 1974 a number of students and I at the University of North Dakota studied the upper part of the Fort Union Group in the Williston basin, mainly in the badlands of western North Dakota. This work was financially supported by a number of University of North Dakota Faculty Research Grants; in part by the North Dakota Water Resources Research Institute, with funds provided by the United States Department of the Interior, Office of Water Resources Research, as authorized under the Water Resources Research Act of 1964, Public Law 88-379; by parts of National Science Foundation Undergraduate Research Participation Grants GY 11184, GY 10699, GY 9732, GY 8753, and GY 7619; by the North Dakota Geological Survey, Edwin A. Noble, State Geologist; and by part of grant AT (05-1)-1633 from the U.S. Energy Research and Development Administration.

Discussions with students and colleagues at the University of North Dakota and the North Dakota Geological Survey, particularly Lee Clayton, were helpful in developing many of the concepts presented here. The assistance of these people is greatly appreciated.

GEOLOGIC SETTING AND HISTORY

Toward the end of the Cretaceous Period the Laramide Orogeny provided highlands to the northwest, west, and southwest of the Williston basin. During the Upper Cretaceous, Paleocene, and Eocene, these highlands served as the source for sediments distributed on an alluvial plain that spread generally eastward across the Williston basin toward the sea. In ascending order, the Hell Creek Formation (uppermost Cretaceous), the Ludlow, Tongue River, and Sentinel Butte Formations (Paleocene), and the Golden Valley Formation (Paleocene and Eocene) are deposits of lignite, sandstone, siltstone, and claystone that all appear to have been deposited mainly on this alluvial plain. The Cannonball Formation consists of mudstone and sandstone deposited in a sea that transgressed generally westward over the Hell Creek Formation during the Early Paleocene. The Ludlow, Tongue River, Sentinel Butte, and Golden Valley Formations were then deposited on the alluvial plain as it prograded generally eastward into the sea as the sea withdrew from the continental interior. So the Ludlow, Tongue River, Sentinel Butte, and perhaps the lower Golden Valley Formations may all correlate with parts of the Cannonball Formation, but no regional

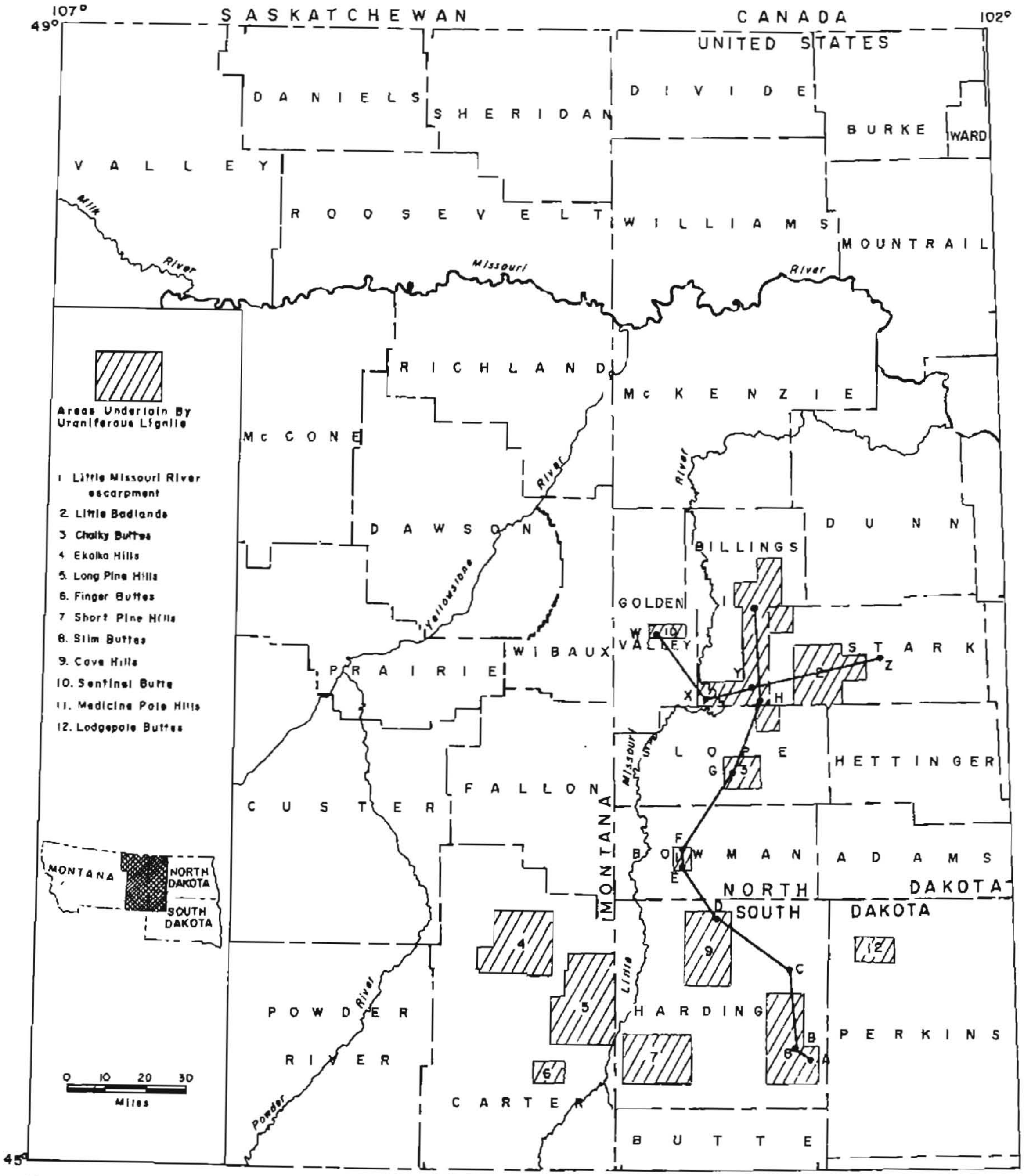

Figure 4. Areas in the Williston basin underlain by known beds of uraniferous lignite. Labeled lines show locations of cross sections in figure 5. (From Denson and Gill, 1956, 1965; Vine, 1962).

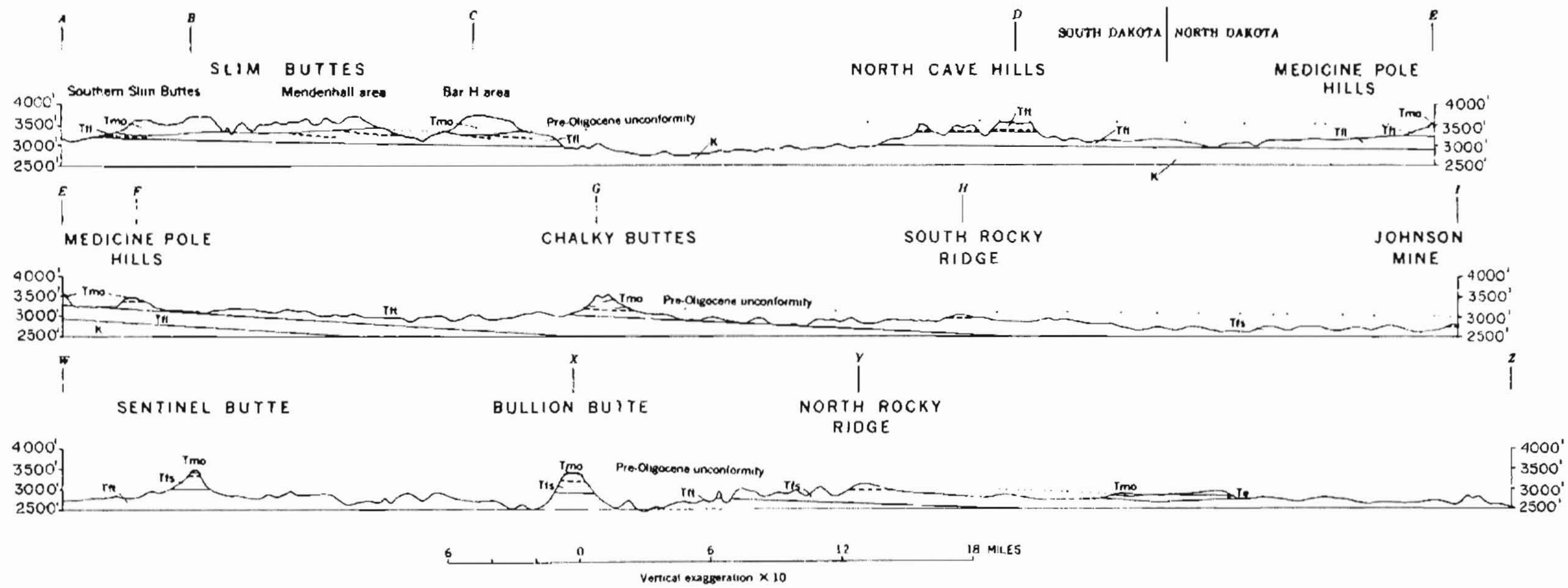

Figure 5. Cross sections of Cretaceous and Tertiary rocks in southwestern Williston basin. Tmo, Miocene and Oligocene rocks; Te, Eocene rocks; Tfl, Tft, and Tfs, Ludlow, Tongue River, and Sentinel Butte Formations of Fort Union Group; K, Cretaceous rocks. Uranium deposit in coaly carbonaceous rock shown by heavy dashed line. Locations of cross sections shown on figure 4 (from Vine, 1962, fig. 36).

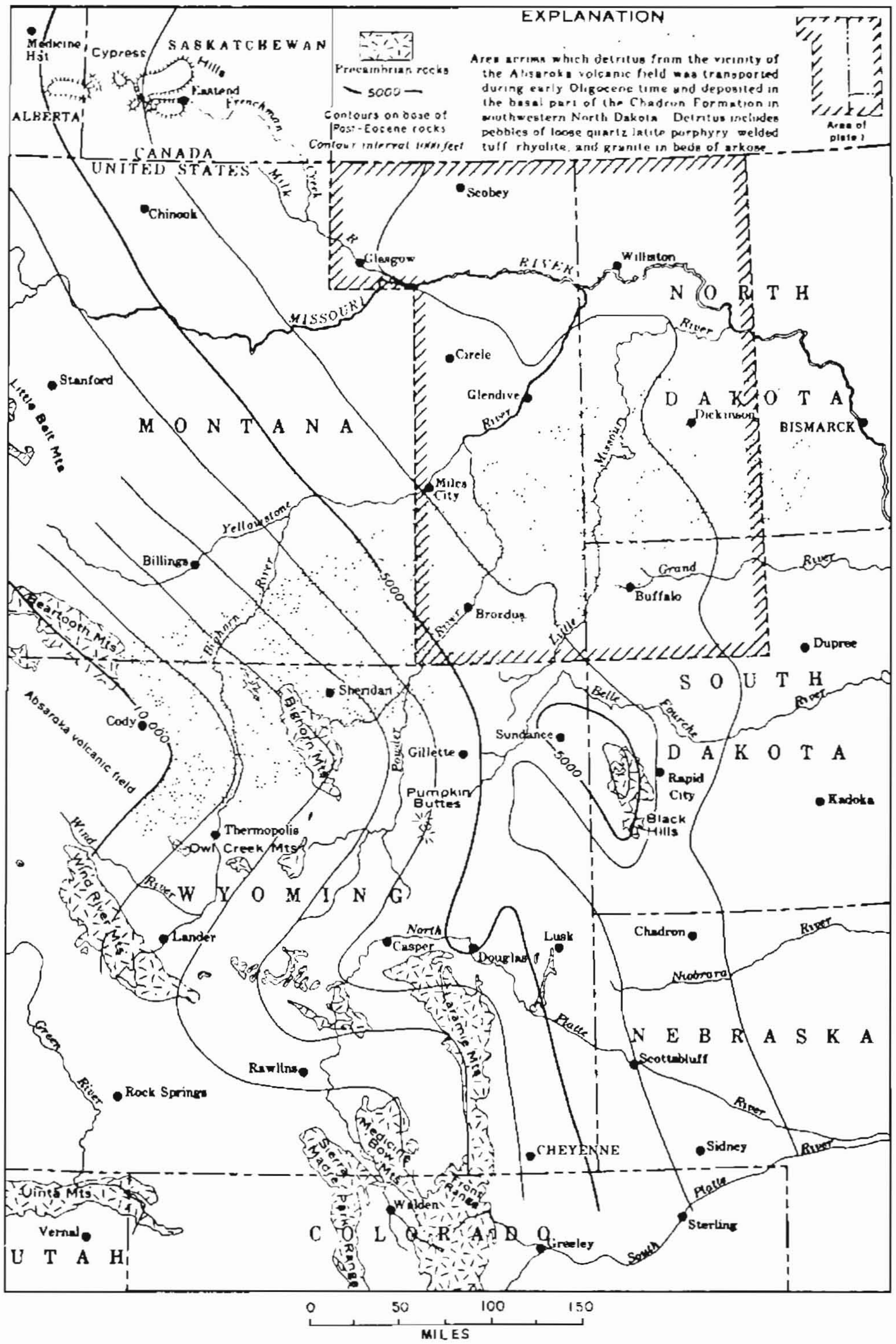

Figure 6. Structure-contour map of the base of the post-Eocene rocks in parts of the Northern Rocky Mountains and Great Plains (from Denson and Gill, 1965, fig. 13).

stratigraphic studies have been done to support or deny this.

Between the Golden Valley Formation and the overlying White River Group (Oligocene), there is an angular unconformity; before deposition of the White River Group, a paleosol formed on the upper part of the Golden Valley by leaching and oxidation to depths of 8 to 33 metres below the unconformity during an episode of intense weathering (Hickey, 1972). The Golden Valley Formation was eroded from the periphery of the basin during development of the unconformity, and the paleosol formed on underlying formations instead (fig. 5). The paleosol is the Eocene paleosol described by Pettyjohn (1966).

During the Oligocene and Miocene Epochs, widespread volcanic activity occurred in the Black Hills region and in the Yellowstone-Absaroka region (Love, McGrew, and Thomas, 1963), and perhaps in other regions. The volcanic activity may have been related to plate subduction along the western edge of North America as described by Christiansen and Lipman (1972) and Lipman, Prostka, and Christiansen (1972). The volcanic activity led to deposition of the White River Group (Oligocene) and the Arikaree Formation (Miocene) in the Williston basin and surrounding areas; both units are rich in volcanic debris.

By the end of the Miocene Epoch, the sedimentary basins of the central Rocky Mountains that had formed during the Laramide Orogeny were filled with sediment rich in volcanic matter. Only the highest mountain tops protruded above a plain of aggradation that spread from Wyoming to Colorado and eastward to Nebraska (Love, McGrew, and Thomas, 1963) and probably northeastward to the Dakotas.

Volcanic activity continued in the Yellowstone region during the Pliocene Epoch, but by the end of the Pliocene tremendous uplift in the Rocky Mountains caused streams to expose the mountains again during an erosion cycle that has lasted until the present time (Love, McGrew, and Thomas, 1963). The uplift tilted the Tertiary strata toward the northeast as shown by a structure-contour map of the base of the Oligocene rocks in the northern Rocky Mountains and Great Plains (fig. 6).

TONGUE RIVER FORMATION

Introduction

In 1909 Taff (p. 129) named the "Tongue River coal group" while describing the Sheridan coal field along the Tongue River in the Powder River Basin, Wyoming. Since then, there has been some confusion concerning the term "Tongue River." Royse (1967) reviewed the history of the problem, and he formally suggested that the Tongue River be accepted as a formation in the Fort Union Group, as had already been done for many years by the North Dakota Geological Survey. Outside of North Dakota, the Paleocene deposits as a whole have been mapped as the Fort Union Formation in the Rocky Mountains and northern Great Plains of the United States (Brown, 1949); and Dowling (1915, map 128A) mapped the lignite-bearing deposits in the Canadian part of the Williston basin.

The Tongue River Formation is a lignite-bearing, nonmarine, Paleocene unit whose outcrops are light yellow, light buff, and light gray. Excellent exposures in the Little Missouri Badlands and elsewhere in North Dakota provide an excellent opportunity for sedimentologic studies. The only published sedimentologic work concerned with the origin of the Tongue River Formation is that of Jacob (1973a) and Royse (1970). There are a number of papers on the large-scale stratigraphic relations, paleontology, distribution, or mineral resources (Bergstrom, 1956; Brown, 1948, 1962; Crawford, 1967; Delimata, 1969; Denson and Gill, 1956, 1965; Hares, 1928; Leonard, Babcock and Dove, 1925; Royse, 1967, 1970; and others).

Distribution

The Tongue River Formation occurs at the surface or as bedrock over only perhaps 20 to 30 percent of the North

Dakota part of the Williston basin, mostly around the periphery (fig. 2). The best exposures are in the badlands along the Little Missouri River in Slope, Golden Valley, Billings, and McKenzie Counties, North Dakota, and along the Yellowstone River in eastern Montana and northwestern North Dakota.

Contacts

Throughout most of the area of outcrop, the lower contact of the Tongue River Formation is concealed by glacial drift or, where glacial drift is absent, it is in the subsurface. In the southwest corner of North Dakota, the base of the Tongue River is conformable with the underlying Ludlow Formation. To the east, in Grant and Morton Counties, the base is conformable with the Cannonball Formation. The stratigraphic relations with the underlying formations between the area where the Tongue River overlies the Ludlow and the area where it overlies the Cannonball have not been determined.

Outcrops of the Tongue River are distinguished from those of the Ludlow largely on the basis of color. The Tongue River has light yellow, light buff, and light gray outcrops, and the Ludlow has darker gray and grayish brown outcrops that are similar to those of the Sentinel Butte Formation. Mineralogic and petrologic characteristics, described below, also can be used to differentiate the two formations. The Cannonball does not contain lignite and its outcrops are darker yellow-brown than the outcrops of the Tongue River.

The contact with the overlying Sentinel Butte Formation has been described in some detail by Royse (1967). The contact is conformable, widely exposed, and distinctive on outcrops along the Little Missouri River, where it is marked by a change from the light yellow, light buff, and light gray of the Tongue River Formation to the darker gray and brown of the Sentinel Butte Formation. The HT lignite bed, which is overlain by a sandstone bed in many places, is at the contact (Royse, 1967). The contact is distinctive in the western part of North Dakota, but it becomes more difficult to recognize in the eastern part of the Williston basin.

Thickness

Royse (1970, p. 26) reports that the Tongue River appears to be about 75 to 100 m thick along the southern and western flanks of the Williston basin, and it thickens to about 200 m toward the center of the basin. These observations are generally supported by the basic data on formation thicknesses reported in the bulletins of the North Dakota Geological Survey that concern county groundwater studies in North Dakota. However, the accuracy of the formation thicknesses reported in the bulletins is subject to question because no reliable means for distinguishing the formations in the subsurface were available when the work was done. The reported depths to the tops of formations are little more than well-educated guesses. For this reason, no isopach maps of the formation is presented in this report.

Lithology

General

The Tongue River Formation consists of sandstone, siltstone, claystone, lignite, and small lenses of limestone (micrite). Cement is rare, but where it occurs it is mostly calcium carbonate. Some iron-oxide cement occurs in small concretions in sandstone and siltstone, and some iron-sulfide cement occurs in siltstone and claystone. Most of the formation is poorly consolidated and can be excavated with a pick and shovel.

Sandstone

Sandstone makes up about 10 percent of the Tongue River Formation as indicated by visual estimates in the field. Most of the sandstone is light gray on fresh exposures, and it weathers to light yellow, light yellow-brown, or light gray. It forms smoother surfaces than the overlying Sentinel Butte Formation, and it does not show the closely spaced deep gulleys and caves that the sand of the Sentinel Butte shows (fig. 7). It is almost entirely fine- or

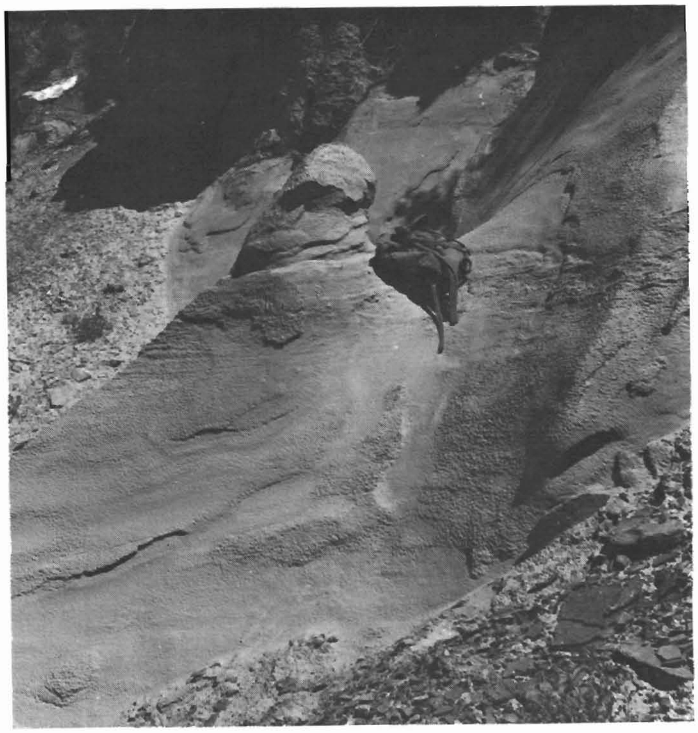

Figure 7. Sandstone bed in the Tongue River Formation near Medora, Billings County, North Dakota. Surfaces are smoother and more rounded than on the Sentinel Butte Formation. Canvas bag is about 0.3 m across. Compare with figure 23 (from Jacob, 1975a).

very-fine grained; the fall diameter of the sand fraction of most sandstone samples is generally 2.5-3.0 phi units (0.17-0.12 mm). Sandstone may be medium to coarse at the base or at the top of the formation in some localities. Permeability of the sandstone in the Tongue River has not been measured, but it is probably low because the grain size is fine; and, as a result, groundwater flow through the formation probably is low.

Jacob (1975a) petrographically analyzed thin sections of 45 samples of sandstone from the Tongue River Formation collected from throughout the Williston basin. These analyses show that feldspar is rare in the Tongue River, and rock fragments are abundant (fig. 8). This indicates a supracrustal rather than a plutonic source for the formation.

Fragments of sedimentary rocks are very abundant in the Tongue River Formation, fragments of volcanic rocks are not very abundant, and fragments of metamorphic rocks are rare (fig. 9). Carbonate rocks make up a greater portion of the sedimentary-rock fraction of the formation than shale or chert (fig. 10). The carbonate-rock fragments in the thin sections are clastic as indicated by their rounded form; lack of replacement textures; hydrodynamic equivalence to other clastic grains, such as quartz; association with other supracrustal rock types, such as chert and volcanic rock; and lack of plutonic minerals such as feldspar.

Because of the abundant carbonate-rock fragments, most samples of the Tongue River Formation classify as carbonate litharenites according to the scheme of Folk, Andrews, and Lewis (1970). The samples were classified by the FORTRAN program FOLKSS (Jacob, 1975b).

Royse (1970) showed that acid-soluble carbonate is more abundant in the Tongue River Formation than in the Sentinel Butte Formation (fig. 11), and it makes up as much as 41 percent of the Tongue River (Royse, 1970, p. 56). The abundant carbonate should have assisted in the dissolution of uranium in the groundwater passing through the Tongue

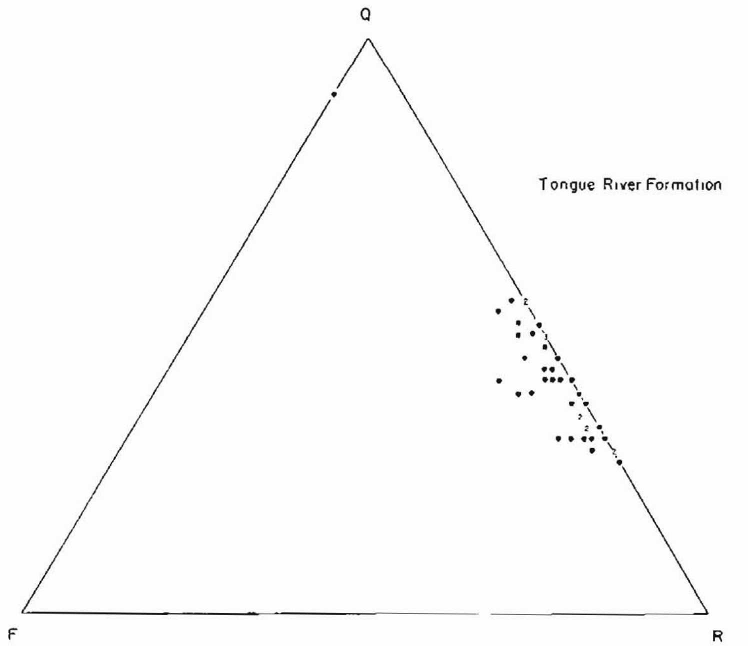

Figure 8. Triangular plot of main components of sandstone of the Tongue River Formation based on thin-section analyses. Q, quartz; F, feldspar; R, rock fragments. Computation of plotted values was made by FORTRAN program FOLKSS (Jacob, 1975b). Figure was drafted from computer printout made by FORTRAN program TRI (Lumsden, 1973) from Jacob, 1975a.

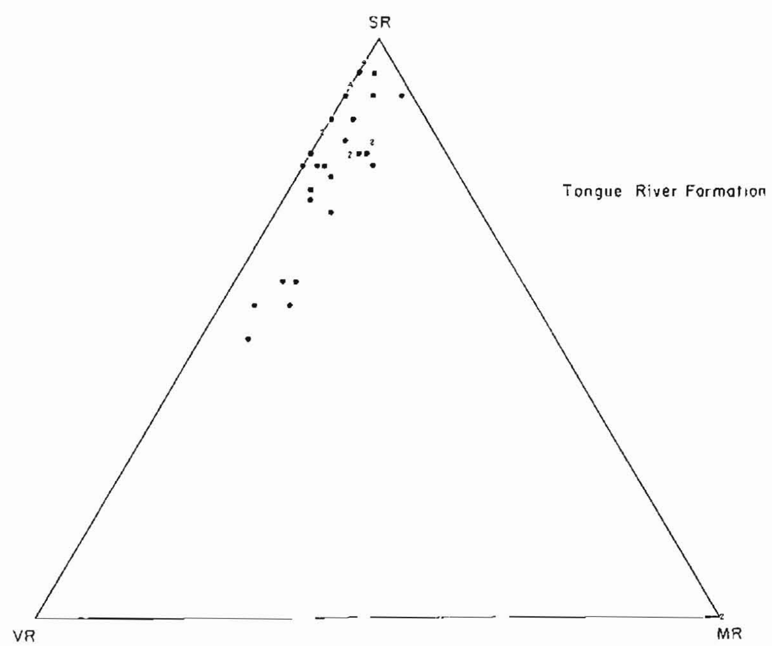

Figure 9. Triangular plot of rock fragments in sandstone of the Tongue River Formation based on thin-section analyses. SR, sedimentary-rock fragments; VR, volcanic-rock fragments; MR, metamorphic-rock fragments. Computation and plotting of values by same method as in figure 8 (from Jacob, 1975a).

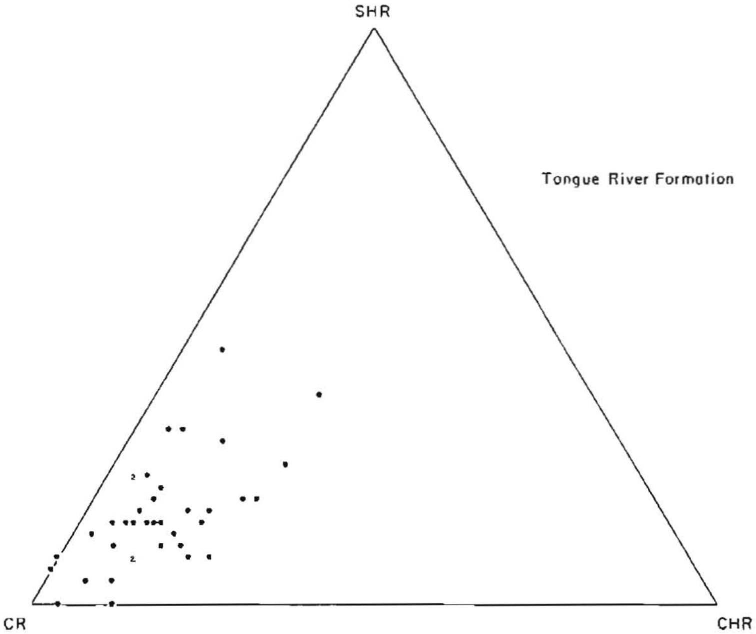

Figure 10. Triangular plot of sedimentary-rock fragments in sandstone of the Tongue River Formation based on thin-section analyses. SHR, shale-rock fragments; CR, carbonate-rock fragments; CHR, chert-rock fragments. Computation and plotting of values by same method as in figure 8 (from Jacob, 1975a).

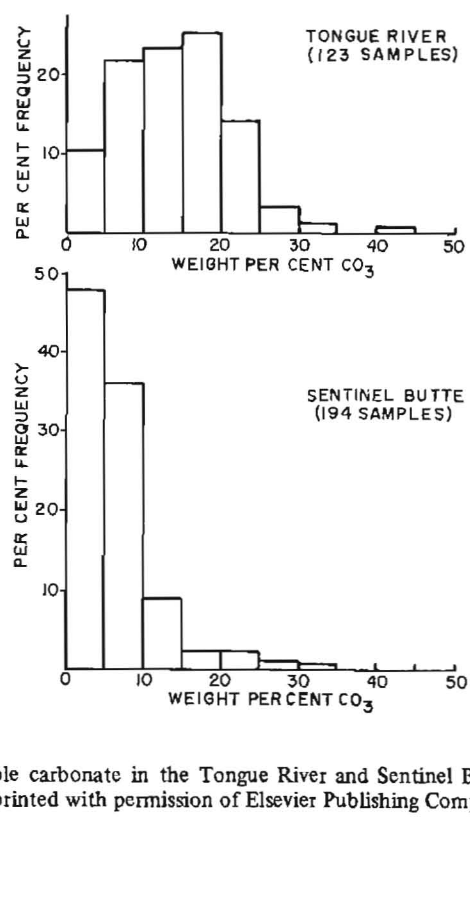

Figure 11. Distribution of acid-soluble carbonate in the Tongue River and Sentinel Butte Formations, North Dakota (from Royse, 1970, fig. 25). Reprinted with permission of Elsevier Publishing Company, Amsterdam.

River (Hostetler and Garrels, 1962).

Siltstone and claystone

Visual estimates in the field indicate that about 70 to 80 percent of the Tongue River Formation consists of siltstone and claystone. Where the siltstone and claystone is interbedded with sandstone, it weathers light to medium yellow-brown; where it is interbedded with claystone, it weathers light to medium gray. It weathers into smoother surfaces than the siltstone and claystone of the Sentinel Butte, and popcorn-like surfaces are not as well developed as on the Sentinel Butte.

Analysis of 80 samples of the clay-size fraction of the Tongue River Formation in Billings County, North Dakota (Emanuel, Jacob, and Karner, 1975) showed that the three groups of clay minerals present in greatest abundance are, in decreasing order of abundance: (1) the mica-group minerals, principally muscovite with some biotite and illite, (2) the kaolinite-group minerals, possibly principally dehydrated halloysite, and (3) the montmorillonite-group minerals. A small amount of chlorite is also present in most samples. Non-clay minerals in the clay-size fraction are quartz, dolomite, calcite, potassium feldspar, and plagioclase.

The low abundance of montmorillonite (which may form by the weathering of volcanic ash) in the clay fraction coincides with the lack of volcanic-rock fragments in the sand fraction, and indicates a lack of input of volcanic matter during deposition of the Tongue River Formation.

Lignite

Lignite makes up less than 10 percent of the Tongue River Formation. Slumping of sediment that overlies the lignite beds commonly causes them to be poorly exposed. However, they are commonly clearly marked on outcrops by bands of vegetation because the lignite beds are aquifers that provide moisture for plant growth.

Ting (1972a, 1972b, 1973, 1974) has made some initial studies of the petrography and paleobotany of lignite in North Dakota. No studies have been made that compare the lignite of the Tongue River with that of the Sentinel Butte. Most samples that he studied were from the Sentinel Butte, so the results of his work and other work will be presented in the discussion of the Sentinel Butte Formation.

Limestone

Only 1 or 2 percent of the Tongue River Formation consists of limestone. The limestone is well cemented, gray micrite that occurs in lenses generally up to about 1 m thick and several metres across that weather medium to dark yellow-brown or orange-brown. The micrite lenses are most abundant in beds of interbedded sandy siltstone and silty sandstone. The micrite itself may be sandy or silty and it may contain various plant fossils.

Depositional Environments

Introduction

Royse (1970) and Jacob (1973a) have published the only detailed sedimentologic work concerned with the depositional environments of the Tongue River Formation. In a well-known paper, Brown (1962) presented a discussion of the Paleocene plant fossils of the Rocky Mountain region, and he concluded that the climate during the Paleocene was generally warmer and more humid than at present. Crawford (1967) briefly discussed a few aspects of the lithology, sedimentary structures, and paleontology of the Tongue River. Delimata (1969) conducted a study of invertebrate fossils of the Fort Union Group in southern Golden Valley and southeastern Billings Counties, North Dakota, and he found no marine fossils.

Jacob (1973a) showed that there are four types of lithologic associations in the Tongue River. These are: (1) gray claystone and siltstone that are commonly lignitic, (2) lignite, (3) yellow siltstone and sandstone that may be clayey, and (4) sandstone. Lithification of all four types generally is very poor.

Gray siltstone and claystone

Units consisting of beds of gray claystone and siltstone range from a fraction of a metre to more than 10 m

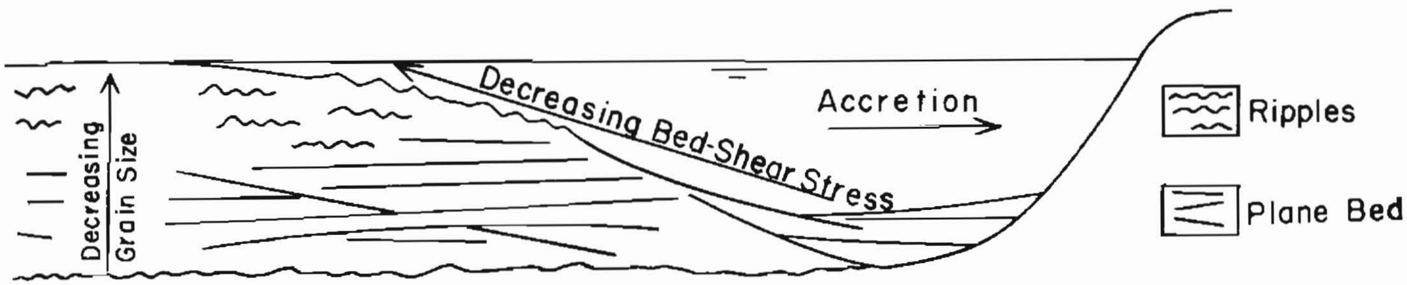

Figure 12. Depositional environments of alluvial plain. Flood basin is subenvironment of flood plain. Modified from Fisk (1960). Reprinted from Jacob (1973a) with permission of American Association of Petroleum Geologists.

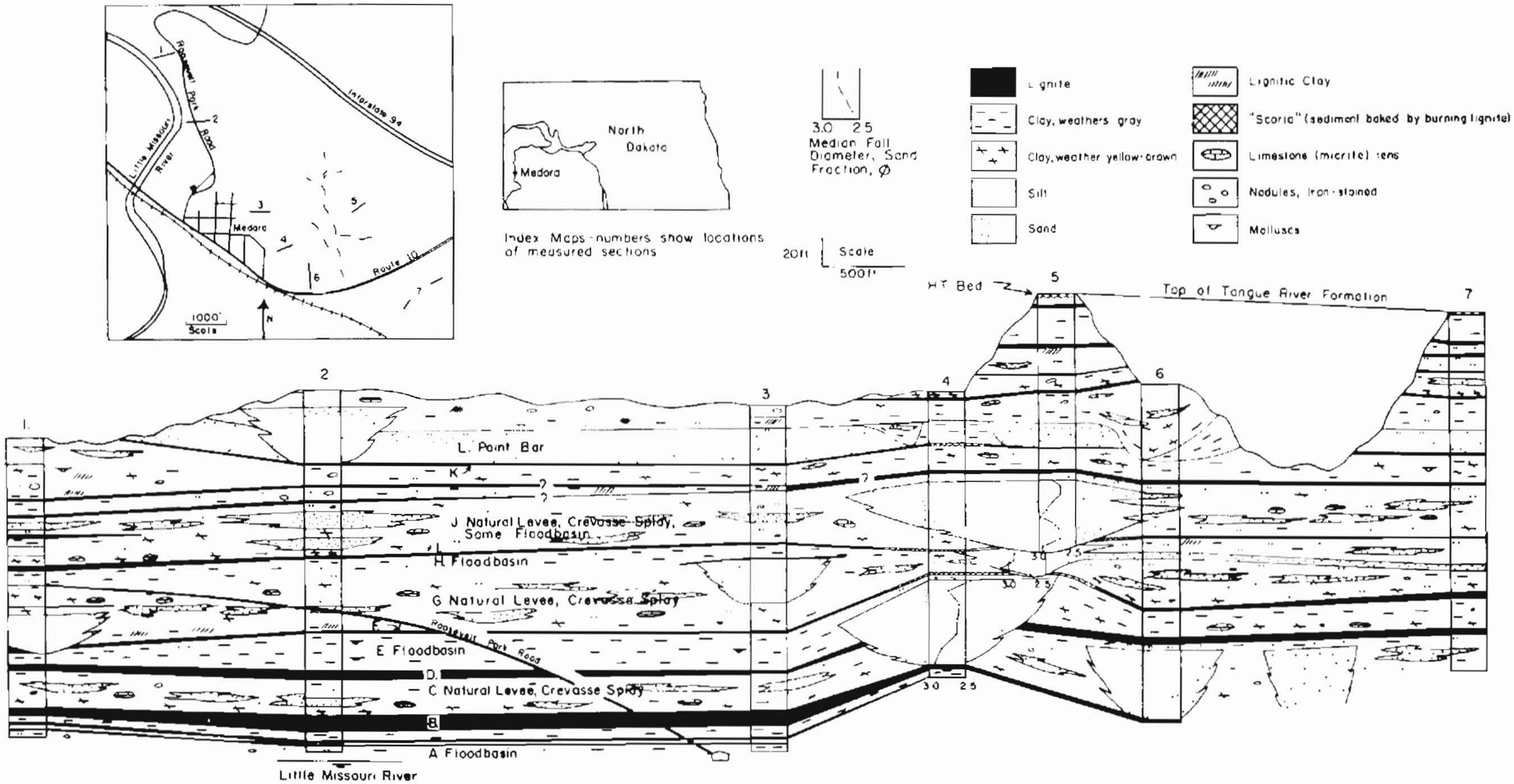

Figure 13. Stratigraphic diagram of part of the Tongue River Formation at Medora, Billings County, North Dakota. Horizontal scale distorted between measured sections 4 and 6. All units were mapped in the field; there are no hypothetical correlations between measured sections. Reprinted from Jacob (1973a) with permission of American Association of Petroleum Geologists.

thick. These units generally weather light to medium gray, but they may weather light to medium yellow-brown in some places. They contain distorted stratification, small-scale sets of cross strata, iron-sulfide nodules, various species of gastropods and pelecypods, abundant plant fragments of various kinds, and thin beds of lignitic claystone or lignite. Thick lignite beds may also be present, usually within these units or at their tops.

These units probably were deposited in a flood basin on a flood plain (Jacob, 1973a) (fig. 12). The abundant lignite, lignitic claystone and plant debris, the fine-grain size, gray color, iron-sulfide nodules, high fossil content compared with surrounding units, disturbed stratification, and association with thick channel sandstone (fig. 13) all indicate deposition in a flood basin (Allen, 1965; Coleman, 1966; Fisk, 1947). Some lake deposits may be contained locally in these units, but planar laminae typical of lake deposits are not common.

Lignite

Thicknesses of lignite beds in the Tongue River Formation range from a few centimetres to almost 13 m (40 ft.) (Leonard and others, 1925, p. 62-67). Thick lignite beds are not present in units of yellow siltstone and sandstone, but they are present in units of gray siltstone and claystone interpreted as flood basin deposits. So the thick lignite beds probably are flood basin deposits also. This interpretation is supported by the close association of the lignite beds with thick channel sandstone (fig. 13).

Many of the lignite beds in the Tongue River are quite continuous laterally, but their thicknesses and elevations change within short distances laterally (fig. 13). Many of these changes probably are due to post-depositional compaction of the stratigraphic section. The lateral continuity of the lignite beds indicates that the flood basins in which they were deposited were extensive, as would be expected on a lower (seaward part) deltaic plain rather than an upper (landward part) deltaic plain. So the Tongue River Formation probably originated on a lower deltaic plain. The characteristics of the sandstone bodies in the formation, discussed below, support this suggestion.

Lignite beds in the Tongue River Formation generally are thicker and more abundant than those in the overlying Sentinel Butte Formation, probably because of lower clastic influx per unit area and less lateral shifting of depositional environments on the lower deltaic plain. Concentration of uranium in the Tongue River Formation is disfavored by the abundant, laterally continuous beds of lignite that may have absorbed uranium from uranium-bearing groundwater during migration, thereby preventing concentration of uranium in most places.

Yellow siltstone and sandstone

Units consisting of beds of yellow-weathering siltstone and sandstone range from a fraction of a metre to more than 16 m (50 ft.) in thickness. Claystone that weathers yellow-brown is also present in many places. Small-scale sets of cross strata and horizontal laminae are widespread. Climbing-ripple stratification is particularly characteristic (fig. 14), and it results from high rates of sedimentation from suspension (Allen, 1970a).

Vertical, cylindrical, iron-stained concretions up to about 30 cm diameter are present, and in places they contain woody remains at their centers. They probably represent trees buried in growth position. Limestone lenses (micrite) as much as 1 m thick and 30 m across (described in the section on Lithology) are confined mostly to beds of yellow siltstone and sandstone. Gastropods and pelecypods are present, but they are not as abundant as in the units of gray claystone and siltstone.

The units of yellow siltstone and sandstone probably originated as natural levees and crevasse splays (fig. 12) where overbank depositional rates on the flood plain are highest (Allen, 1965; Kesel and others, 1974), accounting for the climbing-ripple stratification and the burial of trees in growth position. The poor sorting of these units also is characteristic of natural levees (Allen, 1965). The yellow color probably is caused by an iron content

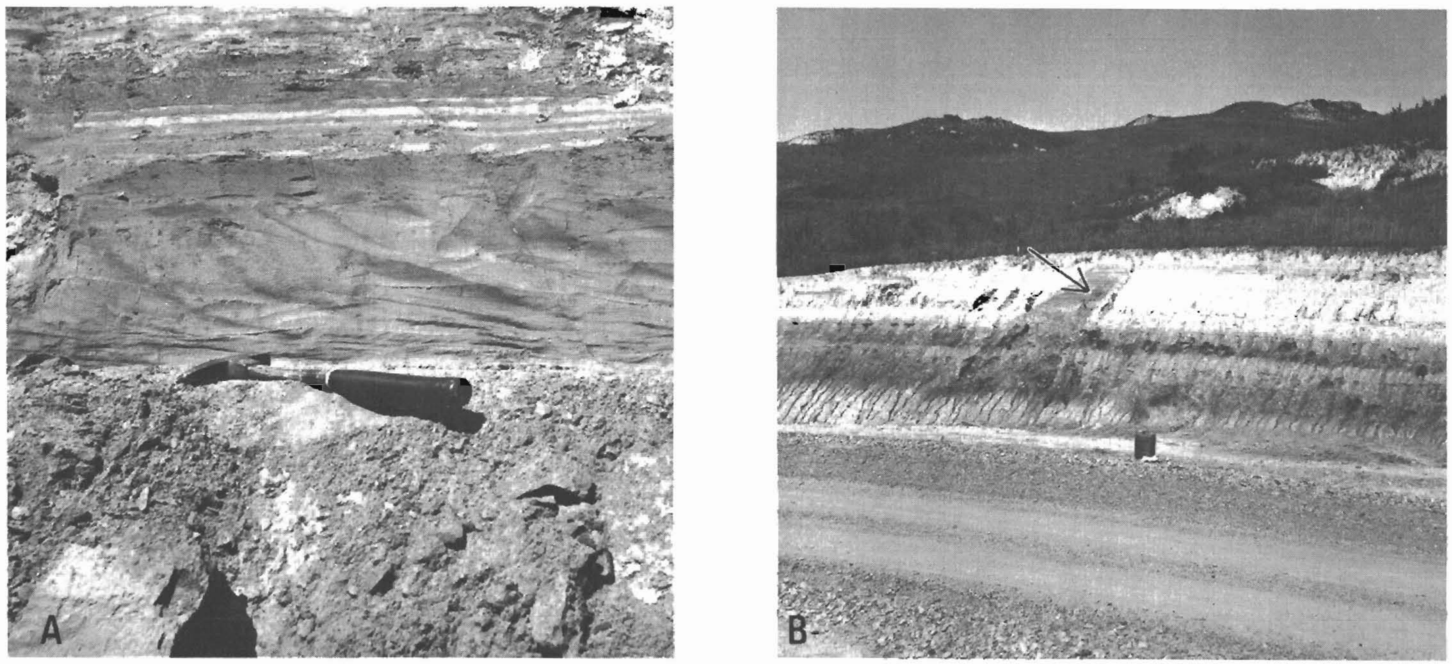

Figure 14. A. Horizontal lamination and climbing-ripple stratification in clayey yellow siltstone and sandstone that overlie lignitic gray claystone. Arrow in B indicates location of photograph. Texture, structures, and stratigraphic position indicate that sediment probably is natural levee or crevasse-splay deposit.

B. Cyclic unit of type shown in figure 18A; arrow gives location of figure 14A. West side of road just north of road junction in SE¼, sec 34, T137N, R101W, Billings County, North Dakota. Light gray at road level is gray claystone and siltstone (flood basin), dark gray to black is lignitic horizon (flood basin), and very light gray at top is yellow siltstone and sandstone (natural levee or crevasse splay). Reprinted from Jacob (1973a) with permission of American Association of Petroleum Geologists.

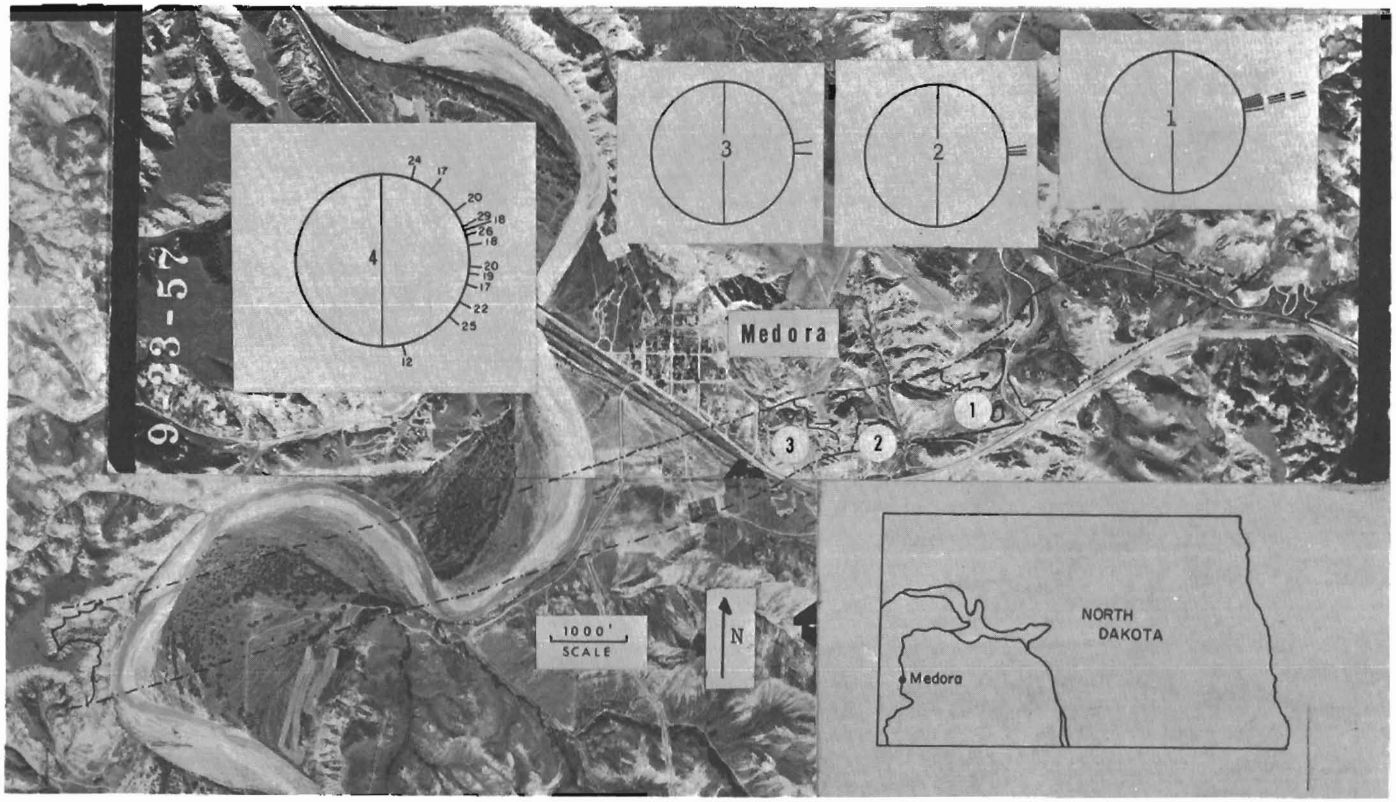

Figure 15. Map of channel sandstone at base of measured section 5, figure 13. Solid line indicates sandstone outcrop; dotted line is projection of channel edge where it is eroded or buried. Diagrams 1, 2, and 3 show orientation of elongate concretions at locations 1, 2, and 3, respectively. Diagram 4 shows direction and dip, in degrees, of foresets of cross strata at location 1. Arrows show average trends of elongate concretions. Reprinted from Jacob (1973a) with permission of American Association of Petroleum Geologists.

that is higher than surrounding units (Jacob, 1973a, table 1). This probably resulted because natural levees form the highest elevations on the flood plains where a highly oxidizing environment favoring precipitation of iron is present.

Trough-shaped sandstone beds

Two types of sandstone beds present in the Tongue River Formation are: (1) trough-shaped beds that are elongate in plan view, and (2) tabular beds that are probably elongate in plan view.

The most abundant type is trough shaped. It is narrow (as much as about 300 m wide) and straight, and its paleocurrent indicators parallel the long axis of the bed (fig. 15). This type of sandstone bed channels deeply into surrounding sediment, commonly downward to a lignite bed (fig. 13). These relationships clearly indicate a fluvial origin.

Sedimentary structures are about 15 percent small-scale sets of cross strata, 25 percent low-angle, straight cross strata ("plane bed"), and 60 percent large-scale, planar sets of high-angle, cross strata. Jacob (1973a) showed that these sedimentary structures probably formed on transverse (lateral) bars in non-braided, low-sinuosity streams. Such streams are common on the lower (seaward part) deltaic plain of a high-constructive delta (Fisher and others, 1969), so this probably was the depositional environment of the Tongue River Formation, as suggested above. Royse (1970, 1972) showed that the overall paleocurrent vectors of the Tongue River Formation have relatively low variability, which probably resulted from deposition in the low-sinuosity streams.

The sandstone beds may be stacked on top of one another in places (fig. 13), but the causes for the stacking are uncertain. Large, elongate, calcite-cemented concretions as much as 5 m wide and a few hundred metres long are common in the sandstone beds (fig. 16), especially near the top, and they help to protect the sandstone beds from erosion. The concretions are oriented with their long axes parallel both to paleocurrent indicators and long axes of the sand beds (Jacob, 1973c) (fig. 15). The concretions are readily visible on air photos, so they can be used to map paleochannel patterns quite rapidly over large areas. Personal experience has shown that such maps may be a good indication of sandstone distribution in the subsurface, apparently because of the stacking of the sandstone beds.

Tabular sandstone beds

Tabular sandstone beds have been observed in only a few places in the Tongue River Formation. Their shape in map view has not been determined, but they probably are elongate. Commonly they are about 3 m thick, but they may be as much as 10-15 m thick. The thicker they are, the less laterally extensive they are. Those that are about 3 m thick extend hundreds of metres laterally. They have scoured bases and sharp to gradational tops.

Low-angle, straight cross strata are in the lower parts of the tabular sandstone beds, and small-scale sets of cross strata are in the upper parts. Curved sets of cross strata are also in the lower parts of thicker beds.

The tabular sandstone beds probably originated as point-bar deposits formed by lateral accretion in high-sinuosity streams (fig. 17). An example of such a deposit is between measured sections 4 and 5 in figure 13 where there is a channel that was plugged after it was abandoned as the stream migrated toward the south. Stream depth was about equal to the thickness of the sand bed.

Cyclic Units

Cyclic units in the Tongue River Formation have been recognized (fig. 18), and figures 19, 20, and 21 show models for the origin of each type. These models were discussed in some detail by Jacob (1973a). In each case lignite and gray claystone and siltstone formed as flood basin deposits on a flood plain, and crevassing and expansion of natural levees across flood basins destroyed any swamps and deposited yellow siltstone and sandstone. Thicknesses of entire cyclic units or of individual beds are very diverse and depend on rates of

Figure 16. Elongate concretions in the Tongue River Formation. View toward the southwest in sec 17, T133N, R93W, Hettinger County, North Dakota. Pick is 0.9 m long.

deposition, rates of decay of organic matter, rates of subsidence, and rates of lateral migration of channel belts.

Marker Beds

A number of marker beds (fig. 22) have been recognized in the Tongue River and Sentinel Butte Formations along the Little Missouri River. Note that marker beds in the Tongue River are lignite beds, but in the Sentinel Butte they are mainly non-lignitic beds. This is because, as discussed earlier, the Tongue River formed on a lower deltaic plain with broad flood basins in which laterally extensive lignite beds could form. The lignite marker beds may be difficult to trace because of their changing thicknesses and elevations. In figure 13, for example, it is not certain which of the lignite beds may be a named marker bed shown in figure 22.

In the upper part of the Tongue River Formation, the Medora unit occurs as a distinctive dark-colored bed (fig. 13) with characteristics similar to the Sentinel Butte Formation (Jacob, 1973a). The Medora unit can be used as a marker bed over an area of many square miles. Because it is similar to the Sentinel Butte, it may cause difficulty in picking the Tongue River-Sentinel Butte contact. The basal sand of the Tongue River Formation is discontinuous, and so it may have limited usefulness as a marker bed.

SENTINEL BUTTE FORMATION

Introduction

Leonard and Smith (1909, p. 18) named the "Sentinel Butte coal group" for exposures of strata that make up most of Sentinel Butte in Golden Valley County, North Dakota. As in the case of the Tongue River, there has been some confusion concerning the use of the term "Sentinel Butte" in stratigraphic terminology. Royse (1967) reviewed the history of this problem, and he suggested that the Sentinel

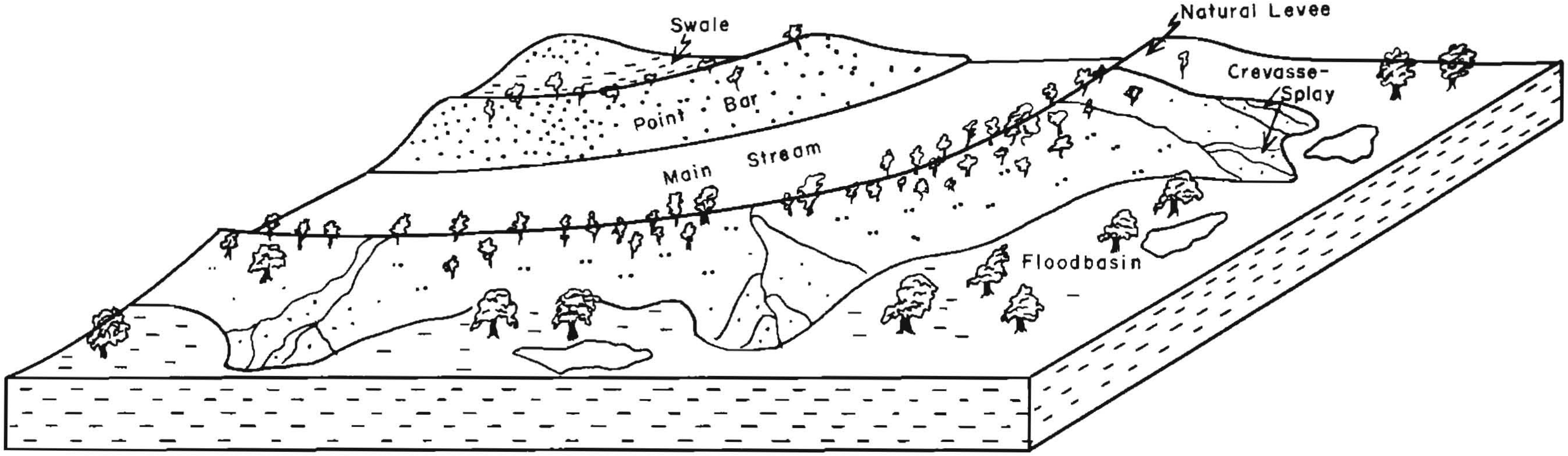

Figure 17. Model for the origin of tabular sandstone beds in the Tongue River Formation. Accretion is taking place toward concave bank of stream bend. Thickness of bed is equal to depth of stream in bend. Curved sets of cross strata are also present in the lower parts of thick beds. Reprinted from Jacob (1973a) with permission of American Association of Petroleum Geologists.

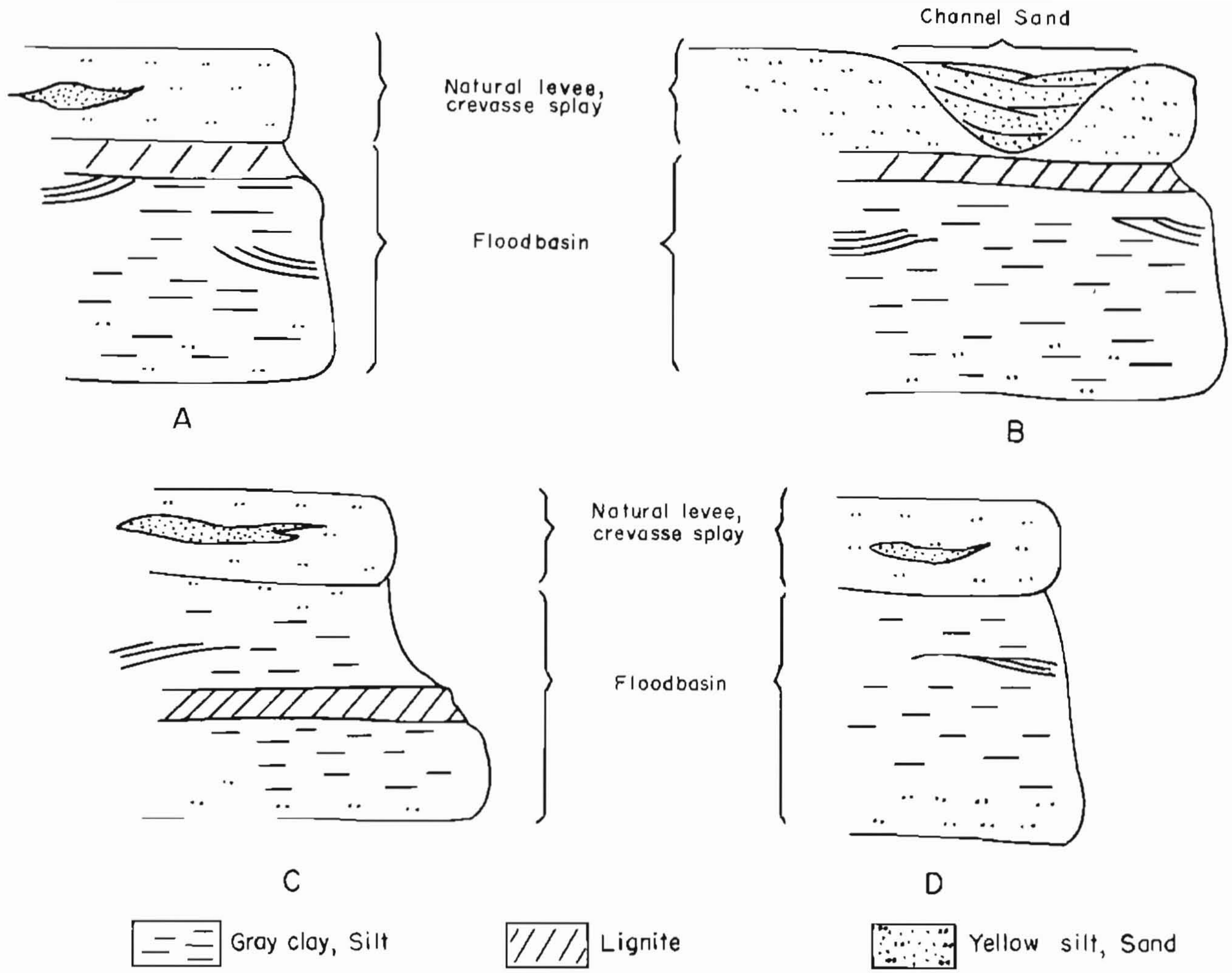

Figure 18. A. Basic cyclic unit in Tongue River Formation. B.-D. Variations of basic unit. Reprinted from Jacob (1973a) with permission of American Association of Petroleum Geologists.

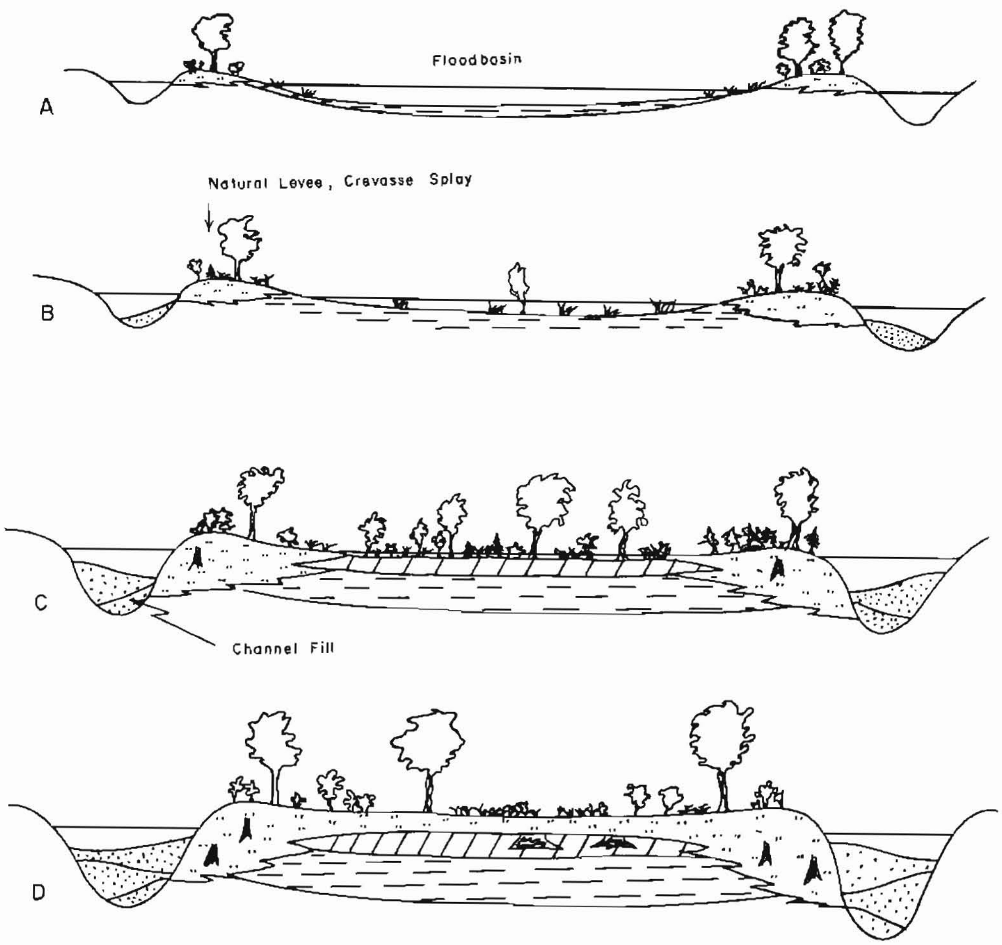

Figure 19. Model for origin of cyclic unit shown in figure 18A. Vertical scale many times horizontal. Legend in figure 18. Reprinted from Jacob (1973a) with permission of American Association of Petroleum Geologists.

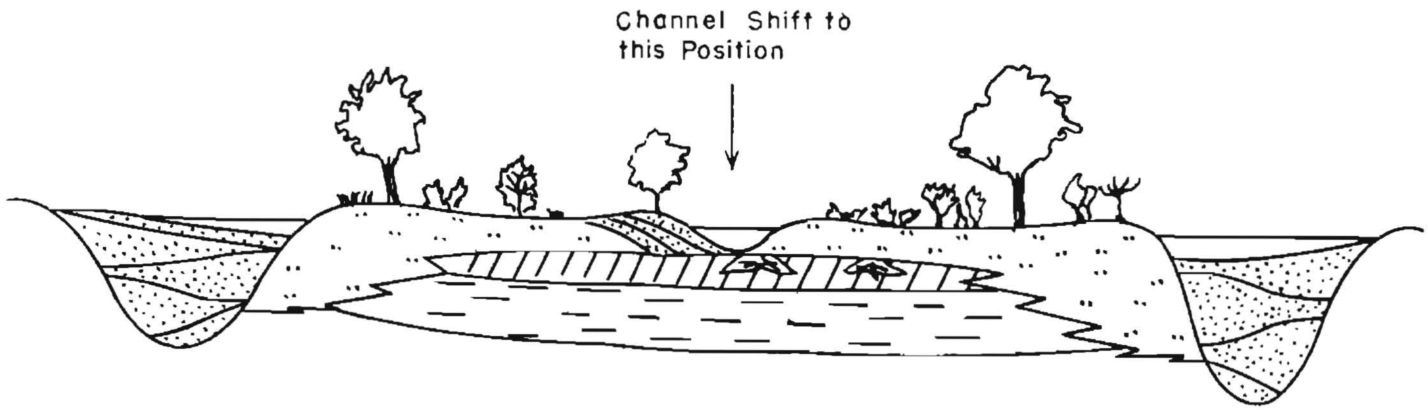

Figure 20. Model for origin of cyclic unit shown in figure 18B. Vertical scale many times horizontal. Legend in figure 18. Reprinted from Jacob (1973a) with permission of American Association of Petroleum Geologists.

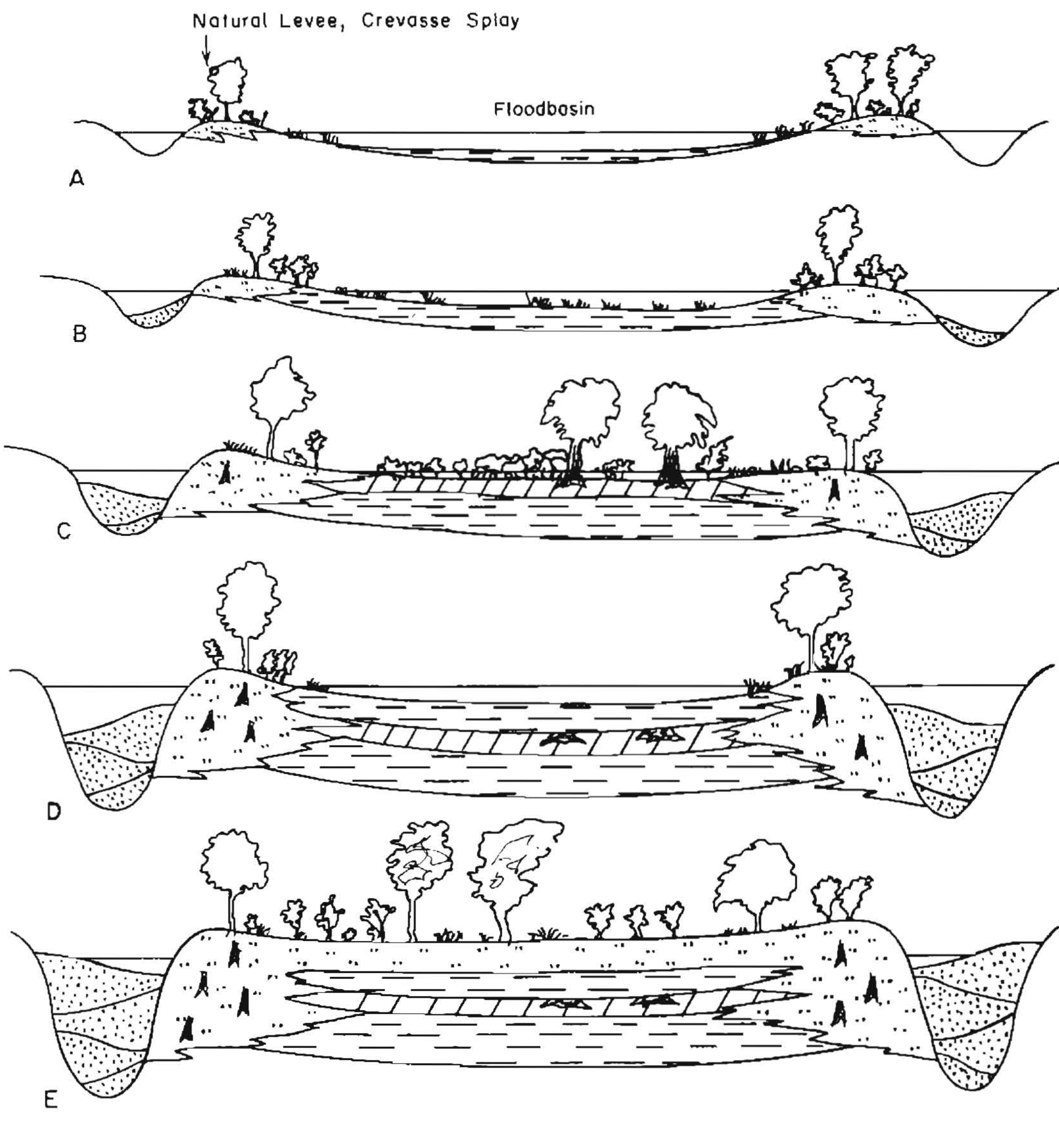

Figure 21. Model for origin of cyclic unit shown in figure 18C. Cyclic unit of figure 18D may originate if overall rate of deposition is high enough to prevent development of persistent swamps as flood basin fills. Vertical scale many times horizontal. Legend in figure 18. Reprinted from Jacob (1973a) with permission of American Association of Petroleum Geologists.

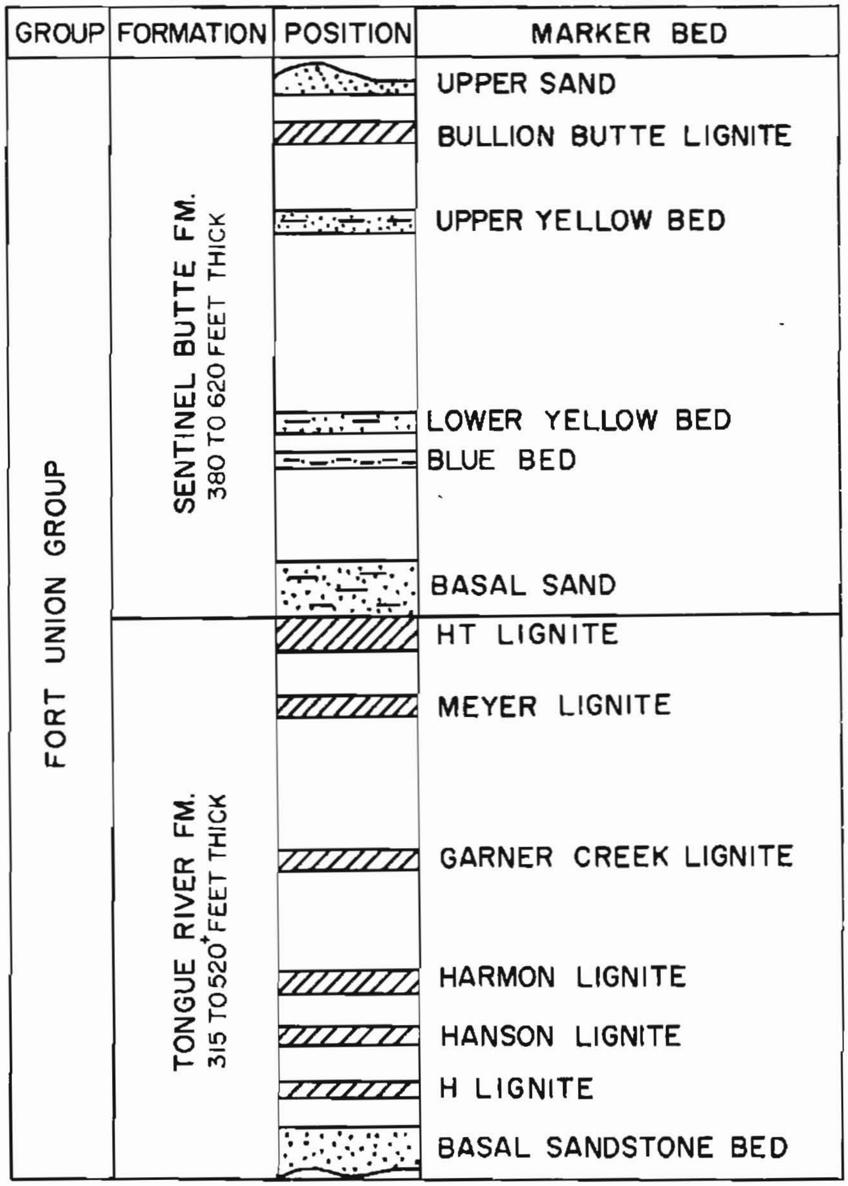

Figure 22. Marker beds in the Tongue River and Sentinel Butte Formations in western North Dakota (modified from Royse, 1972).

Butte be accepted as a formation in the Fort Union Group, a procedure that had been used for some time by the North Dakota Geological Survey.

The Sentinel Butte Formation is a lignite-bearing, nonmarine, Paleocene unit whose outcrops are somber gray and brown, in contrast to the lighter colored outcrops of the underlying Tongue River Formation. Other criteria can also be used to differentiate the Tongue River and Sentinel Butte Formations (Jacob, 1975a).

There are a number of papers on the large-scale stratigraphic relations, paleontology, distribution, or mineral resources (Bergstrom, 1956; Brown, 1948, 1962; Clark, 1966; Delimata, 1969; Denson and Gill, 1956, 1965; Fisher, 1953; Haines, 1958; Herald, 1913; Leonard and Smith, 1909; Leonard and others, 1925; May, 1954; Meldahl, 1956; Pishel, 1912; Royse, 1967, 1970). The sedimentologic work concerned with the origin of the Sentinel Butte Formation is that of Cherven (1973), Jacob (1976), Johnson (1973), and Royse (1970).

Distribution

Carlson (1969) mapped the Sentinel Butte Formation throughout western North Dakota, but the formation has not been reliably mapped outside of the State. It is the most widespread near-surface Tertiary formation in North Dakota, existing as bedrock or at the surface over about 75 percent of the North Dakota part of the Williston basin. Its best exposures are in the badlands along the Little Missouri River in Billings, McKenzie, and Dunn Counties, North Dakota, and along the bluffs of Lake Sakakawea (Garrison Reservoir) in Williams, Mountrail, McLean, Mercer, Dunn, and McKenzie Counties, North Dakota.

Contacts

The contact of the Sentinel Butte Formation with the underlying Tongue River Formation is widely exposed and distinctive. The upper contact of the Sentinel Butte is well exposed only in isolated buttes. Between the buttes the top of the Sentinel Butte is an erosion surface over most of the basin, but it is difficult to determine how much of the formation has been eroded.

In some areas of the axial part of the Williston basin, the Sentinel Butte is conformably overlain by the Golden Valley and the contact is difficult to pick. In peripheral parts of the basin, the Sentinel Butte is disconformably overlain by the White River Group, and a well-developed paleosol is present at the top of the Sentinel Butte. This paleosol is exposed in isolated buttes such as Sentinel, Bullion, HT, and White Buttes.

Thickness

Royse (1970, p. 26) reports that the Sentinel Butte Formation, like the Tongue River Formation, is about 75 to 100 m thick along the southern and western flanks of the Williston basin, and it thickens to about 200 m toward the center of the basin. An isopach map of the Sentinel Butte is not presented because of the poor quality data that is available.

Lithology

General

Sandstone, siltstone, claystone, lignite, and limestone make up the Sentinel Butte Formation. As in the case of the Tongue River Formation, well-cemented sediment is rare, but the formation as a whole is more consolidated than the Tongue River. Most cement in the formation is carbonate, but some iron-oxide cement is present. Iron-oxide concretions are present, but they are darker colored and more of them are maroon than in the Tongue River.

Sandstone

Visual estimates in the field indicate that sandstone makes up about 30 percent of the formation. The sandstone weathers darker gray than in the Tongue River Formation, and there is almost no yellow-brown. It weathers into steeper slopes than on the Tongue River, and the slopes show closely spaced, deep, straight, almost vertical rills that join to form peculiar inverted-V-shaped patterns (fig. 23). Caves are common as are modern drying cracks, which are caused by the expansion and contraction during wetting and drying of the abundant montmorillonitic clay in the formation.

It is not yet possible to construct a map of sandstone distribution in the Sentinel Butte Formation because of a lack of data and the poor quality of much of the data that does exist. Sandstone in the Sentinel Butte is coarser than in the Tongue River in many places, but even medium sand is not common. So

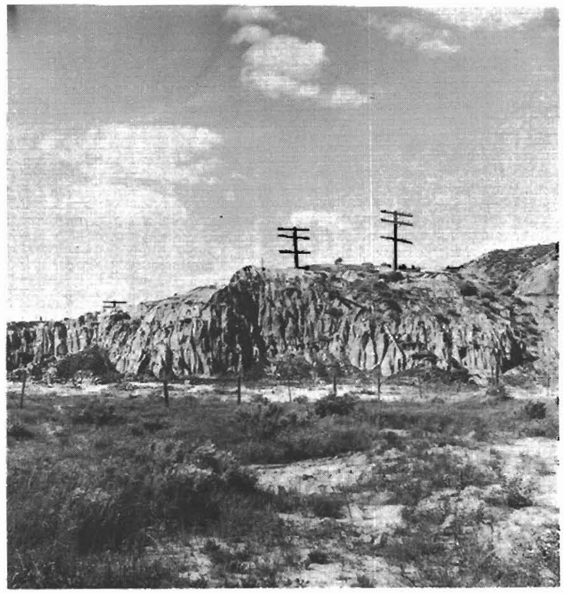

Figure 23. Sandstone bed in the Sentinel Butte Formation about 10 km west of Fryburg, Billings County, North Dakota. Surface slopes are steeper than in the Tongue River Formation, and the surface is more irregular. Steep-sided, straight gulleys that intersect to form inverted-V patterns are almost never present in the Tongue River Formation. Dark colored talus slopes are well-cemented purple, dark brown, and maroon concretions that have rarely been observed in the Tongue River Formation. Compare with Ludlow Formation in figure 30 (from Jacob, 1975a).

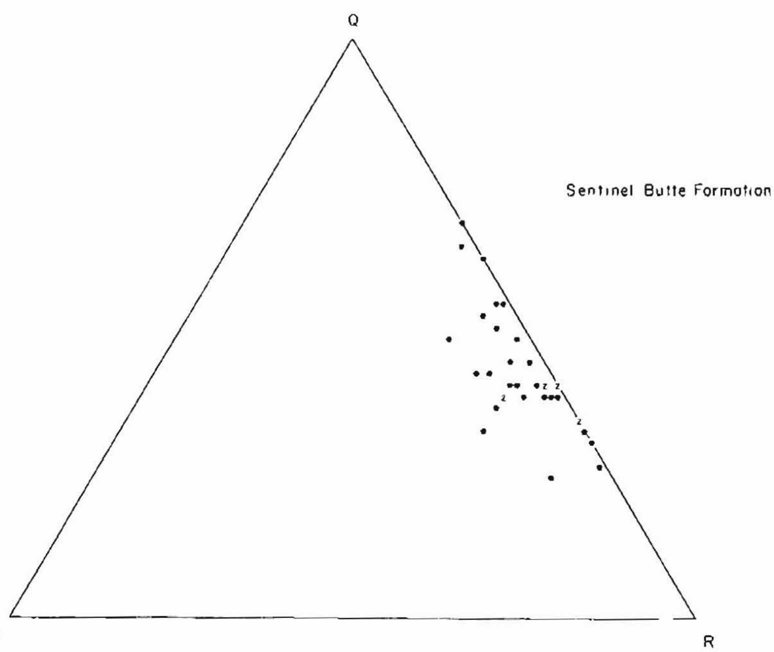

Figure 24. Triangular plot of main components of sandstone of the Sentinel Butte Formation based on thin-section analyses. Q, quartz; F, feldspar; R, rock fragments. Computation and plotting of values by same method as in figure 8 (from Jacob, 1975a).

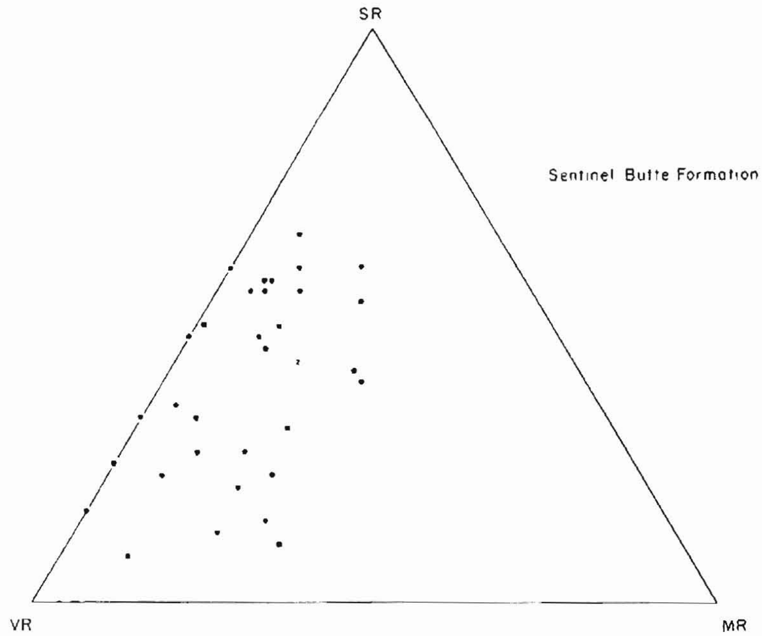

Figure 25. Triangular plot of rock fragments in sandstone of the Sentinel Butte Formation based on thin-section analyses. SR, sedimentary-rock fragments; VR, volcanic-rock fragments; MR, metamorphic-rock fragments. Computation and plotting of values by same method as in figure 8 (from Jacob, 1975a).

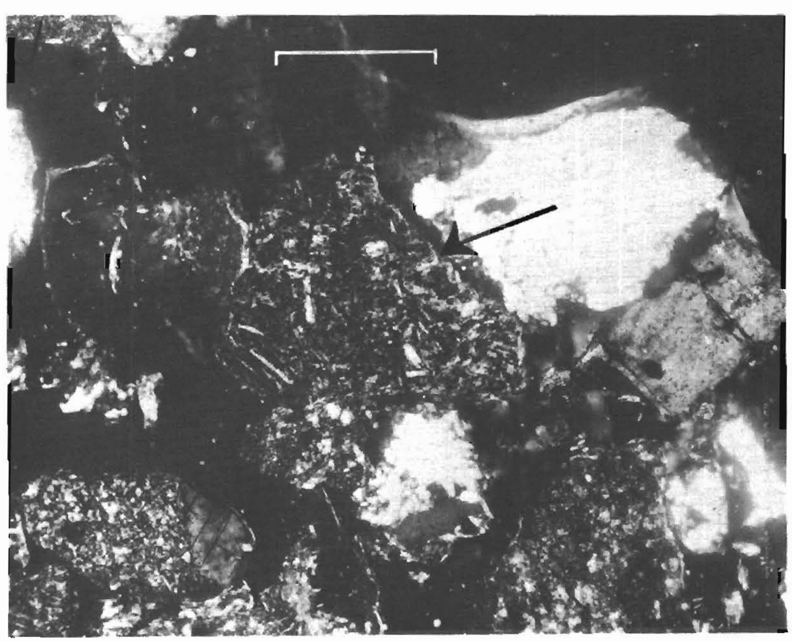

Figure 26. Photomicrograph of thin section of sand from the Sentinel Butte Formation. Arrow indicates fragment of volcanic rock. Bar is 0.2 mm long. Crossed nicols.

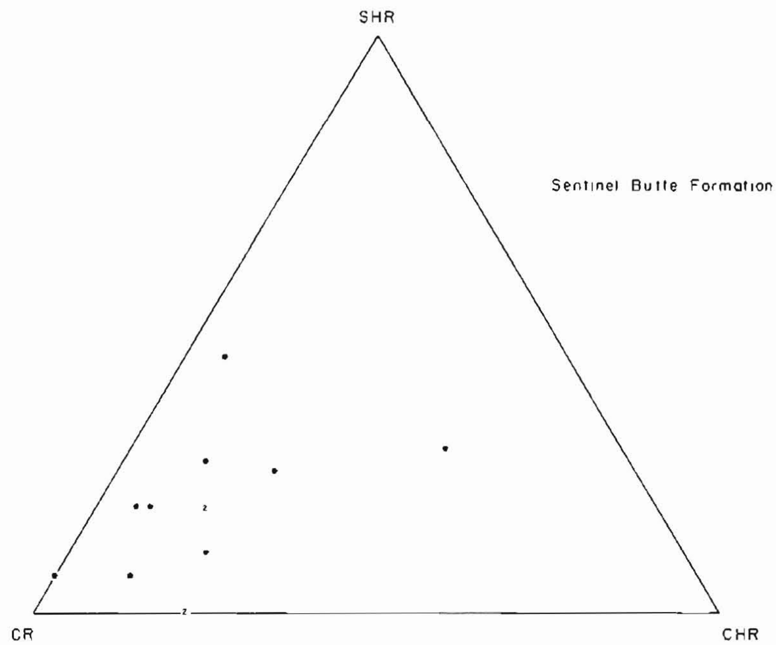

Figure 27. Triangular plot of sedimentary-rock fragments in samples of sandstone of the Sentinel Butte Formation based on thin-section analyses. SHR, shale-rock fragments; CR, carbonate-rock fragments; CHR, chert-rock fragments. Computation and plotting of values by same method as in figure 8 (from Jacob, 1975a).

permeabilities in the Sentinel Butte probably are not much higher than in the Tongue River.

Jacob (1975a) petrographically analyzed 48 samples of sandstone from the Sentinel Butte Formation collected from throughout the Williston basin. These analyses show that feldspar is rare in sandstone of the Sentinel Butte, and rock fragments are abundant (fig. 24). This indicates a supracrustal rather than a plutonic source for this formation also.

Volcanic rocks were the most abundant type in the source area, sedimentary rocks were fairly abundant, and metamorphic rocks were present (fig. 25). The abundant volcanic-rock content of the Sentinel Butte (fig. 26) has not been generally recognized, but it is important in that it provides a ready source for uranium.

In the case of the Sentinel Butte Formation, carbonate rocks make up a greater portion of the sedimentary rocks than shale or chert (fig. 27). The carbonate-rock fragments in the thin sections have the same clastic characteristics as those in the Tongue River Formation. In the Sentinel Butte carbonate-rock fragments make up a smaller proportion of the total sandstone than in the Tongue River. Royse (1970) found that the acid-soluble carbonate in the Sentinel Butte is less than in the Tongue River (fig. 11), and this is probably because of the smaller amount of clastic carbonate grains in the sandstone.

Because of the abundant volcanic-rock fragments most samples of sandstone from the Sentinel Butte classify as volcanic litharenite according to the scheme of Folk, Andrews, and Lewis (1970). The samples were classified by the FORTRAN program FOLKSS (Jacob, 1975b).

Siltstone and claystone

Siltstone and claystone make up about 65 percent of the Sentinel Butte Formation, and they weather mostly medium gray and medium to light brown. Emanuel, Jacob, and Karner (1975) analyzed the mineralogy of the clay-size fraction of seven samples of the Sentinel Butte near Medora, Billings County, North Dakota. They found that the three groups of clay minerals present in greatest abundance are, in decreasing order of abundance: (1) the montmorillonite-group minerals, (2) the kaolinite-group minerals, possibly principally dehydrated halloysite, and (3) the mica-group minerals, principally muscovite with some biotite and illite. A small amount of chlorite is also present in most samples. Non-clay minerals that are present are quartz, dolomite, calcite, and feldspar.

It is evident that the same clay minerals are present in both the Sentinel Butte and Tongue River Formations, but montmorillonite-group minerals are most abundant in the Sentinel Butte, whereas mica-group minerals are most abundant in the Tongue River, at least in the Medora area. More work is needed to see if these differences in clay mineralogy persist outside of the Medora area, but preliminary work indicates that they do. The clayey units of the Sentinel Butte weather to a popcorn-like texture on the surface in many areas suggesting the presence of abundant montmorillonite outside the Medora area. The abundant montmorillonite coincides with the abundant volcanic-rock fragments in the sandstone because montmorillonite may form by the alteration of volcanic ash.

These data show that during deposition of the Sentinel Butte, there was a larger input of volcanic matter than during deposition of the Tongue River. This volcanic matter could have served as a source for the uranium in the Sentinel Butte, and it probably is this volcanic matter that gives the Sentinel Butte its peculiar weathering characteristics described above. Also, amorphous silica, which is more soluble than crystalline silica, is abundant in volcanic-rock fragments from which it may be released during weathering, and it may be released during the alteration of volcanic ash to montmorillonite, at the same time that uranium may be released (Waters and Granger, 1953). So silicified wood is more abundant in the Sentinel Butte Formation than in the Tongue River Formation, but it is not known to what extent the silicified wood of the Sentinel Butte is uraniferous.

Lignite

Ting (1972a, 1972b, 1973, 1974) reviewed the petrography of lignite in North Dakota. He did not differentiate between lignite from the Tongue River and Sentinel Butte Formations, but it is likely that most of his samples came from the Sentinel Butte Formation, where lignite makes up only a few percent of the formation. An interesting and useful study would be a comparison of the petrology and chemistry of the lignite of the two formations as it relates to the depositional environment of each formation.

Lignite from North Dakota has a low sulfur content of 0.1-1.9 percent, and an average sulfur content of 0.6 percent (Ting, 1972b). The sulfur occurs as iron sulfide or organic sulfur. The three major petrographic components of North Dakota lignite are vitrinite, resinite, and fusinite (Ting, 1972b). In transmitted light, vitrinite is orange to brownish red and it may or may not show cell structure; resinite is yellow to orange and occurs as small bodies of various shapes; and fusinite is opaque and shows well-defined cell structure (International Committee for Coal Petrology, 1963).

Unfortunately, there are not many data on relative abundances of these components. In two samples from near Underwood, McLean County, North Dakota, vitrinite made up 80 percent of the samples and resinite and fusinite made up the rest (Ting, 1972b). Schopf and Gray (1954) found that there is no apparent correlation between uranium content and the petrologic constituents of coal. However, they did find that the samples richest in uranium contain relatively large amounts of humic matter, which results from decomposition of plant materials. Of course, not all samples rich in humic matter are rich in uranium.

Ting (1972a, 1973) reported that silicified peat from a lignite bed in the lower part of the Sentinel Butte Formation southeast of Medora, Billings County, North Dakota, and from a lignite bed in the Tongue River Formation (?) near Center, Oliver County, North Dakota, contains well-preserved conifer stems, twigs, roots, and leaves. Also present are various seeds, pollen grains and spores, spore cases (sporangia) of ferns, and tissue of unidentified higher plants. There are abundant pollen grains of angiosperms, but little angiosperm wood.

Limestone

Limestone lenses occur in the Sentinel Butte Formation, but they are rarer than in the Tongue River. Probably this is because carbonate is rarer in the Sentinel Butte, and so there was less carbonate in the groundwater that flowed into shallow surface pools in which the limestone precipitated. The limestone lenses have characteristics similar to the limestone lenses in the Tongue River Formation.

Depositional Environments

Similarities with Tongue River Formation

Sedimentological work concerned with the depositional environments of the Sentinel Butte Formation is that of Cherven (1973), Jacob (1975d), Johnson (1973), and Royse (1970). This work showed that the Sentinel Butte, as the Tongue River, was deposited in a fluvial environment.

The units of claystone and siltstone that weather mostly gray are flood basin deposits (fig. 12), as indicated by the abundant twigs, leaves, rootlets, and stumps, distorted and irregular laminae, small-scale sets of cross strata, gray color, freshwater gastropods and pelecypods, tabular shape, and association with channel sandstone. The sediment may have been deposited largely in swamps, marshes, or lakes, but large tree stumps in growth position indicate swamps rather than marshes. Lignite beds are present within these units.

Units of clayey siltstone and sandstone weather mostly tan or brown. They are poor in organic matter, but tree stumps occur in growth position. They contain horizontal laminae, distorted laminae, small-scale sets of cross strata, and climbing-ripple cross strata that climb at high angles. These characteristics (particularly the last one) are typical of natural-levee and crevasse-splay deposits.

Both the elongate, trough-shaped sandstone beds and elongate, tabular sandstone beds that are present in the Tongue River Formation are present in the Sentinel Butte (pls. 1, 2). Both kinds of sandstone beds channel into the surrounding sediment, and paleocurrents are oriented parallel to the long axes of the sandstone beds (fig. 28). These data clearly indicate a fluvial origin for the sandstone beds. As in the Tongue River Formation, the elongate, trough-shaped sandstone beds are low-sinuousity, probably non-braided stream deposits, and the elongate, tabular sandstone beds are high-sinuosity stream deposits.

Both types of sandstone beds tend to be stacked (pls. 1, 2), and elongate concretions are oriented parallel to the long axes of both types.

The tan or brown units of clayey siltstone and sandstone (natural-levee and crevasse-splay deposits) discussed above may be either wedge-shaped or tabular. The wedge-shaped deposits border the elongate, trough-shaped sandstone beds with their thin edges away from the sandstone beds (pl. 1), and the tabular units commonly either overlie, or are adjacent to, tabular sandstone beds (pl. 2). These relationships are typical of natural-levee and crevasse-splay deposits associated with low- and high-sinuosity stream deposits (Moody-Stuart, 1966).

Differences from Tongue River Formation

Elongate, tabular sandstone beds in the Sentinel Butte Formation are thicker (as much as 30 m thick), wider (more than 2 km wide in many places), more abundant, and they contain more abundant curved sets of cross strata than the elongate, tabular sandstone beds in the Tongue River Formation (pls. 1, 2; fig. 28). This indicates that high-sinuosity streams were more abundant, deeper, and occupied wider meander belts where the Sentinel Butte Formation was deposited than where the Tongue River Formation was deposited. High-sinuosity streams generally are more characteristic of the upper (landward) parts of the delta plain (Fisher and others, 1969), so the Sentinel Butte Formation probably was deposited further landward on the delta plain than the Tongue River Formation.

Lignite beds in the Sentinel Butte Formation appear to be generally less continuous than in the Tongue River Formation. This indicates that the lignite beds of the Sentinel Butte were deposited

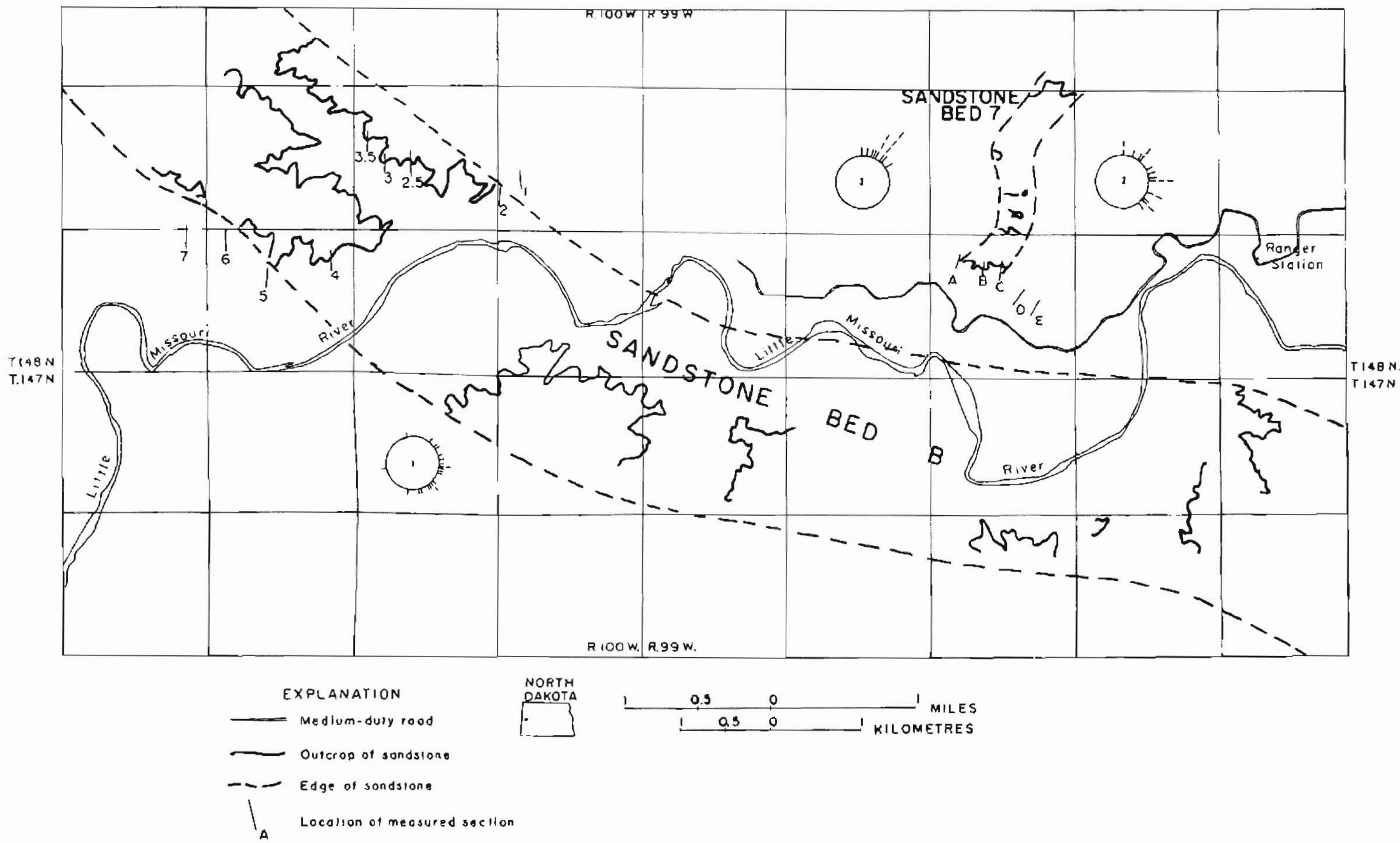

Figure 28. Map of elongate, trough-shaped, sandstone bed (sandstone bed 1) shown in plate 1, and elongate, tabular, sandstone bed (sandstone bed B) shown in plate 2. Letters indicate measured sections shown in plate 1, numbers indicate measured sections shown in plate 2. Circular diagrams 1 and 2 show dip directions of foresets in large-scale, curved sets of cross strata in sandstone bed B and sandstone bed 1, respectively. Circular diagram 3 indicates orientations of elongate concretions in sandstone bed 1. Each tick on circular diagram is one measurement. Map is in the area of the North Unit, Theodore Roosevelt National Memorial Park, McKenzie County, North Dakota. Modified from Cherven (1973, figures 7 and 13).

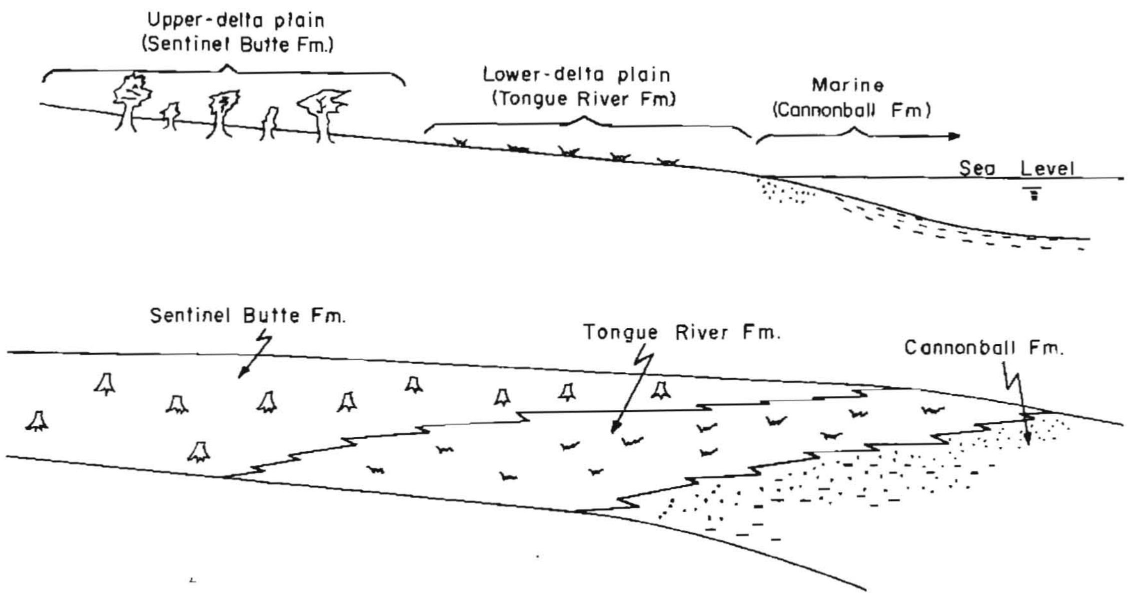

Figure 29. Hypothetical model for the origin of the Cannonball, Tongue River, and Sentinel Butte Formations by seaward building of a delta.

in flood basins that were less widespread than the flood basins in which the lignite beds of the Tongue River Formation were deposited. This further shows that the Sentinel Butte was deposited further landward on the delta plain than the Tongue River Formation, where flood basins would be narrow.

Marker Beds

Lignite beds do not generally serve as marker beds in the Sentinel Butte Formation (fig. 22), because of the variability of the lignite beds (pl. 3). The basal sandstone bed is not present in some places. It probably is a lateral-accretion deposit that formed in high-sinuosity streams, and the streams were present only where the sandstone bed is now found.

The two yellow beds (fig. 22) consist mostly of calcareous siltstone, and the blue bed consists mostly of montmorillonitic claystone. These three beds are readily visible in the north wall of the trench of the Little Missouri River where viewed toward the north from U.S. Highway 85, and they are most readily visible in the afternoon sun.

Clark (1966) mapped the two yellow beds and the blue bed in a limited area of McKenzie County, North Dakota. S. G. Stancel (unpubl. report) mapped the three beds in the trench of the Little Missouri River in McKenzie and Dunn Counties, North Dakota. The three units are continuous, mappable units, except where they were eroded and replaced by sandstone beds (pl. 3). No attempts have yet been made to establish criteria for identifying the three units in the subsurface.

STRATIGRAPHIC RELATIONSHIPS BETWEEN THE CANNONBALL, TONGUE RIVER, AND SENTINEL BUTTE FORMATIONS

The open-marine and shoreline deposits of the Cannonball Formation are conformably overlain by the Tongue River Formation, which was deposited on a lower deltaic plain, but in some places the contact may be disconformable. Conformably overlying the Tongue River Formation is the Sentinel Butte Formation, which was deposited on an upper deltaic plain.

These relationships suggest that the three formations formed by seaward building of a large delta during submergence (fig. 29) and that time surfaces cross through the three formations, but no stratigraphic work has been done to locate ash beds or fossil occurrences that might mark such surfaces. In fact, there are no published stratigraphic cross sections of the Tertiary rocks of the Williston basin based on subsurface data.

URANIUM OCCURRENCES

General

Uranium occurrences in the Williston basin have been described by Bergstrom (1956), Beroni and Bauer (1952), Denson, Bachman, and Zeller (1959), Denson and others (1955), Denson and Gill (1956, 1965), Gill (1959), Gill, Zeller, and Schopf (1959), Haines (1958), King and Young (1956), Moore, Melin, and Kepferle (1956), Noble (1972, 1973), Pipiringos, Chisholm, and Kepferle (1965), Towse (1957), U.S. Atomic Energy Commission (1956), Vine (1962), Wyant and Beroni (1950), and Zeller and Schopf (1959). The following discussion is based on these references. Denson and Gill (1965) provided an excellent summary of the uranium occurrences in the Williston basin, exclusive of the Cave Hills area, which was described by Pipiringos, Chisholm, and Kepferle (1965).

Descriptions of uranium deposits in the Williston basin are also in the semiannual progress reports on geologic investigations of radioactive deposits conducted by the U.S. Geological Survey and published by the U.S. Atomic Energy Commission Technical Information Service between 1953 and 1958 (see bibliography in Denson and Gill, 1965); most of the information in these reports is published in the references cited in the previous paragraph.

Lignitic shale or impure lignite contains most of the uranium deposits discovered in the Williston basin, but there are a few minor uranium occurrences in claystone, siltstone, or sandstone. It is not clear why so few uranium deposits have been found in sandstone in the basin. Perhaps the abundant lignite in the Tertiary rocks in the basin caused immobilization of most uranium in solutions passing through the rocks, and a lack of pyrite in the sandstone may have been another factor.

All known significant deposits occur less than 100 m below the unconformity at the base of the Oligocene or Miocene rocks where it exists today or where it existed before the Oligocene and Miocene rocks were eroded away; most significant deposits are less than 65 m below this surface (Vine, 1962, p. 141-142). This has suggested to most workers that the volcanic matter in the Oligocene and Miocene rocks served as the main source of the uranium. However, it has not been recognized that some formations just below this unconformity contain abundant volcanic matter, and weathering may have occurred mobilizing uranium from these formations which was then precipitated below the unconformity before deposition of the Oligocene and Miocene rocks.

Where a thick sandstone bed is directly adjacent to a carbonaceous host rock, the uranium content of the host generally is greater than where a sandstone bed is absent. This suggests that percolating groundwater may have transported uranium dissolved from overlying formations and (or) the sandstone itself.

In some cases the uranium content in a lignite bed decreases downward, indicating a downward flow of uranium-bearing solutions. In other cases uranium-rich zones may occur at any horizon within a bed, indicating lateral migration of uranium-bearing solutions (King and Young, 1956; Pipiringos, Chisholm, and Kepferle, 1965).

Denson and Gill (1956) pointed out that many high-grade uranium deposits in the Williston basin occur in areas where springs contain 30 ppb uranium or more. The same authors showed that the known uranium deposits are aligned about north-south along the axis of the structurally lowest part of the Williston basin (1965, pl. 5).

Areas of Important Reserves

Little Missouri River escarpment

The important reserves of ore-grade uraniferous lignite containing more than 0.1 percent uranium are in the North Cave Hills and Slim Buttes area, Harding County, South Dakota, and in the areas of the Little Missouri River escarpment in eastern Billings and northwestern Stark Counties, North Dakota. In the Little Missouri River escarpment area the uranium deposits occur in lignite beds in the Sentinel Butte Formation. The beds commonly underlie tabular sandstone beds, which appear to be lateral-accretion, point-bar deposits of the type described in the section on depositional environments of the Sentinel Butte Formation. The sandstone beds themselves probably served both as a source of the uranium and as aquifers for solutions transporting uranium from the overlying Oligocene and Miocene formations.

Denson and Gill (1965) described the deposits of the Missouri River escarpment area in some detail, so a detailed description is not given here. The sample with the highest uranium content in the area (0.7 percent uranium) appears to be from a carbonaceous shale in sec 7, T141N, R99W, Billings County (Denson and Gill, 1965, pl. 8).

North Cave Hills and Slim Buttes

King and Young (1956) and Pipiringos, Chisholm, and Kepferle (1965) reported that the deposits of the North Cave Hills are in the Tongue River Formation, but a visit to this area showed that the deposits are in the Ludlow Formation. The color of the formation is darker than the Tongue River Formation, and its weathering characteristics (fig. 30) are similar to those of the Sentinel Butte Formation, which is typical of the Ludlow.

Examination of 13 thin sections showed an abundance of fragments of volcanic rock, which indicates a partial volcanic source for the formation. Point counts of five of the thin sections showed an average content of 17 percent volcanic-rock fragments, with a maximum of 19 percent and a minimum of 14 percent. This is too high for the Tongue River Formation.

Table 1 shows that the montmorillonite (smectite) content of five samples of clay-size material from the formation averages 76 percent. This also is much too high for the Tongue River Formation, and it further indicates a volcanic source.

Interbedded with the Ludlow (previously called Tongue River) are three previously unrecognized tongues of the Cannonball Formation, the lowermost of which is sand bed E of Pipiringos, Chisholm, and Kepferle (1965). It forms the topographically distinct rim of the North Cave Hills, and it directly underlies the major uranium-bearing bed in the area, coal bed E of Pipiringos, Chisholm, and Kepferle (1965). The next higher tongue of the Cannonball is the sand bed at about 700 feet above the base of the composite section of Pipiringos, Chisholm, and Kepferle (1965, fig. 2), and the highest tongue of the Cannonball is at the top of the Paleocene in the same measured section. The three tongues are darker yellow brown than the Tongue River Formation; each is about 17-22 m (50-65 ft.) thick.

The lowest of the three tongues (fig. 30) was found to become coarser grained toward the top (fig. 31), and it contains abundant low-angle, straight cross strata (fig. 32). Pipiringos, Chisholm, and Kepferle (1965, p. 10) report that there are remains of sharks and other fishes in a thin (1 m or less) shale bed at the base of the sand bed, and these fossils indicate a marine or brackish environment.

These data indicate that a marine transgression took place during which the shale bed was deposited. The sand bed then was deposited during regression of the shoreline toward the east. The abundant, low-angle, straight cross strata are typical of shoreline deposits, and regressive shoreline deposits become coarser upward (Reineck and Singh, 1973, fig. 462). The thickness of the sand bed (20 m) was about the water depth at the sand-mud transition in the sea in which the sand bed was

Table 1. Analyses of clay-size fraction of Ludlow Formation (previously reported incorrectly as Tongue River Formation), North Cave Hills, Harding County, South Dakota.

[Analyses performed by Materials Evaluation Laboratory, 4275 Perkins Road, Baton Rouge, La., using the X-ray diffraction method of Griffin (1971).]

	WEIGHT PERCENT		
Sample No.	Kaolinite and chlorite	Illite	Smectite
L 10-13-2	0	1	99
L 10-13-4	0	5	95
L 10-13-6	3	12	85
L 10-17-4	9	36	55
L 10-17-7	28	27	45
	Average 8	16	76

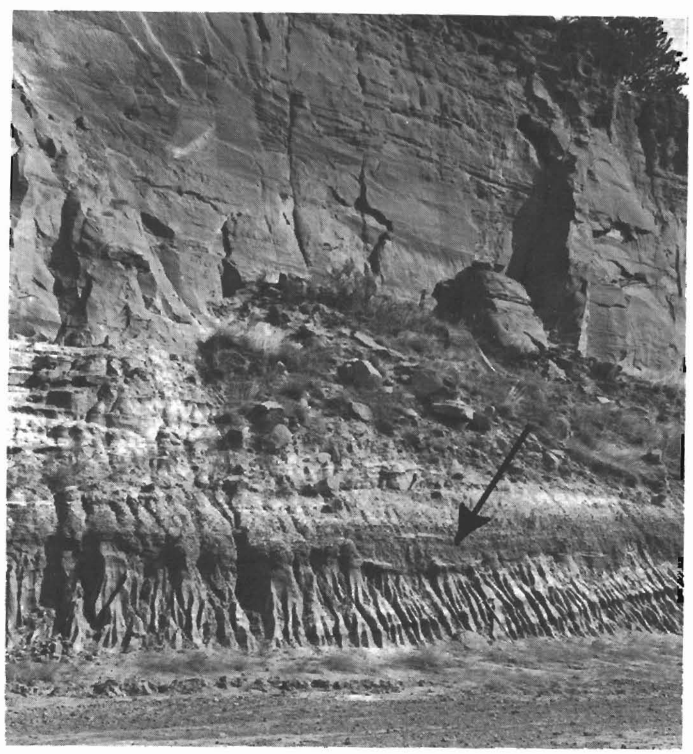

Figure 30. Lowest tongue of the Cannonball Formation in Ludlow Formation at South Riley Pass, North Cave Hills, South Dakota. Arrow shows marine shale at base of the tongue. Deep vertical rills are on Ludlow Formation; compare with Sentinel Butte Formation in figure 23. View toward east. Pick at bottom right is 0.9 m long.

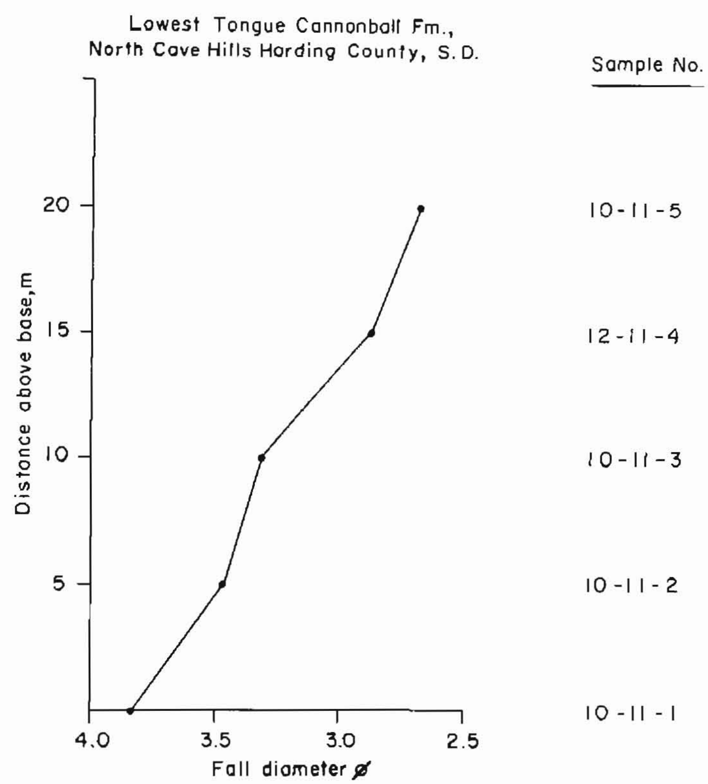

Figure 31. Vertical distribution of grain size, lowest tongue of Cannonball Formation at South Riley Pass, North Cave Hills, Harding County, South Dakota.

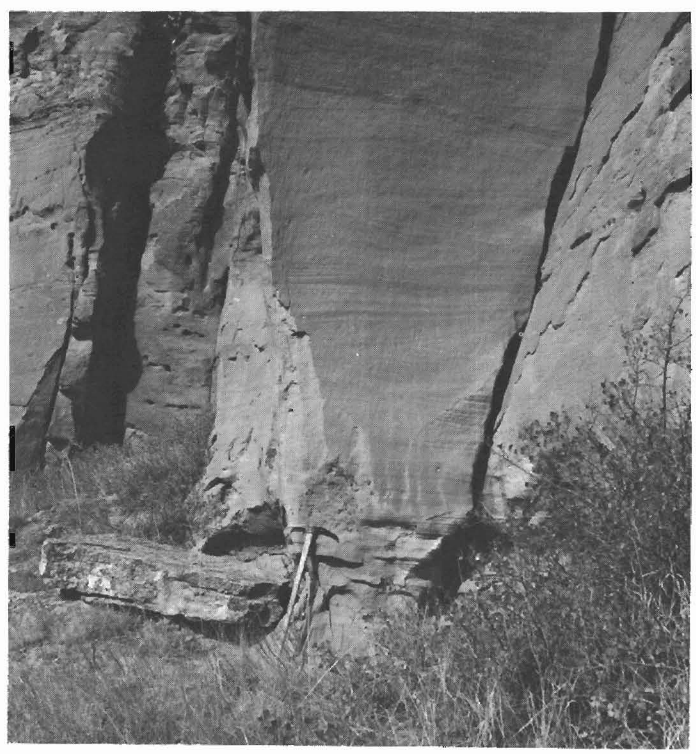

Figure 32. Low-angle, straight cross strata in the lowest tongue of the Cannonball Formation, South Riley Pass, North Cave Hills, Harding County, South Dakota.

deposited (Klein, 1974). The sand bed could not have been formed by lateral accretion in a high-sinuosity stream because such a deposit becomes finer toward the top, and, if it were fluvial, it should contain more abundant curved sets of cross strata (Allen, 1970b).

The three tongues of the Cannonball, being shoreline deposits, probably served as good aquifers for groundwater that percolated through the section. The lateral continuity of the tongues may have favored lateral rather than vertical movement of groundwater. King and Young (1956) suggested that uranium-bearing groundwater probably moved mostly laterally in the area because there are four barren lignite beds overlying the most uraniferous bed. Also, the uranium content does not decrease downward in a bed, and there is no preferred horizon for the most uraniferous part of a lignite bed.

Like the deposits in North Cave Hills, the deposits in Slim Buttes are in the Ludlow Formation. So the three areas that contain important reserves of ore-grade uraniferous lignite (Little Missouri River escarpment, North Cave Hills, and Slim Buttes) are in formations that appear to contain significant amounts of volcanic matter. Denson and Gill (1965) have described the uranium deposits in Slim Buttes.

Form of Uranium

Unweathered uranium deposits in coaly rocks generally contain no visible uranium minerals, even in rock with as much as 1 percent uranium (Vine, 1962, p. 146). If visible uranium minerals are present, they are the result of weathering processes that redistributed uranium originally disseminated in unweathered carbonaceous matter. Table 2 shows that the uranium minerals in the coaly carbonaceous rocks of the Williston basin include nine phosphates, and a few oxides, arsenates, and vanadates. Denson and Gill (1965, p. 30) stated that meta-autunite, meta-tyuyamunite, and abernathyite are the most common uranium minerals in the Williston basin.

Source of Uranium

Until now many, if not most, workers have considered that the Oligocene, Miocene, and Pliocene sediments that contain volcanic debris were the main source of the uranium deposits in the Williston basin (Denson and Gill, 1965; Vine, 1962). It is thought that the uranium was precipitated from groundwater solutions by carbonaceous matter following coalification (Vine, 1962, p. 150).

Denson and Gill (1965, table 8) analyzed the uranium content of the "tuffaceous rocks" of the Chadron, Brule, Arikaree, and Flaxville Formations. The lower Chadron Formation ("Oligocene arkosic rocks") had uranium detected in only a few samples. Nine samples of the upper Chadron Formation and the Brule Formation ("Oligocene rocks") had an average uranium content equal to the average crustal abundance (0.0002 percent), a low value. Nineteen samples of the Arikaree Formation ("Miocene rocks") had an average uranium content of 0.0005 percent, a value 2.5 times the average crustal abundance. Five samples of the Flaxville Formation ("Upper Miocene and Pliocene rocks") had an average uranium content of 0.00055 percent, a value almost three times the average crustal abundance.

These data suggested to Denson and Gill (1965) that the Arikaree and Flaxville Formations may have been the main uranium source, but the data certainly do not eliminate the Chadron and Brule as possible sources. Denson and Gill (1965, p. 29) stated that the highest grade uranium ore occurs where the Chadron and Brule are absent beneath the Arikaree, as at Slim Buttes, South Dakota. However, at the Little Missouri River escarpment area in North Dakota, the Chadron and Brule very likely were present below the Arikaree before all three formations were eroded away; and this area is one of the three areas containing the highest-grade uranium deposits in the Williston basin.

Besides the Oligocene and younger sediments, the rocks that directly surround

Table 2. Uranium minerals in coaly carbonaceous rocks, Williston basin.

[Data from Vine (1962, Table 14) and Denson and Gill (1965, p. 30).]

Mineral	Formula
Oxides	
Uraninite	UO_2
Becquerelite	$7UO_3 \cdot 11H_2O$
Silicates	
Coffinite	$U(SiO_4)_{1-x}(OH)_{4x}$
Uranophane	$Ca(UO_2)_2Si_2O_7 \cdot 6H_2O$
Phosphates	
Autunite	$Ca(UO_2)_2(PO_4)_2 \cdot nH_2O$
Meta-autunite	$Ca(UO_2)_2(PO_4)_2 \cdot nH_2O$
Sodium-autunite	$Na_2(UO_2)_2(PO_4)_2 \cdot 8H_2O$
Hydrogen-autunite	$H_2(UO_2)_2(PO_4)_2 \cdot 8H_2O$
Meta-uranocircite	$Ba(UO_2)_2(PO_4)_2 \cdot 8H_2O$
Saleeite	$MG(UO_2)_2(PO_4)_2 \cdot 8\text{-}10H_2O$
Metatorbernite	$Cu(UO_2)_2(PO_4)_2 \cdot 12H_2O$
Bassetite	$Fe(UO_2)_2(PO_4)_2 \cdot 8H_2O$
Sabugalite-saleeite	$(HA1, Mg)_{1-2}(UO_2)_4(PO_4)_4 \cdot 16H_2O$
Arsenates	
Abernathyite	$K_2(UO_2)_2(AsO_4)_2 \cdot 8H_2O$
Metazeunerite	$CU(UO_2)_2(AsO_4)_2 \cdot 8H_2O$
Novacekite	$MG(UO_2)_2(AsO_4)_2 \cdot 9H_2O$
Metanovacekite	$Mg(UO_2)_2(AsO_4)_2 \cdot 8\text{-}10H_2O$
Vanadates	
Carnotite	$K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$
Metatyuyamunite	$Ca(UO_2)_2(VO_4)_2 \cdot 3\text{-}5H_2O$

the lignite beds that contain the ore are another possible source of uranium. Clay-mineral data and quantitative petrologic data from the Sentinel Butte Formation show an abundance of volcanic matter, and the Sentinel Butte contains the richest uranium deposits in North Dakota. Data from the Ludlow Formation in the North Cave Hills, South Dakota, also indicate the presence of volcanic matter, and the Ludlow contains the richest uranium deposits outside of North Dakota. The Tongue River Formation has little volcanic matter and it contains little discovered uranium.

It seems likely that volcanic matter in

the formations that contain uranium ore could have served as the additional source of uranium necessary to make the formations ore bearing, and in at least some, if not most, cases the volcanic matter in the uranium-bearing formations may have served as the main source of the uranium. At least some of the uranium may have been released during devitrification of glassy volcanic matter following deposition, and the devitrification could have formed the montmorillonite observed in the uranium-bearing formations (Waters and Granger, 1953). Mobilization of the uranium may have occurred, for the most part, during the formation of the Eocene paleosol of Pettyjohn (1966).

Uranium Reserves

Surface and subsurface data are not available to obtain a good estimate of the uranium reserves in the Williston basin. Denson and Gill (1965, p. 64) estimate that the probable reserves of rock with greater than 0.1 percent uranium are in excess of 1 million tons. Much of the uranium-bearing rock in the Williston basin is near the surface, so it may be mined by stripping methods.

FUTURE EXPLORATION

Tongue River Formation

Throughout most of the Williston basin, the Tongue River Formation lies further below the restored pre-Oligocene unconformity (Eocene paleosol) than the Sentinel Butte Formation, so it is a less favorable exploration target for uranium than the Sentinel Butte. Only around the flanks of the basin, where the Sentinel Butte has been eroded away, does it occur close to the restored pre-Oligocene unconformity. It is here that uranium is most likely to occur because it is here that the Tongue River is closer stratigraphically to where possible uranium-source rocks were before they were eroded, and it is here that weathering of the formation (which could have mobilized uranium) may have occurred during development of the unconformity.

Volcanic-rock fragments and montmorillonitic clay are less abundant in the Tongue River than in the Sentinel Butte, indicating less input of volcanic debris during deposition. This also makes the Tongue River a less favorable uranium-exploration target than the Sentinel Butte. It is possible that the volcanic matter of the Sentinel Butte served as a source for uranium in the Tongue River in the more central parts of the basin, but this possibility seems unlikely.

Boardman and others (1956) showed that the long axes of uranium-ore bodies are parallel to paleocurrent indicators and long axes of sandstone beds in the Uravan district, Colorado. Meschter (1958) found a direct relationship between the trends of the distribution of uranium deposits and long axes of elongate concretions in the Monument Hill area, southern Powder River Basin, Wyoming. These two studies indicate that if uranium were discovered in the sandstone beds of the Tongue River Formation, mapping elongate concretions on air photos would be a useful approach to uranium exploration in the Tongue River.

Sandstone bodies in the Tongue River Formation generally are much narrower and less abundant than those in the Sentinel Butte, so they are more difficult to locate. Therefore, uranium ore in sandstone will be more difficult to locate in the Tongue River. Maps of sandstone distribution based on subsurface data should be helpful, but the lack of a subsurface stratigraphic framework for the Tertiary rocks of the Williston basin is a great hindrance to this approach, as is the poor quality and low quantity of subsurface data.

One factor that favors exploration for uranium in the Tongue River is its high carbonate content, which should have favored dissolution of uranyl ions. However, in the subsurface both the Tongue River and Sentinel Butte are various shades of gray and green in color. This indicates a lack of strong oxidation, so dissolution of uranium may not have been extensive. Uranium dissolved in groundwater passing through the sandstone bodies should have been precipitated as the solutions contacted the surrounding gray and black siltstone, claystone, and lignite beds. So if uranium is to be discovered in the sandstone bodies of the Tongue River, a likely place is along the flanks of the bodies in areas along the periphery of the basin. Similarly, a likely place to discover uranium ore in gray and black siltstone, claystone, and lignite beds is near sandstone beds in the same region.

Sentinel Butte Formation

Throughout most of the Williston basin the Sentinel Butte Formation is closer to the restored pre-Oligocene unconformity than the Tongue River Formation, and it contains more abundant volcanic-rock fragments and montmorillonitic clay, so it is a more favorable target for uranium exploration than the Tongue River. The Sentinel Butte overlies the Tongue River, so it occurs closer to the earth's surface over most of the basin. As a result, any uranium discovered in the Sentinel Butte will be more accessible for mining.

Sandstone beds are more abundant in the Sentinel Butte and they are wider than in the Tongue River, so uranium ore in sandstone should be easier to locate in the Sentinel Butte. Some carbonate occurs in the formation, although less than in the Tongue River, and it should have aided in the dissolution of uranium.

In the axial part of the Williston basin the Sentinel Butte is conformably overlain by the Eocene Golden Valley Formation, which does not appear to be rich in volcanic matter (Benson, 1954; Freas, 1962; Hickey, 1969, 1972). So the axial part of the basin does not appear to be a particularly likely location for the occurrence of uranium ore in the Sentinel Butte.

Toward the periphery of the basin, however, as at Sentinel Butte, Bullion Butte, and HT Butte, the Golden Valley is thin or absent, and the White River Group rests disconformably on the Sentinel Butte (fig. 5). At many of these places the Eocene paleosol on the Sentinel Butte indicates a long period of weathering before deposition of the White River Group.

The Sentinel Butte is more likely to contain uranium deposits where it contains a paleosol at its top and where it is overlain by the White River Group, or Arikaree or Flaxville Formations, because of two factors. First, the White River, Arikaree, and Flaxville are rich in volcanic matter, which, along with the volcanic matter in the Sentinel Butte itself may have served as a source of uranium that could have been deposited in the Sentinel Butte from groundwater moving downward and laterally. The Arikaree and Flaxville Formations are richer in uranium than the White River Group (Denson and Gill, 1965), so localities where the Arikaree or Flaxville may have directly overlain the Sentinel Butte are good targets for uranium exploration. Second, weathering of the Sentinel Butte during development of the Eocene paleosol may have dissolved uranium from volcanic matter in the Sentinel Butte itself in oxidizing, near-surface groundwater; uranium then may have been deposited in the subsurface in reducing zones. The first factor has been emphasized by most workers in the area (Denson and Gill, 1965); but the second factor has been almost completely overlooked, although it may be the most important one.

One favorable geologic setting in which to search for uranium deposits is under paleosols that developed on ancient topographically high areas where oxidizing groundwater may have flowed away from recharge areas into more reducing environments of adjacent topographically low areas. The Eocene paleosol is a deeply weathered horizon throughout the northern Great Plains (Pettyjohn, 1966), below which particular attention should be given to uranium exploration, especially where rocks that contain volcanic matter are present below the paleosol in areas that were topographically high at the time it formed.

It is difficult to use this paleosol as an exploration guide throughout much of the Williston basin, because it has been eroded away in most areas. One approach would be to explore where the interval between

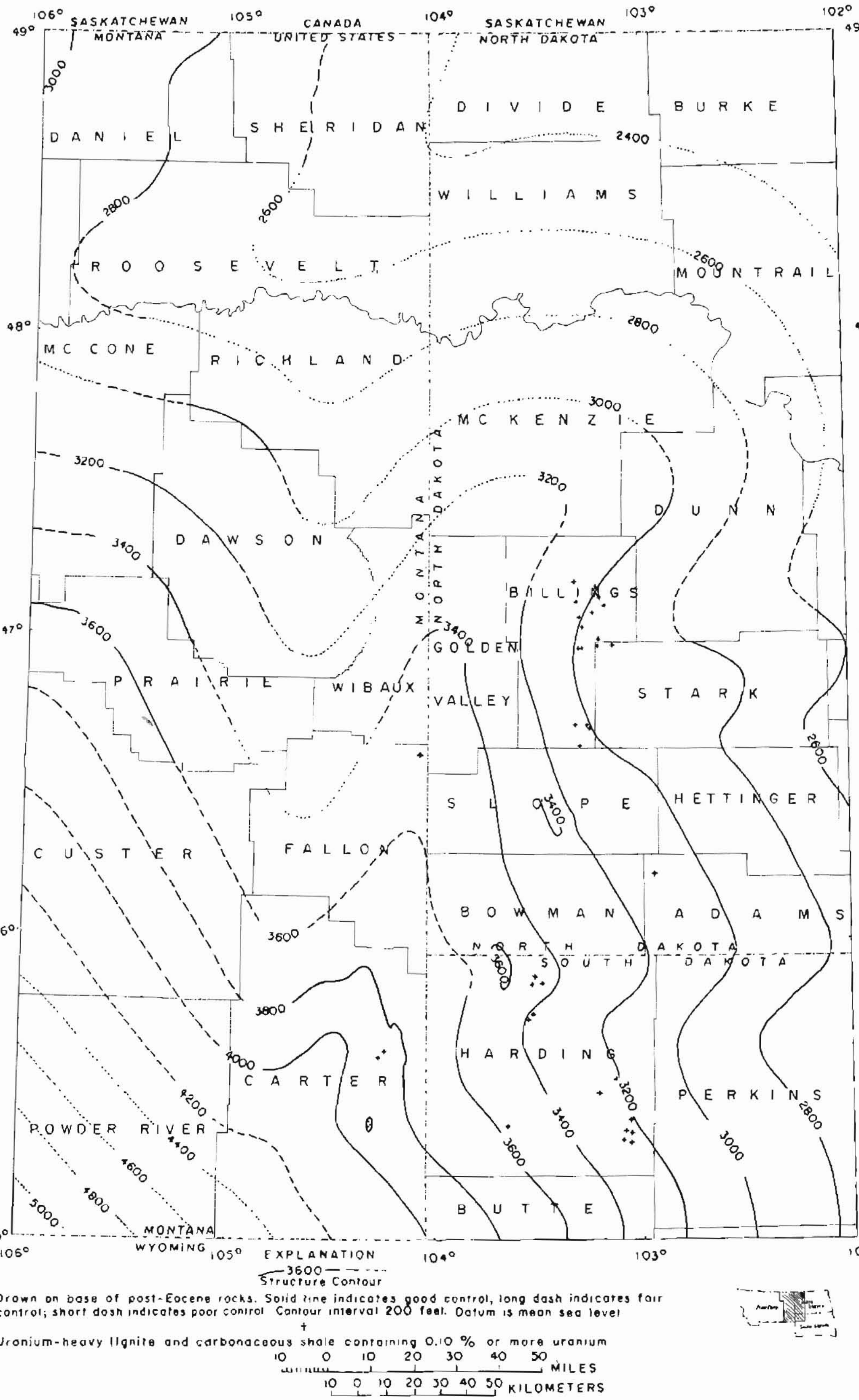

Figure 33. Structure-contour map of the base of post-Eocene rocks, southwestern Williston basin, Montana, North Dakota, and South Dakota showing location of lignite and carbonaceous shale containing 0.10 percent or more uranium (modified from Denson and Gill, 1965, pl. 1).

the projected base of the now-eroded post-Eocene rocks (fig. 5) and the present topography is smallest, because it is here that rocks would be closest to the (restored) paleosol in which uranium may have been mobilized. Another approach would be to explore where structural highs are located on structure-contour maps of the base of the post-Eocene rocks, because these areas would be the topographically high areas where oxidizing groundwater (possibly uranium-bearing) probably would have been flowing downward and laterally toward reducing environments of adjacent topographically low areas where uranium may have precipitated at the time the paleosol was forming. Many of the higher grade uranium deposits in the Williston basin occur on the flanks of such structural highs (fig. 33). This approach assumes that the structure contours show the shape of the paleotopographic surface at the time the paleosol formed, and that the shape of the surface was not strongly affected by later tectonic activity.

Particularly attractive targets for uranium exploration are the edges of sand beds near surrounding flood-basin deposits that are rich in organic matter, especially in areas just below the Eocene paleosol. Beds of lignite or carbonaceous siltstone or claystone just below the now-eroded paleosol also may be targets for uranium exploration, especially where these beds are adjacent to sand beds.

Other Formations

Upper Cretaceous and Tertiary Formations in the Williston basin that have characteristics similar to the Sentinel Butte Formation should be favorable targets for uranium exploration. The steep topography, almost-vertical deep gulleys whose intersections form peculiar inverted-V-shaped patterns, the modern dessication cracks, the caves, and the popcorn-like texture on clay beds are all weathering characteristics found on the Sentinel Butte Formation that probably are important general guides to formations that contain volcanic debris. The Hell Creek, Ludlow, Chadron, Brule, Arikaree, and perhaps the Flaxville, are all formations with these characteristics. Silicified wood is much more abundant in the Sentinel Butte because of the greater content of volcanic debris so the presence of abundant silicified wood in other formations may also indicate favorability for uranium exploration.

The Hell Creek, Ludlow, and Chadron Formations have tabular sandstone beds similar to those in the Sentinel Butte Formation described in this report. Examination of these beds in the field indicates that many of them are laterally extensive, lateral-accretion, point-bar deposits formed in high-sinuosity streams. The lateral extent of the beds may make it relatively easy to locate them in the subsurface. Examination of 19 thin sections of sandstone from the Hell Creek Formation shows that volcanic-rock fragments are quite abundant, but no point counts were made. The Hell Creek contains less carbonaceous matter than some other units, and it may be a particularly attractive target for uranium exploration.

REFERENCES

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

Allen, J. R. L., 1970b, A quantitative model of grain size and sedimentary structures in lateral deposits: Geol. Jour., v. 7, pt. 1, p. 129-146.

Benson, W. E., 1954, Kaolin of Early Eocene age in North Dakota: Science, no. 5, v. 119, p. 387-388.

Bergstrom, J. R., 1956, The general geology of uranium in southwestern North Dakota: North Dakota Geol. Survey Rept. Inv. 23, 1 sheet.

Beroni, E. P., and Bauer, H. L., Jr., 1952, Reconnaissance for uraniferous lignites in North Dakota, South Dakota, Montana, and Wyoming: U.S. Geol. Survey TEI-123, 93 p., issued by U.S. Atomic Energy Comm. Tech. Inf. Service, Oak Ridge, Tenn.

Boardman, R. L., Ekren, E. B., and Bowers, H. E., 1956, Sedimentary features of upper sandstone lenses of the Salt Wash Member and their relation to uranium-vanadium deposits in the Uravan District, Montrose County, Colorado: U.S. Geol. Survey Prof. Paper 300, p. 221-226.

Brown, R. W., 1948, Correlation of the Sentinel Butte Shale in western North Dakota: Am. Assoc. Petroleum Geologists Bull., v. 32, p. 1265-1274.

Brown, R. W., 1949, Paleocene deposits of the Rocky Mountains and plains: U.S. Geol. Survey Prelim. map.

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

Carlson, C. G., 1969, Bedrock geologic map of North Dakota: North Dakota Geol. Survey Misc. Map no. 10.

Cherven, V. B., 1973, High- and low-sinuosity stream deposits of the Sentinel Butte Formation (Paleocene) McKenzie County, North Dakota: North Dakota Univ. M.S. Thesis, 73 p.

Christiansen, R. L., and Lipman, P. W., 1972, Cenozoic volcanism and plate-tectonic evolution of the western United States, II. Late Cenozoic: Royal Soc. London Philos. Trans., ser. A., v. 271, p. 249-284.

Clark, M. B., 1966, The stratigraphy of the Sperati Point Quadrangle, McKenzie County, North Dakota: North Dakota Univ. M.S. Thesis, 108 p.

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

Crawford, J. W., 1967, Stratigraphy and sedimentology of the Tongue River Formation (Paleocene), southeast Golden Valley County, North Dakota: North Dakota Univ. M.S. Thesis, 73 p.

Delimata, J. J., 1969, Fort Union (Paleocene) mollusks from southern Golden Valley and southeastern Billings Counties, North Dakota: North Dakota Univ. M.S. Thesis, 73 p.

Denson, N. M., Bachman, G. D., and Zeller, H. D., 1959, Uranium-bearing lignite in northwestern South Dakota and adjacent states: U.S. Geol. Survey Bull. 1055-B, p. 11-57.

Denson, N. M., Bachman, G. O., Zeller, H. D., Gill, J. R., Moore, G. W., and Melin, R. E., 1955, Uraniferous coal beds in parts of North Dakota, South Dakota, and Montana: U.S. Geol. Survey Coal Inv. Map C-33.

Denson, N. M., and Gill, J. R., 1956, Uranium-bearing lignite and its relation to volcanic tuffs in eastern Montana and North and South Dakota: U.S. Geol. Survey Prof. Paper 300, p. 413-418.

Denson, N. M., and Gill, J. R., 1965, Uranium-bearing lignite and carbonaceous shale in the southwestern part of the Williston basin—a regional study: U.S. Geol. Survey Prof. Paper 463, 75 p.

Dowling, D. B., 1915, Coal fields and coal resources of Canada: Canada Geol. Survey Mem. 59, 174 p.

Emanuel, R., Jacob, A. F., and Karner, F. R., 1975, Mineralogy of the clay-size fraction of the Tongue River and

Sentinel Butte Formations near Medora, North Dakota: North Dakota Acad. Sci. Proc., v. 28, pt. II, in press.

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

Fisher, S. P., 1953, Geology of west central McKenzie County, North Dakota: North Dakota Geol. Survey Rept. Inv. 11, 1 sheet.

Fisher, W. L., Brown, L. F., Jr., Scott, A. J., and McGowen, J. H., 1969, Delta systems in the exploration for oil and gas: Bur. Econ. Geol., Texas Univ., Austin, 78 p.

Fisk, H. N., 1947, Fine-grained alluvial deposits and their effects on Mississippi River activity: Mississippi River Commission, Vicksburg, Mississippi.

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, Deerlen, 1958, Compte rendu, Maastricht, Netherlands, p. 187-199.

Folk, R. L., Andrews, P. B., and Lewis, D. W., 1970, Detrital sedimentary rock classification and nomenclature for use in New Zealand: New Zealand Jour. Geol. Geophys., v. 13, p. 937-968.

Freas, D. H., 1962, Occurrence, mineralogy, and origin of the lower Golden Valley kaolinitic clay deposits near Dickinson, North Dakota: Geol. Soc. America Bull., v. 73, p. 1341-1364.

Gill, J. R., 1959, Reconnaissance for uranium in the Ekalaka lignite field, Carter County, Montana: U.S. Geol. Survey Bull. 1055, p. 167-180.

Gill, J. R., Zeller, H. D., and Schopf, J. M., 1959, Core drilling for uranium-bearing lignite, Mendenhall area, Harding County, South Dakota: U.S. Geol. Survey Bull. 1055, p. 97-146.

Griffin, G. M., 1971, Interpretation of X-ray diffraction data, *in* Carver, R. A., Procedures in sedimentary petrology: Wiley-Interscience, N. Y., p. 541-569.

Haines, G. I., Jr., 1958, Uraniferous lignite deposits of southwestern North Dakota: U.S. Atomic Energy Comm. Tech. Memorandum DBO-1-TM-9, 21 p.

Hares, C. J., 1928, Geology and lignite resources of the Marmarth field, southwestern North Dakota: U.S. Geol. Survey Bull. 775, 110 p.

Herald, F. A., 1913, The Williston lignite field, Williams County, North Dakota: U.S. Geol. Survey Bull. 531-E, p. 91-157.

Hickey, L. J., 1969, Stratigraphy of the Golden Valley Formation of western North Dakota: Geol. Soc. America Abstracts with Programs, pt. 7, p. 100.

Hickey, L. J., 1972, Stratigraphic summary of the Golden Valley Formation (Paleocene-Eocene) of western North Dakota, *in* Depositional environments of the lignite-bearing strata in western North Dakota, Ting, F. T. C. (ed.): North Dakota Geol. Survey Misc. Ser. 50, p. 105-122.

Hostetler, P. B., and Garrels, R. M., 1962, Transportation and precipitation of uranium and vanadium at low temperatures, with special reference to sandstone-type uranium deposits: Econ. Geology, v. 57, p. 137-167.

International Committee for Coal Petrology, 1963, International handbook of coal petrography: Centre National de la Recherche Scientifique, Paris.

Jacob, A. F., 1973a, Depositional environments of Paleocene Tongue River Formation, western North Dakota: Am. Assoc. Petroleum Geologists Bull., v. 57, p. 1038-1052.

Jacob, A. F., 1973b, Descriptive classification of cross stratification: Geology, v. 1, p. 103-106.

Jacob, A. F., 1973c, Elongate concretions as paleochannel indicators, Tongue River Formation (Paleocene), North Dakota: Geol. Soc. America Bull., v. 84, p. 2127-2132.

Jacob, A. F., 1975a, Criteria for differentiating the Tongue River and Sentinel Butte Formations

(Paleocene), North Dakota: North Dakota Geol. Survey Rept. Inv. 53, 55 p.

Jacob, A. F., 1975b, FOLKSS: A FORTRAN program for the petrographic classification of sandstones: Computers and Geosciences, v. 1, p. 97-104.

Jacob, A. F., 1976, Stratigraphy and depositional environments of Paleocene deposits in the Husky Lignite Mine, Dickinson, North Dakota: North Dakota Acad. Sci. Proc., v. 28, pt. II, in press.

Johnson, R. P., 1973, Depositional environments of the upper part of the Sentinel Butte Formation, southeastern McKenzie County, North Dakota: North Dakota Univ. M.S. Thesis, 63 p.

Kesel, R. H., Dunne, K. C., McDonald, R. C., Allison, K. R., and Spicer, B. E., 1974, Lateral erosion and overbank deposition on the Mississippi River in Louisiana caused by 1973 flooding: Geology, v. 2, p. 461-464.

King, J. W., and Young, H. B., 1956, High-grade uraniferous lignites in Harding County, South Dakota: U.S. Geol. Survey Prof. Paper 300, p. 419-431.

King, P. B., and Beikman, H. M., 1974, Geologic map of the United States (exclusive of Alaska and Hawaii): U.S. Geol. Survey, 3 sheets.

Klein, G. deV., 1974, Estimating water depths from analysis of barrier island and deltaic sedimentary sequences: Geology, v. 2, p. 409-412.

Leonard, A. G., and Smith, D. C., 1909, The Sentinel Butte lignite field, North Dakota and Montana: U.S. Geol. Survey Bull. 341, p. 15-35.

Leonard, A. G., Babcock, E. J., and Dove, L. P., 1925, The lignite deposits of North Dakota: North Dakota Geol. Survey Bull. 4, 240 p.

Lipman, P. W., Prostka, H. J., and Christiansen, R. L., 1972, Cenozoic volcanism and plate-tectonic evolution of the western United States, I. Early and Middle Cenozoic: Royal Soc. London Philos. Trans., ser. A., v. 271, p. 217-248.

Love, J. D., McGrew, P. O., and Thomas, H. J., 1963, Relationship of latest Cretaceous and Tertiary deposition and deformation to oil and gas in Wyoming, *in* Childs, O. E., and Beebe, B. W. (eds.). Backbone of the Americas: Am. Assoc. Petroleum Geologists Mem. 2, p. 196-208.

Lumsden, D. N., 1973, TRI: A FORTRAN subroutine to plot points on a triangular diagram: Geol. Soc. America Bull., v. 84, p. 1765-1768.

May, P. R., 1954, Strippable lignite deposits in Wibaux area, Montana and North Dakota: U.S. Geol. Survey Bull. 995-G, p. 267-268.

Meldahl, E. G., 1956, The geology of the Grassy Butte area, McKenzie County, North Dakota: North Dakota Univ. M.S. Thesis, 42 p.

Meschter, D. Y., 1958, A study of concretions as applied to the geology of uranium deposits: U.S. Atomic Energy Comm., Tech. Mem. Rept. TM-D-1-14, 10 p.

Moody-Stuart, M., 1966, High- and low-sinuosity stream deposits with examples from the Devonian of Spitsbergen: Jour. Sed. Petrology, v. 36, p. 1102-1117.

Moore, G. W., Melin, R. E., and Kepferle, R. L., 1956, Preliminary geologic map of the Chalky Buttes area, Slope County, North Dakota: U.S. Geol. Survey Coal Inv. Map C-38.

Noble, E. A., 1972, Metalliferous lignite in North Dakota, *in* Ting, F. T. C. (ed.), Depositional environments of the lignite-bearing strata in western North Dakota: North Dakota Geol. Survey Misc. Ser. 50, p. 133-134.

Noble, E. A., 1973, Uranium in coal, *in* Mineral and water resources of North Dakota: North Dakota Geol. Survey Bull. 63, p. 80-85.

Pettyjohn, W. A., 1966, Eocene paleosol in the Northern Great Plains: U.S. Geol. Survey Prof. Paper 550-C, p. C61-C65.

Pipiringos, G. N., Chisholm, W. A., and Kepferle, R. C., 1965, Geology and uranium deposits in the Cave Hills area, Harding County, South Dakota: U.S. Geol. Survey Prof. Paper 476-A, 64 p.

Pishel, M. A., 1912, Lignite in the Fort Berthold Indian Reservation, North Dakota, north of the Missouri River: U.S. Geol. Survey Bull. 471-C, 173 p.

Reineck, H. E., and Singh, I. B., 1973, Depositional sedimentary environments: Springer-Verlag, New York, 439 p.

Royse, C. F., Jr., 1967, Tongue River-Sentinel Butte contact in western North Dakota: North Dakota Geol. Survey Rept. Inv. 45, 53 p.

Royse, C. F., Jr., 1970, A sedimentologic analysis of the Tongue River-Sentinel Butte interval (Paleocene) of the Williston basin, western North Dakota: Sed. Geol., v. 4, p. 19-80.

Royse, C. F., Jr., 1972, The Tongue River and Sentinel Butte Formations (Paleocene) of western North Dakota: A review, *in* Ting, F. T. C. (ed.), Depositional environments of the lignite-bearing strata in western North Dakota: North Dakota Geol. Survey Misc. Ser. 50, p. 31-42.

Sandberg, C. A., 1962, Geology of the Williston basin, North Dakota, Montana, and South Dakota, with reference to subsurface disposal of radioactive wastes: U.S. Geol. Survey Rept. TEI-809, 148 p.

Schopf, J. M., and Gray, R. J., 1954, Microscopic studies of uraniferous coal deposits: U.S. Geol. Survey Circ. 343, 10 p.

Taff, J. A., 1909, The Sheridan coal field, Wyoming: U.S. Geol. Survey Bull. 341, pt. 2, p. 123-150.

Ting, F. T. C., 1972a, Petrified peat from a Paleocene lignite in North Dakota: Science, v. 177, p. 165-166.

Ting, F. T. C., 1972b, Petrographic and chemical properties of selected North Dakota lignite, *in* Ting, F. T. C. (ed.), Depositional environments of the lignite-bearing strata in western North Dakota: North Dakota Geol. Survey Misc. Ser. 50, p. 63-68.

Ting, F. T. C. (ed.), 1972c, Depositional environments of the lignite-bearing strata in western North Dakota: North Dakota Geol. Survey Misc. Ser. 50, 134 p.

Ting, F. T. C., 1973, Petrology and palynology of a silicified peat from a Paleocene lignite bed in North Dakota: Geoscience and Man, v. 7, p. 65-66.

Ting, F. T. C., 1974, Petrography and paleobotany of a petrified Paleocene peat and its bearing on the coalification of lignite: Geol. Soc. America Abs. with Programs, v. 6, no. 7, p. 988.

Towse, D. F., 1957, Uranium deposits in western North Dakota and eastern Montana: Econ. Geology, v. 52, p. 904-913.

U.S. Atomic Energy Comm., 1956, Location of uranium deposits in southwestern North Dakota and the Cave Hills and Slim Buttes areas, Harding County, South Dakota: U.S. Atomic Energy Comm. Tech. Inf. Service RME-1076, 12 p.

Vine, J. D., 1962, Geology of uranium in coaly carbonaceous rocks: U.S. Geol. Survey Prof. Paper 356-D, p. 113-170.

Waters, A. C., and Granger, H. C., 1953, Volcanic debris in uraniferous sandstones and its possible bearing on the origin and precipitation of uranium: U.S. Geol. Survey Circ. 224, 26 p.

Wyant, D. G., and Beroni, E. P., 1950, Reconnaissance for trace elements in North Dakota and eastern Montana: U.S. Geol. Survey TEI-61, 29 p., issued by the U.S. Atomic Energy Comm. Tech. Inf. Service, Oak Ridge, Tenn.

Zeller, H. D., and Schopf, J. M., 1959, Core drilling for uranium-bearing lignite in Harding and Perkins Counties, South Dakota, and Bowman County, North Dakota: U.S. Geol. Survey Bull. 1055-C, p. 59-96.

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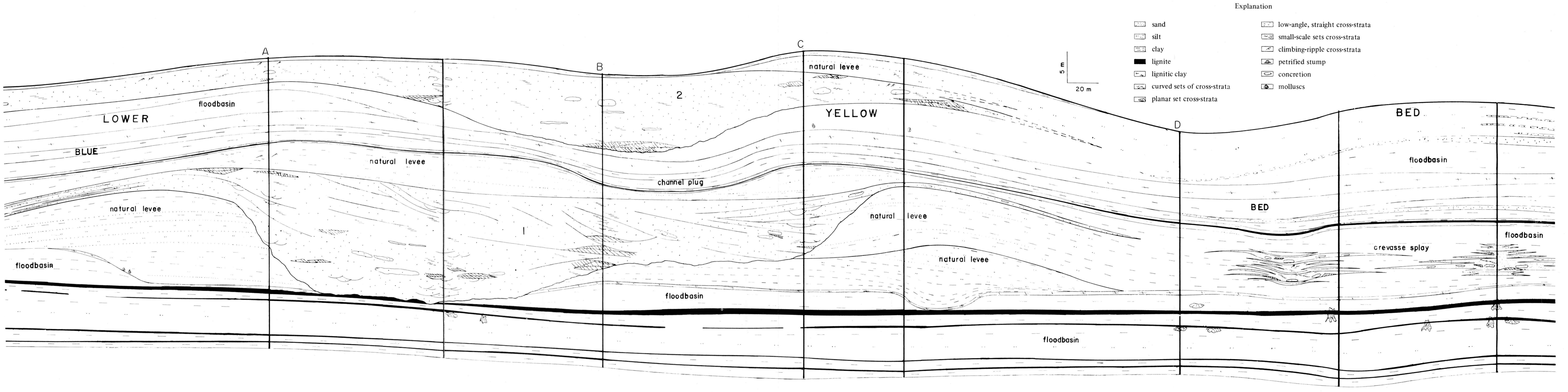

Plate 1. Cross section of elongated, trough-shaped, sandstone beds in the Sentinel Butte Formation, McKenzie County, North Dakota. Map of sandstone bed 1 and locations of measured sections shown in figure 28. Modified slightly from Cherven (1973, 1.2).

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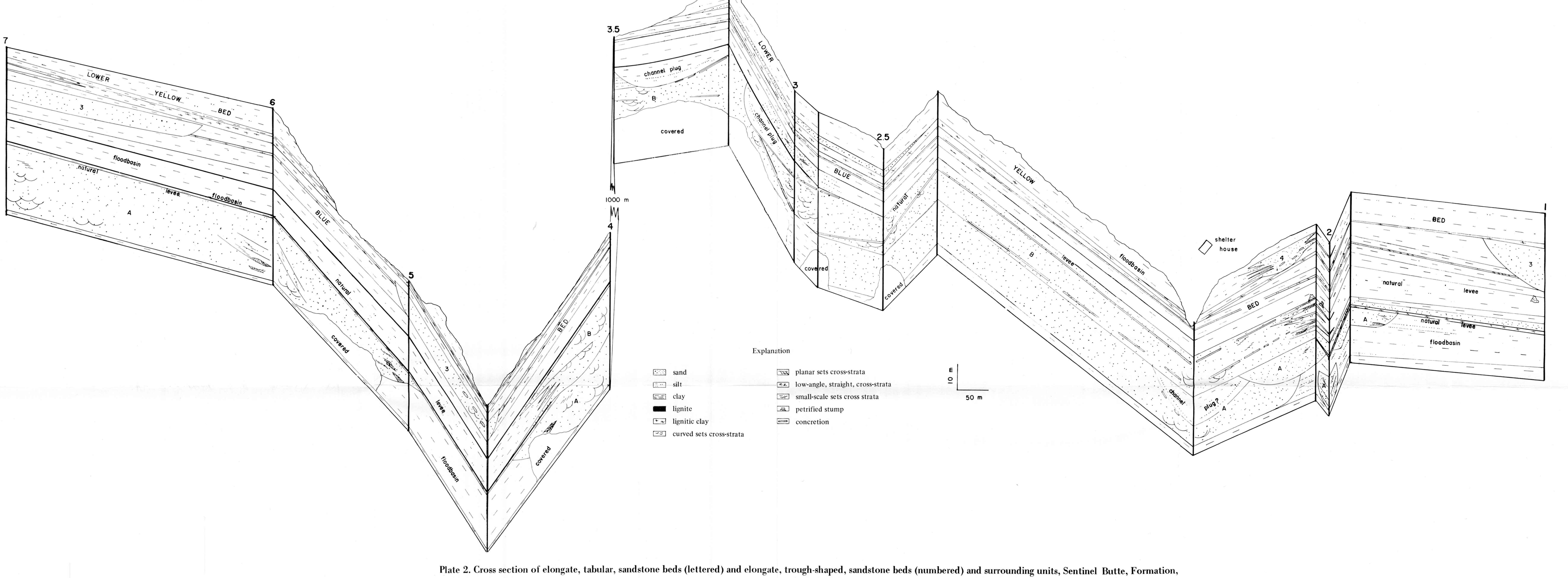

Plate 2. Cross section of elongate, tabular, sandstone beds (lettered) and elongate, trough-shaped, sandstone beds (numbered) and surrounding units, Sentinel Butte, Formation, McKenzie County, North Dakota. Map of sandstone bed B and locations of measured sections shown in figure 28. Modified slightly from Cherven (1973, 1.1).

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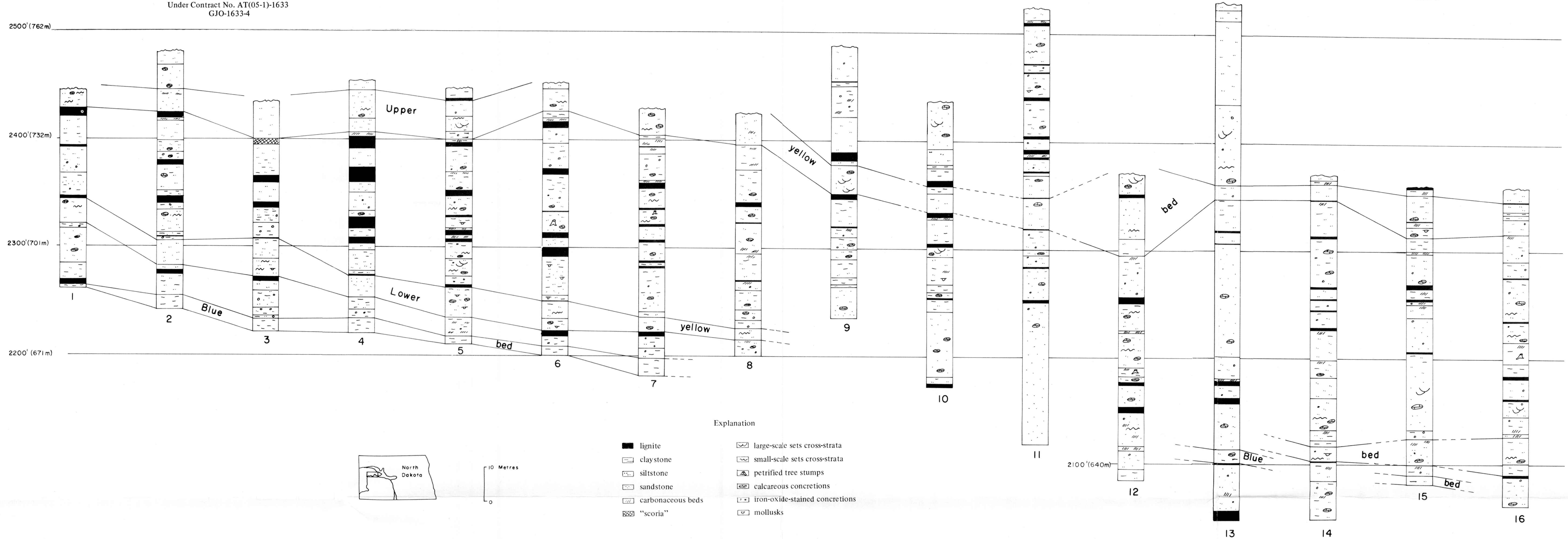

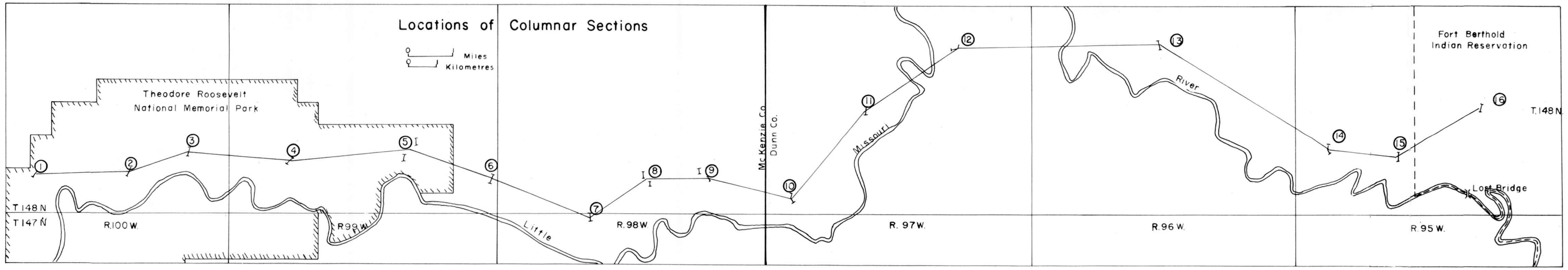

Plate 3. Stratigraphic cross section of the Sentinel Butte Formation, McKenzie and Dunn Counties, North Dakota. Upper yellow bed, lower yellow bed, and blue bed visually traced through the area of the cross section. (From S. G. Stancel, unpubl. report.)