GEOLOGY OF THE FOX HILLS FORMATION (LATE CRETACEOUS) IN THE WILLISTON BASIN OF NORTH DAKOTA, WITH REFERENCE TO URANIUM POTENTIAL

by

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ABSTRACT

The Fox Hills Formation is a marine and brackish sequence of primarily medium and fine clastics within the Late Cretaceous Montana Group. In the Williston basin of North Dakota, four members (in ascending order) are recognized: Trail City, Timber Lake, Iron Lightning (with Bullhead and Colgate lithofacies), and Linton. The Fox Hills conformably overlies the Pierre Shale and conformably and disconformably underlies and interfingers with the Hell Creek Formation; it occurs in about the western two-thirds of the state. Principal lithology includes poorly consolidated sandy shale and siltstone (Trail City); fine- to medium-grained, poorly consolidated and well-indurated sandstone (Timber Lake); interbedded, poorly consolidated sandstone and shale or siltstone (Bullhead lithofacies); medium-grained, poorly consolidated, muddy sandstone (Colgate lithofacies); and very fine- to fine-grained, indurated, siliceous sandstone (Linton). A conspicuous volcanic ash occurs in the formation and rises in the section from central Emmons County to southeastern Morton County. Lignite beds occur in the subsurface in part of southwestern North Dakota. Considerable lithologic variation occurs in the subsurface away from the main outcrop area in the south-central part of the state, and the members are difficult to trace. The thickest recognized sequence is 391 feet in northwestern Hettinger County; sequences thicker than 300 feet also occur in two other areas—Dunn and Mercer, and Burke and Ward Counties. Nearly 300 feet of Fox Hills has also been reported as far east as western Pierce County. Fox Hills rocks generally dip about 10-20 feet per mile toward the center of the Williston basin; regionally, dip values may be considerably greater (few to many degrees on the flanks of the Cedar Creek anticline) or less. Principal macrofossils are bivalve and gastropod mollusks that occur primarily in limestone and sandstone concretions and indurated sandstone. A barrier bar (or island)—deltaic model is followed for the deposition of Fox Hills sediments. The lower Fox Hills, of the Trail City and Timber Lake Members, is believed to represent the lower to upper shoreface of a barrier bar environment. The upper Fox Hills, of the Iron Lightning and Linton Members, suggests deposition within a deltaic complex as does the overlying Hell Creek Formation. Specific environments may have included tidal channel, bay, estuary, prodelta, and various environments associated with a delta-plain and the seaward part of a distributary system. Water depths may have been a few hundred feet and less.

Since the Hell Creek, Fox Hills, and Pierre Formations are at least in part penecontemporaneous, a variety of depositional environments were in areal juxtaposition during Late Cretaceous time. Streams originating or passing through coastal plain bogs (of the Hell Creek) could have carried uranium ions (derived from volcanic materials) into bays, lagoons, or the open sea where they were deposited syngenetically. Epigenetic uranium may occur in finer clastics in the Fox Hills that directly underlie a volcanic ash bed.

INTRODUCTION

The Fox Hills Formation is a marine and brackish unit of mostly medium and fine clastics deposited primarily in the northern Great Plains during Late Cretaceous time. It conformably overlies the Pierre Shale and both conformably and unconformably underlies the Hell Creek Formation.

This report summarizes the geology of the Fox Hills Formation in North Dakota, the stratigraphy of which is based on previous surface information and recent subsurface data, and evaluates its potential for uranium.

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MATERIALS AND METHODS

The cross sections prepared for this report (pls. 1-3) are, with one exception, based exclusively on recent unpublished and published subsurface data of the North Dakota State Water Commission because outcrop sections are rarely complete. These subsurface data, although based on samples, are, in certain cases, difficult to use because of inconsistent or incomplete descriptions. Contacts of the Fox Hills were changed in several instances from those placed by previous workers. The datum for the cross sections is the top of the Pierre Shale. The isopach map (pl. 4) is based on the same type of Water Commission data as well as on mechanical logs; about 200 control points were used for this map. About 90 electric logs (resistivity, spontaneous potential, and laterolog) from oil and gas wells were used to supplement the Water Commission subsurface data. On these logs, the Pierre-Fox Hills contact was picked where the curves gradually but notably began to depart from the shale line as they are traced from the Pierre Shale into the overlying Fox Hills. In the Water Commission wells, this contact was picked so as to include shale and silty shale in the Pierre and siltstone and sandstone in the Fox Hills. The upper contact was more difficult to pick consistently on the logs; it was generally taken where the spontaneous potential and resistivity decreased abruptly at the top of what was interpreted to be a sandstone bed about 20 feet or more in thickness. A pronounced sandstone bed may not always be present at the top of the Fox Hills (e.g., as indicated in pl. 2, section 13) and the thicknesses gained from logs in places may be less than they are in reality. Thicknesses of the unit from logs was also partly gauged by a continuous plot of values on a working map as the study progressed. Depths to the top of the Fox Hills and other similar data are on file in the Department of Geology, University of North Dakota. The letter designation in the legal description of well or outcrop localities is that of the North Dakota State Water Commission.

STRATIGRAPHY

Definition and Relationship to Other Rock Units

The Fox Hills Formation, originally "Formation No. 5" (Meek and Hayden, 1856, p. 63), was named by Meek and Hayden (1861, p. 419, 427) for the youngest marine sandy deposits in the western interior. The name is from Fox Hills (or Fox Ridge), an ill-defined part of the divide between the Cheyenne and Moreau Rivers in Ziebach and Dewey Counties, north-central South Dakota. Waage (1968, fig. 1) has outlined the approximate "historical type locality," and proposed a larger type or reference area (fig. 2) that includes the Fox Hills outcrop in most of Ziebach and Dewey Counties and in Corson County south of the valley of Oak Creek.

Good stratigraphic discussions of the formation are by Waage (1968) in the type area and by Feldmann (1972) and Erickson (1971, 1974) in North Dakota.

Waage (1968, p. 18-48) has comprehensively discussed the history of study of the formation in the type area, including the development of the classification and nomenclature of the unit (his fig. 4). His proposed revision of subdivision includes three members (in ascending order): Trail City, Timber Lake, and Iron Lightning. Feldmann (1972, p. 5-15) has traced the history of study of the Fox Hills in North Dakota. His subdivision of the formation recognized three members (in ascending order), the Timber Lake, Bullhead, and Colgate. Erickson (1974, fig. 3) recognized a subdivision essentially that of Waage (1968, fig. 5) with the addition of another member, the Linton (Klett and Erickson, 1976), at the top of the sequence (fig. 2). I prefer to follow the subdivision scheme of Erickson (1974) in North Dakota.

The Fox Hills Formation overlies the Pierre Shale with gradational contact. It conformably (Waage, 1968, p. 119) and unconformably (Frye, 1969, p. 20-24) underlies the Hell Creek Formation. The Fox Hills and Pierre Formations constitute the Montana Group, which might include the Hell Creek Formation as well (Gill and Cobban, 1973, p. 12).

Distribution

The Fox Hills Formation occurs in western North and South Dakota, eastern Wyoming, eastern Montana, and eastern Colorado south to the Colorado Springs area (Cobban and Reeside, 1952; Gill and Cobban, 1973). In North Dakota this unit occurs in about the western two-thirds of the state (pl. 4), occurring primarily in the subsubsurface. The outcrop area (fig. 1) is primarily in a slightly arcuate band extending north-south across the state at about mid-length, with a smaller area in the southwesternmost part of the state. Most of the northern two-thirds of the primary outcrop band, however, is covered by glacial drift. The best outcrops are in the south-central part of the state in Sioux, Morton, and Emmons Counties in the drainage of the Missouri River (Feldmann, 1972, fig. 1).

Lithology and Sedimentary Structures

The following summary of the lithology and sedimentary structures of the Fox Hills Formation is largely after Erickson (1974), Feldmann (1972), and Waage (1968).

The lower Fox Hills in North Dakota consists of the Trail City and Timber Lake Members (fig. 2). The Trail City, the basal member, is of brown- to gray-weathering sandy shale or siltstone that passes upward to brown- and greenish-gray-weathering, poorly consolidated sandstone (Fisher, 1952, p. 10) with abundantly fossiliferous, medium to dark gray, limestone concretions that weather light tan to light gray. These concretions are as large as more than three feet in diameter. Erickson (1974, p. 145) recognized this member in a few outcrops in Emmons, Logan, and southeastern Sioux Counties, but Feldmann (1972) did not recognize it in the state. In the type area of South Dakota, the Trail City consists of two lithofacies, the Little Eagle and Irish Creek. The Little Eagle lithofacies is of gray-weathering "clayey silt and clayey sand" containing abundantly fossiliferous concretions and generally lacking well defined bedding; this lithofacies occurs generally in the eastern part of the type area. The Irish Creek lithofacies is of gray-weathering "clay and silt with some fine-grained sand" in which fossiliferous concretions are lacking or rare and thin interbedding is well defined; this lithofacies generally occurs in the western part of the type area (Waage, 1968, p. 61-73).

Overlying the Trail City with gradational contact is the Timber Lake Member, which consists primarily of buff to yellowish, fine- to medium-grained, poorly consolidated sandstone that weathers yellowish or reddish brown. Lenticular ledges of reddish-brown weathering, well-indurated sandstone occur throughout but are more numerous toward the top of the member. Well-indurated, abundantly fossiliferous, sandstone concretions are common. Lenticular beds (up to several inches thick) of well-indurated, red- or orange-weathering claystone and the trace fossil *Ophiomorpha* are also conspicuous, and are particularly abundant near the top of the member, where trough and tabular crossbedding is also characteristic. The sandstone is lithic graywacke and subgraywacke. Sand grains consist mostly of about 25-30% quartz, 35-40% rock fragments, 10-15% feldspar, 0-5% biotite, and a minor amount of glauconite; the remainder of the sandstone is of interstitial limonite or calcite (Feldmann, 1972, p. 25-26). Lindberg

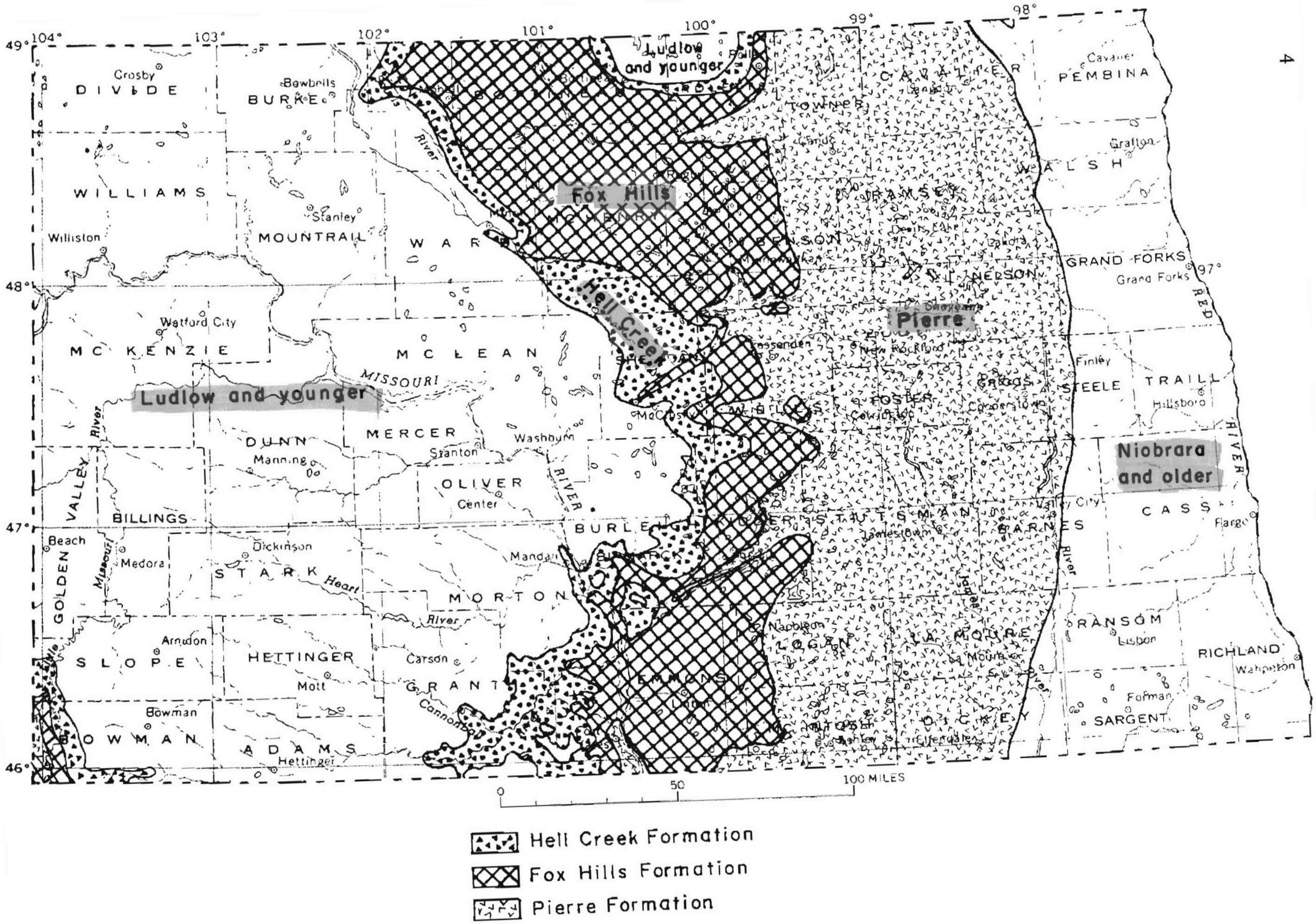

Figure 1. Fox Hills and adjacent Formations in North Dakota (modified from Carlson, 1973).

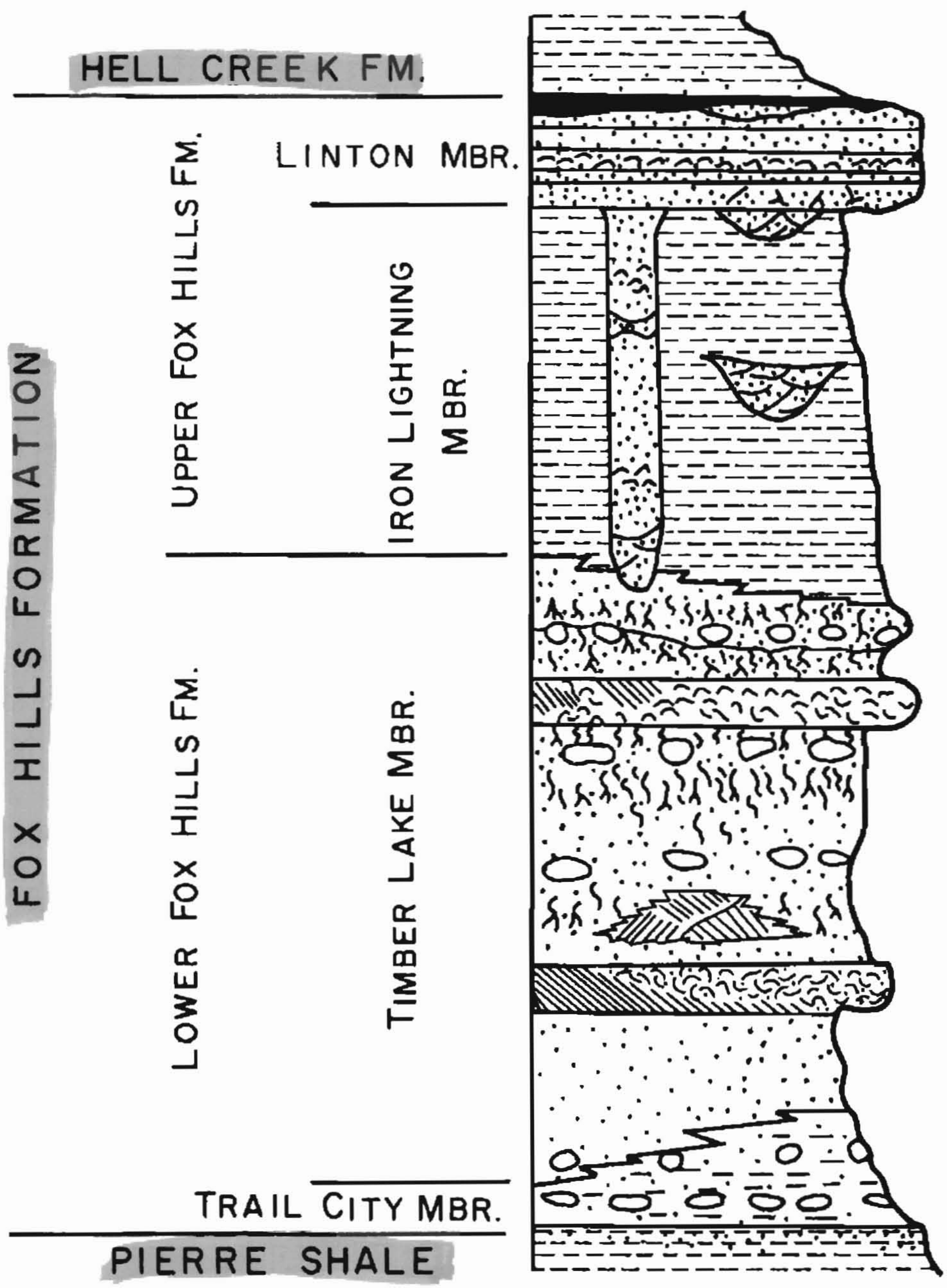

Figure 2. Schematic stratigraphic column of Fox Hills Formation in North Dakota (modified slightly from Erickson, 1974, p. 144). The Linton Member was named by Klett and Erickson (1976).

(1944) identified 16 heavy minerals presumably from this member from 10 samples at two sections in southern Morton County; green amphibole was the characteristic heavy mineral. The Timber Lake Member has been recognized in all the major areas of outcrops to as far west as Bowman County.

The upper Fox Hills consists of the Iron Lightning and Linton Members (fig. 2). Within the Iron Lightning are two so-called lithofacies, the Bullhead and Colgate (Waage, 1968). Feldmann (1972) treated these lithofacies as members. The Bullhead, conformably overlying the Timber Lake Member, is of interbedded, poorly consolidated sandstone and siltstone or shale. The sandstone interbeds, about 1-11 inches thick, are buff, thinly laminated, and weather buff or reddish buff; the sandstone is fine-grained and a subgraywacke. The siltstone or shale interbeds, about 1-7 inches thick, are chocolate brown and weather light gray or buff. Lignite laminae or very thin beds occur throughout this lithofacies (Feldmann, 1972, p. 28-30). Lindberg (1944) identified 16 heavy minerals presumably from this lithofacies from eight samples at three sections in Morton and Sioux Counties; epidote and green amphibole were the dominant heavy minerals.

The Colgate lithofacies overlies the Bullhead or completely or partially replaces it laterally as in southern Morton County along the lower Cannonball River (Laird and Mitchell, 1942, p. 6). In places, the Colgate overlies the Bullhead disconformably, as in northern Sioux County (134-81-33b; Feldmann, 1972, p. 30) and may form channels within it (Erickson, 1972, pl. 1). The Colgate is characteristically of medium-grained, white, muddy graywacke with uncommon, thin laminae or beds of lignitic shale. Weathered surfaces are characteristically fluted (Feldmann, 1972, p. 31). The Colgate is recognized in outcrop in Bowman County and at least as far east as north-central Sioux County (134-81-33; Feldmann, 1972, p. 31). In the type area of the Fox Hills in South Dakota, the Bullhead and Colgate are intimately associated laterally. The Bullhead is of "thinly interbedded clay, silt and very fine-grained sand that weathers to a markedly banded, light-brownish-gray outcrop"; the Colgate is of "very fine- to medium-grained, clayey, subgraywacke sand that usually weathers to fluted light-gray or grayish-white outcrops. . ."(Waage, 1968, p. 116). Sandy beds in the Bullhead are commonly crossbedded, and trough crossbedding (mostly) and tabular crossbedding is common in the Colgate. The sand fraction of the Colgate is generally 30-50%, of mostly quartz with the remainder rock fragments, chiefly quartzite, foliated rock fragments, and chert (Waage, 1968, p. 121-123). Lindberg (1944) identified 15 heavy minerals presumably from the Colgate from 21 samples at four sections in Morton and Sioux Counties, North Dakota; green amphibole and epidote were the dominant heavy minerals.

The uppermost member of the Fox Hills is the Linton (fig. 2). It consists of light olive gray to grayish brown, very fine- to fine-grained, subangular, moderately to poorly sorted, indurated, siliceous sandstone that weathers light gray to brown. The unit is generally massive but flat bedding and large-scale trough(?) or planar crossbedding are present locally. Ripple marks and mud cracks are rare. The sandstone is compositionally a subgraywacke to a feldspathic arenite, contains generally about 28% matrix and a substantial percentage of volcanic shards. The Linton Member is known to cap buttes in Emmons and eastern Sioux Counties, North Dakota, and extends southward well into the type area of the Fox Hills in South Dakota (Klett and Erickson, 1976).

A volcanic ash occurs within the Fox Hills Formation in central and southern Emmons, northeastern Sioux, and southeastern Morton Counties (Artzner, 1974, fig. 2). The ash is about 80% volcanic glass, 10% quartz, 7% feldspar, 1% hornblende, and 2% minor constituents. This ash apparently rises up section as it is traced from east to west (Feldmann, 1972, fig. 11). It occurs from very near the base of the Fox Hills in central Emmons County (Fisher, 1952, p. 15) to about 48 feet above the Fox Hills-Hell Creek contact in southeastern Morton County (Artzner, 1974, p. 7).

I have not attempted to portray the members in subsurface sections (pls. 1-3) because of the difficulty in recognizing them. In well 9 (pl. 1) perhaps the Trail City, Timber Lake, and Lightning (Bullhead lithofacies) Members are represented. In well 22 (pl. 3), perhaps the Trail City, Timber Lake, Iron Lightning (? Bullhead lithofacies), and Linton Members are represented. In general, away from the main outcrop area in the south-central part of the state, considerable lithologic variation exists, and the various members seem to be difficult to recognize. The relatively thick lignites reported in certain sections (e.g., pl. 1, sections 5 and 6) are particularly conspicuous.

Persistence of Lithologic Units

In the main outcrop area in the south-central part of the state, the various members of the Fox Hills have been traced a few to several tens of miles as implied in the previous section. The volcanic ash bed is distributed over an area of about 600 square miles (Artzner, 1974, p. 7) in Emmons, Morton, and Sioux Counties. In the subsurface, away from the main area of exposure, there seems to be decreasing persistence of recognizable members as well as individual beds.

Contacts

In North Dakota, the Pierre-Fox Hills contact is gradational. It is poorly exposed in the state and is best seen near Linton in Emmons County (132-76-17d) and on the east flank of the Cedar Creek anticline in Bowman County (131-106-4bb). At the Emmons County locality, the contact, in going up section, is marked by the first appearance of layers of jarosite. At this general level, sandy or silty shale of the Pierre changes gradually to fine- to medium-grained sandstone of the Fox Hills. The contact is also about 10-12 feet below the lowest concretions of the lower Fox Hills. At the Bowman County locality, the gradational contact occurs through a sequence of about 10 feet; gray-weathering shale of the Pierre gives way to buff- or yellow-weathering fine-grained sandstone with brownish shale or siltstone of the Fox Hills (Feldmann, 1972, p. 23-25). In the type area in South Dakota, the contact is drawn at the lithologic change from silty shale of the upper Pierre to clayey siltstone of the lower Fox Hills. This corresponds to a marked concentration of jarosite ("lower jarositic zone"), which should not be confused with other occurrences of jarosite in the lower Fox Hills and upper Pierre (Waage, 1968, p. 57-58, fig. 7). In the subsurface of North Dakota, I have included reported siltstones in the lowest Fox Hills and shales or silty shales in the uppermost Pierre. On electric logs, the Pierre-Fox Hills contact was drawn where the curves gradually but notably began to depart from the shale line as they are traced from the Pierre into the overlying Fox Hills.

The Fox Hills-Hell Creek contact in North Dakota in outcrop is generally picked at the base of a lignite or lignitic shale (Feldmann, 1972, p. 32), or lignitic sandstone (Frye, 1969, p. 20-22; figs. 3-4). Either poorly consolidated interbedded sandstone and shale (Bullhead lithofacies); poorly consolidated white sandstone (Colgate lithofacies); indurated, light gray to brown sandstone (Linton Member); or volcanic ash (Frye, 1969, p. 20) may be at the top of the Fox Hills. The contact is both gradational and erosional. Along the valley of the Missouri River and its tributaries south of Bismarck, North Dakota, the contact is gradational, and the Fox Hills and Hell Creek interfinger in places as in southern Morton County (134-80-21d). In the Little Missouri Valley in Slope and Bowman Counties, the contact is gradational or erosional (Frye, 1969, fig. 4, also p. 20-22). In the type area of the Fox Hills in South Dakota, the upper contact is placed "at the base of the first appreciably thick lignite or lignitic clay or shale" (Waage, 1968, p. 118). The contact is considered to be gradational; locally, in the type area, interfingering of the Hell Creek and Fox Hills occurs within an interval of a few tens of feet and at a much larger scale to the west (Waage, 1968,

p. 119, pl. 11).

In the subsurface cross sections (pls. 1-3), I have generally not been able to place the upper contact at the base of lignitic lithology. This lithology generally did not exist (or was not reported) at about the level where the top of the Fox Hills might be expected based on projected thicknesses of this formation and younger formations in adjacent wells. On electric logs, the upper contact was generally taken where the spontaneous potential and resistivity decreased abruptly at the top of what was interpreted to be a sandstone bed about 20 feet or more in thickness. Because a pronounced sandstone bed may not always occur at the top of the formation, this procedure may have resulted in erroneous thicknesses in places.

Thickness

The area of greatest thickness of the Fox Hills Formation in North Dakota appears to be in Bowman, Slope, Hettinger, and possibly Grant Counties (pl. 4). I have interpreted a maximum thickness of 391 feet in northwestern Hettinger County (pl. 2, well 12). Two other thick areas, with thicknesses greater than 300 feet, occur primarily in Mercer and Dunn Counties and in Burke and Ward Counties (pl. 4). The formation thins markedly southwestward along the flanks of the Cedar Creek anticline in western Bowman and Slope Counties. In western Pierce County the reported Fox Hills is nearly 300 feet thick (pl. 2, well 16). This locality is not too distant from the eastern limit of the Fox Hills (pl. 4), implying that the formation probably once extended considerably farther eastward.

In outcrop, the thickness of the Trail City Member is poorly known but seems to be at least 75 feet thick (Fisher, 1952, p. 10); it thins northward from the type area (Waage, 1968, p. 58). The Timber Lake Member is at least 128 feet thick (Sioux County; Feldmann, 1972, p. 25); it thickens northeastward from the type area (South Dakota) at the expense of the Trail City Member (Waage, 1968, p. 91). The Bullhead lithofacies of the Iron Lightning Member is at least 112 feet thick (Morton County; Laird and Mitchell, 1942, p. 6) and the Colgate lithofacies is at least 40 feet thick (Bowman County; Feldmann, 1972, p. 31). The Linton Member is up to about 23 feet thick but averages about 6.5 feet; it is known to thin westward in Sioux County (Klett and Erickson, 1976). The volcanic ash is up to more than 40 feet thick in central Emmons County (Artzner, 1974, fig. 4) and thinner elsewhere.

STRUCTURE

An overview of structure affecting the Fox Hills Formation in North Dakota is provided by Anderson (1969) and Osterwald and Dean (1957). The major structural feature is the north-northwest-trending Williston basin. Two main structural lows within the basin occur in the vicinity of Williston in McKenzie and Williams Counties and in a region centered along the common boundary of Dunn and Mercer Counties (Anderson, 1969). The two main structural highs within the basin are the northwest-trending Cedar Creek anticline in the southwesternmost part of the state and the north-trending Nesson anticline in the northwestern part (Sandberg, 1962, p. 10).

The regional dip toward the center of the Williston basin is generally about 10-20 feet per mile but may be less or considerably higher in the vicinity of local or regional structures. Dips on the Fox Hills on the Cedar Creek anticline are 5-20° on the west limb and 3° or less on the east limb (Hares, 1928, p. 44). Along the east and west flanks of the Nesson anticline the regional dip is about 71 feet per mile (Anderson, 1969). In southern Morton County, using the base of the Ludlow as datum, the regional dip is about 15 feet per mile to the north or northwest, and small domes and noses are superimposed on this structure (Laird and Mitchell, 1942, p. 38). In Emmons County, using the base of the Linton Member of the Fox Hills as datum, the regional dip is generally 10-20 feet per mile to the northwest but dips up to 50 feet per mile are common (Fisher, 1952, p. 29). In Burleigh County the Fox Hills has a regional dip of about 14-15 feet per mile to the west and northwest (Kume and Hansen, 1965, p. 42-43). In the Souris River area of north-central North Dakota, Upper Cretaceous and Tertiary strata are believed to lie within a broad, northwest-trending syncline whose axis is approximately in the position of the eastern part of the Souris River loop. Within the syncline are minor folds and undulations. Steepest dips occur near the Coteau du Missouri (may mark the edge of the southwestern limb) and decrease northeastward, so that 10 miles from the escarpment the strata are nearly horizontal (Lemke, 1960, p. 108).

Besides the large scale and small scale structures mentioned above, numerous other small scale structures, particularly folds, faults and joints, are known to affect Upper Cretaceous and Tertiary strata (many summarized, for example, by Osterwald and Dean, 1957).

PALEONTOLOGY

Fossil Groups

The Fox Hills biota consists of foraminiferids (Lemke, 1960, p. 27; Mello, 1969), a sponge (borings; Palubniak, 1972), bryozoans (Palubniak, 1972), linguloid brachiopods (Meek, 1876, p. 10; Mello, 1969, p. 38), mollusks (Cvancara, 1956; Erickson, 1974; Feldmann, 1967; Meek, 1876; Palubniak, 1972; Speden, 1970; Waage, 1965), annelid worms (shell blisters, burrows; Palubniak, 1972), a limulid arthropod (Holland, Erickson, and O'Brien, 1975), barnacles (borings; Palubniak, 1972), ostracodes (Lemke, 1960, p. 27), the crustacean burrow *Ophiomorpha* (Land, 1972, p. 38, 49; Waage, 1968, pl. 8), an echinoid (Holland and Feldmann, 1967), vertebrates (sharks, other fishes, crocodiles and turtles and other vertebrates; Palubniak, 1972; Waage, 1968, p. 127, pl. 12), various trace fossils (*Arenicolites, Cylindrichnus?, Rhizocorallium*; Land, 1972, p. 41, 39, and 32), dinoflagellates and hystrichospaerids (Artzner, 1974), and various lower and higher plants (Artzner, 1974; Brown, 1939; Klett and Erickson, 1976; Knowlton, 1916). (The references given above to document the existence of various organisms in the Fox Hills are not intended to be comprehensive.) Mollusks, chiefly bivalves and gastropods, are the most frequently found macro-organisms.

Occurrence of Fossils

In the type area of South Dakota, in the Trail City and lower part of the Timber Lake Member, most macrofossils occur in limestone concretions. In the upper part of the Timber Lake Member and the Iron Lightning Member, macrofossils occur primarily in shellbeds or are scattered through the matrix (Speden, 1970, p. 15). In the Trail City and lower Timber Lake, several fossil zones restricted to concretions have been recognized. From oldest to youngest, they are: Lower *nicolleti* Assemblage Zone, *Limopsis-Pseudoptera* Assemblage Zone, Upper *nicolleti* Assemblage Zone, *Protocardia-Oxytoma* Assemblage Zone, *Nucula* layer, *Abyssinus* concretions, *Sphenodiscus* layer, *Cucullaea* Assemblage Zone, and *Cymbophora-Tellinimera* Assemblage Zone. Most of the zones or assemblages are interpreted to be essentially isochronous. A notable exception is the overlying *Tancredia-Ophiomorpha* biofacies of the upper Timber Lake (Waage, 1968, p. 54-56, 153; Speden, 1970, p. 10-12, 16).

In North Dakota, macrofossils occur principally in limestone and sandstone concretions and well indurated, lenticular sandstone. Most fossiliferous exposures are in south-central North Dakota; those in Bowman County in the southwestern part of the state are essentially unfossiliferous (Erickson, 1971, p. 12).

The fossil zonation in North Dakota is not as well known as in the type area of South Dakota, but at least five assemblages have been recognized (Feldmann, 1972, p. 41-43). In the lower "thirty to forty feet of the Timber Lake Member" (p. 41) (= Trail City Member as used here) is an assemblage of *Scaphites* (*Hoploscaphites*) *nicoletti*, *Limopsis*, *"Gervillia"* and other mollusks similar to the lowest two assemblage zones of Waage (1968). In the middle Timber Lake (up to about 50 feet below the top) is an assemblage of *Nucula*, *Sphenodiscus*, *Cucullaea*, and other mollusks corresponding to perhaps several zones in the type area of South Dakota. The upper part of the Timber Lake is less fossiliferous than it is below; it is characterized by an assemblage of *Ophiomorpha*, *Tancredia*, *Crassostrea*, and other mollusks depending on locality. This assemblage presumably corresponds to the *Tancredia-Ophiomorpha* biofacies of Waage (1968). The Bullhead lithofacies of the Iron Lightning Member is the least fossiliferous unit of the Fox Hills in North Dakota; it contains an assemblage of such fossils as vertebrate remains and oyster fragments. The Colgate lithofacies is generally unfossiliferous but may contain an assemblage of abundant oysters (*Crassostrea*), *Corbicula*, and other mollusks in places. In addition to these assemblages is that of the Linton Member. Faunal remains are rare in the member; but common *Equisetum*, mangrove-like root systems, and other plant remains are characteristic (Klett and Erickson, 1976).

AGE AND CORRELATION

The age and correlation of the Fox Hills Formation has been discussed by Erickson (1974, p. 146-149) and Waage (1968, p. 139-146). Although the formation generally has been considered Maestrichtian (latest Cretaceous) (e.g., Cobban and Reeside, 1952), it is unclear what part of the Maestrichtian is represented (Waage, 1968, p. 143). Jeletzky (1962, p. 1006) said the lower part of the Fox Hills was Early Maestrichtian in age and showed (figs. 1-2) that part of the Fox Hills was also Late Maestrichtian. Recently, Gill and Cobban (1973, fig. 12) have given the age of the Fox Hills as generally Early Maestrichtian.

Several correlatives or possible correlatives of the Fox Hills occur in North America. In the western interior, selected correlative units are the Horsethief and Lennep Formations (central and western Montana; Gill and Cobban, 1973, fig. 9), Dad Sandstone Member of the Lewis Shale (south-central Wyoming; Gill and Cobban, 1973, p. 20), Trinidad Sandstone (southeastern Colorado and northeastern New Mexico), Lion Canyon Sandstone Member of the Williams Fork Formation (McGookey et al., 1972, fig. 50), and the Boissevain Formation (southern Manitoba; Williams and Burk, 1961, p. 169, 174-175). Selected approximate correlatives in the Atlantic Coastal Province are the Red Bank Sandstone (New Jersey) and Pedee Formation (North and South Carolina) (summarized by Murray, 1961, p. 360). Selected probable correlatives in the Gulf Coastal Province are the Corsicana Marl and Kemp Clay (both in Texas; Stephenson, 1941, p. 26, 29) and the Arkadelphia Marl (Arkansas, Louisiana, and Texas; Stephenson, 1941, p. 29).

DEPOSITIONAL ENVIRONMENTS

During much of the Late Cretaceous, the western interior was covered by an epicontinental sea that extended from the Gulf of Mexico to the Arctic Ocean and from the present Rocky Mountains to about eastern Minnesota (Gill and Cobban, 1973, fig. 1). A cordilleran highland flanked the epicontinental sea on the west and served as a source of sediments deposited to the east. During this time, variations in the rate of epeirogenic subsidence, amount of orogenic activity, and eustatic change of sea level resulted in four major transgressive-regressive cycles (McGookey et al., 1972; Weimer, 1960). The Fox Hills is the record of a regressive phase of the last major cycle. Regression was generally to the east but regionally to the north, south, and west as well. The Fox Hills regression from Montana is believed to have begun about 72 million years ago and to have taken about 2.5 million years. It was slow at first, averaging about 35 miles per million years, but near the end the strand line moved more than 250 miles in less than 0.5 million years (Gill and Cobban, 1973, p. 28, 33-34, figs. 18-19). As the Fox Hills was being deposited, deeper-water marine sediments of the Pierre Formation were being laid down generally to the east and largely continental sediments of the Hell Creek Formation were being deposited generally to the west (McGookey et al., 1972, fig. 50).

The continental climate in North America during the Late Cretaceous was possibly largely subtropical (data summarized by Dott and Batten, 1971, p.

384-385 and fig. 13.43; Sloan, 1970, p. 428-429). A sharp climatic zonation may not have existed, although seasonal weather changes may have occurred. Ocean temperatures may have been on the order of 60-75°F in present middle latitudes (Dott and Batten, 1971, p. 384-385). In North Dakota, the Fox Hills Formation was possibly deposited adjacent to lowlands supporting vegetation growing within a humid, subtropical to tropical climate (Artzner, 1974, p. 41, 43). Prevailing winds may have been from the west (Dott and Batten, 1971, fig. 13.43). If so, the source of the volcanic ash in the Fox Hills of North Dakota may have been the Elkhorn Mountains and Deer Creek volcanic centers in western and southern Montana (Gill and Cobban, 1973, fig. 19).

A barrier bar (or island)—deltaic model has been proposed for the Fox Hills Formation in the type area of South Dakota (Waage, 1968). This model has been accepted, with modification, by Erickson (1971), Feldmann (1972), and Speden (1970). I, too, accept this general model with little modification and elaboration.

In the outcrop area of the Fox Hills in southern North Dakota, the Trail City and Timber Lake Members of the lower Fox Hills suggest a barrier bar or barrier island sequence (characteristics summarized by Spearing, 1974). A barrier island sequence has also been recognized for part of the Fox Hills in Wyoming (e.g., Land, 1972). Evidence in North Dakota includes a sequence that generally and gradually becomes coarser grained upward (in going upward from the Trail City to the Timber Lake and in going upward within the Timber Lake), mostly horizontal bedding in the lower part of the sequence and common crossbedding near or at the upper part, and common to abundant fossils of near normal salinity (Feldmann, 1972, p. 50). The interbedded shale, siltstone, and sandstone of the Trail City Member and the lower Timber Lake Member suggests deposition in the lower shoreface or "transition zone"; the sandstone interbeds were probably deposited during storms (Reineck and Singh, 1973, p. 285, 307-308). The moderately- to well-sorted, commonly tabular, and trough crossbedded, *Ophiomorpha*-bearing sandstone of the upper Timber Lake is suggestive of the middle and upper shoreface environment. Concentrations of worn and oriented mollusks in the well-indurated sandstones of the upper Timber Lake imply periodic storms (Erickson, 1971, p. 44-48). Paleocurrent analysis of cross-strata in the upper Timber Lake indicate primary marine currents coming from the northeast (Chayes and Erickson, 1973) and moving sandy sediment well into the type area (Waage, 1968, figs. 19-23).

Waage (1968) interpreted the upper Fox Hills as a deltaic sequence that overstepped the barrier bar sequence upon regression. Hubert, Butera, and Rice (1972) have proposed a deltaic model for the somewhat older Parkman Sandstone in the Powder River basin of Wyoming. The upper Fox Hills seems to reflect a similar depositional setting. Evidence in South Dakota for a deltaic sequence includes correlative units to the southwest of the type area bearing lignite and *Ophiomorpha*, a sequence similar to present-day deltaic successions including thin and regular bedding and contorted bedding, abundant plant remains, and marine and brackish animal fossils that are generally sparse and of low species diversity. In addition, the upper Fox Hills sequence passes upward and interfingers with the Hell Creek sequence. In south-central North Dakota the Hell Creek consists of marine, brackish, freshwater, and terrestrial sediments that indicate deposition within a deltaic complex on a coastal plain (Frye, 1967). This deltaic complex is apparently that labelled the "Sheridan delta" by Gill and Cobban (1973, fig. 19). This is one of three or possibly four deltaic complexes that affected sedimentation in the Rocky Mountain region during Late Cretaceous time (Weimer, 1970). Waage (1968) did not recognize a strict lagoonal facies because (p. 154-155) the Timber Lake was not recognizable in places where the Iron Lightning Member persists, the contact between the Iron Lightning and Timber Lake Members was not observed to be gradational, and the Colgate lithofacies appears to directly overlie the Timber Lake at several places.

I generally agree with Waage's (1968) deltaic complex but suggest that at least part of the interbedded sandstone and shale or siltstone of the Bullhead lithofacies represents a lagoonal facies, at least in parts of south-central North Dakota and possibly within the northern part of the type area. In the outcrop area of North Dakota, the Timber Lake–Bullhead contact is gradational (Feldmann, 1972, p. 28). It is also possible, in places at least, that a barrier island, lagoon, and delta-complex were all in existence concurrently as where the Guadalupe River enters the Texas Gulf (Donaldson, Martin, and Kanes, 1970). The Bullhead lithofacies, therefore, may have been deposited within the delta front, prodelta, bay, or lagoon environments. The commonly crossbedded, muddy sandstone of the Colgate lithofacies, occurring commonly as channel fills as well as beds and containing brackish and marine fossils, suggests deposition within a tidal channel or distributary (Reineck and Singh, 1973, p. 268) system. The generally massive sandstone of the Linton Member, containing common *Equisetum* and mangrove-like root systems but rare faunal remains, suggests deposition within an estuarine, tidal channel, or deltaic distributary system (Klett and Erickson, 1976).

Water depths for the Fox Hills sequence can be inferred from different approaches. On the basis of comparing depth preferences of Fox Hills bivalve genera with living analogues, the maximum depth for the deposition of Fox Hills sediments has been approximated at 80 fathoms or 480 feet (Feldmann, 1972, p. 44). The presence of *Ophiomorpha* in well-sorted sandstone (as in the upper Timber Lake) indicates intertidal or shallow subtidal depths, but somewhat greater depths in poorly sorted sandstone (Weimer and Hoyt, 1964, p. 766). Assuming minimal compaction and subsidence, the thickness of the sediments may be used to estimate water depth for presumed barrier island sequences (Klein, 1974). If the lower Fox Hills is a barrier island sequence, one might extrapolate a water depth by using the Pierre-Fox Hills contact as the base of the coarsening-upward sequence and assuming the top of the Timber Lake Member to represent the approximate position of sea level. This approach gives a water depth of at least 240 feet (upper part of section incomplete) for a composite section of the lower Fox Hills (sections 38, 30, 196, 199) in western Dewey County, South Dakota (Waage, 1968, figs. 25, 15). This same section suggests a wave base of more than 140 feet (thickness of Timber Lake) at this locality.

In the subsurface, to the north and northwest of the main outcrop area in south-central North Dakota, the Fox Hills sequence appears to become more variable. This implies a greater complexity of depositional environments. The presence of lignite in the sequence at wells 4, 5, 6, 12, and 18 (pls. 1-3) suggests the influence of a complex of delta-plain environments similar to what produced the lignite-bearing Fox Hills in west-central South Dakota (Pettyjohn, 1967).

URANIUM POTENTIAL

General

Denson and Gill (1965) summarized the uranium occurrences in the Williston basin except those in the Cave Hills of South Dakota, which have been described by Pipiringos, Chisholm, and Kepferle (1965). Noble (1973) discussed uranium production in North Dakota. Estimated reserves in the basin of rock containing 0.1 percent uranium are greater than 1 million tons (Denson and Gill, 1965, p. 64).

Uranium in the basin occurs primarily in impure lignite and lignitic shale (Vine, 1962) but has been found also in carbonaceous siltstone, phosphatic claystone, and sandstone. Generally, a thick sandstone directly overlies or underlies the uranium-bearing host rock. The richer deposits are aligned about north-south along the axis of the Williston basin. The more significant deposits, containing 0.1 percent or more uranium, occur in the Cave Hills (northern Harding County, South Dakota; Ludlow and

Tongue River Formations), Slim Buttes (southeastern Harding County, South Dakota; Ludlow Formation), and along the Little Missouri River escarpment in the vicinity of Saddle Butte and Rocky Ridge (eastern Billings and northwestern Stark Counties, North Dakota; Sentinel Butte Formation). All significant uranium deposits are less than 300 feet stratigraphically below the base of the pre-Oligocene unconformity or its projected base (Vine, 1962, p. 141-142). Overlying this unconformity are middle and late Tertiary rocks containing volcanic materials. A common belief (e.g., Denson and Gill, 1956) is that these volcanic materials were the source of the uranium. Groundwater leached the uranium from the volcanic materials and carried it downward and laterally. Lignite and carbonaceous rocks served as receptors that may have extracted uranium by ion exchange or by the formation of organometallic compounds. Uranium mineralization may have occurred since Oligocene (Pipiringos, Chisholm, and Kepferle, 1965, p. A50) or late Miocene (Denson and Gill, 1965, p. 67) time.

Fox Hills Formation

Although uranium in the Williston basin has been found almost entirely in Early Tertiary lignite and nonmarine carbonaceous rocks, a good possibility exists for its occurrence in the Late Cretaceous marine and brackish strata of the Fox Hills. Uranium is known from marine sandstone (e.g., Clinton and Carithers, 1956) and marine black shales (e.g., Swanson, 1956). A model for the syngenetic origin of possible uranium in the Fox Hills is as follows.

It is clear that the Hell Creek, Fox Hills, and Pierre Formations are at least in part penecontemporaneous; these formations, therefore, represent a variety of depositional environments that were areally in juxtaposition. Streams originating or passing through coastal plain bogs (sites of later lignite formation within Hell Creek environments) could have carried uranium ions, fixed by organic matter in solution (Vine, 1962, p. 161), that would be carried into bays or lagoons or out into the open sea. (The source of the uranium ions might have been the volcanic materials, now in the form of bentonite and bentonitic sediments, in the Hell Creek Formation.) The uranyl humates may have been concentrated as a flocculant precipitated by the action of sea water (Vine, 1962, p. 161), or plant debris and other organic matter may have extracted uranyl ions out of solution. Following this model, one might search for syngenetic uranium primarily in the interbedded mudstone and sandstone sequence of the Bullhead lithofacies that contains laminae of lignite and other organic material. Secondarily, uranium could be present in the sandy shale or siltstone of the Trail City Member or perhaps the shale of the uppermost Pierre Formation.

Epigenetic uranium might be searched for in the Fox Hills below the volcanic ash that is known to occur in central and southern Emmons, northeastern Sioux, and southeastern Morton County (Artzner, 1974, fig. 2). Specific areas to search might be in central Emmons County where the ash is generally thickest and is in the lower part of the Fox Hills; in eastern Sioux County where it is at the top of the Bullhead lithofacies; and in southeastern Morton County where it is about 48 feet above the Fox Hills-Hell Creek contact (Artzner, 1974, p. 7). Groundwater could leach possible uranium from the volcanic ash and redeposit it in the finer clastics containing organic materials in the Fox Hills and Hell Creek Formations. It is also possible that uranium might be deposited in permeable sandstone (as of the Timber Lake Member) because of a reducing environment provided by localized carbonaceous material or hydrogen sulfide.

To provide a sound basis for further exploration in the Fox Hills Formation, considerable additional stratigraphic study is warranted. This study might be concentrated in a fringe area surrounding the known occurrence of the volcanic ash in the south-central part of the state and also farther west where lignite and carbonaceous shale occurs in the Fox Hills section.

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PLATE I NW-SE CROSS SECTION OF FOX HILLS FORMATION IN SOUTHWESTERN NORTH DAKOTA

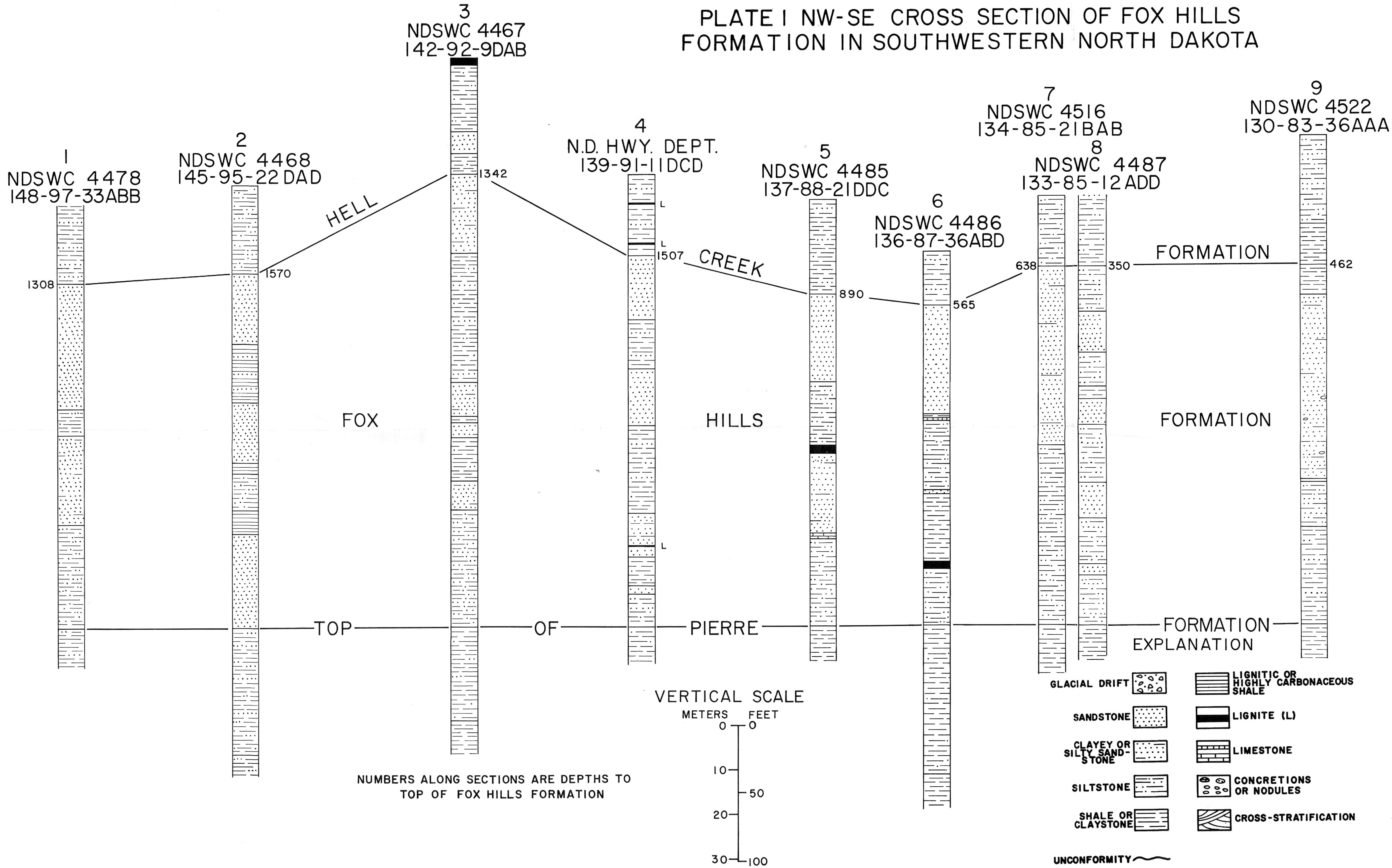


PLATE 2 SW-NE CROSS SECTION OF FOX HILLS FORMATION IN WESTERN NORTH DAKOTA

PLATE 3 SW-NE CROSS SECTION OF FOX HILLS FORMATION IN SOUTHWESTERN NORTH DAKOTA

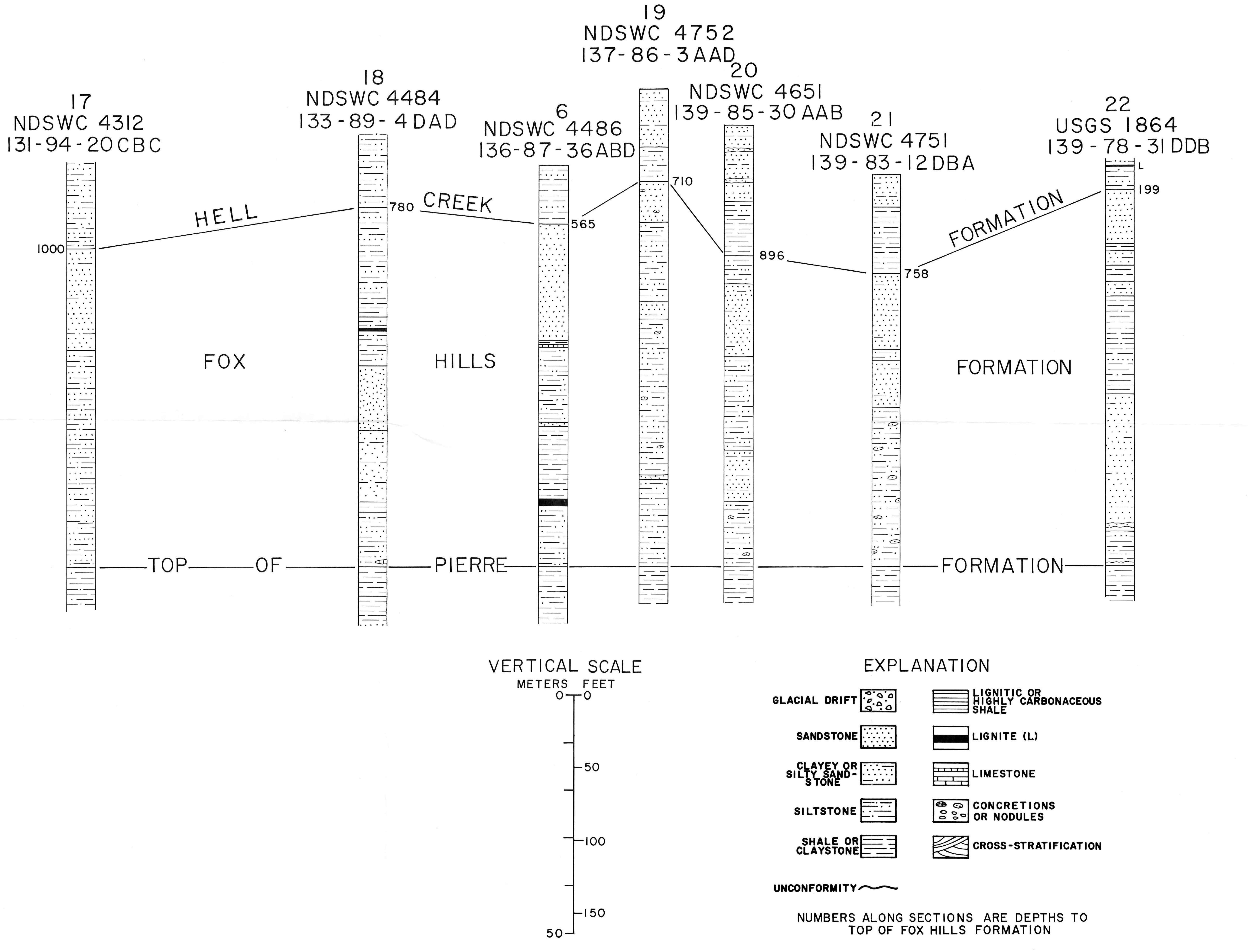
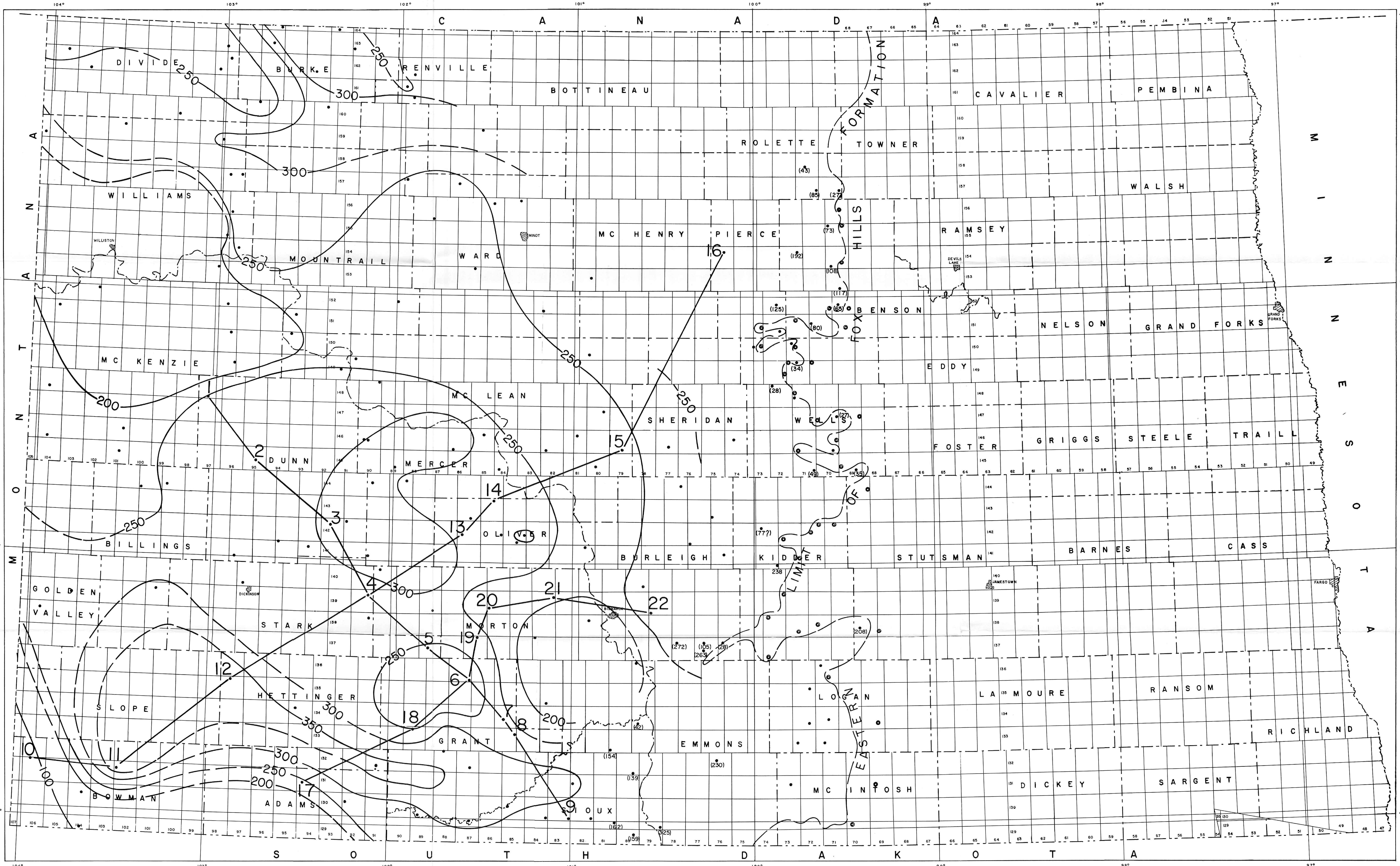


PLATE 4 ISOPACH MAP OF FOX HILLS FORMATION IN NORTH DAKOTA



SCALE 1/500000

10 0 10 20 30 40 MILES

10 0 10 20 30 40 50 KILOMETERS

CONTOUR INTERVAL 50 FEET
238 SPOT THICKNESS OF FOX HILLS
(154) SPOT THICKNESS OF ERODED FOX HILLS
FOX HILLS FORMATION ABSENT
LINE OF CROSS-SECTION

EASTERN LIMIT OF FOX HILLS FORMATION MODIFIED FROM ANDERSON (1969) EXCEPT IN LOGAN AND MC INTOSH COUNTIES WHERE LIMIT IS FROM CLAYTON (1962)