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Stratigraphy and sedimentary history of middle Cenozoic (Oligocene and Miocene) deposits in North Dakota

William J. Stone
University of North Dakota

STRATIGRAPHY AND SEDIMENTARY HISTORY OF MIDDLE CENOZOIC (OLIGOCENE AND MIOCENE) DEPOSITS IN NORTH DAKOTA

by
William J. Stone

Bachelor of Science, Bowling Green University, 1964

Master of Science, Kent State University, 1969

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(Chairman)

Dean of the Graduate School

Permission

Title STRATIGRAPHY AND SEDIMENTARY HISTORY OF MIDDLE CENOZOIC (OLIGOCENE AND MIOCENE) DEPOSITS IN NORTH DAKOTA

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ABSTRACT

Middle Cenozoic (Oligocene and Miocene) continental deposits of North America have been most studied in southwestern South Dakota and western Nebraska where the White River Group constitutes a fairly complete Oligocene record, and the Arikaree Group of early Miocene age is commonly the sole remaining record of that epoch. Isolated outcrops in adjacent states also offer opportunities for studying the middle Cenozoic history of the Midcontinent but disagreement as to the physical stratigraphy of such deposits has hindered further work in these areas. The main purpose of this study is to present a viable stratigraphic framework for the middle Cenozoic deposits of one of these isolated outcrop regions, southwestern North Dakota. A secondary purpose is to report preliminary findings concerning the petrography and sedimentary history of these rocks.

Middle Cenozoic strata in North Dakota are largely restricted to isolated buttes in Adams, Bowman, Dunn, Golden Valley, Grant, Hettinger, Slope, and Stark Counties. These deposits consist of 125 to 560 feet of cross-bedded sandstone, clay, claystone, silty claystone, siltstone, and minor limestone and dolostone, spanning Chadronian (early Oligocene) through Arikareean (early Miocene) times.

The Chadron and Brule Formations of the White River Group are

recognized in North Dakota. Proposed subdivision of these formations includes six new rock-stratigraphic units of bed and member rank. The name "Arikaree Formation," previously applied to the strata overlying the White River in North Dakota, is rejected and a new formation name proposed for these deposits because they are lithologically distinct from type Arikaree in Nebraska and Arikaree of even closer outcrops in the Big Badlands of South Dakota.

Three new members are proposed for the Chadron Formation in North Dakota: the Amidon, Chalky Buttes, and South Heart Members in ascending order. The Amidon includes 7 to 16 feet of clay and silty claystone that weather very pale orange or light brown but are very pale orange to grayish orange where fresh. The Chalky Buttes is made up of 8 to 75 feet of medium-grained to very coarse-grained, cross-bedded sandstone that weathers white, very pale orange, dark yellowish orange, or light brown and is very pale orange to pinkish gray where fresh. The South Heart consists mainly of 8 to 55 feet of clay that weathers pale greenish yellow and is yellowish gray to pale olive where fresh.

Two new members and one new bed are proposed for the Brule Formation in North Dakota: the Dickinson Member below, including the Fitterer Bed, and the Schefield Member above. The Dickinson consists of 60 to 130 feet of clay and pitted-weathering, silty claystone. The clay is yellowish gray where weathered but pale olive to light olive gray where fresh; the claystone weathers very pale orange and is yellowish gray where fresh. The Fitterer Bed is a 5-foot to 9-foot thick, cross-bedded, fine-grained to medium-grained sandstone, occurring at various horizons within the Dickinson. The Fitterer sandstone weathers pale greenish yellow but is yellowish gray where fresh. The Schefield includes 16 to 85 feet of alternating beds of siltstone and clay. The siltstone weathers very pale orange but is grayish orange pink to yellowish gray where fresh; the clay weathers moderate reddish orange but is pale reddish brown where fresh. Chadronian, Orellan, and Whitneyan fossils have been previously reported from the Chadron and Brule of North Dakota.

The name "Killdeer Formation" is proposed for the strata overlying the White River Group in North Dakota but below unconsolidated deposits whose source and age are unknown. The Killdeer consists of 25 to 200 feet of green-colored, concretionary, calcareous sandstone, siltstone, silty claystone, and dolostone. Meager fossil evidence [Paleocastor sp., Hypertragulus minor, and Amphicaenopus(?)] suggests an Arikareean (early Miocene) age for the Killdeer.

From petrographic analyses it has been determined that the sandstones of the Chadron, Brule, and Killdeer Formations are arkose. X-ray-diffraction analyses showed that montmorillonite is the predominant clay mineral in these deposits and that the zeolites clinoptilolite, erionite, and heulandite are present in both the mudstone and sandstone units. No distinct mineralogic criterion for distinguishing the new units was found. Although previous workers have mentioned the tuffaceous aspect of these deposits and several lines of evidence were found in the present study to suggest the presence of ash in some of the beds, no attempt is made to apply a pyroclastic nomenclature to them until further work has been done.

The source of the detritus in the middle Cenozoic deposits was probably the Tertiary igneous intrusions of the northern Black Hills, based on (1) an examination of available radiometric dates of Tertiary igneous rocks there, (2) a cursory comparison of igneous rock types in the gravel of the Chalky Buttes Member of the Chadron with igneous rock types in the northern Black Hills, (3) an approximation of the pre-Oligocene slope between the Black Hills and the study area, and (4) a review of what is known of the Cenozoic geomorphic history of the Black Hills.

The middle Cenozoic strata of North Dakota represent deposition in various fluvial subenvironments: channel, floodplain, and flood-basin. All of the deposits may be accounted for by a fluvial model in which divides are low such that flood waters of adjacent streams co-mingle to form large but shallow, temporary lakes. Possible modern analogs of such conditions include the Punjab region of Pakistan, the Amazon River Basin of Brazil, and the Pampa of Argentina.

INTRODUCTION

General Statement

Middle Cenozoic continental deposits have been most extensively studied in the major outcrop areas of southwestern South Dakota, western Nebraska, northeastern Colorado, and southeastern Wyoming (Figure 1). However, their original extent in the Midcontinent was considerably broader, and isolated outcrops also occur in various parts of Montana, southwestern North Dakota, and southwestern Saskatchewan. Throughout the Great Plains of the United States, the White River Group constitutes a fairly complete Oligocene record, and in many places, the Arikaree Group of early Miocene age is the sole remaining record of that epoch. Middle Cenozoic continental deposition in adjacent parts of Canada is represented by the Cypress Hills Formation of early Oligocene age (Douglas, 1970, p. 481 and Furnival, 1946, p. 5, 119).

Problem and Purpose

White River deposits were first recognized in North Dakota and assigned an Oligocene age by Cope (1883). The inconsistencies in published stratigraphic nomenclature applied to these deposits since their discovery reflect disagreement among the various workers as to their definition, rank, age, and regional correlation, and attest to the need for a re-

Fig. 1.--Outcrops (in black) of middle Cenozoic deposits in the North American Midcontinent.

examination of these strata. This need was intensified in 1965 when strata in southwestern North Dakota, included in the White River Formation by the North Dakota Geological Survey, were remapped as Arikaree Formation and assigned a Miocene age by Denson and Gill (1965, p. 13, 14). Wilson M. Laird, State Geologist at the time, felt that this reassignment warranted a re-evaluation of the entire middle Cenozoic section of North Dakota. Several specific questions raised by the reassignment are the focus of this study:

1. Is the reassignment consistent with lithostratigraphic and chronostratigraphic evidence; in other words, are the rocks in question referrable to the classical Arikaree Group on the one hand and the Miocene on the other?

2. What is the physical stratigraphy of the middle Cenozoic deposits of North Dakota, and what is the appropriate rank, nomenclature, and resulting stratigraphic framework for these deposits?

3. What is the general petrography of the middle Cenozoic deposits of North Dakota?

4. Are there any distinct mineralogic criteria by which the various middle Cenozoic rock units of North Dakota may be distinguished?

5. How do the middle Cenozoic deposits of North Dakota compare lithologically and chronologically with those of the classical exposures of South Dakota and Nebraska?

6. What was the source and general mode of deposition of the North Dakota deposits?

The end result and main contribution of the study is a new stratigraphic framework for the middle Cenozoic deposits of North Dakota. This framework includes seven new rock-stratigraphic units ranging in rank from bed to formation. In addition to the definition and description of new stratigraphic units, this report also includes a summary of previous work on middle Cenozoic deposits in North Dakota; discussions of the age, correlation, physical equivalence, and sedimentary history of the middle Cenozoic units recognized; and the results of petrographic and x-ray-diffraction analyses of the major rock types present in the middle Cenozoic section of the state.

Location of Outcrops

The outcrops studied occur in widely separated buttes or clusters of buttes in southwestern North Dakota (Figure 2). For ease of discussion these exposures are grouped into four more or less distinct outcrop areas defined here: 1) the Killdeer Mountains (includes buttes by the same name in northwestern Dunn County), 2) the Little Badlands (includes outcrops in western Stark County, south of South Heart), 3) the Lefor Buttes (includes buttes in northern Hettinger and southern Stark Counties, near the town of Lefor), and 4) the Chalky Buttes Area (includes the Chalky Buttes and nearby buttes in eastern Slope County). Other small exposures occur in Adams, Bowman, Golden Valley, and Grant Counties. The three main outcrop areas are the Killdeer Mountains, the Little Badlands, and the Chalky Buttes Area. A list of middle Cenozoic exposures in North Dakota with names of specific topographic features and study sites included in each of the outcrop areas defined above is

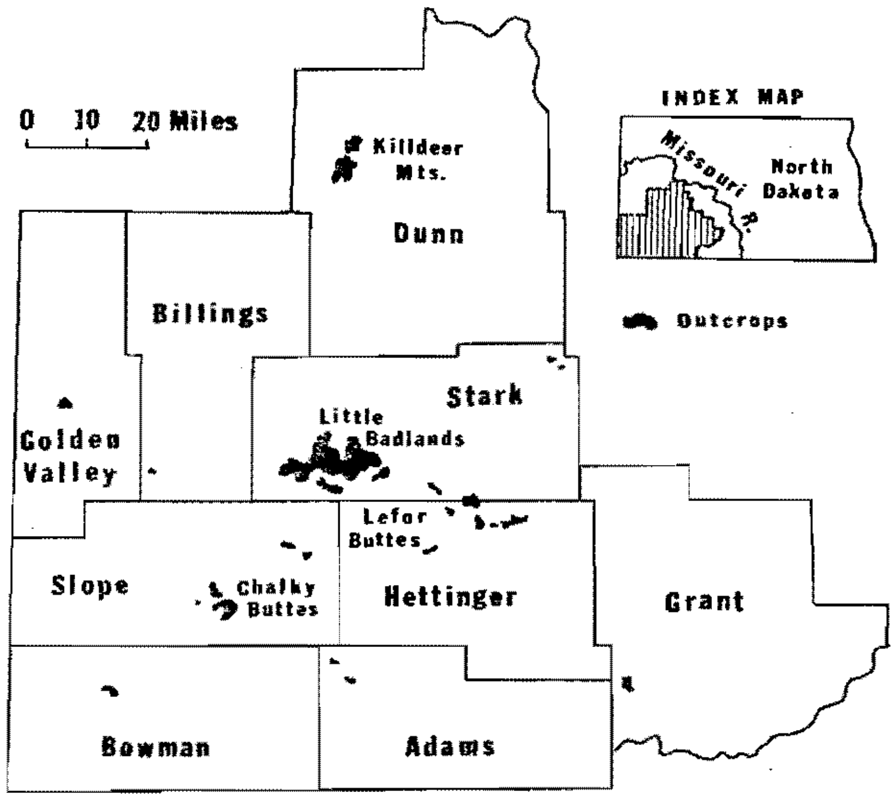

Fig. 2.--Outcrops of middle Cenozoic deposits in North Dakota.

given in Table 1. Legal descriptions of each of these localities, as well as the rock units present, are given in Appendix A.

The coarse-micaceous-sandstone caprock of the Blue Buttes in McKenzie County was included in the White River by Leonard (1922) and Nevin (1946), but, as pointed out by Benson (1952, p. 98), the sandstone capping these buttes is probably referrable to the Golden Valley Formation. Likewise, the micaceous sandstone capping the Davis Buttes a few miles northeast of Dickinson, and on Dobson Butte, a few miles southeast of Dickinson, was reported by Hickey (1966, p. 67) to be part of the White River Group; however, I found no middle Cenozoic deposits at these sites and this sandstone is either equivalent to that referred to the Golden Valley Formation by Denson (1970) or a separate, yet unnamed unit.

Methods and Approach

For background in the middle Cenozoic stratigraphy of the Midcontinent, I studied the type sections of the various rock units involved in South Dakota and Nebraska, attended formal field conferences on Cenozoic stratigraphy in these areas, consulted with the principal investigators of these sections in both states, and visited exposures of White River and Arikaree deposits in the parts of South Dakota and Montana adjacent to the study area. I examined collections of Oligocene, Miocene, and Pliocene fossils at the Carter County Museum (Ekalaka, Montana), the South Dakota School of Mines Geology Museum, and the University of Nebraska State Museum.

TABLE 1

LOCATION OF OUTCROPS OF MIDDLE CENOZOIC DEPOSITS IN NORTH DAKOTA*

Chalky Buttes Area, Slope County	Little Badlands, Stark County	Killdeer Mountains, Dunn County	Lefor Buttes, Hettinger and Stark Counties	Other Small Exposures
Chalky Buttes Proper	Fitterer Ranch (3)	South Mt. (7)	Antelope Butte	Bullion Butte, Billings and Golden Valley Counties
White Butte (1)	Abandoned House Site (4)	North Mt.	Black Butte	Coffin Buttes, Grant Co.
Northern Chalky Buttes (2)	Little Badlands Proper (5)		Bull Butte	Flattop Butte, Golden Valley County
HT or Black Butte	White Butte (6)		Cogrove Butte	Medicine Pole Hills, Bowman County
Rainy Buttes	DeMar Site		Long Butte	Sentinel Butte, Golden Valley County
Slide Butte	Golden Butte		School Butte	Whetstone and Wolf Buttes, Adams Co.
	Turtle Valley		Schultz Butte	
			Shepard Butte	
			Straight Butte	
			Youngman's Butte	

*Legal descriptions of all localities are given in Appendix A; numbers in parentheses refer to measured sections given in Appendix C and shown on Plate 1.

For a better understanding of the local problem, I examined all of the sections illustrated by Denson and Gill (1965, Plate I). I then measured stratigraphic sections at each major exposure of middle Cenozoic rocks in North Dakota (Appendix C) with hand level and Jacob staff or tape and constructed and correlated representative composite sections for each of the three main outcrop areas (Plate I). The field work was conducted in the summer and early fall months of 1968 and 1969. Procedures followed in measuring sections are given in Appendix C. I also analyzed the main rock types by X-ray diffraction and studied the various sandstones in thin section with a petrographic microscope. All terminology used is defined in Appendix B. Methods employed in the X-ray-diffraction and thin-section analyses are given in Appendix D.

I consulted various authorities at the American Museum of Natural History, the South Dakota School of Mines Geology Museum, and the University of Nebraska State Museum for verification of the identifications of fossils collected.

REGIONAL SETTING

Tectonic Framework

The study area lies generally in the unglaciated part of North Dakota southwest of the Missouri River within the southwestern part of the Williston Basin (Figures 2 and 3). An excellent discussion of the sedimentary and tectonic history of the North Dakota part of this basin was given by Carlson and Anderson (1965). The brief summary which follows is drawn largely from this source.

The Williston Basin is a large, intracratonic, structural and sedimentary basin occupying western North Dakota, northwestern South Dakota, northeastern Montana, southern Saskatchewan, and a small part of southwestern Manitoba. It is about 525 miles long, 400 miles wide, underlies about 51,600 square miles of western North Dakota, and contains deposits from all periods of Phanerozoic time. The maximum known stratigraphic thickness of sedimentary rocks in the Williston Basin is 15,128 feet recorded in a well in McKenzie County, North Dakota. The maximum structural relief is about 10,000 feet (Denson and Gill, 1965, p. 26).

Two major structural features occurring within the Basin are the Nesson and Cedar Creek Anticlines (Figure 3). Subsurface evidence indicates that these uplifts originated in Paleozoic time but came into promi-

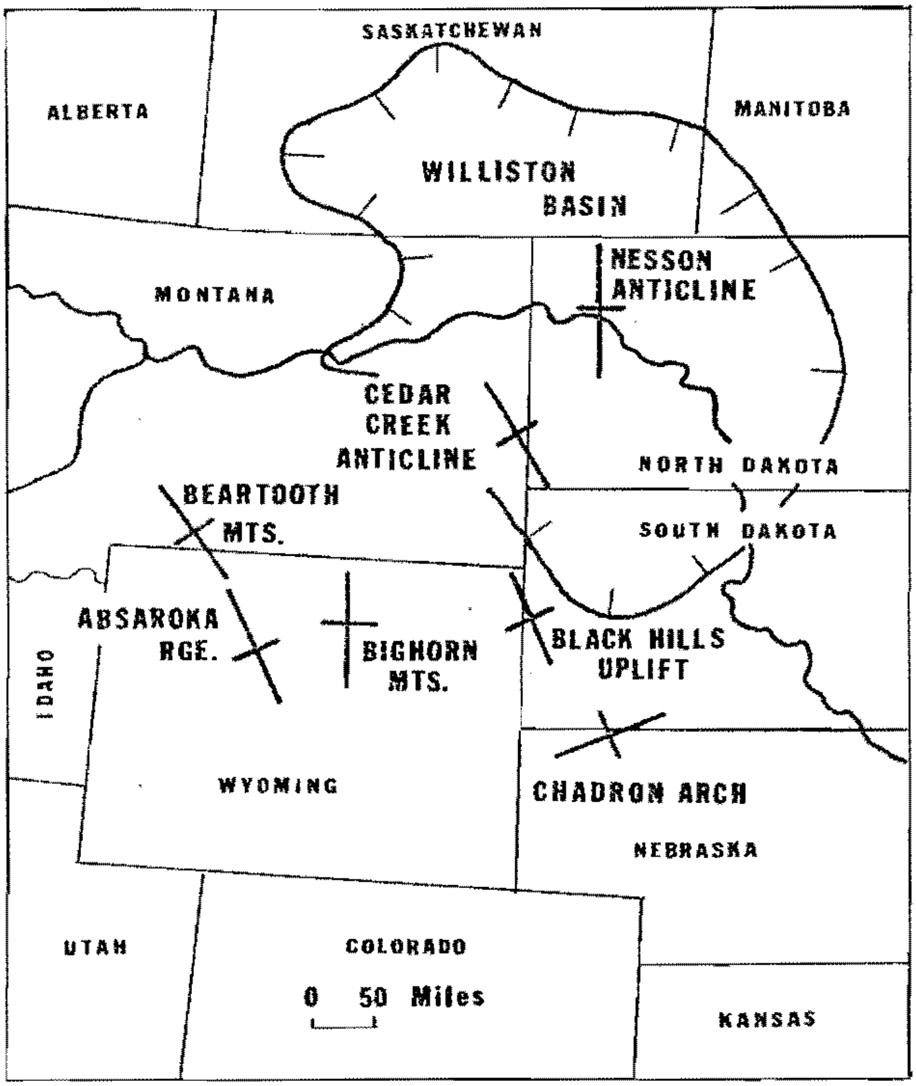

Fig. 3.--Major structural features in the North American Midcontinent.

nence as a result of Laramide folding during late Cretaceous to early Eocene time (Denson and Gill, 1965, p. 26). Another important structural feature in the region is the Black Hills Uplift, which lies south of the study area (Figure 3). This northwest-trending, asymmetrical dome is the easternmost of the outer ranges of the Laramide Cordillera (Eardley, 1962, p. 361, 374-376).

An episode of more recent shallow folding of middle Cenozoic rocks in the Little Badlands and Chalky Buttes areas of North Dakota has been suggested by Denson and Gill (1965, p. 26). These folds were said to trend northeastward in contrast to the Laramide and older folds which trend northwestward. Denson and Gill (1965, Plates 10 and 11) mapped these structures on the base of the Chadron Formation. Their map of the Little Badlands shows a northeast-trending syncline along the Little Badlands escarpment which marks the northwestern limit of the Stark County outcrops. However, my field investigation indicated that they had mistaken pre-Chadron relief for post-Chadron structure; the "syncline" is more likely a pre-Chadron valley, and the "anticline" is more likely a pre-Chadron divide. No deformation is apparent in the Chadron deposits; only their base is irregular where they disconformably overlie the Interior Formation (Figure 4). Therefore, the 150 feet of structural relief mapped by Denson and Gill (1965, Plate 10) for this episode of folding is actually erosional relief. Similarly, the southeast-trending syncline mapped by Denson and Gill (1965, Plate 11) at the Chalky Buttes is also probably an erosional feature. In the Chalky Buttes the Chadron deposits thicken abruptly toward the southeast, apparently into a large

Fig. 4.--Disconformable contact of Interior Formation and overlying Chadron Formation, White Butte, Stark County; measured section 6 (Appendix C); NE¼NW¼ sec. 32, T. 139 N., R. 97 W.; view looking west.

pre-Chadron valley. The base of the Chadron Formation is an erosional surface throughout the région and thus makes a poor structural datum. Some other means must be employed to prove post-Chadron folding. I found no evidence of such an episode of folding.

Local structural complexities on a smaller scale are present throughout the region. The best examples of this occur at Reva Gap in the Slim Buttes of northwestern South Dakota. The disruption of bedding there has been ascribed an amazing variety of origins, but Lillegraven concluded (1970, p. 831) that these structures are the result of "normal faulting with some rotation of . . . grabens due to minor translatory movement along one or more low-angled, gravity controlled detachment faults accompanied by lateral spreading of soft clay from beneath firmer material." Normal faults also locally disrupt the middle Cenozoic record of North Dakota as noted by Skinner (1951, p. 52).

Mass movement during the Quaternary has buried the base of most of the buttes in the study area obscurring the lower part of the section. This is especially common in the Killdeer Mountains, where extemely large blocks of the resistant caprock have rotated away from their original positions. This may have been aided by groundwater solution along fractures in these highly calcareous rocks. Another example of mass movement of probable Quaternary age was described in the Little Badlands by Douglass (1909, p. 235), where "the face of the higher northern portions of the bluffs does not rise in an abrupt manner from the adjoining flatland but in peculiar terraces formed by landslides."

In summary, the strata of interest are essentially horizontal except where disrupted locally by normal faulting and mass movement of probable

Quaternary age. No post-middle-Cenozoic folding was detected.

General Bedrock Geology

The oldest bedrock unit exposed in the study area is the Pierre Formation of Cretaceous age; however, most of the area is immediately underlain by the Tongue River and Sentinel Butte Formations, which constitute the upper part of the Fort Union Group of Paleocene age. The rest of the area is immediately underlain by the Golden Valley Formation. Hickey (1972, p. 106) found that most of the Golden Valley Formation is of Wasatchian (early Eocene) age but that the lowermost member of this formation may be Clarkforkian (late Paleocene). The only other Eocene rock unit in the region is the Slim Buttes Formation exposed in the Slim Buttes of Harding County in northwestern South Dakota. From fossil vertebrates collected at Slim Buttes, Bjork (1967, p. 227) determined a Duchesnean (latest Eocene) age for this rock unit.

Throughout the region the White River Group overlies a widespread, brightly colored, weathering zone, named the Interior Formation by Ward (1922, p. 18-20) for exposures near Interior, South Dakota. This formation has been interpreted by Pettyjohn (1967, p. C66) to be a paleosol developed atop several rock units of various ages: the Skull Creek, Niobrara, Pierre, Fox Hills, Ludlow, Tongue River, Sentinel Butte, Golden Valley, and Slim Buttes Formations, which range in age from early Cretaceous to late Eocene. Where earliest Oligocene deposits, such as the Yoder Formation of Wyoming, are present, the Interior Formation is absent. Because the Interior Formation is always overlain by early, but not earliest, Oligocene, it has generally been assigned a latest Eocene to earliest Oligocene age.

The Interior Formation in North Dakota is characterized at most places by brightly colored, fine-grained deposits (Figure 4) as it is elsewhere in the region. In section 2 at the northern end of the Chalky Buttes, however, an oxidized, erosion-resistant, reddish-purple bed (Figure 5), composed almost entirely of the mineral analcite and termed analcimolite by Furman (1970a), is interpreted to represent the Interior Formation there. Identical beds also occur on HT, Bullion, and Slide Buttes (Appendix A).

As a rule, the Interior Formation in North Dakota overlies the Golden Valley Formation. However, the Golden Valley Formation has not been previously recognized in the Chalky Buttes. The strata directly below the analcimolite bed at measured section 2 are here assigned to the Golden Valley because of (1) their stratigraphic position above typical Fort Union strata, (2) their position above a massive sandstone that was recently reassigned to the Golden Valley Formation by Denson (1970, p. B63), and (3) their position below the Chadron Formation and what is interpreted to be the Interior Formation here.

Another possibility is that these strata correlate with the Slim Buttes Formation of northwestern South Dakota. Hickey (1972, p. 118) did not agree with Denson's reassignment of the massive sandstones to the Golden Valley and concluded they represent "another episode of deposition. . . . " Further work is warranted to determine the age of these beds and their relationship to either specific informal members of the

Fig. 5.--Bed of analcimolite interpreted to be the Interior Formation, northern end of the Chalky Buttes; tan material below the analcimolite is treated here as Golden Valley, undifferentiated; white beds above are middle Chadron Formation; measured section 2 (Appendix C); NE¼NW¼ sec. 15, T. 134 N., T. 101 W.; view looking northeast; scale given by rock pick at left.

Golden Valley Formation as described by Hickey (1966 and 1972) or to the Slim Buttes Formation as originally described by Malhotra and Tegland (1959). Here, these strata are treated as Golden Valley, undifferentiated.

MIDDLE CENOZOIC STRATIGRAPHY OF THE MIDCONTINENT

Previous Work in the Midcontinent

As suggested by Harksen and Macdonald (1969a, p. 2, 3), the nomenclatural history of Oligocene and Miocene deposits in the Midcontinent is typical of that of many rock units of the West in that it is characterized by "roving type localities and the substitution of names." From the outset, major work has centered upon deposits in the Big Badlands of South Dakota and those in western Nebraska. Excellent detailed summaries of the development of the nomenclature for middle Cenozoic deposits of South Dakota were given by Macdonald (1951) and Harksen and Macdonald (1969a and 1969b). The history of nomenclature of the Oligocene deposits of Nebraska was well summarized by Schultz and Stout (1955). The brief descriptions that follow were drawn from these summaries.

In 1941, Wood and others proposed a provincial time scale for the North American Tertiary. No comprehensive revision of this time scale has ever been published, and it remains the standard for stratigraphic research. Time terms used here are those of Wood and others (1941). The stratigraphic nomenclature and provincial ages for middle Cenozoic deposits in South Dakota and Nebraska are given in Figure 6.

AGE	NEBRASKA	SOUTH DAKOTA
Early Miocene (Arikareean)	ARIKAREE GROUP Harrison Fm. Monroe Creek Fm. Gering Fm. Mitchell Pass Mbr. Helvas Canyon Mbr.	ARIKAREE GROUP Harrison Fm. Monroe Creek Fm. Sharps Fm. Rockyford Mbr.
Oligocene (Chadronian, Orellan, Whitneyan)	WHITE RIVER GROUP Brule Fm. Whitney Mbr. Orella Mbr. Chadron Fm.	WHITE RIVER GROUP Brule Fm. Poleslide Mbr. Scenic Mbr. Chadron Fm.

Fig. 6.--Summary of middle Cenozoic stratigraphic nomenclature in Midcontinent.

White River Group

Meek and Hayden visited the Big Badlands of South Dakota in the 1850s to collect fossils (Harksen and Macdonald, 1969b, p. 2). They originally defined the strata there, though somewhat informally, as the "White River Formations" and collectively called them a "series" rather than a group. In 1857, they published a more formal definition of the White River, although they included much younger strata than would be assigned to it today.

In 1899, Darton (p. 736, 759) named the Chadron and Brule Formations and collectively regarded them as the White River Group. He did not designate precise type sections or localities but referred generally to the typical regions of the White River Badlands of South Dakota. After much controversy in the literature as to where Darton intended the type sections, Harksen and Macdonald (1969a) published what they believed to be the type sections for the Chadron and Brule Formations in the Big Badlands. They based their conclusions on locations given by Evans (1852), Darton (1901), Osborn (1929), and Bump (1956). Because their paper is the most recent attempt to resolve the type-section problem for these units and deals with the closest occurrence of White River deposits to the study area, it is freely drawn upon for the following descriptions.

Chadron Formation

At the type section in the Big Badlands the Chadron Formation consists of 103 feet of noncalcareous to slightly calcareous, dark green clay

(Harksen and Macdonald, 1969a, p. 3, Figure 2). The clay weathers to produce a popcornlike surface and forms low, hummocky mounds often referred to as "haystack buttes" or "haystacks." The lower 10 feet locally contain sand and gravel. At various levels in the clay are 2-foot to 3-foot thick beds of white-weathering, tan marl with many inclusions of light green, noncalcareous clay, which weather out to leave a pocked surface (Harksen and Macdonald, 1969a, Figures 2 and 4).

The three-fold subdivision of the Chadron Formation suggested by Clark and others (1967) is applicable only locally and for that reason it was not employed by Harksen and Macdonald (1969a). I found that not only are the members of the Chadron recognized by Clark (1954) and Clark and others (1967) restricted to a small part of the Big Badlands, but other lithologic units in the Chadron that are widespread and even recognizable outside the Big Badlands are either unnamed or erroneously excluded from the Chadron. Subdivision of the Chadron is further discussed under "Middle Cenozoic Deposits of North Dakota" below.

The base of the Chadron in the Big Badlands is unconformable and sharp. It is marked by an abrupt change from the red, yellow, and purple colors of the underlying Interior Formation, which is developed on the Pierre Shale, to the green color of the Chadron clay above. The Chadron was considered conformable with the overlying Brule by Clark and others (1967, p. 22). The upper contact is marked by changes in weathering habit, color, lithology, and fauna. The Chadron "haystacks" and popcornlike weathering surfaces give way to the "tread and riser" profile of the Brule. The Chadron clay is green in contrast to the brown clay beds of the Brule. Aside from the marls, the Chadron is only slightly calcareous; the Brule is generally calcareous. The early faunal name for the Chadron, "Titanotherium zone," was appropriate because in the Big Badlands remains of titanotheres are found only in the Chadron Formation.

Brule Formation

Bump (1956) defined two members of the Brule Formation in the Big Badlands of South Dakota: the lower or Scenic Member and the upper or Poleslide Member. Harksen and Macdonald (1969a, p. 6) believed that, lacking a specific type section from Darton's original definition of the Brule Formation, the type sections published by Bump (1956) for the Scenic and Poleslide Members should be collectively considered the type section of the Brule as well. The descriptions and terminology given below are based on Bump's definitions as summarized by Harksen and Macdonald (1969a, p. 9).

Scenic Member.--The Scenic Member of the Brule was named for exposures near the small town of Scenic, South Dakota. It is about 160 feet thick and includes the "lower" and "upper nodular zones" of the early terminology. The "lower nodular zone" consists of brown to gray clay beds that weather pink to gray; these beds contain numerous clay-lime concretions that have rust-colored, oxidized surfaces. The "upper nodular zone" includes, in ascending order, 90 feet of gray, usually unfossiliferous clay, "with irregularly spaced brown banding" (Harksen and Macdonald, 1969b, p. 24) and bedded, lensoid silt concretions; 20 feet of vertical, cliff-forming, gray clay beds with occasional, spherical, sparsely fossiliferous, silty concretions; and at the top, 15 feet of light, cream-colored clay with a thin zone of fossiliferous, clay-lime concretions. The "*Metamynodon* channel sandstones" of older terminology lie within this member. The Scenic Member is underlain by the Chadron Formation and overlain by the Poleslide Member of the Brule Formation. The contact with the Poleslide Member is conformable and placed at the base of the lowest dark clay bed in the Brule section.

Poleslide Member.--The Poleslide Member was named for exposures on Sheep Mountain Table[1] near a place where poles were once gathered and slid down the cliff. At the type section it is 295 feet thick and has been subdivided into three parts called "zones" by Bump (1956). The lower zone includes 100 feet of gray to brown clay. The middle zone consists of 110 feet of moderately fossiliferous "*Protoceras* channel sandstones" of older terminology occurring at various horizons within the upper 40 feet. The upper zone is an 85-foot thick, evenly bedded, gray siltstone in which beds of siltstone alternate with beds of clay to give an irregular, vertical, washboard-like surface.

The Poleslide Member of the Brule is underlain by the Scenic Member of the Brule and is overlain by the Rockyford Member of the Sharps Formation, Arikaree Group.

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[1]Flat-topped buttes in the Big Badlands are called "Tables."

Arikaree Group

In 1899, Darton (p. 735) proposed the name "Arikaree Formation" for 400 to 500 feet of gray sand, characterized by layers of dark gray, tubular concretions or "pipes," overlying the Brule Formation in western Nebraska. This name was chosen because the Arikaree Indians once lived in the area. Darton pointed out that the formation includes conglomeratic channel fills and a large amount of volcanic ash, both as sizable beds and as a major lithologic constituent of the sands.

In 1902, Hatcher redefined the Arikaree and elevated it to group status. He included in it the Gering and Monroe Creek Formations. As used today, the Arikaree is a group including, in ascending order, the Gering, Monroe Creek, and Harrison Formations in Nebraska and the Sharps, Monroe Creek, and Harrison Formations in South Dakota (Figure 6).

Gering Formation

Darton (1899, p. 735) named the Gering Formation for the coarse-grained, laminated, massive and cross-bedded, light gray sand and poorly consolidated sandstone unconformably overlying the Brule Formation but lying below the Arikaree Formation in Nebraska. The Gering locally reaches a thickness of 200 feet and in places consists of two distinct units separated by a disconformity (Darton, 1899, p. 736). The type locality is Helvas Canyon about 6 miles south of Scotts Bluff National Monument near the town of Gering, Nebraska.

Two new members were defined within the Gering Formation in Nebraska by Vondra and others (1969), the Helvas Canyon Member below and the Mitchell Pass Member above. These members are separated by the disconformity recognized by Darton. The disconformity is marked by a pumice-pebble conglomerate, at the base of the upper or Mitchell Pass Member, which has been designated the Twin Sisters Pumice Conglomerate Bed (Vondra and others, 1969, p. 4).

Sharps Formation

The Sharps Formation was named by Harksen and others (1961, p. 674-678) for about 350 feet of moderately indurated, pink, tuffaceous siltstone and claystone beds overlying the Brule Formation and underlying the Monroe Creek Formation in the Sharps Corners area of the South Dakota Badlands. The Sharps Formation is characterized by many small, irregularly spherical, randomly spaced, calcareous concretions. A light-colored, impure, indurated volcanic ash bed or tuff up to 55 feet thick marks the base of the Sharps Formation and was formally named the Rockyford Member by Nicknish and Macdonald (1962). Both the upper and lower boundaries of the Sharps Formation are gradational, apparently as a result of reworking by wind (Harksen and Macdonald, 1969b, p. 19).

Vondra and others (1969, p. 1) felt that the Sharps Formation "is not a recognizable unit in Nebraska being mostly, if not wholly, a synonym of the Gering and perhaps includes even a part of the Monroe Creek." This is a reflection of the erroneous idea held by some Tertiary stratigraphers that because two deposits, in this case the Sharps and Gering, are similar in age they must belong to the same formation regardless of lithology. My observations in South Dakota and Nebraska revealed no lithologic basis for the alleged synonomy; the two units are distinctly different lithologically and deserve different names.

Monroe Creek Formation

Hatcher (1902, p. 116) defined the Monroe Creek Formation as the 200-foot thick interval of "very light colored, finer-grained, not very hard but firm and massive sandstones," overlying the Gering Formation and underlying the Harrison Formation. The best exposure cited by Hatcher, and apparently that intended as his type section, is the north face of Pine Ridge at the mouth of Monroe Creek Canyon, 5 miles north of Harrison, Nebraska.

Harrison Formation

The Harrison Formation was named by Hatcher (1902, p. 117) for the 200-foot thick interval near Harrison, Nebraska, consisting of "fine-grained, rather incoherent sandstones, permeated by great numbers of siliceous tubes arranged vertically rather than horizontally. They are further characterized by the presence, often in the greatest abundance, of those peculiar and interesting, but as yet not well understood, fossils known as Daemonelix[1] and by a considerable variety of fossil mammals belonging to characteristic Miocene genera." The Harrison Formation conformably overlies the Monroe Creek and is overlain by what Hatcher called "the Nebraska beds of Scott." These beds, also once called "upper Harrison," have since been removed from the Arikaree Group and formally

[1]Daemonelix is now known to be the filled burrow of a Miocene beaver.

defined by Schultz (1938, p. 443) as the Marsland Formation, the basal unit of the overlying Hemingford Group.

MIDDLE CENOZOIC STRATIGRAPHY OF NORTH DAKOTA

Previous Work in North Dakota

The earliest description of middle Cenozoic deposits in North Dakota is that found in a letter written by E. D. Cope (1883) to the Secretary of the American Philosophical Society from Sully Springs, Dakota, September 7, 1883, and published in the Proceedings of the Society for that year. In this correspondence Cope announced the discovery of "the locality of a new lake of the White River Epoch . . . nearly 200 miles northwest of the nearest boundary of the deposit of this age hitherto known." He listed field identifications for 20 species of fossils, including fish, turtles, rodents, carnivores, perissodactyls, and artiodactyls, which he felt clearly indicated correlation with the White River of South Dakota. For some time the specific location of the outcrops described by Cope was uncertain; however, from an examination of Cope's diary, Skinner (1951, p. 51) concluded that there can be little doubt that the outcrops that Cope studied are those of the Chalky Buttes in Slope County, North Dakota. It is unclear why Cope did not expand or follow up this brief report of his discovery because, according to Skinner, his diary indicates he found an abundant fauna.

The Chalky Buttes exposures were next studied in 1905 by Douglass (1909) as a part of a geologic reconnaissance of North Dakota, Montana, and Idaho for the Carnegie Museum of Pittsburgh. During his visit to North Dakota, Douglass discovered a second major exposure of middle Cenozoic deposits, the Little Badlands area, southwest of Dickinson. In 1908, Douglass (1908a and 1908b) described specimens of fossil rhinoceroses and horses collected on this expedition from both the Chalky Buttes and Little Badlands sections. In 1909, Douglass published the first detailed measured sections for the Chalky Buttes exposures discovered by Cope, as well as the Little Badlands area, and listed the various fossils collected at these sites. He also summarized the geologic history recorded by the White River strata at the Chalky Buttes and concluded (p. 231) that they were the result of deposition in fluvial, lacustrine, and marsh environments in a river valley cut into the Eocene strata.

Leonard (1908) reported that Douglass had expanded the known occurrences of the White River Formation in North Dakota to include the Chalky Buttes, the Little Badlands, and Sentinel Butte but that searches for evidence of White River on Bullion, Flattop, and Black (HT) Buttes had turned up nothing. He also defined three informal lithologic units (lower, middle, and upper) for the White River Formation. Leonard also reported that fossils from the White River Formation in North Dakota compared very well with specimens from the "Oreodon beds" of the White River Group in South Dakota.

Quirke (1918) assigned the strata of the Killdeer Mountains to the White River Formation and gave a composite section for these exposures.

He gave (p. 266) his reasons for correlating this section with the White River as follows:

> These rocks are unconformable on the Fort Union Formation. The only sedimentary beds which are known to lie on the Fort Union Formation in North Dakota belong to the White River Formation.

Similarly, he reasoned that the beds capping Sentinel Butte were White River also. He suggested a fluvial origin for the lower beds of the Killdeer Mountains but concluded that the uppermost beds were lacustrine, having formed in a lake fed by a north-flowing stream from the Black Hills. According to Quirke, no fossils were found despite a diligent search.

In 1922, Leonard summarized the status of the White River Formation in the state, and discussed previous work by Douglass and Quirke, as well as his own studies of this unit. He included stratigraphic sections for the major White River deposits in the state, a mention of minor exposures, and common names and brief descriptions of the Oligocene mammals found in the state. He followed Douglass' fluvial interpretation for sandstone beds in the section but believed that most of the strata were lacustrine.

Wood and others (1941) assigned the "White Butte local fauna" from the Chalky Buttes a Whitneyan age, but pointed out that the strata there differ faunally and lithologically from typical Whitneyan Brule elsewhere and might represent a separate formation.

In 1942, Kline listed (p. 357) four isolated outcrop areas of White River Formation in North Dakota: the Killdeer Mountains, White Butte

(Slope County), Sentinel Butte, and the Little Badlands. Seager and others (1942) pointed out that White River exposures are not restricted to these four areas but also occur in Youngman's, Antelope, East Rainy and West Rainy Buttes, and in numerous buttes in the Lefor area. They erroneously included Blue Buttes in McKenzie County, now believed to be capped by Golden Valley Formation, in their list of White River outcrops. They also pointed out that no attempt had been made in North Dakota to separate the White River into formal units, and that although these strata were considered to be Oligocene, Miocene strata might be present as well.

Powers (1945) reported three units for the White River Formation within the state, as had Leonard, and used the old faunal names to identify them: lower or "*Titanotherium* beds," middle or "Oreodon beds," and upper or "*Protoceras* beds."

In 1946, Nevin briefly mentioned the White River Formation but erroneously suggested correlation of the sandstone capping the Blue Buttes in McKenzie County with the White River Formation.

Clarke (1948) studied the clay beds of the Little Badlands and the Chalky Buttes, some of which were within the White River Formation. He found (p. 24) the main difference between the North Dakota clays and the bentonites of Wyoming and South Dakota to be the presence of uncombined silica or quartz in all of the North Dakota clays.

Skinner (1951) gave the first detailed description of the White River section at an important new locality, the Fitterer Ranch, south of the Little Badlands proper. He also reported collecting Orellan and

Whitneyan fossils from the White River at this locality and attempted to show the relationship of the section there to those of all other areas except the Killdeer Mountains. Skinner suggested that a fairly complete Oligocene section was present at the Fitterer Ranch.

Beroni and Bauer (1952) included a massive sandstone, now considered to be Golden Valley (Denson, 1970), in the White River Formation of southwestern North Dakota.

Benson (1952) visited all previously recorded White River outcrops and identified the White River in four new localities: the Medicine Poles Hills, Bowman County; Whetstone and Wolf Buttes, Adams County; and Shepard Butte, Hettinger County. He referred to three lithologic units in the White River Formation of North Dakota (apparently the same as those of Leonard, 1922) and concluded that the White River was not overlain by younger deposits.

Hansen (1953) gave detailed geologic maps of buttes here collectively called the "Lefor Buttes." He reported that three species of freshwater gastropods collected from the strata in these buttes indicate correlation with Oligocene strata of South Dakota, and on the basis of lithology the deposits were assigned to the Chadron Formation.

Kepferle and Culbertson (1955) treated all the sandstones capping buttes in southwestern North Dakota as one and erroneously correlated the sandstone on HT or Black Butte in Slope County with that capping the Rainy Buttes to the northeast. They also pointed out that the late Jean Hough, formerly of the University of Chicago, had identified an Oligocene fauna from an eastern outlier of the Chalky Buttes (probably White Butte).

Holland (1957) employed the three subdivisions of the White River Formation suggested by Leonard (1922) and considered the White River to be the youngest rock unit in the state.

Feldmann (1962) reported an Oligocene age for specimens of fossil fish collected from the top of Sentinel Butte, based upon lithologic correlation of the fish beds with White River deposits in the vicinity from which Oligocene mammals had been recovered.

Chinburg and Holland (1965) reported that rhinoceros remains collected from the Fitterer Ranch represented the middle Oligocene genus *Subhyracodon*.

Denson and Gill (1965) reported on uraniferous lignites in the southwestern part of the Williston Basin. It was in this report that they revised the middle Cenozoic stratigraphy of North Dakota. As mentioned earlier, this revision led to the present study.

In 1966, Boyer reported on the petrography of the lacustrine carbonates or fish beds atop Sentinel Butte. He referred these beds to the White River Formation and assigned them an Oligocene age. Jepsen (1969) stated that Boyer had no new age evidence but was simply following previous workers and that the age of the beds capping Sentinel Butte could probably not be determined from the fish present.

A new species of fossil frog was described from the Fitterer Ranch section and assigned a middle Oligocene age by Estes (1970). The discovery and significance of a large rhinoceros mandible from the sandstone caprock of White Butte, Slope County, was reported by Stone (1970a). Affinities with *Subhyracodon*, *Diceratherium*, and *Amphicaenopus* were discussed, but the identity and age of this critical specimen remain uncertain because lower dentition is not diagnostic.

An alternative to the Absaroka Mountain source for the gravel in the Chadron of North Dakota suggested by Denson and Gill (1965, p. 19) was given by Stone (1970b). A northern Black Hills source was proposed and supported by several lines of evidence.

A fossil beaver skull collected by Jean Hough, University of Chicago, from strata capping Golden Butte near the Fitterer Ranch was reported by Stout and Stone (1971) to be Paloecastor sp., similar to forms from the upper Brule or lower Gering Formations of Nebraska. Preliminary findings of a stratigraphic study of the middle Cenozoic deposits of North Dakota were reported by Stone (1971). A revision of the stratigraphic nomenclature for the middle Cenozoic deposits of North Dakota was informally proposed by Stone (1972). This revision included new members of the Chadron and Brule Formations and a new formation for deposits referred to the Arikaree Formation by Denson and Gill (1965, p. 14).

Rock-Stratigraphic Framework

Previous Nomenclature

Previous stratigraphic nomenclatures for the middle Cenozoic deposits of North Dakota are given in Figure 7. As shown in this figure, the White River has mainly been treated as a formation; the only subdivisions previously suggested were the informal units of Leonard (1922) and Skinner (1951).

Denson and Gill (1965) were the first to clearly apply the classical cussed, but the identity and age of this critical specimen remain uncertain because lower dentition is not diagnostic.

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Rock-Stratigraphic Framework

Previous Nomenclature

Previous stratigraphic nomenclatures for the middle Cenozoic deposits of North Dakota are given in Figure 7. As shown in this figure, the White River has mainly been treated as a formation; the only subdivisions previously suggested were the informal units of Leonard (1922) and Skinner (1951).

Denson and Gill (1965) were the first to clearly apply the classical

<table>
<tr><th colspan="2">Leonard, 1922</th><th colspan="2">Skinner, 1951</th><th colspan="2">Denson and Gill, 1965</th><th>Carlson, 1969</th><th colspan="3">Proposed, this report</th></tr>
<tr><td rowspan="8">White River Formation</td><td>Upper Member</td><td rowspan="8">White River Formation</td><td>Banded Clays and Sandstone</td><td colspan="2">Arikaree Formation</td><td>Arikaree Formation</td><td colspan="3">Killdeer Formation</td></tr>
<tr><td rowspan="4">Middle Member</td><td rowspan="2">Clay Above Nodules</td><td rowspan="7">White River Group</td><td rowspan="4">Brule Formation</td><td rowspan="7">White River Formation</td><td rowspan="7">White River Group</td><td rowspan="4">Brule Formation</td><td>Schefield Member</td></tr>
<tr><td>Dickinson Member</td></tr>
<tr><td>Nodular Zone</td><td>Fitterer Bed</td></tr>
<tr><td rowspan="2">Transition Zone</td><td></td></tr>
<tr><td rowspan="3">Lower Member</td><td rowspan="3">Chadron Formation</td><td rowspan="3">Chadron Formation</td><td>South Heart Member</td></tr>
<tr><td rowspan="2">Chadron-like clays</td><td>Chalky Buttes Member</td></tr>
<tr><td>Amidon Member</td></tr>
</table>

Fig. 7.—Previous and proposed nomenclatures for the middle Cenozoic deposits of North Dakota.

middle Cenozoic terminology to the North Dakota section. Recent work by geologists of the North Dakota Geological Survey has begun to reflect the revisions suggested by Denson and Gill. For example, Clayton (1969) followed Denson and Gill in showing the Killdeer Mountains to be composed largely of Arikaree Formation. The latest geologic bedrock map of the state by the North Dakota Geological Survey, compiled by Carlson (1969), includes the Arikaree Formation which, because of problems of scale, is lumped with the White River Formation.

Need for Revision

A revision of the stratigraphic framework for middle Cenozoic deposits in North Dakota is warranted for two general reasons: (1) the present framework is not in keeping with the current regional stratigraphic framework, and (2) the present framework neither reflects the detail possible nor that which will be required for further research on this part of the North Dakota section (Figure 7). More specifically, the White River is treated as a group elsewhere in the region and consists of the Chadron and Brule Formations. I agree with Denson and Gill (1965) that these units are clearly identifiable in North Dakota as well. Both of these formations in North Dakota may be subdivided into easily recognizable members. These members do not correspond lithostratigraphically to the formal members of the Chadron or Brule Formations in South Dakota or Nebraska, and new names are thus required. Furthermore, lithologic units in South Dakota to which some of the North Dakota members do correspond are either unnamed or erroneously excluded from the White

River Group. For example, a white, gravelly sandstone at the base of the Chadron in some places in the Big Badlands, to which the middle Chadron of North Dakota is lithostratigraphically identical, was not recognized as Chadron by Clark (1954) or Clark and others (1967) but was assigned by them to the Slim Buttes Formation. From my own examination of the type section of the Slim Buttes Formation, these strata are not lithologically referrable to that unit. This, together with their stratigraphic position above the Interior Formation, support their inclusion in the Chadron. Because no valid name exists for this unit in South Dakota it is named here for its exposures in North Dakota.

The caprock or upper part of the middle Cenozoic section of North Dakota, originally included in the White River (Figure 7), was remapped as Arikaree Formation by Denson and Gill (1965, p. 13, 14). The criteria cited by Denson and Gill (1965, p. 13, 14) for this reassignment are as follows: (1) "their unconformable relationship to the underlying Brule . . . ," (2) "their lithologic similarity to the rocks in the Big Badlands in west-central South Dakota from which Miocene fossils have been collected," and (3) differences between the mineralogy of limestones and sandstones in the upper or Arikaree part of the section and those in typical White River deposits below.

These criteria are felt to be inconclusive or weak and not consistent with good stratigraphic practice. The unconformable relationship cited by Denson and Gill does not make these strata Arikaree; it could just as easily mean that these rocks are an upper member of the Brule Formation or an entirely different unit such as the Ogallala Group

(Pliocene). Lithologic similarity of the North Dakota rocks in question to Arikaree deposits, rather than to rocks in South Dakota containing Miocene fossils, is what has to be demonstrated in support of the reassignment. Age should not be a consideration in rock-stratigraphic nomenclature. There is some fossil evidence of an early Miocene age for the North Dakota caprock but that alone does not make it Arikaree. In fact, from personal observations, the caprock is not lithologically referrable to any part of the Arikaree Group in the type area in Nebraska or more importantly to that recognized in nearby South Dakota. The mineralogic differences between the North Dakota Brule Formation and the overlying caprock, cited by Denson and Gill (1965), could also exist if the caprock were upper Brule or another formation. Mineralogic similarity with type Arikaree deposits is what has to be demonstrated, not a difference from that of the underlying units.

Denson and Gill (1965) made no comment as to the part or parts of the classical Arikaree Group their Arikaree represents suggesting that they too found it difficult to refer the North Dakota caprock to any previously described part of the classical Arikaree Group. The situation is complicated by the variability of the Arikaree Group across its outcrop area. As shown above, in the discussion of the dispute over the synonomy of the Gering and Sharps Formations, even the Nebraska and South Dakota sections do not closely correspond. The idea that any sandstone-bearing sequence above the Brule Formation is Arikaree Formation was invalidated by the elevation of the Arikaree to group status and the discovery of the overlying Ogallala Group. Because the middle Cenozoic caprock of North Dakota is not referrable to the Brule, Arikaree, or Ogallala, a new name is required.

Proposed Nomenclature

A new, more detailed nomenclature for the middle Cenozoic deposits of North Dakota is here proposed. All new names have been cleared and reserved for my use by the Geologic Names Committee of the United States Geological Survey. In Figure 8, the proposed nomenclature is compared with that of western Nebraska, and the Big Badlands and Slim Buttes of South Dakota; the generalized column for middle Cenozoic deposits in North Dakota is given in Figure 9.

The Chadron and Brule Formations are recognizable in North Dakota and should be treated collectively as the White River Group as suggested by Denson and Gill (1965). The Chadron Formation of North Dakota is divided into three new members, in ascending order: the Amidon, Chalky Buttes, and South Heart Members. Two new members are defined for the Brule Formation: the Dickinson and the Schefield Members, in ascending order. The name "Fitterer," suggested by Skinner (1951, p. 54) for a fossiliferous sandstone within the interval now assigned to the Dickinson Member on the Fitterer Ranch, Stark County, is retained for the sandstone facies of the Dickinson Member of the Brule Formation in North Dakota.

Because of the objections to the use of "Arikaree" for the strata capping the North Dakota section outlined above, these strata are assigned to a new rock-stratigraphic unit, the Killdeer Formation. The age and placement of this and other new North Dakota rock units in the Great Plains

<table>
<tr><th colspan="2">AGE</th><th colspan="4">NEBRASKA</th><th colspan="3">BIG BADLANDS</th><th colspan="3">SLIM BUTTES</th><th colspan="3">NORTH DAKOTA</th></tr>
<tr><td rowspan="3">MIOCENE</td><td rowspan="3">ARIKAREEAN</td><td rowspan="3">ARIKAREE GP.</td><td colspan="3">HARRISON FORMATION</td><td rowspan="3"></td><td colspan="2">HARRISON FORMATION</td><td colspan="3" rowspan="3">ARIKAREE FORMATION(?)</td><td colspan="3" rowspan="3">KILLDEER FORMATION</td></tr>
<tr><td colspan="3">MONROE CREEK FORMATION</td><td colspan="2">MONROE CREEK FORMATION</td></tr>
<tr><td colspan="3">GERING FORMATION</td><td colspan="2">SHARPS FM.
ROCKYFORD MEMBER</td></tr>
<tr><td rowspan="11">OLIGOCENE</td><td rowspan="3">WHITNEYAN</td><td rowspan="11">WHITE RIVER GROUP</td><td rowspan="8">BRULE FORMATION</td><td rowspan="3">WHITNEY MEMBER</td><td>C</td><td rowspan="11">WHITE RIVER GROUP</td><td rowspan="8">BRULE FORMATION</td><td rowspan="3">POLE-SLIDE MEMBER</td><td rowspan="11">WHITE RIVER GROUP</td><td rowspan="8">BRULE FORMATION</td><td>H</td><td rowspan="11">WHITE RIVER GROUP</td><td rowspan="8">BRULE FORMATION</td><td rowspan="3">SCHEFIELD MEMBER</td></tr>
<tr><td>B</td><td>G</td></tr>
<tr><td>A</td><td>F</td></tr>
<tr><td rowspan="5">ORELLAN</td><td rowspan="5">ORELLA MEMBER</td><td>D</td><td rowspan="5">SCENIC MEMBER</td><td>E</td><td rowspan="4">DICKINSON MEMBER</td></tr>
<tr><td>C</td><td>D</td></tr>
<tr><td>B</td><td>C</td></tr>
<tr><td rowspan="2">A</td><td>B</td></tr>
<tr><td>A</td><td>FITTERER BED</td></tr>
<tr><td rowspan="3">CHADRONIAN</td><td rowspan="3">CHADRON FORMATION</td><td colspan="2">C</td><td rowspan="3">CHADRON FORMATION</td><td>PEANUT PEAK MEMBER</td><td rowspan="3">CHADRON FORMATION</td><td>"TYPICAL" MEMBER</td><td rowspan="3">CHADRON FORMATION</td><td>SOUTH HEART MEMBER</td></tr>
<tr><td colspan="2">B</td><td>CRAZY JOHNSON MEMBER</td><td>"DAZ-ZLING WHITE" MEMBER</td><td>CHALKY BUTTES MEMBER</td></tr>
<tr><td colspan="2">A</td><td>AHEARN MEMBER</td><td>"GOLDEN BROWN" MEMBER</td><td>AMIDON MEMBER</td></tr>
<tr><td colspan="2" rowspan="2"></td><td colspan="4">INTERIOR FORMATION</td><td colspan="3">INTERIOR FORMATION</td><td colspan="3">INTERIOR FORMATION</td><td colspan="3">INTERIOR FORMATION</td></tr>
<tr><td colspan="4">LANCE FORMATION</td><td colspan="3">PIERRE FORMATION</td><td colspan="3">SLIM BUTTES FORMATION</td><td colspan="3">GOLDEN VALLEY FORMATION</td></tr>
<tr><td colspan="2">SOURCE:</td><td colspan="4">Schultz and Stout, 1955</td><td colspan="3">Harksen & Mac-donald, 1969b</td><td colspan="3">Lillegraven, 1970</td><td colspan="3">This paper</td></tr>
</table>

Fig. 8.--Nomenclature and correlation of middle Cenozoic deposits in the Midcontinent; letters identify faunal zones.

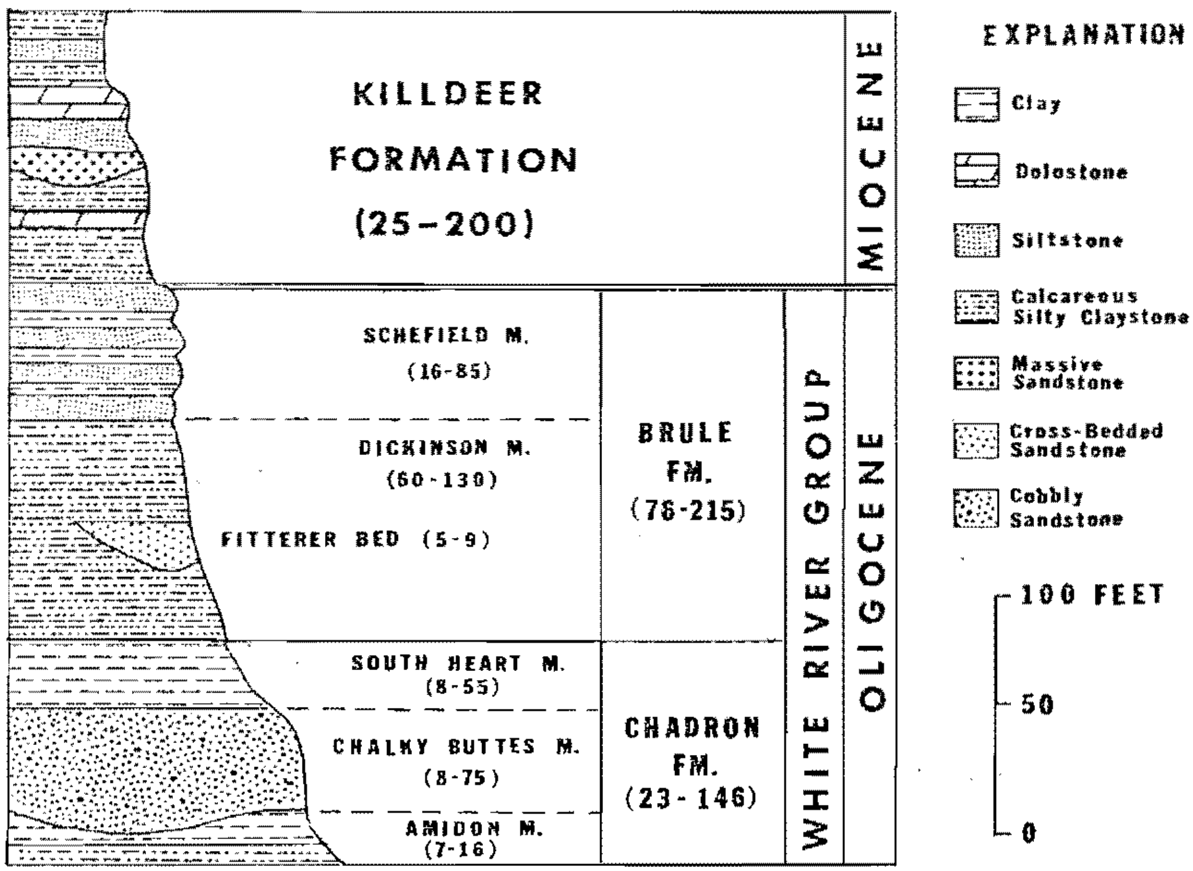


Fig. 9.—Generalized composite column and stratigraphic nomenclature for middle Cenozoic deposits in North Dakota.

standard are only approximate at this time and should be the topic of further studies. The new nomenclature (Figure 8) is felt to provide a solid basis for such studies.

CHADRON FORMATION

Amidon Member

Name and Type Section

The name "Amidon Member" is here proposed for the strata constituting the lowermost part of the Chadron Formation in North Dakota (Figure 10). It is named for exposures at the northern end of the Chalky Buttes near the small town of Amidon, the county seat of Slope County, North Dakota. The type section (measured section 2, Appendix C) is the south-facing exposure near the head of a deep, unnamed gully at NE¼NE¼ sec. 15, T. 134 N., R. 101 W., Slope County and is located 4¼ miles southwest of Amidon and about 18 miles north of Bowman, Bowman County, North Dakota.

Definition and Description

The Amidon Member is that interval of clay and silty claystone overlying the Interior Formation but below the so-called "dazzling white" (Lillegraven, 1970), gravel-bearing sandstone of the Chadron Formation (the new Chalky Buttes Member). At the type section, the lower contact is unconformable and sharp and is placed at the top of the reddish purple analcimolite bed of the Interior Formation below (Figure 5). The upper contact of the Amidon Member is also unconformable and sharp and is marked by an abrupt change to coarse clastics; the contact is placed at the base

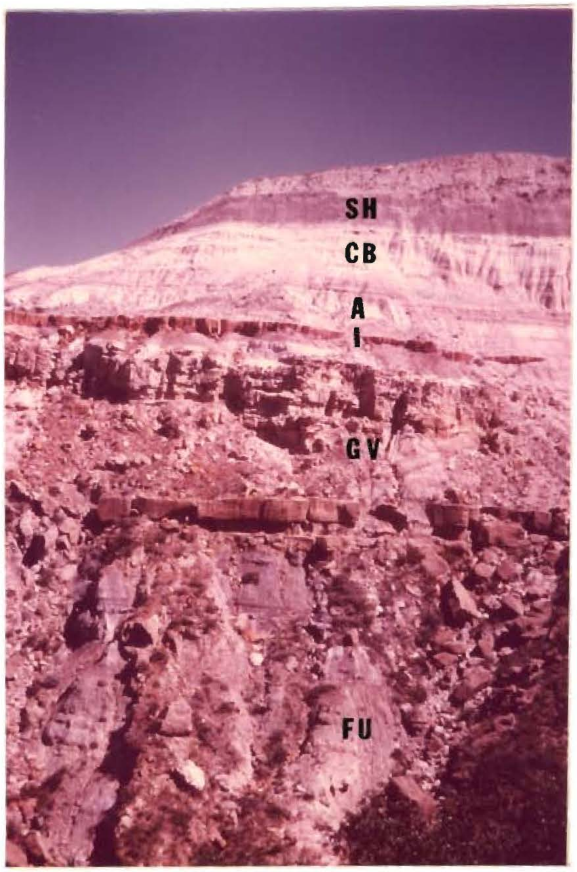


Fig. 10.--Type section of the Amidon (A) and Chalky Buttes (CB) embers of the Chadron Formation, northern end of the Chalky Buttes; ther units shown include the Fort Union Group (FU), the Golden Valley ormation, undifferentiated (GV), the Interior Formation (I), and the outh Heart (SH) Member of the Chadron Formation; measured section 2 Appendix C); NE¼NW¼ sec. 15, T. 134 N., R. 101 W.; view looking ortheast.

of a limonite-stained zone developed at the bottom of the overlying pebbly sandstone (Figure 11).

The analcimolite bed, representing the Interior Formation at the type section of the Amidon Member, reaches a thickness of 3 feet but appears to wedge out laterally across the exposure and is replaced in a short distance by a bed of what has been identified elsewhere as "silicified, silty bentonite" (Denson and Gill, 1965, Plate 3). This apparent discontinuity may simply be a result of localized cutting and filling. That is, erosion may have occurred after the Interior Formation formed but prior to the deposition of the White River Group. If one could dig back into the exposure far enough, one should find the analcimolite bed to be continuous across the section. This is supported by the fact that the analcimolite bed is present on the eastern side of the butte where section 2 was measured.

The Amidon Member is 16 feet thick at the type section and consists principally of massive clay but also contains beds of massive, silty claystone, 1 to 3 feet thick. These beds grade upward and downward into massive clay, that constitutes the bulk of the unit. The Amidon strata weather to very pale orange (10 YR 8/2) or light brown (5 YR 6/4) but are very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) on fresh surfaces.

At section 3-A (Appendix C) on the Fitterer Ranch in Stark County, 12 feet of clay are exposed below the "dazzling white" sandstone of the new Chalky Buttes Member (Plate 1). This interval contains a thin zone of limonite nodules 2 feet above the base of the gully where the section

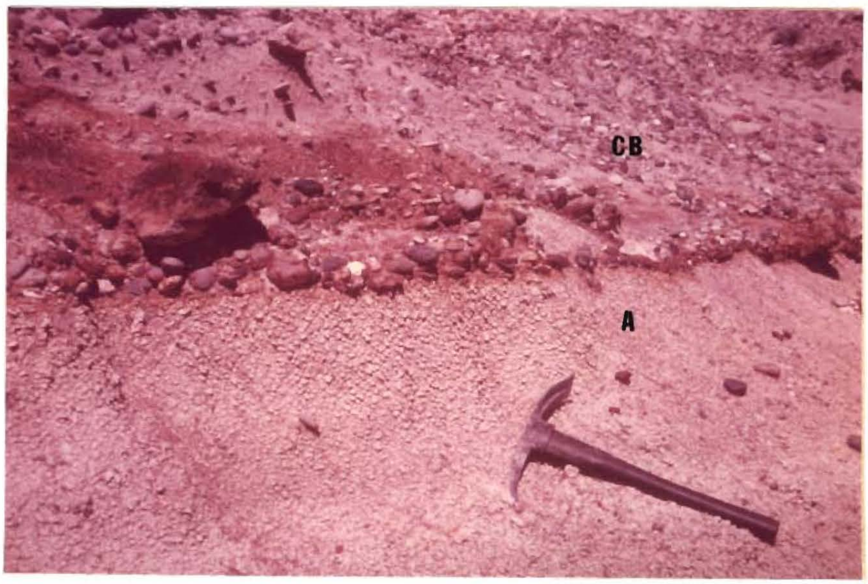


Fig. 11.--Contact between the Amidon (A) and Chalky Buttes (CB) Members of the Chadron Formation at their type sections, northern end of Chalky Buttes; measured section 2 (Appendix C); NE¼NW¼ sec. 15, T. 134 N., R. 101 W.; view looking north; scale given by pick mattock.

was measured and another zone of limonite nodules at its contact with the "dazzling white" sandstone (Chalky Buttes Member) above. Not enough of the underlying strata are exposed to identify the interior or Golden Valley Formations. The major limonite zone 2 feet above the base of section 3 may mark the Interior Formation and the top of the Golden Valley Formation here. If this is the case, the Amidon Member is 10 instead of 12 feet thick at this site.

Northwest of the Fitterer Ranch, at a site called Turtle Valley by Hickey (1966), the Amidon Member is represented by about 7 feet of siltstone and silty claystone lying above the Golden Valley Formation but beneath the "dazzling white" sandstone.

At White Butte (measured section 6, Appendix C) in Stark County, northeast of the Fitterer Ranch, the Amidon Member is absent. In the Killdeer Mountains, the Chadron Formation is so poorly exposed that the presence of the Amidon Member there cannot be determined.

<u>Distinguishing Characteristics</u>

The general lithology of this unit is not unique because clay also occurs in the South Heart Member of the Chadron Formation and clay and silty claystone also occur in the Dickinson Member of the Brule Formation. However, the Amidon Member is the lowest occurrence of clay in the Chadron Formation, and the silty claystone of the Amidon is not pitted as is that of the Dickinson Member of the Brule Formation. The Amidon may also be distinguished from the other subdivisions of the Chadron Formation in North Dakota by its position above the brightly colored Interior Formation and below the "dazzling white," pebbly sandstone of the Chalky Buttes Member.

Age and Correlation

No fossils have as yet been found in the Amidon Member, and its specific age is uncertain.

Physical Equivalence

Although the Amidon Member is lithologically distinct from other basal Chadron deposits in the region it does have a stratigraphic position similar to that of member "A" of the Chadron in Nebraska (Schultz and Stout, 1955), and the Ahearn Member of the Chadron in South Dakota (Clark, 1954). Schultz and Stout (1955, p. 31) believed their Chadron "A" to be essentially equivalent to the Yoder Formation of southeastern Wyoming (Schlaikjer, 1935) and that the Ahearn of Clark may prove to be a synonym for Yoder. The Amidon Member is also similar in stratigraphic position to the "Golden Brown" member of the Chadron Formation at Slim Buttes, South Dakota (Lillegraven, 1970).

Chalky Buttes Member

Name and Type Section

The name "Chalky Buttes Member" is here proposed for the middle or sandy part of the Chadron Formation of North Dakota (Figure 12). It is named for exposures in the Chalky Buttes in Slope County, North Dakota. It is probably this sandstone which gave these buttes their name because at a distance their white color suggests that the buttes are composed of

Fig. 12.--General view of the Chalky Buttes (CB) Member of the Chadron Formation, northern end of the Chalky Buttes; gold-colored beds below this unit are the Interior Formation; gray material above the white sandstone is the South Heart Member of the Chadron Formation; vicinity of measured section 2 (Appendix C) taken along left profile of butte in left background; NE¼NW¼ sec. 15, T. 134 N., R. 101 W.; view looking north.

chalk. The type section was selected to be the same as that for the Amidon Member so that relationships with this underlying unit would be clear.

Definition and Description

The Chalky Buttes Member is that interval of "dazzling white," gravel-bearing sandstone overlying the Amidon Member of the Chadron but lying below the green clay of the upper Chadron (the new South Heart Member). At the type section, the lower contact is unconformable and sharp and is placed at the limonite-stained base of the gravel-bearing strata (Figure 11). The upper contact of the Chalky Buttes Member appears to be conformable but is also fairly sharp (Figures 10 and 12) and is placed at the horizon where the main lithology changes from sandstone below to clay above.

At the type section the Chalky Buttes consists of 24 feet of medium- to very coarse-grained, cross-bedded sandstone. The Chalky Buttes is not everywhere white (N 9) but in places is very pale orange (10 YR 8/2) or dark yellowish orange (10 YR 6/6) to light brown (5 YR 5/6) where weathered, and very pale orange to pinkish gray (5 YR 8/1) where fresh. The grains are subangular to rounded and consist of cleavage fragments of clear feldspar, rock fragments, and quartz. The rock fragments were seen in thin section to be of fine-grained, igneous rock types. Modal analysis of thin sections showed the sandstone to be arkose (Appendix D, samples 1, 2, and 3).

The Chalky Buttes also contains clasts up to cobble size occurring as thin zones up to a few cobbles in thickness (Figure 13). Where these pebbles and cobbles have been eroded out and become temporarily plastered onto the weathered slopes, the Chalky Buttes Member appears to be a conglomerate; however, on fresh vertical slopes, the restriction of the gravel to distinct, thin beds is clearly evident.

The gravel in the Chalky Buttes Member consists mainly of igneous rock types but quartzite, petrified wood, Knife River Flint (Clayton and others, 1970, p. 48), and chert are also present. Denson and Gill (1965, p. 9) identified quartz latite porphyry (Figure 14a), welded tuff (Figure 14b), rhyolite, and granite from this gravel. The quartz latite porphyry is the most striking rock type seen among the pebbles and cobbles; this porphyry weathers pale reddish brown (10 R 5/4) and is moderate red (5 R 5/4) on fresh surfaces. Parsons (1970) also identified volcanic breccia (Figure 14b) and volcanic conglomerate in specimens of typical pebbles and cobbles from the Chalky Buttes Member. The source and significance of this gravel, as suggested by Stone (1970b), are discussed under "Sedimentary History" below.

The Chalky Buttes Member reaches a thickness of 75 feet elsewhere in the Chalky Buttes. In an exposure just below the television tower on the butte west of White Butte, Slope County (SW¼SW¼ sec. 23, T. 134 N., R. 101 W.), more than 100 feet of the gravel-bearing sandstone are exposed, but faulting and slumping may account for the great thickness displayed there. As shown on Plate 1, the Chalky Buttes Member is 8 feet thick on the Fitterer Ranch (measured section 3-A) and 12 feet thick at the Little Badlands proper (measured section 5-A). The thickness of this unit reaches

Fig. 13.--Thin zones of coarse clastics and vague suggestion of large scale trough or pi cross-bedding in the Chalky Buttes Member of the Chadron Formation as seen on the west side of the Chalky Buttes; SE¼SE¼ sec. 22, T. 135 N., R. 101 W.; view looking east; scale given by rock pick at left.

(a)

(b)

Fig. 14.--Pebbles and cobbles from the Chalky Buttes Member of the Chadron Formation, collected throughout the study area: (a) quartz latite porphyry; (b) welded tuff and volcanic breccia; 6-inch ruler gives scale in both views.

47 feet at White Butte, Stark County (measured section 6), where it rests directly on the Interior Formation (Figure 14a). Although Denson and Gill (1965) did not report any Chadron in the Killdeer Mountains, there are two indications that the Chalky Buttes Member is present. First, an exposure of what is possibly unslumped Chalky Buttes Member occurs on the south side of the road between North Mountain and South Mountain (SW¼NW¼ sec. 11, T. 146 N., R. 96 W.); only about 5 feet of the "dazzling white" sandstone is exposed at this locality. Also, typical Chalky Buttes gravel was observed on the south end of South Mountain (SW¼SW¼ sec. 11, T. 146 N., R. 96 W.) in a large slump block. A red-colored sandstone, probably representing the Interior Formation at this locality and apparently in place, was seen about 15 feet below the horizon of this gravel.

Distinguishing Characteristics

The general "dazzling white" color, the abundance of clear feldspar cleavage fragments, coarseness of the sand grains, and the occurrence of thin beds of gravel of mainly igneous rock types (especially a pink-colored porphyry), distinguish the Chalky Buttes Member from the other sandstone beds in the middle Cenozoic section of North Dakota. Its position below the massive clay of the South Heart Member of the Chadron Formation and above the Amidon Member, or Interior Formation where the Amidon is absent, further distinguish it from all other units in the section.

Age and Correlation

No fossils were found in the Chalky Buttes Member in this study. Leonard (1922, p. 220) reported collecting parts of lower jaws of titanotheres from a bed similar to that now assigned to the Chalky Buttes Member 6 to 7 miles southeast of Rhame, Bowman County and 20 miles southwest of the Chalky Buttes. Correlation with the lower part of the classical Chadron Formation is therefore probable.

Physical Equivalence

The Chalky Buttes Member is lithologically distinct from other Chadron deposits in the region but does have a stratigraphic position similar to that of member "B" of the Chadron in Nebraska (Schultz and Stout, 1955) and the Crazy Johnson Member of the Chadron in South Dakota (Clark, 1954). The Chalky Buttes is similar in both lithology and stratigraphic position to the "Dazzling White" member of the Chadron in the Slim Buttes of northwestern South Dakota (Lillegraven, 1970).

South Heart Member

Name and Type Section

The name "South Heart Member" is here proposed for the strata constituting the uppermost part of the Chadron Formation in North Dakota (Figure 15). The member was named for exposures in the Little Badlands proper near the town of South Heart, North Dakota. The type section (measured section 5-A, Appendix C) is about 12 miles south of South Heart in SE¼SW¼ sec. 7, T. 137 N., R. 97 W. Although the South Heart Member is thickest at White Butte, Slope County, a type section in the

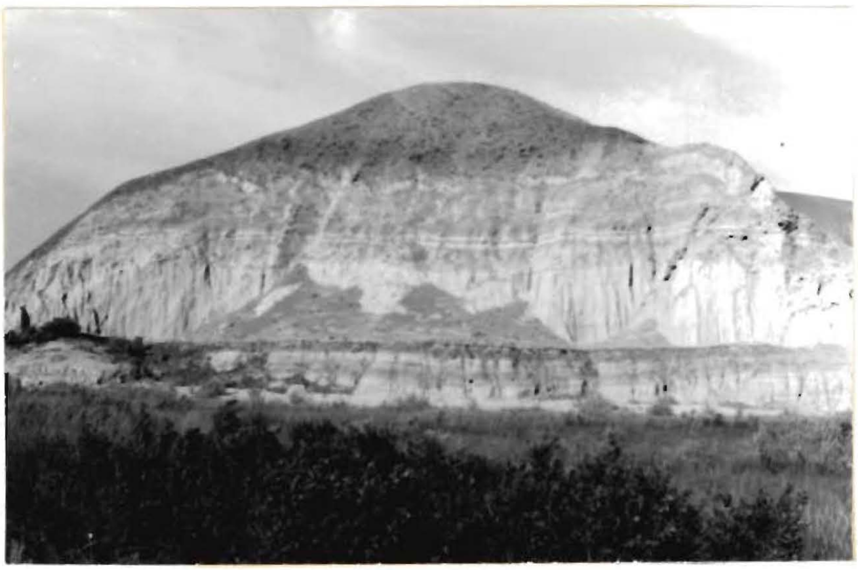


Fig. 15.--Typical "haystack butte" produced by erosion of the South Heart Member of the Chadron Formation (dark material capping butte) in the Little Badlands proper, western Stark County; NE¼SE¼ sec. 22, T. 138 N., R. 98 W.; view looking northwest.

Little Badlands proper was chosen because the South Heart Member is more widely exposed and covers more of the surface there than anywhere else in the state.

Definition and Description

The South Heart Member is that interval of massive, green clay and minor limestone overlying the Chalky Buttes Member of the Chadron but lying below the Brule Formation in North Dakota. At the type section, the lower contact is conformable and fairly sharp and is placed at the horizon where the lithology changes from sandstone below to clay above. The upper contact is also conformable and sharp and is placed at the top of the uppermost bed of the limestone which generally occurs at the top of this unit.

At the type section, the South Heart Member consists of 15 feet of swelling clay that is yellowish gray (5 Y 7/2) to pale olive (10 Y 6/2) where fresh and pale greenish yellow (10 Y 8/2) where weathered. Thin beds of pitted limestone occur at the top of the South Heart Member.

The South Heart Member is 55 feet thick at White Butte, Slope County (measured section 1, Appendix C, and Plate 1); 15 feet thick at the north end of the Chalky Buttes (measured section 2, Appendix C, and Plate 1); 10 to 20 feet thick at the Fitterer Ranch (measured sections 3-A, Appendix C, and Plate 1); 8 to 12 feet thick at White Butte, Stark County (measured section 6, Appendix C, and Plate 1) and 15 feet thick at Antelope Butte, east of Dickinson, Stark County. In the Killdeer Mountains the South Heart Member was only seen at the south end of South Mountain where it is poorly but unmistakably exposed in a slump block. This is the first report of its occurrence in the Killdeers; Denson and Gill (1965, Plate 1) did not report any Chadron Formation in their section of these exposures. The thickness of the South Heart Member in the Killdeer Mountains could not be determined due to thick cover on the lower slopes.

The South Heart Member is also characterized by the occurrence, often in great abundance, of calcareous nodules. These nodules weather out of the top of this unit and form an extensive lag deposit where the South Heart is at the surface. The nodules reach 6 inches in maximum diameter and consist of radiating fibrous growths (Figure 16). The outside of the nodules is light brown (5 YR 6/4) and somewhat irregular; on the inside, the nodules are very pale orange (10 YR 8/2) to white (N 9). X-ray-diffraction analysis showed that the nodules are composed of calcite. The fibrous habit suggests that the nodules may have originally been composed of aragonite that has been converted to the more stable carbonate mineral.

Similar nodules have been reported from the upper Chadron clay elsewhere. Workman (1964) studied blue barite nodules in the montmorillonitic clays of the White River Formation of northeastern Colorado. In his Plate 22 (p. 107) he showed a nodule of what he interpreted as a pseudomorph of chalcedony after barite, but it is identical in appearance to and has the same radiating fibrous habit as the South Heart nodules of North Dakota. It is possibly a pseudomorph after aragonite or calcite. I have seen such chalcedony pseudomorphs in the Reva Gap area of the Slim

Fig. 16.--Calcite nodules in place at the top of the South Heart Member of the Chadron Formation, on the eastern side of White Butte, Slope County; NE¼SE¼ sec. 30, T. 134 N., R. 100 W.; scale given by rock pick.

Buttes of South Dakota as well as in the study area. No barite nodules have been observed in these areas, however.

At the base of the member at White Butte in Stark County (measured section 6, Appendix C) an unusual rock type is present (Figure 17). This fine-grained silicified material has been called "silicified, silty bentonite" by Denson and Gill (1965, Plate 1). It is 2 to 15 feet thick at White Butte, Stark County.

Distinguishing Characteristics

Although the South Heart Member is not the only massive clay in the Chadron, it is the thickest and the only one containing fibrous calcite nodules. It may be further distinguished by its position immediately above the "dazzling white," sandstone of the Chalky Buttes Member. The South Heart Member is also that clay in which the numerous "haystack buttes" or low, rounded mounds (Figure 15), covering an extensive area south of South Heart, are developed.

The rock type called "silicified, silty bentonite" by Denson and Gill (1965, Plate 1), which occurs at the base of the South Heart Member at some localities (Figure 17), is not restricted to this unit but also occurs at the type section of the Amidon Member.

Age and Correlation

I found traces of ostracods and algal crusts in the limestones overlying the South Heart clay at Colgrove Butte, Hettinger County but found nothing that provided an age for these beds. Hansen (1953, p. 12) reported Oligocene gastropods from these limestones and correlated them

Fig. 17.--Rock type called "silicified silty bentonite" (ssb) by Denson and Gill (1965, Plate 1) South Heart Member of the Chadron Formation, White Butte, Stark County; measured section 6 (Appendix C); NE¼NW¼ sec. 32, T. 139 N., R. 97 W.; view looking southeast.

generally with the White River of South Dakota.

Physical Equivalence

The South Heart Member has a stratigraphic position similar to that of member "C" of Nebraska (Schultz and Stout, 1955) and the Peanut Peak Member of the Chadron of South Dakota (Clark, 1954) but differs somewhat from these units in lithology. The South Heart is, however, similar in both lithology and stratigraphic position to the "Typical" member of the Chadron in the Slim Buttes of northwestern South Dakota (Lillegraven, 1970).

BRULE FORMATION

Dickinson Member

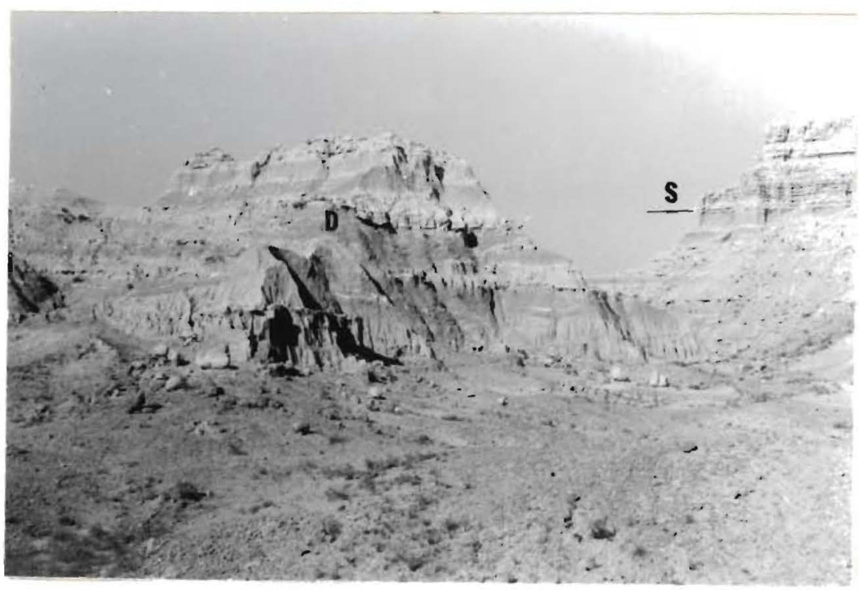
Name and Type Section

The name "Dickinson Member" is here proposed for the strata constituting the lower part of the Brule Formation in North Dakota (Figure 18). The name was selected for typical exposures on the Fitterer Ranch about 15 miles southwest of the town of Dickinson. The type section (measured section 3-B, Appendix C, and Plate 1) is in a small butte about ¼ mile northeast of the Fitterer Ranch house in NW¼SE¼ sec. 7, T. 137 N., R. 97 W., Stark County, North Dakota. There are excellent exposures southeast of the Fitterer Ranch house and in the Little Badlands proper, as well (measured sections 3-C and 5, Appendix C, and Plate 1).

Definition and Description

The Dickinson Member is defined as that sequence of clay, cross-bedded sandstone, and pitted-weathering, silty claystone overlying the South Heart Member of the Chadron Formation but underlying the Schefield Member of the Brule Formation or younger deposits where the Schefield is absent. The base of the Dickinson Member is everywhere gradational with the top of the South Heart Member of the Chadron below. The upper boundary is likewise conformable but more distinct or sharp. In the type

(a)



(b)

Fig. 18.--Dickinson (D) Member of the Brule Formation, north of the Fitterer Ranch house: (a) type section, *capped by Schefield (S) Member of the Brule Formation*, *measured* section 3-B (Appendix C), *NW¼SE¼* sec. 7, T. 137 N., R. 97 W.; (b) small exposure of Dickinson Member just south of type section; both views looking northwest.

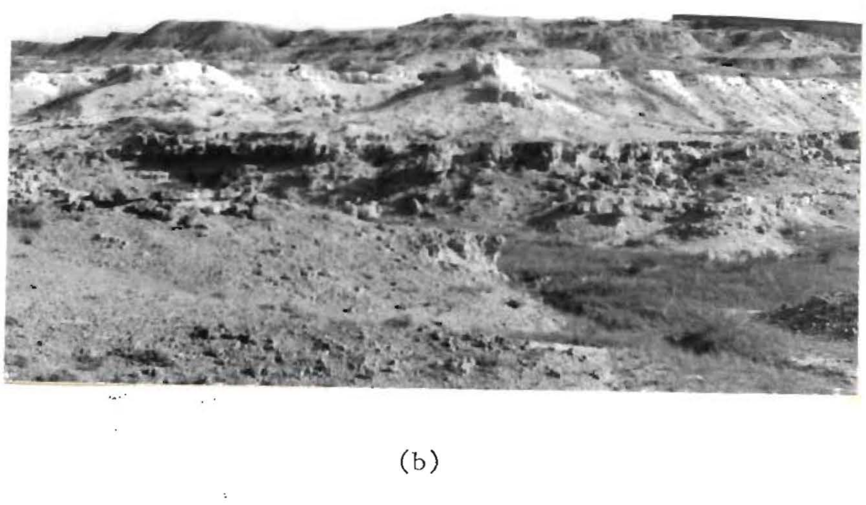
area the top of the Dickinson Member is marked by an abrupt change from the fluted-weathering slopes below to the steep or vertical, banded cliffs of the Schefield Member above (Figure 18). In the Little Badlands proper, the Dickinson Member is not overlain by any other bedrock unit but caps the section there. In the Chalky Buttes, the upper contact is marked by an abrupt change in lithology from clay and claystone below to the sandstone of the Killdeer Formation above.

The Dickinson Member is quite variable in thickness across short distances. At the type section (measured section 3-B, Appendix C, and Plate 1) it is 70 feet thick; only 5 miles away in the Little Badlands proper (measured section 5, Appendix C, and Plate 1), it is 130 feet thick and may have been thicker because it is the uppermost unit there today and has no doubt undergone some erosion. In the Chalky Buttes the Dickinson Member is about 60 feet thick. Because of thick cover and slumping, the Dickinson Member could not be identified in the Killdeer Mountains.

The clay of the Dickinson Member is yellowish gray (5 Y 7/2) where weathered and pale olive (10 Y 6/2) to light olive gray (5 Y 5/2) where fresh. The pitted-weathering, silty claystone is very pale orange (10 YR 8/2) where weathered and yellowish gray (5 Y 7/2) where fresh.

Near the middle of the Dickinson Member at the type section is a 3-foot thick, calcareous, somewhat silty, claystone (Figure 19). On weathered surfaces this claystone is grayish pink (5 R 8/2) or white (N 9) and is grayish pink, very pale orange (10 YR 8/2) or white (N 9) on fresh surfaces. This is the "white marker bed" of Skinner (1951, p. 54

(a)



(b)

Fig. 19.--"White marker bed" of Skinner (1951) near middle of Dickinson Member of the Brule Formation, north of the Fitterer Ranch house; NW¼SE¼ sec. 7, T. 137 N., R. 97 W.: (a) distant view looking south; (b) close-up looking north, scale given by rock pick on left.

57). Though not everywhere white, the bed is very light colored and makes a distinctive and useful marker for local correlations (Plate 1). In the Chalky Buttes (measured section 1, Appendix C, and Plate 1), an 11-foot thick sequence of alternating beds of claystone and clay 20 feet above the base of the Dickinson Member, may correspond to the "white marker bed" seen in the Little Badlands section. The "white marker bed" could not be identified in the Killdeer Mountain section.

A 4-foot thick, reddish, weathering zone occurs about 22 feet above Skinner's "white marker" in the Little Badlands (measured section 5-B, Appendix C, and Plate 1). It consists of slightly silty claystone that weathers to light brown (5 YR 6/4) and is light brown or pale reddish brown (10 R 5/4) where fresh. The darker color is contributed by small inclusions of swelling clay.

The characteristic pitted surface of the Dickinson Member is formed when small clay clasts weather out of the silty matrix. At most places these clasts have a maximum diameter of 1 inch and the matrix is silty claystone (Figure 20); however, in the Little Badlands near measured section 5-B, the lower part of the Dickinson Member consists of clay clasts a foot in diameter in a calcite matrix.

Throughout western Stark County, a 5-foot to 9-foot thick, very fossiliferous, cross-bedded sandstone occurs at different levels within the Dickinson Member. Skinner (1951, p. 54) informally named this unit the "Fitterer channel" for excellent exposures on the Fitterer Ranch. The name "Fitterer Bed" is here proposed for this unique lithology within the Dickinson Member. Its lower contact is everywhere disconformable

Fig. 20.--Clay clasts in upper part of the Dickinson Member of the Brule Formation, southeast of Fitterer Ranch house; measured section 3-C (Appendix C); NW¼NW¼ sec. 17, T. 137 N., R. 97 W.; scale given by rock pick at left.

and sharp and placed at the horizon where the lithology changes from clay, claystone, or silty claystone below to sandstone above. At the Fitterer Ranch (measured section 3-C, Appendix C, and Plate 1) the erosion represented by this disconformity penetrated down to the South Heart Member of the underlying Chadron Formation (Figure 21b). The upper contact is conformable but sharp and likewise placed at the horizon of lithologic change from sandstone below to clay, claystone, or silty claystone above. The relationship between the Fitterer Bed and Skinner's "white marker" is not certain because nowhere were they seen together in the same outcrop. Their general relationship may, however, be inferred from adjacent sections in the Little Badlands (Plate 1: measured sections 3-B, 3-C, 4-A, 4-B, 5-A, and 5-B) where the Fitterer Bed is seen to lie at or more commonly above, but not below the "white marker."

On the Fitterer Ranch (measured section 3-C, Appendix C, Plate 1) the Fitterer Bed lies at or near the base of the Dickinson Member and is 7 feet thick. It is characterized by large-scale trough or pi cross-bedding (Figure 21). The beds are distinct, irregular, uneven, and laminar within sets up to 1-foot thick. This sandstone is pale greenish yellow (10 Y 8/2) where weathered and yellowish gray (5 Y 7/2) where fresh. It consists of fine to medium, moderately sorted, subrounded grains of feldspar, quartz, rock fragments, heavy minerals, and clasts up to 1 inch in maximum diameter of green clay similar to that of the South Heart Member of the Chadron Formation below. Clear, acicular crystals of zeolite occur in the pores of the sandstone. X-ray-diffraction analysis of the Fitterer sandstone revealed the presence of the zeolites clinoptilo-

(a)

(b)

Fig. 21.--Fitterer Bed, Dickinson Member, Brule Formation southeast of Fitterer Ranch house at type section; measured section 3-C (*Appendix C*); *SE¼NW¼* sec. *17*, *T. 137 N.*, R. *97 W.*: (a) general view; (b) view of pi cross-bedding and contact *with the South Heart Member* of the Chadron Formation below, scale given by rock pick at left.

lite, erionite, and heulandite. Thin-section modal analyses showed the Fitterer sandstone to be arkose (Appendix D, samples 4, 5, and 6).

About 30 feet above the base of the Dickinson Member at White Butte, Slope County (measured section 1, Appendix C, and Plate 1) is a 15-foot thick, very fine-grained, non-calcareous, cross-bedded sandstone (Figure 22). This unit probably represents the Fitterer Bed in the Chalky Buttes area. The Fitterer Bed could not be identified in the Killdeer Mountains because of heavy cover and slumping in the lower part of the section there.

Distinguishing Characteristics

The pitted-weathering habit and inclusion of clay clasts distinguish the claystone of the Dickinson Member from any claystone unit in either the Chadron Formation below or the Killdeer Formation above. The position of the Dickinson Member directly above the South Heart Member of the Chadron Formation, the characteristic fluted slopes, the presence within its boundaries of the Fitterer Bed and Skinner's "white marker" distinguish this member from the overlying, banded-weathering, vertical-cliff-forming Schefield Member of the Brule Formation.

Age and Correlation

Chinburg and Holland (1965) reported remains of the middle Oligocene (Orellan) rhinoceros Subhyracodon from the Fitterer Bed on the Fitterer Ranch. This unit may therefore correlate with the "Metamynodon channel sandstones" in the Scenic Member of the Brule Formation in the Big Badlands of South Dakota. Estes (1970, p. 329) named a new species of frog,

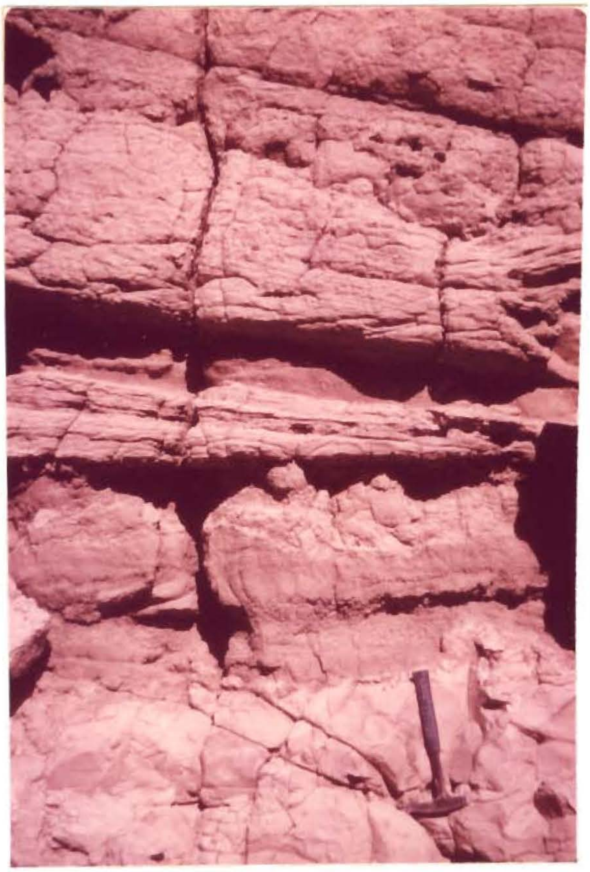


Fig. 22.--Fitterer Bed of the Dickinson Member of the Brule Formation at White Butte, Slope County; measured section 1 (Appendix C), NE¼SE¼ sec. 25, T. 134 N., R. 101 W.; view looking east; scale given by rock pick at lower right.

Scaphiopus skinneri, from specimens collected by Skinner in 1951 from strata now assigned to the Dickinson Member. The type specimen was collected on the Fitterer Ranch, 15 feet above the base of the Fitterer Bed. A middle Oligocene or Orellan age was determined for this specimen by Estes (1970, p. 329) indicating correlation with the Scenic Member of the Brule Formation in South Dakota.

Physical Equivalence

The Dickinson Member is quite widespread and strata referrable to this unit occur in eastern Montana and northwestern South Dakota. The Dickinson has a similar stratigraphic position to that of the Orella Member of the Brule in Nebraska (Schultz and Stout, 1955) and the Scenic Member of the Brule in South Dakota (Harksen and Macdonald, 1969a and 1969b) but differs somewhat from these units lithologically. This member corresponds lithologically and stratigraphically to the transitional unit "A" and possibly also units "B" through "E" of the Brule, which Lillegraven (1970, p. 835, 842) informally defined at Reva Gap in the Slim Buttes of northwestern South Dakota.

Schefield Member

Name and Type Section

The name "Schefield Member" is here proposed for the banded-weathering, vertical-cliff-forming strata of the uppermost part of the Brule Formation in North Dakota (Figure 23). The name is derived from the small settlement of Schefield about 6 miles southeast of the type section of this unit. The type section (measured section 3-C, Appendix

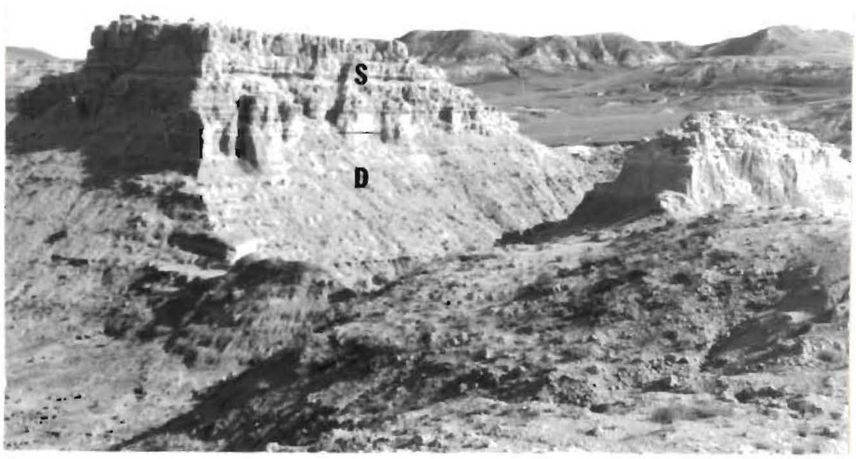


Fig. 23.--Schefield (S) and underlying Dickinson (D) Members of the Brule Formation, north of the Fitterer Ranch house; measured section 3-B (Appendix C); NW¼SE¼ sec. 7, T. 137 N., R. 97 W.; view looking southeast.

C, and Plate 1) is located in exposures about 3/4 mile southeast of the Fitterer Ranch house in SE¼NW¼ sec. 17, T. 137 N., R. 97 W., Stark County, North Dakota. Excellent exposures also occur about ½ mile northeast of the Fitterer Ranch house in NW¼SE¼ sec. 7, T. 137 N., R. 97 W. (Figure 22).

Definition and Description

The Schefield Member is that sequence of alternating silty claystone and clay constituting the upper Brule Formation in North Dakota and lying above the Dickinson Member of the Brule but below the Killdeer Formation. The upper contact of the Schefield Member at the type section is covered but probably corresponds to an observed break in slope between barren, vertical cliffs below and grass-covered, moderate to steep slopes above. The lower contact is conformable and sharp and placed at the change from the fluted slopes of the Dickinson Member below to the vertical, banded cliffs of the Schefield Member above.

At the type section (measured section 3-C, Appendix C, Plate 1), the Schefield Member is 77 feet thick. Just north of the type section (measured section 3-B, Appendix C, and Plate 1), 25 feet of Schefield Member remain as the uppermost middle Cenozoic strata there (Figure 23). No Schefield was found in the Little Badlands proper. In the Chalky Buttes, strata referrable to the Schefield Member occur only at the north and south ends of White Butte. An especially good exposure of the Schefield Member occurs at the south end of White Butte (SW¼ sec. 30, T. 134 N., R. 100 W.) where about 85 feet of interbedded silty claystone and swelling clay form a narrow ridge with steep cliffs (Figure 24). The central part of White Butte consists mainly of the younger strata of the Killdeer Formation. As with the Dickinson Member, the Schefield Member may be present in the Killdeer Mountains under the thickly covered and slumped lower slopes. One very small exposure of concretionary mudstone that may belong to the Schefield Member occurs on the lower slope of South Mountain, on the Leonard Davis ranch, along a path from the site of the now defunct settlement of Oakdale to the top of the butte.

The bulk of the Schefield Member at the type section consists of noncalcareous, clayey siltstone to silty claystone that weathers very pale orange (10 YR 8/2) but is grayish orange (10 YR 7/4) where fresh. The lower part of the member is characterized by sharp, regular, even beds up to 6 inches thick (Figure 25a). The upper part has thicker beds with a blocky weathering habit (Figure 25b).

The clay of the Schefield Member is moderate reddish orange (10 R 6/6) where weathered but pale reddish brown (10 R 5/4) where fresh. It occurs in massive, distinct, regular, even beds up to 3 inches thick (Figure 25a).

The alternation of silty claystone with clay gives the Schefield Member a banded appearance (Figures 23 and 25a), and Skinner (1951, p. 53) referred to this portion of his Fitterer Ranch section as the "Banded Zone."

The pitted-weathering habit of the Dickinson Member below is also displayed to some extent by the silty claystones of the Schefield Member.

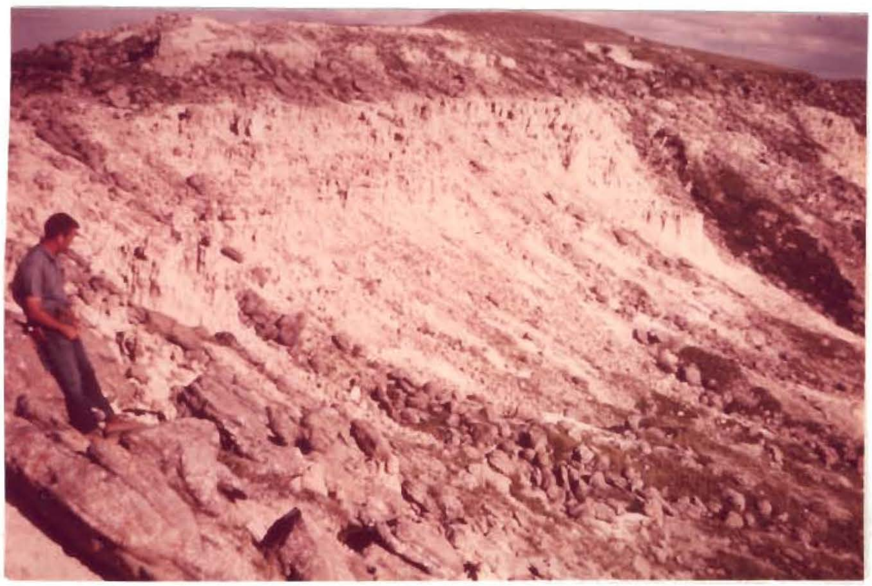
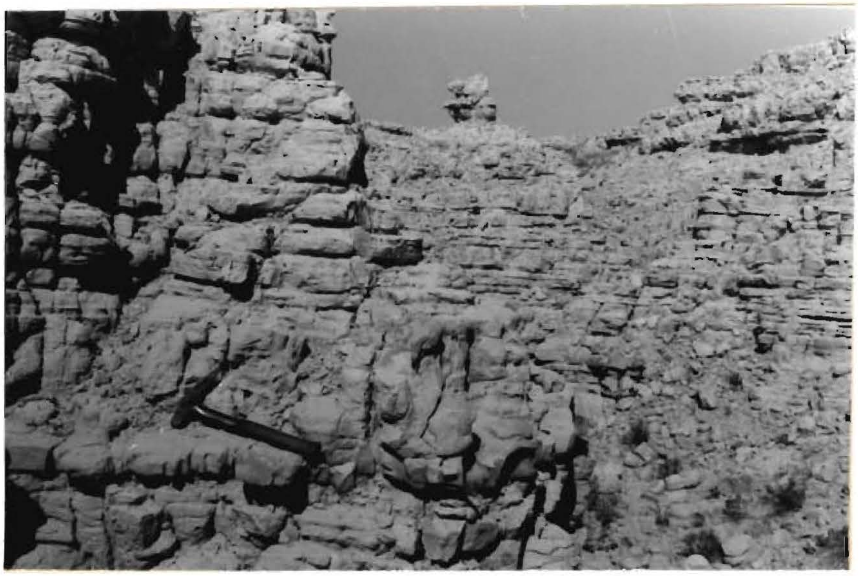


Fig. 24.--Schefield Member of the Brule Formation (forming light-colored, fluted slopes) at the southern end of White Butte, Slope County; large green blocks are calcareous concretions from sandstone of the overlying Killdeer Formation; just southeast of measured section 1 (Appendix C); NW¼SW¼ sec. 30, T. 134 N., R. 100 W.; view looking southeast; scale given by figure at left.



(a)

(b)

Fig. 25.--Close-up views of the Schefield Member of the Brule Formation, north of the Fitterer Ranch house; measured section 3-B (Appendix C); NW¼SE¼ sec. 7, T. 137 N., R. 97 W.; (a) characteristic banded appearance; (b) blocky weathering habit in upper part; both views looking east; scale given by rock pick in both views.

In addition to being pitted, the Schefield claystones are characterized by calcareous concretions. Many of these are tubular in shape, vertically oriented, ½ inch in diameter, and up to 5 inches long. A few are spherical or irregularly oblong, horizontally oriented, up to 2 inches in diameter, and 4 inches long. The latter may be mammalian coprolites and warrant further study.

Distinguishing Characteristics

The banded-weathering and vertical-cliff-forming habits distinguish the Schefield Member from the fluted-weathering, moderate-slope-forming Dickinson Member of the North Dakota Brule. The position of the Schefield Member above the Dickinson Member but below the sandstone-rich Killdeer Formation further distinguishes this unit stratigraphically from all others in the middle Cenozoic section of the state.

Age and Correlation

The age of the Schefield Member is probably late Orellan through Whitneyan. Fossil rodents collected at the Fitterer Ranch by Skinner (1951) from strata now included in the Schefield Member were found to be no younger than Orellan by Stout (1971); however, according to Skinner (1973), other vertebrate remains indicate a Whitneyan age for the upper Brule beds at the Fitterer Ranch. Wood and others (1941, p. 36) referred to fossils from White Butte, in the Chalky Buttes, as the "White Butte local fauna." They gave the age of this fauna as Whitneyan but pointed out (p. 36) that the "Upper White River of this area . . . differs strikingly from the Whitney Member of the Brule both faunally and lithologically.

It seems to be a distinct facies, member or even formation. . . ." Wood and others (1941) were apparently using "Upper White River" in the same sense as had Leonard (1922). This terminology, of course, did not distinguish between the beds now included in the Schefield Member or upper Brule and those now included in the Killdeer Formation. In places at White Butte, because of cutting and filling, the Killdeer Formation and the Schefield are side-by-side. It is, therefore, not clear which unit the "White Butte local fauna" came from.

A complete turtle carapace (Figure 26) was found near measured section 3-C within 10 feet of the top of the Schefield Member, in a 5-foot thick, pinkish claystone just below the resistant ledge which caps the Schefield Member there. The Schefield specimen is referred to Stylemys, the typical small terrestrial turtle so abundant in the Brule of the South Dakota Badlands.

Physical Equivalence

The Schefield Member has a stratigraphic position similar to that of the Whitney Member of the Brule of Nebraska (Schultz and Stout, 1955) and that of the Poleslide Member of the Brule in South Dakota (Harksen and Macdonald, 1969a and 1969b) but differs somewhat from these units lithologically. The Schefield is also similar in stratigraphic position to units "F" through "H" of the Brule in the Slim Buttes of northwestern South Dakota (Lillegraven, 1970) but differs from these units in lithology.

Fig. 26.--Carapace of fossil turtle Stylemys in place as found in the upper part of the Schefield Member of the Brule Formation, southeast of Fitterer Ranch house; measured section 3-C (Appendix C); SE¼NW¼ sec. 17, T. 137 N., R. 97 W.; looking west; scale given by nickel at lower right of specimen.

KILLDEER FORMATION

Name and Type Section

The name "Killdeer Formation" is here proposed for the strata in North Dakota previously referred to the Arikaree Formation by Denson and Gill (1965) and constituting the bulk of the Killdeer Mountains, the major part of White Butte in the Chalky Buttes, and capping a few buttes in the Little Badlands area (Figures 27 and 28). This name was selected because the unit reaches its maximum thickness and is the predominant rock unit present in the Killdeer Mountains, near the town of Killdeer, Dunn County, North Dakota. The type section (measured section 7, Appendix C, and Plate 1) is located in NW¼NW¼ sec. 15, T. 146 N., R. 96 W., 9½ miles northwest of Killdeer, Dunn County, North Dakota.

Definition and Description

The Killdeer Formation is that sequence of concretionary, calcareous sandstone, silty claystone, and dolostone overlying the White River Group in North Dakota but below unconsolidated deposits (largely of gravel) whose source and age are unknown. The Killdeer Formation is usually the caprock where present. The contact between the Killdeer and Brule Formations is covered everywhere except at White Butte in the Chalky Buttes, where it is disconformable.

Fig. 27.--General view of the Killdeer Formation at the southeast end of South Mountain in the Killdeer Mountains; NE¼NE¼ sec. 27, T. 146 N., R. 96 W.; view looking west; scale given by figure standing at right.

Fig. 28.--Brule and Killdeer Formations (in foreground) at southeastern tip of White Butte, Slope County; "haystack buttes" or low rounded hills in right background are composed of the Chadron Formation; measured section 1 (Appendix C); NE¼SE¼ sec. 25, T. 134 N., R. 101 W.; view looking east.

At the type section, 150 feet of Killdeer Formation are exposed. Strata constituting the lower 50 feet of the Killdeer Mountains are concealed by slumping, heavy vegetative cover, thick colluvium, and talus. This covered interval may include additional Killdeer Formation as well as an undetermined thickness of the Chadron and Brule Formations, judging from small exposures of strata referrable to these units on the southern and eastern slopes of South Mountain. At White Butte in the Chalky Buttes the Killdeer Formation is 105 feet thick (Figure 28); on the Fitterer Ranch and in buttes to the northeast it is about 50 feet thick but is missing everywhere else in the Little Badlands.

The lower 65 feet of exposed Killdeer Formation at the type section consists of very fine-grained, calcareous, concretionary sandstone. This concretionary unit is the main ledge-former in the Killdeer section (Figure 29). It weathers to yellowish gray (5 Y 7/2) and is pale olive (10 Y 6/2) where fresh. The lower half of this concretionary unit is characterized by small-scale ripple and laminar bedding. The carbonate content of the sandstone increases upward such that, within the upper 30 feet, this unit appears to be sandy limestone. As pointed out by Quirke (1918, p. 265) beds referrable to this unit are almost pure limestone in exposures on North Mountain. Calcareous concretions are numerous in the upper half of the sandstone and also increase in abundance toward the top (Figure 29). A few of the concretions reach 2 inches in diameter, but most are less than 1 inch across. The concretions are irregularly shaped, branch both vertically and horizontally (Figure 30), and have a small opening running through their long axis.

Fig. 29.--Main concretionary, ledge-forming sandstone in the Killdeer Formation at the southeastern end of South Mountain of the Killdeer Mountains, Dunn County; SE¼SE¼ sec. 22, T. 146 N., R. 96 W.; view looking east.

Fig. 30.--Close-up view of calcareous concretions in the main ledge-forming sandstone of the Killdeer Formation at the southeastern end of South Mountain of the Killdeer Mountains; SE¼SE¼ sec. 22, T. 146 N., R. 96 W.; view looking northwest; scale given by rock pick.

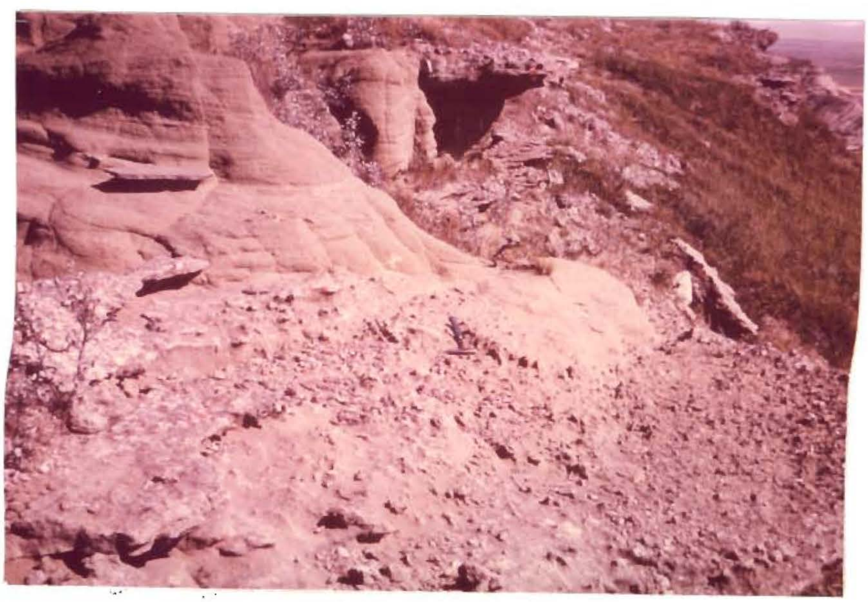
A similar concretionary, ledge-forming, cross-bedded sandstone occurs in the Killdeer Formation at White Butte (measured section 1, Appendix C, and Plate 1) in the Chalky Buttes (Figures 31 and 32). At this site the concretionary bed is only 24 feet thick; however, there is a total of 55 feet of sandstone in the section at White Butte (measured section 1, Appendix C, and Plate 1). This total thickness of sandstone compares fairly well with the 68 feet of concretionary sandstone in the Killdeer Mountain section (measured section 7, Appendix C, and Plate 1). Larger, horizontally oriented, non-branching concretions, lacking an axial opening, were observed in the sandstone above and below the main concretionary bed at White Butte.

Carbonate was also noted to occur in two other ways in the Killdeer Formation at White Butte: as a coating and cementing agent in gravelly zones in the laminar-bedded part of the sandstone and as variously sized, spherical concretions associated with the most cross-bedded part of the main concretionary, ledge-forming unit.

The section above the concretionary sandstone unit at the type section consists of about 90 feet of interbedded, silty claystone, microcrystalline dolostone, dolomitic sandstone, and silty dolostone, all of which are more or less green in color.

On the Fitterer Ranch (measured section 3-C, Appendix C, Plate 1) the lowermost unit in the Killdeer Formation is a silty claystone which weathers grayish orange pink (5 YR 7/2) and contains pale olive (10 Y 6/2) chert nodules. A similar green-chert-bearing, silty claystone occurs 10 feet below the top of the Killdeer Formation at the type section.

(a)



(b)

Fig. 31.--Main concretionary, ledge-forming sandstone in Killdeer Formation, White Butte, Slope County: (a) view looking west at northeastern end of White Butte, NE¼SE¼ sec. 25, T. 134 N., R. 101 W.; (b) view looking southeast at western end of White Butte, NW¼SE¼ sec. 25, T. 134 N., R. 101 W.; scale given by rock pick in both views.

Fig. 32.--Close-up view of calcareous concretions in the main ledge-forming sandstone of the Killdeer Formation at the northeastern end of White Butte, Slope County shown in Figure 31a; NE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 25, T. 134 N., R. 101 W.; view looking west; scale given by camera lens cover at left.

The main concretionary sandstone and other lithologies that occur below the cherty claystone at the type section are missing in the Fitterer Ranch section. A 5-foot thick, green, fine-grained to medium-grained sandstone overlies the cherty, silty claystone on the Fitterer Ranch and caps the section there (measured section 3-C, Appendix C, and Plate 1). The sandstone caprock is massive at the Fitterer Ranch but was observed to contain large-scale trough or pi cross-bedding where it caps Whetstone and Wolf Buttes in Adams County, Coffin Butte in Grant County, Black Butte in Hettinger County, and the Rainy Buttes in Slope County (Figure 33). The cherty claystone bed and green sandstone are also well exposed in buttes northeast of the Fitterer Ranch (measured section 4-B, Appendix C, and Plate 1).

Distinguishing Characteristics

The Killdeer Formation may be distinguished from the other middle Cenozoic deposits of North Dakota by its predominantly concretionary sandstone lithology, its characteristic green color, and its position above the Brule Formation. It is also more variable in lithology than any unit of the White River Group.

Age and Correlation

Fossils from this unit are somewhat rare and none were found in the type section. Quirke (1918, p. 265) reported finding no fossils in the Killdeer Mountains "in spite of diligent search." At the Little Badlands and Chalky Buttes exposures, however, fragmentary remains and teeth of mammals are fairly common. More complete specimens from the

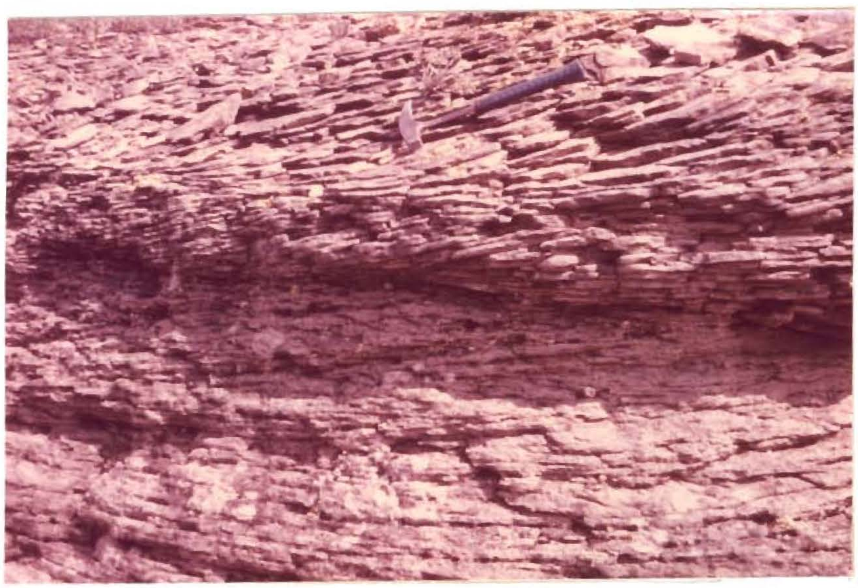


Fig. 33.--Large-scale trough or pi cross-bedding in sandstone of the Killdeer Formation capping Rainy Butte, Slope County; SW¼SE¼ sec. 34, T. 135 N., R. 98 W.; view looking northeast; scale given by rock pick at top.

Killdeer include: a beaver skull from the top of Golden Butte, northeast of the Fitterer Ranch; half of a lower jaw of a small primitive deer, and a complete rhinoceros mandible, both from near the top of the section at White Butte, in the Chalky Buttes (measured section 1, Appendix C, and Plate 1).

The beaver skull was collected in the summer of 1958 by Jean Hough and Robert DeMar, University of Chicago. It occurred in the sandstone caprock of Golden Butte (NE¼ sec. 33, T. 138 N., R. 97 W.) according to DeMar (1969). After Hough's death the specimen was sent to the American Museum of Natural History, New York. From a cast provided by that institution, Stout and Stone (1971) have identified it as *Paleocastor* sp. (Figure 34) and found it to be similar to forms of that genus collected from the Gering Formation (early Miocene) of Nebraska.

The deer jaw was collected by Jack Harksen, South Dakota Geological Survey, while visiting the field area with me in the fall of 1970. It occurred as float about 5 feet below the top of the White Butte section (measured section 1, Appendix C, and Plate 1). According to Stout (1972), "this specimen compares fairly well with the Gering type of Mr. Frick's '(?) *Hypertragulus minor*,' the holotype of which is in our collection from the Gering near Bridgeport, Morrill County, Nebraska." He added, however, that there was not sufficient comparative material from the Harrison or Monroe Creek Formations on hand to determine affinities with forms from those units. All that could be concluded, he felt, was that the specimen was an Arikareean form.

The rhinoceros mandible was recovered in the summer of 1970 with

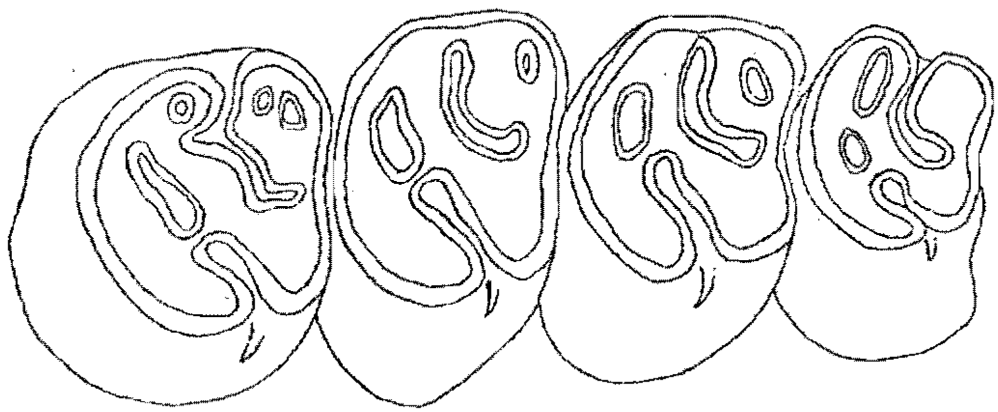


Fig. 34.--Left upper dentition of fossil beaver, Paleocastor sp., collected by Jean Hough from caprock on Golden Butte, Stark County (SW¼NW¼ sec. 34, T. 137 N., R. 97 W.); drawn and identified from a cast of American Museum of Natural History specimen no. 55545 by T. M. Stout, University of Nebraska, 1971; anterior is to left; X 8.

the help of Thomas M. Brobeck. It occurred at SE¼NE¼ sec. 25, T. 134 N., R. 101 W. in the concretionary sandstone 20 feet below the top of White Butte, Slope County. Because lower dentition is not diagnostic for rhinoceros identification, various other measurements were made of the White Butte specimen for comparison with published values for similar genera (Table 2). It was found to be larger than Subhyracodon, the common Oligocene rhinoceros, and Diceratherium, the early Miocene form. However, it compares quite favorably with the late Oligocene to Miocene genus Amphicaenopus. The main points of similarity are (1) the shape and size of the ramus, (2) the overall length of the mandible, (3) the size and placement of the tusk-like incisors, (4) the length of the symphysis, and (5) the height and width of the dentary (Stone 1970a).

From the specimens studied thus far, correlation of the Killdeer Formation with some part of the Arikaree Group of Nebraska, perhaps the Gering Formation (early Arikareean), seems reasonable (Stout and Stone, 1971).

Physical Equivalence

The Killdeer Formation has a similar stratigraphic position to the Gering Formation of Nebraska (Schultz and Stout, 1955) the Sharps Formation of South Dakota (Harksen and Macdonald, 1969b), and the Arikaree Formation (?) in the Slim Buttes of northwestern South Dakota (Lillegraven, 1970) but differs lithologically from each of these units.

TABLE 2

COMPARISON OF MEASUREMENTS OF RHINOCEROS MANDIBLE FROM WHITE BUTTE, SLOPE COUNTY AND THOSE PUBLISHED FOR THREE COMMON MIDDLE CENOZOIC GENERA (SCOTT, 1941, P. 793, 811): NUMBERS IN PARENTHESES ARE NUMBERS OF INDIVIDUALS REPRESENTED BY DATA

Lengths (mm)	White Butte Specimen	*Amphicaenopus* (3)	*Subhyracodon* (2)	*Diceratherium* (1)
Mandible	535	501, 530	409, 375	450
Lower Molar Series	131	133, 135, 142	103, 93	120
Strati-graphic Range	?	Upper Chadron to Upper Brule	Lower Brule	Upper Brule

Suggestions for Further Stratigraphic Work

Although the development of a stratigraphic framework for the middle Cenozoic of North Dakota solves some problems, it also creates new ones, namely, those of the relationships with other areas. Further stratigraphic study is therefore needed to determine whether the North Dakota terminology can be applied to the strata of other areas such as the outcrops of adjacent parts of Montana and South Dakota. Also, further stratigraphic collection and comparative study of fossils from the North Dakota strata are necessary to enhance correlations with the Oligocene and Miocene records of South Dakota and Nebraska. Further study of the strata between the Interior and Chadron Formations at the northern end of the Chalky Buttes may clarify whether they should be referred to (1) the Golden Valley Formation, (2) the Slim Buttes Formation of South Dakota, or (3) an entirely new unit.

PETROGRAPHY OF THE MIDDLE CENOZOIC DEPOSITS OF NORTH DAKOTA

General Statement

Although detailed petrographic analyses of the various rock types in the middle Cenozoic record of North Dakota are desirable, they were beyond the scope of the present study. Now that a stratigraphic framework has been established such detailed studies can logically proceed and the petrography of rocks in the Killdeer Mountains, here assigned to the Killdeer Formation, is the topic of dissertation research now under way by John Delimata (University of North Dakota). Cursory petrographic analyses of the major sandstone and mudstone units were, nonetheless, made. The main purpose of these studies was simply to obtain basic information regarding the composition of the rocks involved so that they could be properly classified. A secondary purpose was to determine if the various sandstone or mudstone units could be distinguished by their mineralogy. The petrographic data were also used in reconstructing the sedimentary history of the deposits. All terminology used is defined in Appendix B, and the methods employed in the collection of samples and the petrographic analyses are given in Appendix D.

Sandstones

Modal analyses (Appendix E) were made of nine sandstone thin sections (three from the Chadron Formation, two from the Brule Formation, and four from the Killdeer Formation). A general study of three additional thin sections (Appendix E) of a sandstone, here included in the Killdeer Formation, was also made.

Thin-section study of the Chalky Buttes sandstone yielded the following constituents, in order of decreasing abundance: nonmetamorphic quartz, fine-grained igneous rock fragments, and feldspar. Muscovite, biotite, and other unstable or mafic minerals are scarce. The Chalky Buttes sandstone consists largely of framework with only minor clay matrix and cement (Figure 35). Chalcedony is abundant as a cementing or secondary intergranular-filling material in two of the three specimens studied (Appendix E: samples 2 and 3). Little cement was otherwise noted in the Chalky Buttes samples. According to Folk's classification (1965), the sandstone of the Chalky Buttes Member is arkose (Figure 36 and Appendix E: samples 1, 2, and 3).

Major constituents observed in samples of the Fitterer Bed, Dickinson Member, Brule Formation, in order of decreasing abundance, include: nonmetamorphic quartz, igneous rock fragments, and feldspar. The rock fragments are of fine-grained to medium-grained igneous types. Unstable minerals are more abundant in the Fitterer sandstone than in the Chalky Buttes sandstone and include muscovite, biotite, pyroxenes, and amphiboles. The matrix content of this sandstone is also high, greater than 25 percent (Figure 35). The matrix consists of very fine

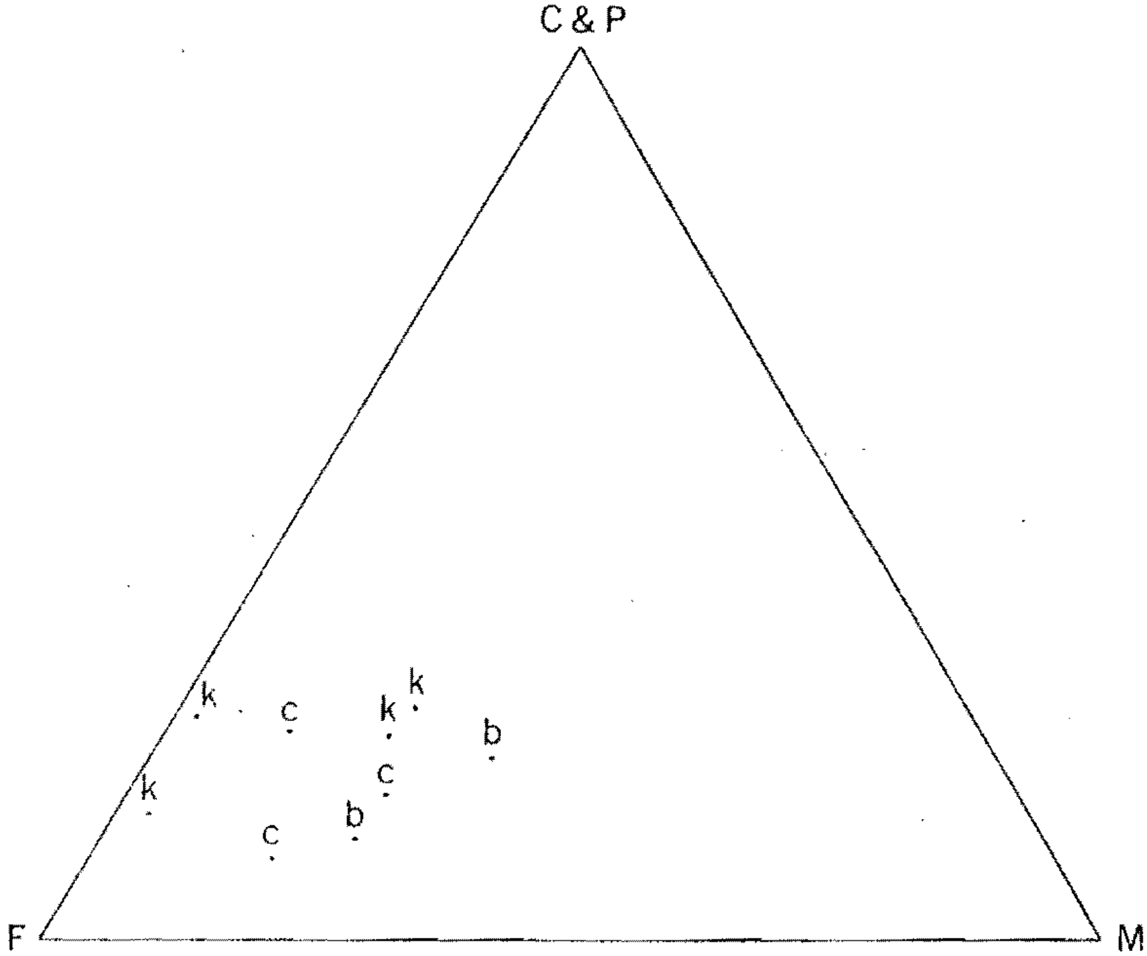


Fig. 35.--Distribution of framework (F), cement and porosity (C & P), and matrix (M) in the middle Cenozoic sandstones of North Dakota; c = Chalky Buttes Member of the Chadron Formation, b = Fitterer Bed of the Dickinson Member of the Brule Formation, and k = Killdeer Formation.

mud and clay. Fine, clear, needlelike crystals of zeolite, often radially arranged, are abundant in the pore spaces and matrix of the Fitterer sandstone. The lack of abrasion, delicate crystal habit, and relationship of this needlelike material to other grains clearly show that it is authigenic. The Fitterer sandstone is also arkose, according to Folk's scheme (Figure 36 and Appendix E: samples 4, 5, and 6).

The composition of the sandstone of the Killdeer Formation is similar to that of the sandstone in the Chadron and Brule Formations. However, nonmetamorphic quartz is not as clearly the predominant mineral constituent of the Killdeer sandstone as it is in the Chadron and Brule sandstones, and fine-grained igneous rock fragments account for a major part of its composition as well (Figure 37). Unstable minerals are minor but include micas, amphiboles, and pyroxenes. Zoned feldspar (Figure 38) and vein quartz were also observed. Feldspar is generally present in amounts greater than 10 percent of the total framework but is everywhere less abundant than quartz or rock fragments. Needlelike crystals of zeolite, like those observed in the Fitterer sandstone, are very abundant in the Killdeer sandstone as well. In one sample (Appendix E: sample 7) such material constitutes 18 percent of the points counted (Figure 39). Chalcedony is likewise an abundant secondary and cementing constituent (Figure 40). It accounted for 20 percent of the points counted in one sample (Appendix E: sample 9). Encrustations and fracture-fillings of opal were noted megascopically, and in thin section opal was noted to occur in the pores of several of the samples. One thin section of the main, ledge-forming, concretionary sandstone in the Killdeer

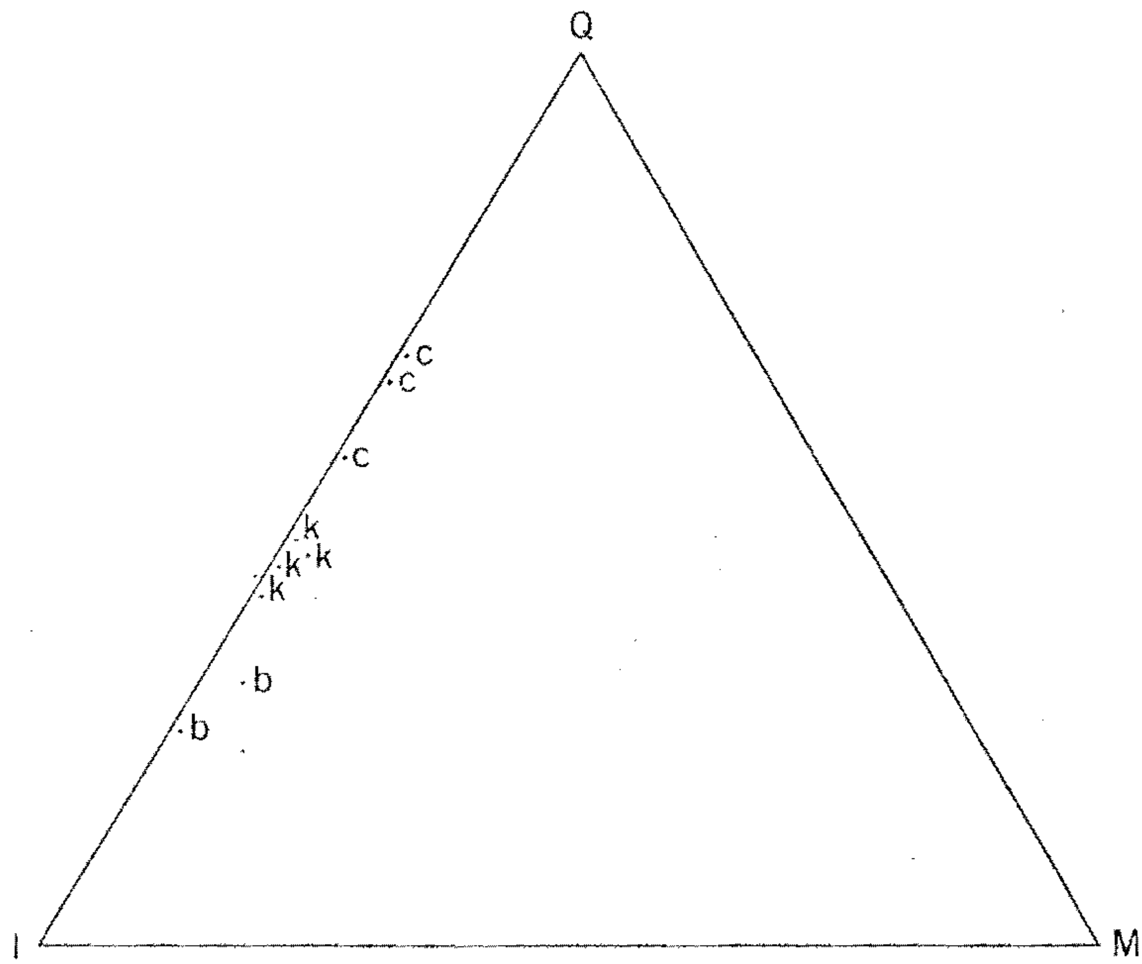
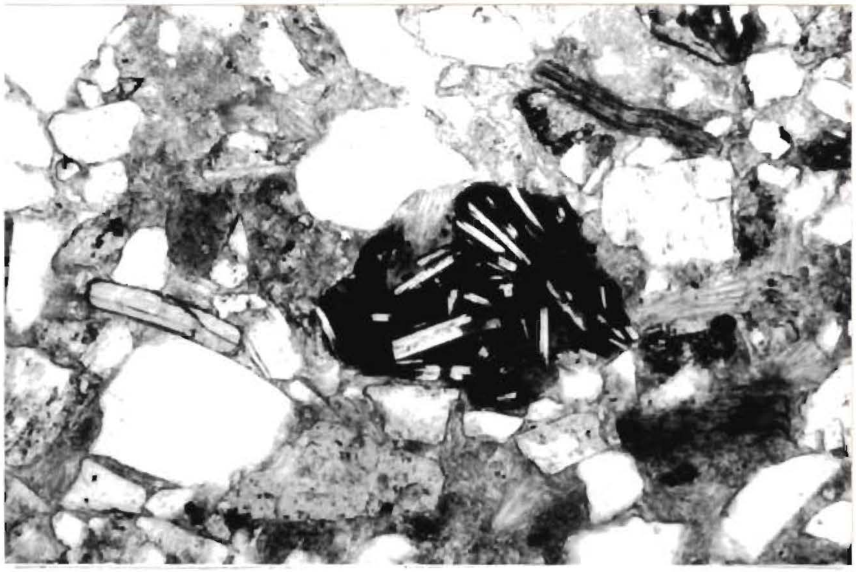
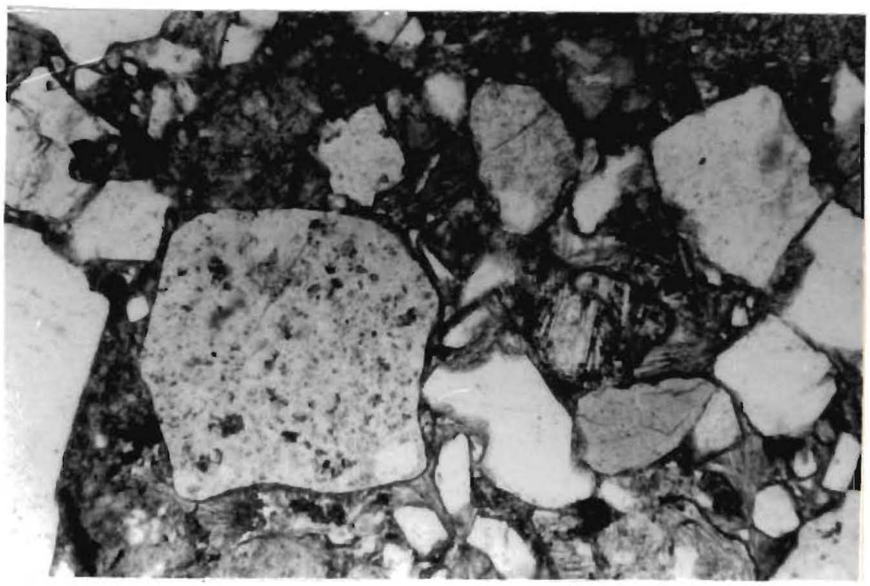


Fig. 36.--Composition of middle Cenozoic sandstones of North Dakota, based on the three end-members of Folk (1965): Q = non-metamorphic quartz, I = igneous constituents, and M = metamorphic constituents; c = Chalky Buttes Member of the Chadron Formation, b = Fitterer Bed of the Dickinson Member of the Brule Formation, and k = Killdeer Formation.



(a)



(b)

Fig. 37.--Photomicrographs (plane polarized light, X3.5) showing porphyritic (a) and nonporphyritic (b) fine-grained igneous rock fragments in sandstone sample 7, Killdeer Formation, Fitterer Ranch; SE¼NW¼ sec. 17, T. 137 N., R. 97 W.

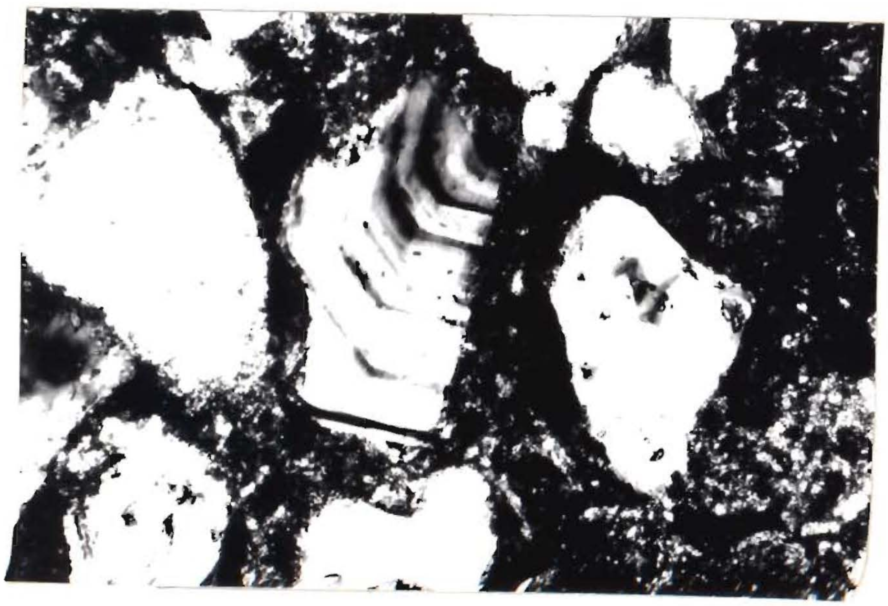


Fig. 38.--Photomicrograph (crossed polars, X10) showing zoned feldspar in sandstone sample 7, Killdeer Formation, Fitterer Ranch; SE¼NW¼ sec. 17, T. 137 N., R. 97 W.

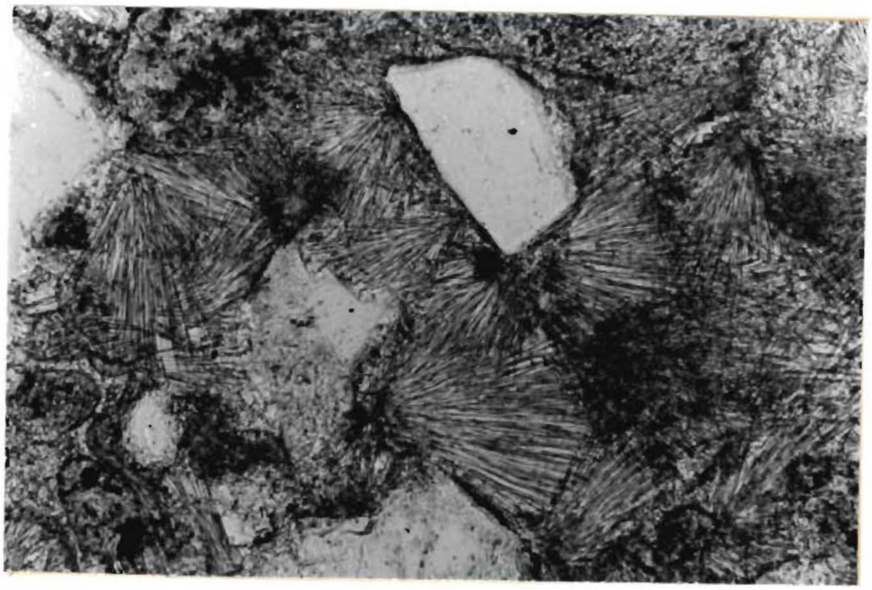


Fig. 39.--Photomicrograph (plane polarized light, X10) showing intergranular, needlelike growths of zeolite in sandstone sample 7, Killdeer Formation, Fitterer Ranch; SE¼NW¼ sec. 17, T. 137 N., R. 97 W.

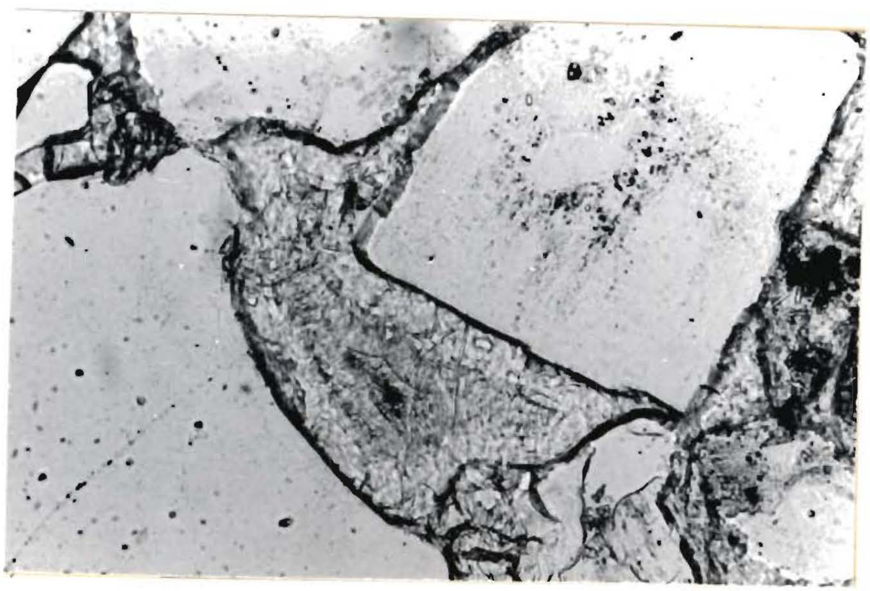


Fig. 40.--Photomicrograph (plane polarized light, X10) showing chalcedony cement in sandstone sample 8, Killdeer Formation, Black Butte, Hettinger County; SE¼NE¼ sec. 12, T. 136 N., R. 95 W.

Mountains (Appendix E: sample 12), consisted mainly of elongated, blade-shaped and crescentic-shaped, volcanic glass shards. Binocular microscope examination revealed the presence of "scoria," the baked-rock product of natural ignition of lignite near the surface (Sigsby, 1966), in coarser-grained samples of the Killdeer sandstone collected near measured section 1 in the Chalky Buttes. This suggests that the lignite-bearing Golden Valley Formation or Fort Union Group were locally exposed at this time. The Killdeer sandstone is arkose according to Folk's classification (Figure 36 and Appendix E; samples 7, 8, and 9).

The specific identity of feldspars was not needed for the general classification of the sandstone samples studied, and specific types were not distinguished in the modal analyses. From binocular microscope examination of most of the sandstone samples, feldspar was noted to occur as clear cleavage fragments. Such grains were especially conspicuous in the Chalky Buttes Member of the Chadron Formation.

Mudstones

A preliminary, qualitative, X-ray-diffraction study fine-grained rock types in the middle Cenozoic section of North Dakota was carried out to learn the general mineralogy of the various mudstone units in the section and if there were any useful mineralogic criteria by which these units might be distinguished. A semiquantitative analysis was made of the Dickinson Member in the Little Badlands proper (near measured section 5-B) to determine the approximate concentrations of the various minerals contained by these mudstone beds and the variation in their concentrations within a single rock unit.

Qualitative Analysis

Twenty-one fresh samples of the fine-grained rock types in the middle Cenozoic section of North Dakota were studied by X-ray diffraction in the qualitative analysis. Samples include six specimens from the South Heart Member of the Chadron Formation, seven specimens from the Dickinson Member of the Brule Formation, one specimen from the Schefield Member of the Brule Formation, and seven specimens from the Killdeer Formation.

The major mineral constituents detected in the samples of mudstone studied include quartz, montmorillonite, kaolinite, plagioclase, potassium feldspar, mica, calcite, clinoptilolite, erionite, heulandite, and dolomite. The distribution of these constituents among the samples studied is given in Table 3. No distinct mineralogic differences are apparent between the various rock units analyzed. Slight differences include the amount of calcite and predominant type of zeolite present. Neither of these is a reliable criterion for distinguishing the rock units, however, because the calcite is secondary and no doubt variable in concentration throughout the section, and all three zeolite minerals occur in all units studied.

Semiquantitative Analysis

Seven fresh samples of the Dickinson Member from the Little Badlands proper (near measured section 5-B) were analysed by X-ray diffraction. The samples studied represent a variety of lithologies and positions within

TABLE 3

RESULTS OF QUALITATIVE X-RAY-DIFFRACTION ANALYSIS OF

MIDDLE CENOZOIC MUDSTONES OF NORTH DAKOTA

	Quartz	Montmorillonite	Kaolinite	Plagioclase	Potassium Feldspar	Mica	Calcite	Clinoptilolite	Erionite	Heulandite	Dolomite
Killdeer Formation (7)	X	X		X	X	X	(X)	(X)	(X)	(X)	(X)
Brule Formation (8)											
Schefield Member (1)	X	X		X	X	X	X		X	X	
Dickinson Member (7)	X	X		X	X	X	(X)		(X)	(X)	
Chadron Formation (6)											
South Heart Member (6)	X	X	(X)	X	X	X	(X)	X	(X)	X	

Notes:

(1) Number of samples analyzed.

(X) Parentheses indicate that the constituent was not present in all samples analyzed.

the Dickinson Member. The samples were selected so that (1) variation in gross mineralogy throughout the section could be determined, (2) bed-to-bed variation in mineralogy could be observed, (3) mineralogy of adjacent cross-bedded and noncross-bedded strata of the same general lithology could be compared, and (4) the mineralogy of two components of a pitted claystone might be learned.

The results of the semiquantitative, X-ray-diffraction analysis are given in Figure 41. Feldspar and quartz are the two main constituents, followed by clay, calcite, and mica, in order of decreasing abundance.

Difficulty in identifying the specific feldspars present in samples of the various mudstone beds was first encountered in the qualitative analysis. The diffractograms of samples of mudstone from the Dickinson Member made in that analysis indicated the presence of perthite. Further work is needed on the isolation and identification of the feldspar types in the mudstone units.

Clay is most abundant in the clasts in the pitted claystone. No strong illite or kaolinite peaks were recorded. Of the four samples glycolated (1, 4b, 7a, and 7b), only one (sample 1) responded with a reasonably sharp diffraction peak at 17 angstroms clearly indicating the presence of montmorillonite. The clay content of the remainder of the samples must be divided among the other major clay minerals.

The zeolites clinoptilolite, erionite, and heulandite are fairly abundant in several of the samples (4a, 4b, 7a, and 7b) as shown on Figure 41. In addition to muscovite, hydrobiotite was also identified in these four beds by strong diffraction peaks at 11.5 and 2.9 angstroms. This probably accounts for the numerous dark mica specks seen in hand specimens.

The semiquantitative analysis revealed little variation in gross mineralogy throughout the section, and bed-to-bed variation is also negligible. The mudstone beds vary mainly in their calcite content and their zeolite content. These two variables may be related in that the beds having high calcite contents contain no zeolite (Figure 41). The

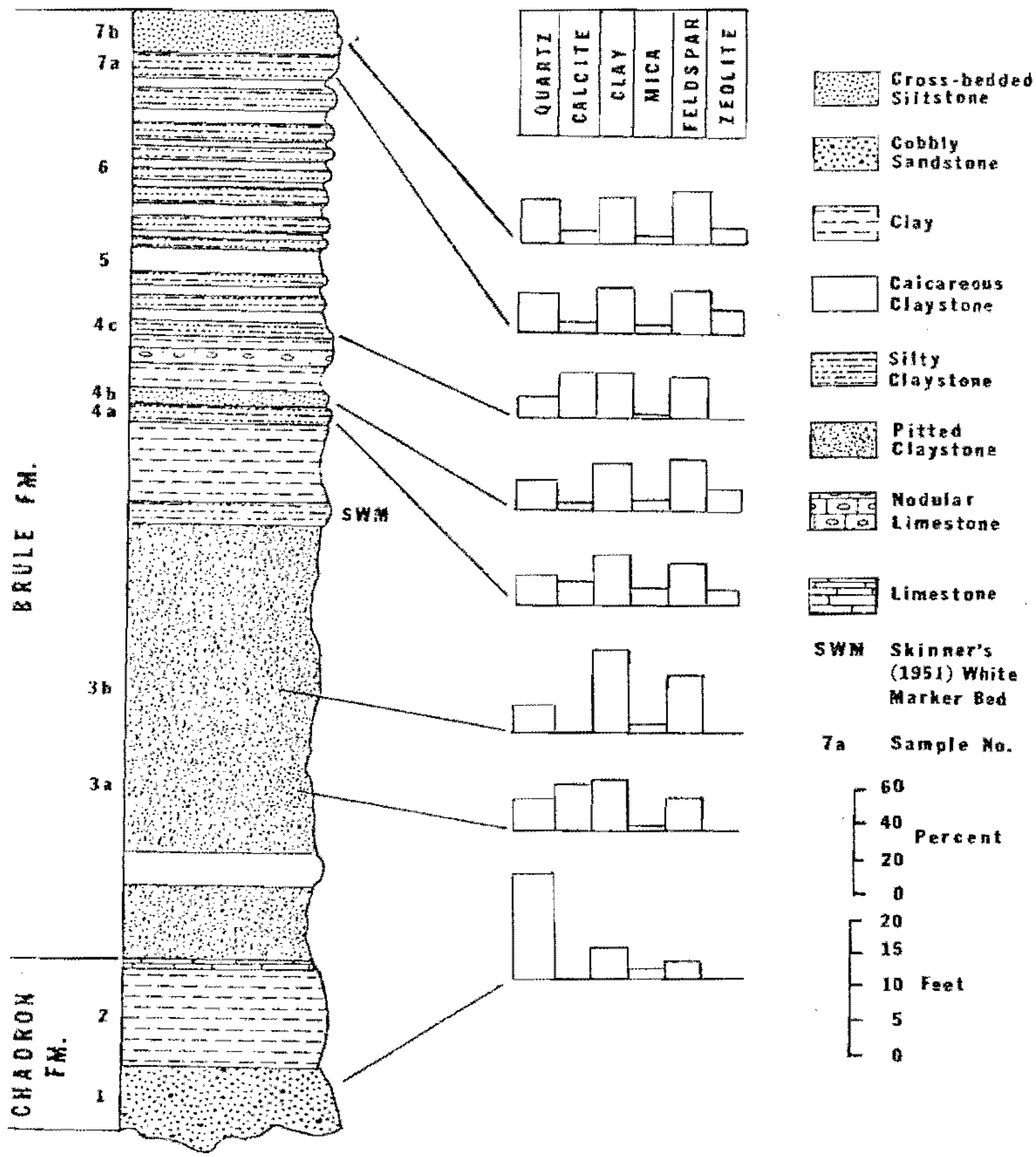


Fig. 41.—Composition of the mudstones of the Dickinson Member of the Brule Formation and the Chalky Buttes Member of the Chadron Formation in the Little Badlands proper as determined by semi-quantitative X-ray diffraction analysis; measured section 5-A (Appendix C); SE¼NW¼ sec. 23, T. 138 N., R. 98 W.

main difference between the sandstone of the Chalky Buttes Member, Chadron Formation and the overlying mudstone beds of the Dickinson Member, Brule Formation is that the Chalky Buttes sandstone contains a higher percentage of quartz but no appreciable calcite and no zeolite.

Volcanic-Ash Content

The volcanic ash in the Oligocene and Miocene deposits of South Dakota and Nebraska has been mentioned by previous workers (Darton, 1899; Clark and others, 1967; Harksen and Macdonald, 1969b; Harksen and others, 1961; Schultz and Stout, 1955; and Wood, 1949). Denson and Gill (1965) concluded that the middle Cenozoic deposits of North Dakota are also tuffaceous. No detailed documentation or description of the volcanic ash content of the deposits from any of these areas has yet been reported, however, and it remains a topic for further study.

Some evidence for the presence of volcanic ash was found in this study, but the search for ash was not a main objective and was therefore not conducted in enough samples or localities to justify the universal application of volcanic-rock nomenclature to these deposits. Evidence found includes: (1) numerous, silt-sized, euhedral mineral grains, believed to represent the crystalline fraction of a volcanic ash, recovered by soaking and washing samples of various mudstone beds of the Brule and Killdeer Formations; (2) similar silt-sized, euhedral mineral grains commonly observed in various mudstone samples in the field with a hand lens and detected in the laboratory examination of samples by binocular microscope; (3) the blocky weathering habit of most of the fine-grained middle Cenozoic deposits in North Dakota, which is identical to that of beds in the South Dakota Badlands reported to be reworked ash by Harksen and others (1961) and which also resembles the weathering habit of ash-bearing beds in other areas such as the Gila and Jemez volcanic regions of New Mexico and the Big Bend region of Texas; (4) the zeolites clinoptilolite, erionite, and heulandite detected in X-ray-diffraction studies of the deposits; (5) the abundance of secondary quartz occurrences in the deposits such as opaline encrustations and chalcedony cement in the Killdeer sandstones, chert nodules in a claystone of the Killdeer, and irregular masses of chalcedony and opal in the clay of the South Heart Member of the Chadron Formation; and (6) abundant glass shards seen in a thin section of sandstone from the Killdeer Formation, Killdeer Mountains. Delimata (1973) has also detected shards and what may be pumice fragments in thin sections of sandstones, from the Killdeer Mountains, here included in the Killdeer Formation.

Glass shards from the main, ledge-forming, concretionary sandstone in the Killdeer on North Mountain, Killdeer Mountains, have a refractive index of 1.502, which is characteristic of a rhyolitic glass (Furman, 1970b). As shown in Figure 42, the compositions of the zeolites identified in samples from throughout the middle Cenozoic section of North Dakota are compatible with that of rhyolitic glass (Deffeyes, 1959, Figure 2).

Taken separately these meager lines of evidence may prove little, but taken together I believe they permit the conclusion that the middle Cenozoic deposits of North Dakota are or were tuffaceous. Nevertheless, no glass shards were observed in the Chadron or Brule Formations, and

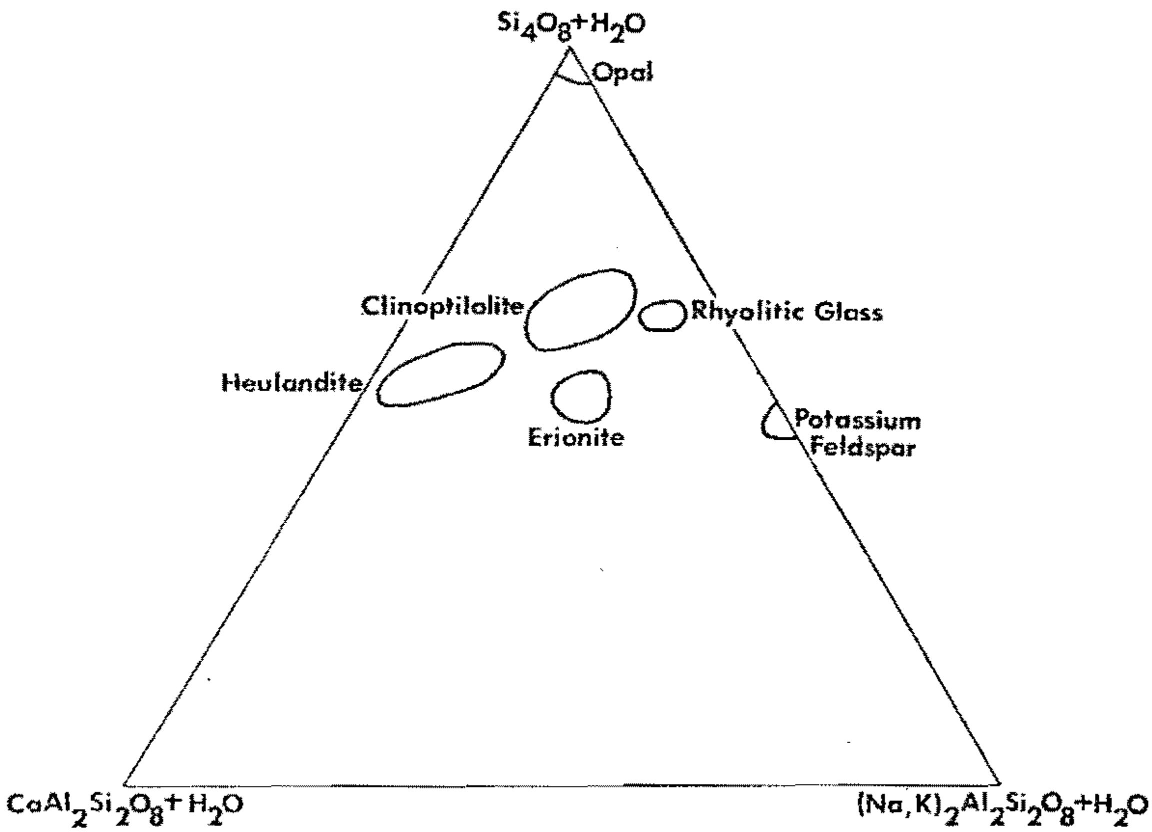


Fig. 42.--Comparison of the compositions of zeolites identified in the middle Cenozoic deposits of North Dakota with those of rhyolitic glass, potassium feldspar and opal (modified from Deffeyes, 1959, Figure 2).

until further specific work is done on the volcanic ash content of all of these deposits, no attempt will be made to apply a pyroclastic rock terminology to any of them.

Suggestions for Further Petrographic Work

Now that a stratigraphic framework has been developed for the middle Cenozoic deposits of North Dakota, further petrographic and mineralogic work on them is not only possible but desirable. Suggested topics for further study of these deposits include (1) the determination of the specific feldspar types in the various sandstone and mudstone units, (2) a detailed, quantitative and geochemical analysis of the zeolite types present in the various sandstone and mudstone units, and (3) a thorough study of the volcanic-ash content of these strata, emphasizing the abundance of ash in the section, the trace element characteristics of the ash, the contribution of this ash to the formation of the clay present in these deposits, and the refractive index or indices of shards in the ash.

SEDIMENTARY HISTORY

Late Mesozoic to Middle Cenozoic Geologic History

In late Cretaceous time a vast shallow sea bisected the North American continent, extending from the Arctic coast of Alaska to the Gulf of Mexico. Latest Cretaceous marine deposition in the Midcontinent is recorded, in ascending order, by the shale of the Pierre Formation, which represents the offshore facies; the sandstone of the Fox Hills Formation, which represents the nearshore facies; and the fine-grained, dinosaur-bearing, lignitic strata of the Hell Creek Formation, which represents the coastal swamp and brackish-water facies.

The history of the Cenozoic Era begins with the Laramide Orogeny. This widespread tectonic episode heralded the retreat of the Cretaceous seas, formed new, mountainous source areas, rejuvenated streams, and initiated the period of continental deposition that has persisted in the adjacent basins for the past 70 million years.

Paleocene time in North Dakota was characterized by a variety of coastal-plain depositional environments, as seen in the beds of sandstone, lignite, and lignitic mudstone of the Fort Union Group. A brief return of marine conditions during Paleocene time is recorded by the Cannonball Formation (Carlson and Anderson, 1965, p. 1845).

On the basis of fossil fish, amphibians, reptiles, birds, mammals, and plants found in the Golden Valley Formation, Jepsen (1963, p. 673) characterized the early Eocene setting in North Dakota as one of " . . . warm, humid, swampy lowlands with subtropical forests bordering sluggish streams." Bjork (1967, p. 227) concluded, from the fauna in the Slim Buttes Formation near Reva Gap, South Dakota, that a permanently flowing river had been present in northwestern South Dakota during late Eocene time. Pettyjohn (1967, p. C65) interpreted the Interior Formation, which was developing at about this same time, as a laterite, which probably formed under "hot, wet climatic conditions in a relatively flat area having deep and widely spaced drainage systems."

The lack of Eocene deposits, such as the Golden Valley or Slim Buttes Formations, over most of the region but the widespread occurrence of the Interior Formation reflects a vast erosional or nondepositional phase in the northern plains in Eocene time. The Black Hills also underwent considerable denudation and were believed by Harksen and Macdonald (1969b, p. 18) to have reached their present topographic expression during Eocene time.

Middle Cenozoic Climate

Two floral paleotemperature curves for the western United States have been published within the past 10 years (Dorf, 1963; Wolfe and Hopkins, 1967). These two curves agree quite well and indicate cooling during the Paleocene, maximum warmth in late Eocene, cooling in Oligocene, and warming again in the middle Miocene. More specifically, the floras indicate that the climate at the start of Oligocene time was probably similar to that of Eocene time or between warm temperature and subtropical, with a mean annual temperature of about 65°F, and by the end of Oligocene time, after a steady drop in temperature, the climate was slightly warmer than temperate, with a mean annual temperature of about 50°F (Axelrod and Bailey, 1969, Figure 1b). Toots (1965, p. 164-165) concluded that there was no consistent trend in Oligocene climatic changes but that early and middle Oligocene times were characterized by alternating humid and arid conditions, whereas, late Oligocene time may have been uniformly dry and cool. The Miocene climate was apparently quite variable with mean annual temperatures ranging from 45°F to 55°F (Axelrod and Bailey, 1969, Figure 1b).

As noted by Singler (1968, p. 122), a general change in moisture regime from humid to semiarid must have accompanied the temperature changes characterizing Oligocene time. The green claystones of the Chadron Formation of Nebraska were interpreted as products of swampy conditions by Schultz and Stout (1955, p. 36). Fossil wood reported from the Chadron of Nebraska by Harvey (1960, p. 65) indicates sufficient moisture for tree growth at that time. The lack of petrified wood in the Brule strata may reflect drier conditions in later Oligocene time or simply a lack of proper preservation conditions. From a study of a paleosol in the Orella Member of the lower part of the Nebraska Brule, Harvey (1960, p. 52) concluded that "the mean annual precipitation was within the range of 20 to 25 inches." However, Singler (1968, p. 123) concluded that a paleosol associated with the lower ash bed of the Whitney Member of the upper Brule in Nebraska "developed under 10 to 18 inches of precipitation." If these interpretations are correct, a possible decrease in annual rainfall of 2 to 15 inches is indicated between early and late Brule times alone.

The presence of kaolinite in the Golden Valley Formation but its general absence in the White River Group may also be considered evidence of a change in moisture regime from humid to less humid. According to Krauskopf (1967, p. 191) kaolinite forms under humid conditions where surface waters are acidic, and montmorillonite is characteristic of less humid climates where surface waters are somewhat alkaline. As further evidence of drier conditions in Oligocene time, alligators, whose remains are common in the Golden Valley Formation (Jepsen, 1963, p. 673), diminish in abundance and eventually disappear altogether shortly after Chadronian time (Clark and others, 1967, Figure 27). Furthermore, no lignite is found above the Golden Valley Formation and the warm, moist conditions that produced the Paleocene and Eocene lignites of North Dakota had apparently been altered by Oligocene time.

The persistence of an arkosic composition for the sandstones throughout the North Dakota section gives further climatic evidence, at least regarding conditions in the source area. Folk (1965, p. 177) recognized the following as conditions that would account for the preservation of otherwise unstable feldspar: (1) dry or cold climatic conditions in the source area; (2) rapid erosion of a tectonically active source area, characterized by rugged topography and streams with high gradients; and (3) rapid erosion of a volcanically active source area, in which the addition of fresh rock material to the surface would have the same affect as would an equivalent amount of uplift. Although the climatic information given above indicates that Oligocene time was increasingly cooler or drier than Eocene, it was not cold, nor was it unusually dry. There was apparently enough moisture for the production of the clay matrix, so abundant in the sandstones, but not enough moisture, or perhaps time, to accomplish the complete chemical weathering of the feldspars. Admittedly, some fresh feldspar may have been added to the sediment load during transport due to the break-down of igneous pebbles and cobbles, at least in the case of the Chalky Buttes Member. Likewise, much of the clay matrix seen in the sandstones need not be from a distant source area but could have been derived locally from the erosion of older (Paleocene and Eocene) fine-grained sedimentary rocks. Rapid erosion in the source area, due to the rejuvenation caused by the Laramide tectonic and igneous activity, is the most probable reason for the production of the arkoses studied.

Source of Middle Cenozoic Deposits

The Black Hills uplift is the most obvious and logical source of the middle Cenozoic deposits of North Dakota because it is and probably has been the most prominent highland in the Midcontinent since late Cretaceous and early Tertiary time. Correlative deposits in the South Dakota Badlands were shown to have been derived from the Black Hills by Ritter and Wolff (1958) and Seefeldt and Glerup (1958). Several lines of evidence support this source for the North Dakota deposits as well.

The best evidence of original source material is found in the pebbles and cobbles of the Chalky Buttes Member of the Chadron Formation. The discussion of the source of this gravel that follows is from Stone (1970b). The pebbles and cobbles consist of fine-grained or porphyritic, felsic to intermediate, igneous rock types; medium-grained to coarse-grained, pyroclastic rock types; low-grade metamorphic rock types; petrified wood; flint; and chert. Denson and Gill (1965, p. 19) proposed that the Absaroka volcanic field of northwestern Wyoming was the source of the igneous rock types seen in the gravel. They ruled out the Black Hills, some 250 miles closer, because (1) typical Black Hills rock types were not seen among the pebbles and cobbles, (2) no bedrock counterparts for the rock types seen in the gravel have been found in the Black Hills, and (3) their reconstruction of the pre-Oligocene surface suggested that regional slopes at the time were away from the Absaroka volcanic field.

These criteria are felt to be inconclusive for a number of reasons. First, slopes would probably have been away from the Black Hills in all directions as they are today, and if the Black Hills were the source of Oligocene sediments occurring 375 miles to the east, they could have been the source of sediments deposited a comparable distance to the north. Furthermore, after examining eight typical Chadron pebbles and cobbles, W. H. Parsons (Wayne State University), a leading authority on the geology of the Absarokas, stated (1970): "I can say categorically that none of these specimens look like the Absaroka volcanics."

The Black Hills rock types that Denson and Gill (1965, p. 19) noted as missing in the North Dakota gravel include the Precambrian, medium-grained to coarse-grained, intrusive rocks of the central Black Hills.

Such materials characterize Chadron gravels in the Big Badlands of South Dakota but would probably not have reached southwestern North Dakota because ancient drainage from the central Black Hills was toward the east (Clark and others, 1967, p. 10). The early Tertiary igneous intrusions of the northern Black Hills are closer to the study area and a more likely source of the gravel and other middle Cenozoic deposits in North Dakota. These intrusions include the bulk of the Bear Lodge Mountains and outlying features such as Bear Butte, Inyan Kara Mountain, Sundance Mountain, and Devils Tower. Radiometric ages of rocks in the northern Black Hills, as reported by McDowell (1966, Table 13), indicate that igneous activity in the northern Black Hills was completed prior to Oligocene time (Figure 43), and some of the rock materials formed during this igneous activity may have been available for erosion, transportation, and deposition as part of the early Oligocene record of adjacent areas.

Brown (1952, 1954) and Mukherjee (1968) gave excellent accounts of the lithologies and history of the Tertiary igneous rocks of the northern Black Hills. According to Mukherjee (1968, p. 256) the rocks in an area near Lead, South Dakota "were perhaps derived from differentiation of an intermediate parent magma." The rock types reported by both Brown and Mukherjee are felsic and have extrusive or at least near-surface textures. A period of very forceful intrusion to shallow depths of latite, trachyte, and rhyolite porphyries characterized the later stages of this igneous episode (Mukherjee, 1968, p. xix). The volcanic rock types, from which the North Dakota gravel must have been derived, may have been produced where such intrusions reached the surface.

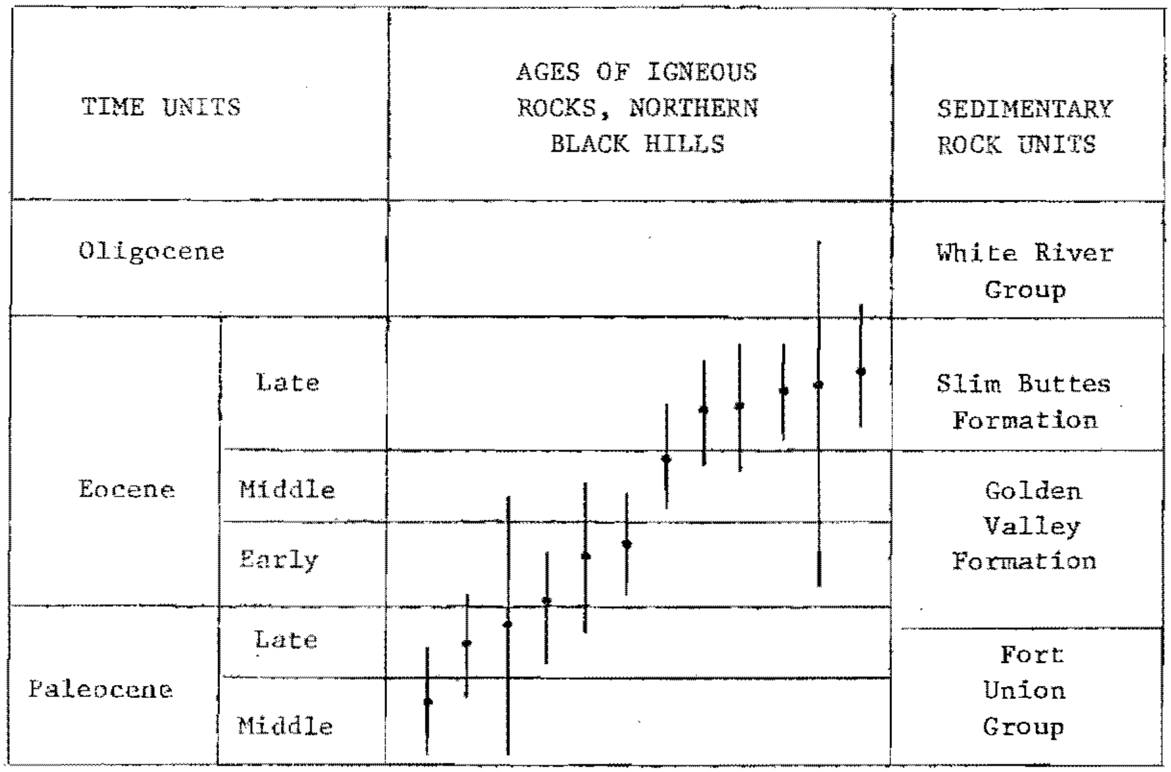


Fig. 43.--Radiometric dates of Tertiary igneous rocks in the northern Black Hills as given by McDowell (1966, Table 13). Each vertical bar represents a single date. The dot indicates the date given and the length of the bar shows the plus-or-minus precision range of the date. Equivalent Tertiary sedimentary rock units are given for reference.

The fact that no bedrock counterparts of the volcanic rock types seen in the gravel occur in the Black Hills today does not rule out their existence at some previous time. In fact, their absence is not surprising in view of the intense denudation the Black Hills have undergone since Eocene time. The early intensity of this erosion is documented by the occurrence of a thick deposit of Chadron Formation inside the broad valley formed in the easily eroded Triassic redbeds south of Rapid City (Harksen and Macdonald, 1969a, p. 94). This deposit indicates considerable pre-Oligocene erosion in the Black Hills and notable early Oligocene deposition adjacent to them. Because the focus of the Tertiary igneous activity was in the northern part of the Black Hills, uplift, erosion, and subsequent deposition should have been at least as intense there.

If Tertiary volcanic deposits were produced in the northern Black Hills, they would have been among the first materials to be removed in any extensive episode of erosion. Brown (1952) has suggested that some deposits were totally removed by pre-Oligocene Tertiary erosion in the northern Black Hills. He reported, as did Darton and O'Harra (1905), a sequence of White River deposits marginal to the Bear Lodge Mountains. Pebbles in one gravel layer of this sequence have trachyte porphyry lithologies typical of the Bear Lodge Mountain intrusives. Thick gravel deposits below this layer, however, contain igneous rock types that, Brown noted are unlike the present Bear Lodge types and must have been derived from rocks now stripped away. He further pointed out (p. 51) that the intrusion was probably not exposed at the time of deposition of the lower gravels. If it was not then exposed, it was covered with either older sedimentary rocks or possibly the volcanic equivalents of the intrusive rocks present today.

Although Denson and Gill's (1965, p. 20) reconstruction of the regional pre-Oligocene surface showed the slopes were away from the Absarokas, a slope away from the Black Hills, toward the north, is indicated by elevations at the base of Oligocene deposits in the northern Black Hills and North Dakota (Figure 44). The base of the Oligocene deposits in North Dakota is everywhere below the elevation of the Belle Fourche River in the northern Black Hills. Pliocene uplift is no doubt responsible in part for these elevations, but they should give an approximation of the pre-Oligocene slope.

A map of regional drainage patterns (Figure 45) suggests how eroded materials from the northern Black Hills could have reached southwestern North Dakota. Rubey concluded (1927, p. 120) that the capture of the Little Missouri drainage by the Belle Fourche River occurred at the end of Pleistocene time. Prior to piracy by the Belle Fourche River, a system consisting of the modern Little Missouri River and the part of the Belle Fourche River above Stone Flats (northeast of Devils Tower) drained the northern Black Hills (Rubey, 1927, p. 120).

Mode of Deposition

Historical Notes

The White River Group was interpreted by early workers as the product of deposition in a vast fresh-water lake. According to Wood (1949, p. 85), this lacustrine theory "so dominated the field that even the

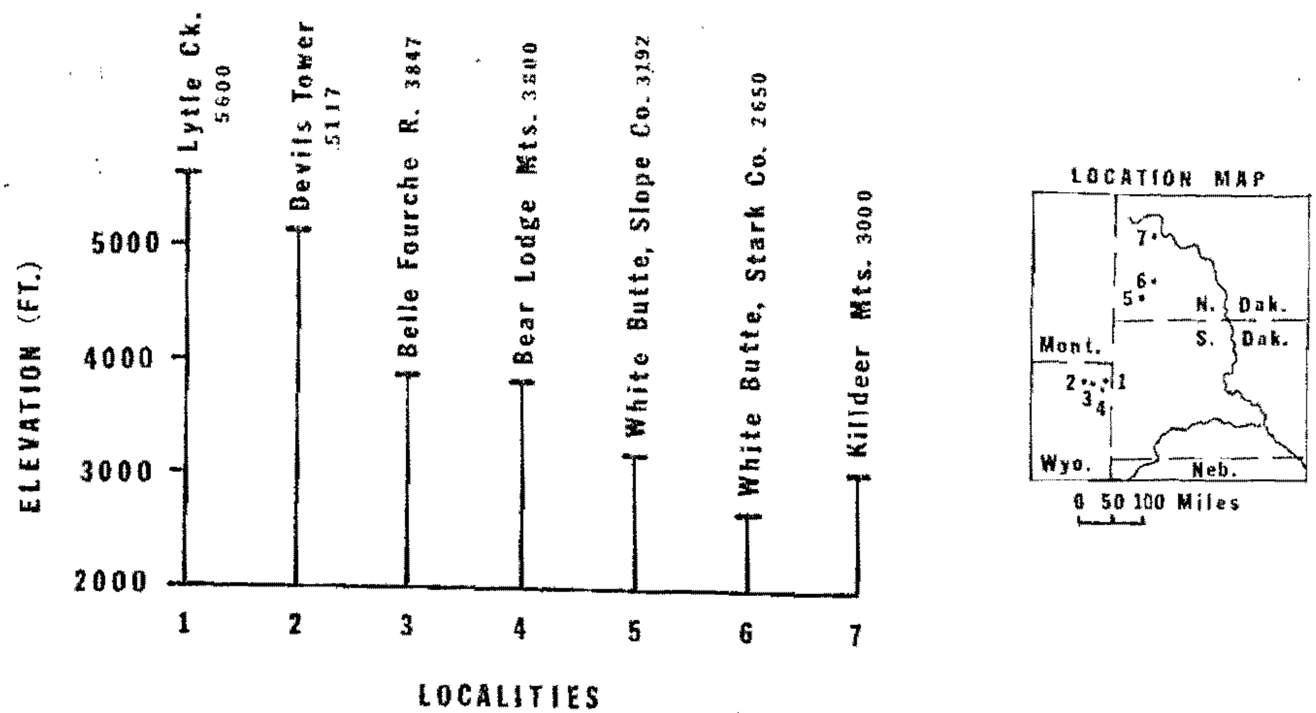


Fig. 44.--Comparison of the present elevations of the base of the White River Group in the study area and the northern Black Hills with those of Devils Tower and the Belle Fourche River, northeastern Wyoming.

Fig. 45.--Regional drainage pattern of Missouri River tributaries in the Midcontinent; note elbow of capture on Belle Fourche River northwest of the Black Hills; stippled areas represent crystalline core of major uplifts.

ablest workers bent the most obvious facts of observation to accord with this ruling theory." The original lacustrine explanation of the origin of the White River Group has been largely abandoned in favor of a fluvial interpretation (Wood, 1949, p. 85). Matthew (1899) is often given sole credit for toppling the lacustrine ruling theory; however, several others challenged it as well (Gilbert, 1896; Haworth, 1897; Davis, 1900; Hatcher, 1902). Table 4 gives the criteria used in support of the various origins previously proposed for the White River Group and principal objections usually raised by opponents.

Numerous, more recent studies of the classical sections of the White River Group in South Dakota and Nebraska have resulted in similar conclusions regarding the Oligocene climate, depositional environments, and sedimentary history. Such studies have yielded the current fluvial interpretation of the origin of these strata that now replaces the lacustrine theory of the early workers.

Interpretation of the North Dakota Deposits

General Statement.--No marine fossils were found and none have ever been reported from the middle Cenozoic record of North Dakota. The last known occurrence of marine conditions in North Dakota is generally regarded to have been that which produced the Cannonball Formation of Paleocene age (Carlson and Anderson, 1965, p. 1845). No evidence of glacial activity was found and to my knowledge none has ever been reported from the Oligocene or Miocene of the Midcontinent. Therefore, the middle Cenozoic deposits of North Dakota are concluded to be of

TABLE 4

VARIOUS ORIGINS PREVIOUSLY PROPOSED FOR THE WHITE RIVER GROUP

AND OBJECTIONS USUALLY RAISED TO THEM

Origin	Authors	Evidence Cited	Objections Raised
Lacustrine	Cope, 1883	Banded appearance; lamination of some mudstones; fine textures in general; presence of fresh water limestones, bentonite.	Lack of lacustrine fauna but preponderance of terrestrial fauna; lack of shoreline terraces and deposits; much of the clay is massive, nonlaminar; required vastness of lake.
Fluvial	Gilbert, 1896 Haworth, 1897 Davis, 1900 Hatcher, 1902 Sinclair, 1921 Wanless, 1922, 1923 Clark and others, 1967	Paleosols; extensive channel sandstones; largely terrestrial fauna, flora; poorly laminated to massive mudstones representing flood plain deposition.	Required vastness of flood plain, doubt as to the ability of fluvial environments to produce the variety of lithologies seen.
Eolian	Matthew, 1899, 1901	Paleosols; high ash content and generally fine grain sizes, unlaminated, massive, internal structure as in loess; terrestrial faunas, especially the snail *Helix*.	Some of the fine-grained deposits *are* bedded; fluvial channel sandstones *are* present; *Helix* not present everywhere.

nonglacial, continental origin. The specific continental environments of deposition which account for the North Dakota deposits are discussed below.

These deposits may be grouped into four types for ease in discussing their origin: (1) cross-bedded sandstone, (2) clay, claystone, and silty claystone, (3) siltstone, and (4) limestone and dolostone. To avoid repetition, all occurrences of a given type are treated together without regard for stratigraphic position or boundaries. Terminology used in the following discussion is defined in Appendix B.

Cross-bedded Sandstone.--Cross-bedded sandstone occurs in the Chalky Buttes Member of the Chadron Formation, the Fitterer Bed of the Dickinson Member of the Brule Formation, and the Killdeer Formation. The predominance of sand-sized clasts in these beds indicates that they were deposited by shoreline, deltaic, bed-load fluvial or bed-load eolian processes. The lack of gently inclined foreshore laminae rules out a beach origin; the absence of symmetrical shoreline ripples rules out a nearshore origin, and the lack of foreset bedding rules out a back beach or deltaic origin. The abundance of large-scale trough or pi cross-bedding in the sandstones (Figures 13, 21, 22, and 33) favors the fluvial or eolian origins. The presence in most of the sandstones of coarse clasts up to pebble size, or cobble size in the case of the Chalky Buttes (Figure 13, 14), rules out an ordinary bed-load eolian origin. The remaining possibility is the bed-load fluvial or channel origin.

Allen (1965, p. 128) recognized three kinds of bed-load fluvial or channel deposits: channel-lag, point-bar, and channel-bar deposits. The thin gravel beds in the Chalky Buttes (Figure 13) and the Killdeer (Appendix C: measured section 1, units 7 and 9a) compare favorably with his channel-lag deposits (p. 129); the bulk of the Chalky Buttes and the other sandstones resemble what he described as point-bar (p. 139-143) or channel-bar (p. 144-145) deposits. According to Allen (p. 139, 143) channel-bar deposits are generally coarser than point-bar deposits and are commonly composed of gravelly sand or sandy gravel. In view of this, the middle Cenozoic sandstones of North Dakota may be point-bar deposits because they are not generally gravelly, and where gravel is present, it is restricted to thin deposits that resemble channel-lag deposits (Figure 13).

The pebble-sized clasts of clay which are common in the Fitterer Bed and sandstones of the Killdeer Formation (Appendix C: measured section 1, unit 9d; measured section 3-C, units 3 and 7; measured section 4-A, unit 5; and measured section 4-b, unit 1) could have been derived from the erosion of clay beds exposed in the area or from the destruction of shrinkage or dessication polygons formed in clay mud in or along the stream's channel. Either of these origins is possible, and both may have contributed clay clasts to the bed load of the streams which produced the sandstones. As seen at measured section 3-C (Appendix C and Figure 21b), the Fitterer Bed directly overlies the South Heart Member of the Chadron at places and the stream which deposited the Fitterer Bed could have picked up eroded fragments from this unit or from clay mud polygons formed in floodplain deposits composed of reworked South Heart clay. If this later process played a major role in producing the clay clasts, some climatic inferences may be made. I have observed the formation of clay clasts by the destruction of clay mud polygons and have noted their presence in channel deposits of intermittent streams in southwestern New Mexico. Such clasts are not common in stream deposits of humid climates (Clayton, 1973) and may be restricted to and indicative of dry regions, or at least regions of intermittent flow.

The branching, calcareous concretions, occurring in the main ledge-forming sandstone of the Killdeer (Figure 29, 30, 31, and 32) could have resulted from precipitation by groundwater, filling and cementing of animal burrows, or accretion around plant-roots. The general shape and branching character of the concretions, together with the presence of a small, axial opening in many specimens, may rule out a groundwater origin but does permit their interpretation as feeding trails of burrowing organisms. In such an interpretation, the axial opening might be considered a remnant of the original burrow, and the irregularities or ribs on the exterior of the concretions might be regarded as distortions of bedding caused by the burrowing. Upon close examination of broken or cut specimens, however, these irregularities are seen to correspond to the original bedding which passes more or less undisturbed through the concretions. Thus, it seems more likely that the irregularities are the result of differential cementation of beds during concretion growth with some beds more strongly cemented than others.

The presence of a small, axial opening, together with the continuity of the bedding through the concretions, suggests their possible origin as growths around plant roots. From personal observations the Killdeer concretions compare quite well with concretions of the Kimball Formation (Ogallala Group, Pliocene) in western Nebraska which are believed to have formed by the accumulation of carbonate around the roots of yucca plants (Stout, 1971). The smaller size of the Killdeer concretions suggests their formation around the roots of smaller plants such as grasses or small shrubs.

The origin of the larger concretions in the Killdeer, such as the horizontally oriented, nonbranching concretions lacking an axial opening, and the variously-sized oval or spherical concretions, is not known, but these types appear to have formed without the influence of plants or burrowing organisms. Concretions of this type are abundant in the sandstones of the Arikaree Group in Nebraska. Schultz (1941, p. 69) pointed out that it has been generally agreed by previous workers that the Arikaree concretions were formed by groundwater. He described (p. 73) them as "horizontal stalactites" and noted that their shape and orientation reflect the regional groundwater flow pattern. The horizontally oriented and spherical concretions in the Killdeer sandstone of North Dakota may have had a groundwater origin similar to that of the Arikaree concretions in Nebraska, but there are too few occurrences to make any judgment concerning the regional groundwater flow.

Carbonate also occurs as a coating and cementing agent in gravelly zones of the Killdeer sandstone (Appendix C: measured section 1, units 7 and 9a). The time and means of precipitation of this carbonate are not known, but these zones compare quite will with cemented gravelly zones in alluvium of the arid Southwest. From personal observation of the various stages of development of such hard pans or caliche horizons in alluvial sediments of southwestern New Mexico, the cementation process begins with precipitation of calcareous coatings on pebbles, this continues until the coatings of adjacent pebbles merge to form a more or less continuous matrix around the coarse clasts. The carbonate in the gravelly zones of the Killdeer sandstone may have had a similar pedogenic origin.

Clay, Claystone, and Silty Claystone.--Generally poorly bedded or massive clay, claystone, and silty claystone are widespread throughout the middle Cenozoic section of North Dakota and occur in the Amidon and South Heart Members of the Chadron Formation, the Dickinson and Schefield Members of the Brule Formation, and the Killdeer Formation. The predominance of clay in these beds rules out their deposition by any bed-load process, fluvial or eolian, and precludes a wash-load eolian origin as well. The absence of distinct bedding in the clay, claystone, and silty claystone rules out their deposition in a lake, at least one lacking burrowing organisms. The remaining possibility is a wash-load fluvial or floodplain origin.

Allen (1965, p. 128) distinguished five types of floodplain deposits, point-bar-swale-fill, abandoned-channel-fill, levee deposits, crevasse-splay deposit, and floodbasin deposit. He also described (p. 153) deposits of floodplains lacking distinct subenvironments, here called "overbank." According to Allen (p. 145-146) the swale-fill, channel-fill, levee, and crevasse-splay deposits are all clearly bedded. Only the floodbasin deposits or overbank are poorly bedded or devoid of bedding as are the middle Cenozoic clay, claystone, and silty claystone deposits of North Dakota. These rock types are therefore concluded to represent deposition in the standing or slow moving waters of the floodbasin or general overbank environments.

Siltstone.--Siltstone is widespread in the section also, occurring in the Dickinson and Schefield Members of the Brule Formation and the Killdeer Formation. The fine grain size of this rock type permits its interpretation as pelagic lacustrine, wash-load eolian, and bed-load or wash-load fluvial sediment. The lack of bedding in most of the siltstone beds rules out the lacustrine origin, and the lack of large-scale trough cross-bedding where the siltstone is well bedded probably rules out a bed-load fluvial origin. The presence of small scale cross-bedding rules out a wash-load eolian origin as well. The remaining possibility is that the siltstone is the result of wash-load fluvial deposition.

Ripple or small scale trough cross-bedding observed in the siltstones (Appendix C: measured section 5-A, units 5 and 8b) suggests affinities between the siltstone and Allen's (p. 145-148) swale-fill, channel-fill, levee, and crevasse-splay deposits and indicates deposition from shallow, moderately moving, floodplain waters.

Limestone and Dolostone.--Minor deposits of carbonate rock types occur within the middle Cenozoic record of North Dakota as follows: thin-bedded limestone at the top of the South Heart Member of the Chadron Formation and massive dolostone in the Killdeer Formation. Although these are both carbonate lithologies, they seem to have had different origins.

Lacking any evidence in the section of a major lake, the limestone at the top of the South Heart may be interpreted as a floodbasin deposit. The close association of the limestone with what may be reasonably regarded as floodplain or floodbasin deposits, based on Allen's (1965) descriptions of alluvial sediments, supports this interpretation.

The origin of the massive dolostone in the Killdeer is not known. It has a porous or spongy appearance even where fresh and is associated with silty claystone containing dense chert nodules (Appendix C: measured section 4-B, units 2b and 4d). No evidence of a pedogenic origin was found. The dolostone and the chert may be secondary alteration products, but outcrops of the dolostone and associated beds are poor and hinder further interpretation.

Modern Analogs

A number of areas have been previously suggested as possible analogs for middle Cenozoic conditions in North America. Hatcher (1902, p. 125) favored an interior South American analog. Clark and others (1967) cited the Punjab region of Pakistan and the Amazon Basin of South America as having fluvial settings which would explain the sedimentologic features of the North American White River Group. In these regions, it was the contemporaneous flooding of parallel streams to form shallow but broad temporary lakes which was cited as analogous to presumed middle Cenozoic conditions in the Midcontinent. This interpretation may even serve to satisfy, in part, the few remaining supporters of the lacustrine origin of the White River Group. Nevertheless, it should be kept in mind that the main influence was that of fluvial processes.

A region with which I feel the Oligocene landscape of North Dakota may have had much in common is the Pampa of Argentina. As pointed out by Bonorino (1966, p. 1026), the Pampa is the treeless, flat, grassland of eastern Argentina. It is intermediate between cold and hot climates and humid and arid conditions (Van Ripper, 1962, p. 394). Bonorino (1966, p. 1028) summarized the climate as humid cool-subtropical in the east, humid steppe in the central part, dry steppe in the west and cool-subtropical steppe in the north.

The material constituting the surface of the Pampa is Quaternary reworked loess of the Pampean Formation (Teruggi, 1957, p. 322). The Pampean includes eolian silts, silty clays, and silty sands which were locally reworked in limnic environments (Bonorino, 1966, p. 1027). The silt fraction contains (1) fresh, calcic-to intermediate plagioclase, often in quantitites surpassing that of quartz, and (2) abundant volcanic glass shards amounting to 70 percent of the silt-sand fraction in places. The principal clay mineral present is montmorillonite, which, together with the presence of abundant glass shards, indicates a volcanic-pyroclastic origin (Terruggi, 1957, p. 322). Discontinuous layers of caliche characterize the upper part of the Pampean Formation, especially in the more humid eastern part of the Pampa (Bonorino, p. 1027). According to Terruggi (p. 329), calcite occurs in Pampean sediments as concretions, veins and caliche layers, and as comminuted particles distributed throughout the sediments. This occurrence of calcite and caliche layers in generally tuffaceous sediments is a point of strong similarity between the Pampean deposits and those of the North American Brule.

I was first impressed by the similarity between the conditions on the Pampa and those that must have characterized the northern plains during Oligocene time while reading Darwin's account of his visit to the Pampa during his famous Beagle voyage. According to Darwin (1860, p. 133-135),

> The period included between the years 1927 and 1830 is called the . . . great drought. During this time so little rain fell that the vegetation . . . failed; the brooks were dried up, and the whole country assumed the appearance of a dusty high road. . . . Very great numbers of birds, wild animals, cattle and horses perished from want of food and water. . . .
>
> I was informed by an eye-witness that the cattle in herds of thousands rushed into the Parana, and being exhauted by hunger they were unable to crawl up the muddy banks, and were drowned. . . .
>
> Subsequently to the drought . . . a very rainy season followed which caused great floods. Hence, it is almost certain that some thousands of skeletons were buried by the deposits of the very next year. What would be the opinion of a

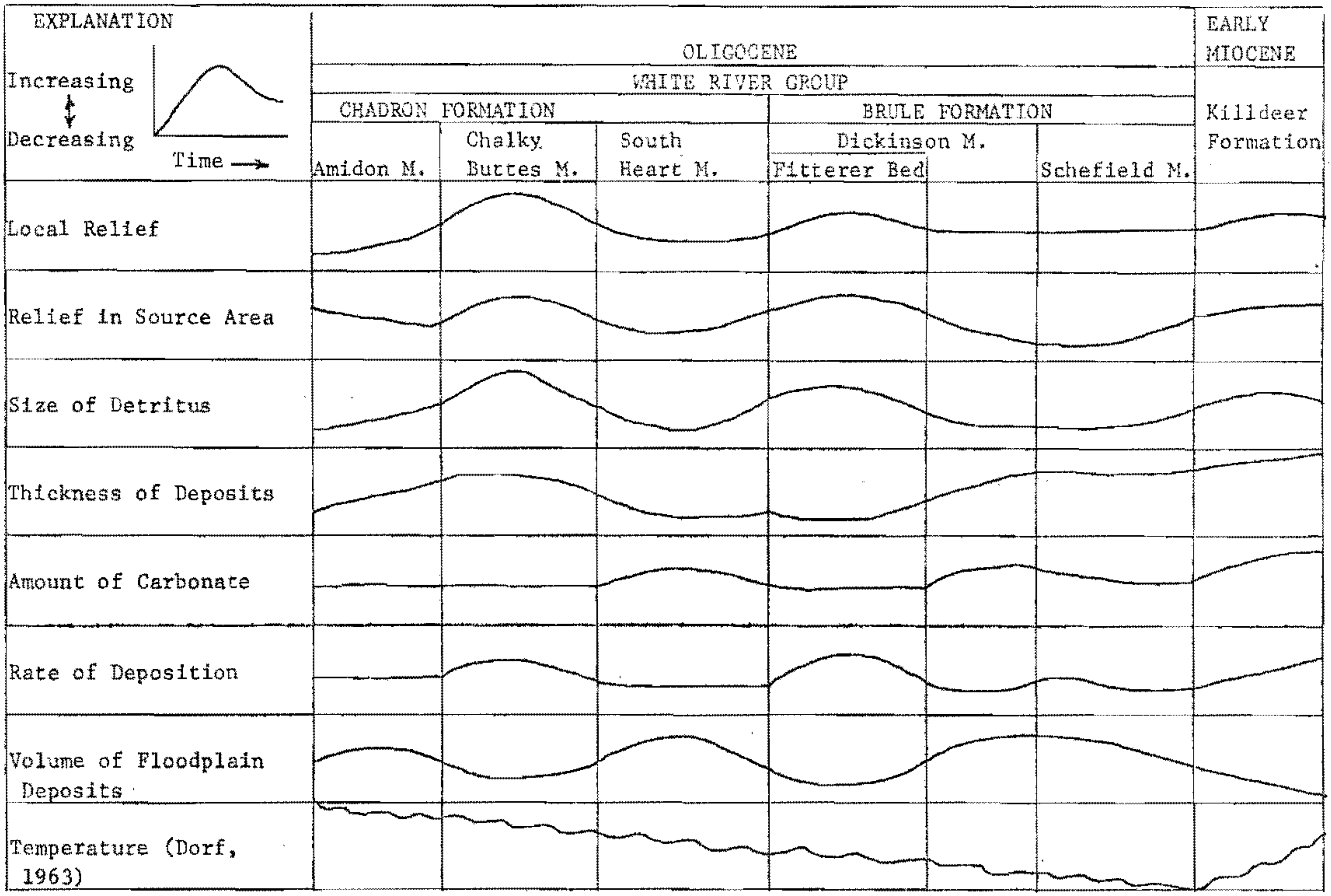
> geologist, viewing such an enormous collection of bones, of all kinds of animals and of all ages, thus embedded in one thick earthy mass? Would he not attribute it to a flood having swept over the surface of the land, rather than to the common order of things?

This suggestion, that mammalian fossils in fluvial beds need not be the direct result of flooding and drowning, may have bearing on the interpretation of the fossiliferous beds of the Brule Formation in the North American Midcontinent.

Summary of Sedimentary History

Oligocene and Miocene times in North Dakota were characterized by a continuation of the continental deposition that began in Paleocene time. Middle Cenozoic climatic conditions in North Dakota were similar to those of the rest of the Midcontinent, warm and humid in the early Oligocene, cooler and drier in the late Oligocene, and variable in the Miocene. The source area for middle Cenozoic deposits of North Dakota was most likely the northern part of the Black Hills uplift. All rock types observed can be accounted for by a fluvial model in which divides are low, floodplains are broad and flood waters from adjacent streams join to form temporary lakes. Possible modern analogs of middle Cenozoic conditions in the Midcontinent include the Punjab region of Pakistan, the Amazon River Basin of Brazil, and the Pampa of Argentina. The interpreted relative fluctuations in various paleogeographic conditions and depositional variables during middle Cenozoic time in North Dakota are summarized schematically in Figure 46.

Fig. 46.—Summary of interpreted relative fluctuations in paleogeographic conditions and sedimentologic variables during middle Cenozoic time in North Dakota.


EXPLANATION
Increasing
Decreasing
Time →
OLIGOCENE
EARLY MIOCENE
WHITE RIVER GROUP
CHADRON FORMATION
BRULE FORMATION
Killdeer Formation
Amidon M.
Chalky Buttes M.
South Heart M.
Dickinson M.
Fitterer Bed
Schefield M.
Local Relief
Relief in Source Area
Size of Detritus
Thickness of Deposits
Amount of Carbonate
Rate of Deposition
Volume of Floodplain Deposits
Temperature (Dorf, 1963)

Suggestions for Further Work on Sedimentary History

Several further studies would expand the state of knowledge concerning the sedimentary history of the middle Cenozoic deposits of North Dakota. Detailed, statistical, grain-size analyses of these deposits have yet to be conducted. Likewise, detailed paleoecological studies have not yet been made of the abundant mammalian remains of the North Dakota deposits. Further detailed studies of the sedimentary structures present in these strata may also prove useful in the interpretation of their genesis. A detailed, quantitative, comparative, petrographic study of the gravel in the Chalky Buttes Member of the Chadron Formation and the Tertiary igneous rock types of the northern Black Hills would perhaps help answer the question of the source of the North Dakota deposits. Radiometric dates of the most pure ash-bearing beds of the section would not only compliment the faunal age interpretations and enhance regional correlations but, together with other evidence, might possibly permit determinations of middle Cenozoic sedimentation rates.

SUMMARY OF CONCLUSIONS

From this study a number of conclusions have been made that should advance the state of knowledge concerning the middle Cenozoic (Oligocene and Miocene) record of North Dakota and that of the Midcontinent in general:

1. In addition to small exposures in Adams, Bowman, Golden Valley, and Grant Counties, there are four major areas of outcrop:

    a) Killdeer Mountains (northwestern Dunn County)

    b) Little Badlands (western Stark County)

    c) Lefor Buttes (northern Hettinger and southern Stark Counties)

    d) Chalky Buttes Area (eastern Slope County)

2. The Chadron and Brule Formations of the White River Group are recognized in North Dakota as elsewhere in the Midcontinent. These formations in North Dakota may be subdivided into several, distinct, new units including three members within the Chadron and two members and one bed within the Brule. The name "Arikaree," previously applied to strata overlying the White River Group in North Dakota, is rejected and a new name proposed because these strata are lithologically distinct from type Arikaree of Nebraska or Arikaree in the Big Badlands of South Dakota. The recommended stratigraphic nomenclature for the middle Cenozoic deposits of North Dakota is as follows:

	Killdeer Formation	
White River Group	Brule Formation	Schefield Member Dickinson Member Fitterer Bed
	Chadron Formation	South Heart Member Chalky Buttes Member Amidon Member

3. The Amidon Member of the Chadron unconformably overlies the Interior Formation and consists of 7 to 16 feet of clay and silty claystone that weather very pale orange or light brown but are very pale orange to grayish orange where fresh.

4. The Chalky Buttes Member of the Chadron unconformably overlies the Amidon Member and consists of 8 to 75 feet of fine-grained to coarse-grained, cross-bedded, gravel-bearing sandstone that weathers white, very pale orange, dark yellowish orange, or light brown and is very pale orange to pinkish gray where fresh.

5. The South Heart Member of the Chadron conformably overlies the Chalky Buttes Member and consists of 8 to 55 feet of clay that weathers pale greenish yellow and is yellowish gray to pale olive where fresh.

6. The Dickinson Member of the Brule, conformably overlies the South Heart Member of the Chadron Formation and consists of 60 to 130 feet of clay and pitted-weathering, silty claystone. The clay is yellowish gray where weathered but pale olive to light olive gray where fresh; the claystone weathers very pale orange and is yellowish gray where fresh.

7. The Fitterer Bed of the Dickinson Member of the Brule is a 5-

foot to 9-foot thick, fossiliferous, fine-grained to medium-grained, cross-bedded sandstone that is pale greenish yellow where weathered and yellowish gray where fresh.

8. The Schefield Member of the Brule conformably overlies the Dickinson Member and consists of 16 to 85 feet of interbedded siltstone and clay; the siltstone is very pale orange where weathered and grayish orange pink to yellowish gray where fresh; whereas, the clay weathers moderate reddish orange and is pale reddish brown where fresh.

9. Unconformably overlying the Brule, but beneath unconsolidated deposits of unknown source and age, is the Killdeer Formation which consists of 25 to 200 feet of green-colored, calcareous, concretionary, cross-bedded, and massive sandstone, siltstone, silty claystone, and dolostone.

10. The middle Cenozoic record of North Dakota spans at least Chadronian through early Arikareean times.

11. Diverse Oligocene fossils have been reported by previous workers from the White River Group of North Dakota, and the occurrence of the beaver, *Paleocastor* sp., the primitive deer, *Hypertragulus minor*, and the rhinoceros, *Amphicaenopus*(?), in the Killdeer Formation suggests its correlation with some part of the Arikaree Group of Nebraska, perhaps the Gering Formation of early Miocene age.

12. No strata corresponding to the middle or late Miocene or Pliocene of South Dakota or Nebraska have been identified in North Dakota.

13. The sandstones of the Chadron, Brule, and Killdeer Formation are arkose according to Folk's (1965) classification.

14. Based on X-ray-diffraction analyses, montmorillonite is the predominant clay mineral in the middle Cenozoic deposits, and the zeolites clinoptilolite, erionite, and heulandite are present as well.

15. No distinct mineralogic criteria were found for distinguishing the various rock units recognized.

16. The source of the middle Cenozoic deposits of North Dakota was probably the Tertiary igneous intrusions of the northern Black Hills.

17. These deposits probably represent deposition in various fluvial subenvironments: channel, floodplain, and floodbasin.

18. All of the deposits can be accounted for by a fluvial model in which divides are low, floodplains are broad, and flood waters of adjacent streams comingle to form large but shallow, temporary lakes.

19. Possible modern analogs of the middle Cenozoic setting include the Punjab region of Pakistan, the Amazon River Basin of Brazil, and the Pampa of Argentina.

20. Further detailed stratigraphic, petrographic, and sedimentologic work needed on the various middle Cenozoic deposits of North Dakota includes:

a) a study of the specific stratigraphic relationships between these units and those of adjacent areas;

b) a detailed paleontologic study of these strata as regards their paleoecology and correlation with the Great Plains standard;

c) a determination of the specific feldspars present in these deposits as well as additional study of the zeolites reported here;

d) a detailed, comparative, petrographic study of the gravel in the Chalky Buttes and rock types in the suspected northern Black Hills source area;

e) a detailed study of the volcanic-ash content of these deposits;

f) detailed textural analyses of both the sandstone and mudstone units;

g) radiometric dates of the purest ash-bearing beds in the Brule and Killdeer Formations.

APPENDIX A

LOCATION OF OUTCROPS

Topographic or informal names, legal descriptions and general stratigraphy of all known exposures of middle Cenozoic deposits in North Dakota are listed here. Localities are arranged alphabetically for easy reference. Numbers in parentheses after some localities identify sections measured there; these sections are described in Appendix C and shown on Plate 1.

The Middle Cenozoic rock units present at a given locality are given after its legal description using the following abbreviations:

K = Killdeer Formation

Brule Formation

S = Schefield Member
D = Dickinson Member
Df = Fitterer Bed

Chadron Formation

SH = South Heart Member
CB = Chalky Buttes Member
A = Amidon Member

These rock-unit abbreviations are listed sequentially in chronologic order and are grouped by formation.

LOCALITY	ROCK UNITS PRESENT
Abandoned House Site, Stark County (4): sec. 29, T. 138 N., R. 97 W.	CB, SH; D, Df, S; K
Antelope Butte, Stark County: sec. 16, 21, T. 139 N., R. 91 W.	CB, SH
Bull Butte, Hettinger County: sec. 18, T. 136 N., R. 93 W.	CB, SH
Bullion Butte, Billings and Golden Valley Counties: sec. 7, 8, 17, 18, 19, 20, 30, T. 137 N., R. 102 W. and sec. 12, 13, 24, T. 134 N., R. 103 W.	A(?)
Black Butte, Hettinger County: sec. 12, T. 135 N., R. 95 W.	CB, SH; D; K
Chalky Buttes, including White Butte, Slope County (1, 2): SE¼ T. 134 N., R. 101 W.	A, CB, SH; D, Df, S; K
Coffin Butte, Grant County: sec. 3, T. 13 N., R. 90 W. and sec. 33, 34, T. 132 N., R. 90 W.	CB, SH: D(?); K
Colgrove or White Butte, Hettinger County: sec. 8, 15, 16, 17, T. 136 N., R. 93 W.	CB, SH
DeMar Site, Stark County: sec. 18, T. 138 N., R. 97 W.	CB, SH; D, Df
Fitterer Ranch, Stark County (3): sec. 7, 17, 18, T. 137 N., R. 97 W.	A, CB, SH; D, Df, S; K
Flattop Butte, Golden Valley County: sec. 8, 9, 16, 17, T. 139 N., R. 103 W.	A(?)

Golden Butte, Stark County sec. 33, 34, T. 138 N., R. 97 W.	CB, SH; D, Df, S(?); K
HT or Black Butte, Slope County: sec. 19, 30, T. 134 N., R. 98 W. and sec. 23, 24, 25, 26, T. 134 N., R. 102 W.	A
Killdeer Mountains, Dunn County (7): most of T. 146 N., R. 91 W., sec. 34, 35, T. 147 N., R. 96 W. and sec. 36, T. 146 N., R. 97 W.	CB, SH; S(?); K
Little Badlands Proper, Stark County (5): sec. 14, 15, 22, 23, T. 138 N., R. 98 W.	A, CB, SH; D, Df
Long Butte, Hettinger and Stark Counties: sec. 19, 29, 30, T. 136 N., R. 94 W. and sec. 12, 13, 24, 25, T. 137 N., R. 95 W.	CB, SH
Medicine Pole Hills Bowman County: N½ T. 130 N., R. 104 W.	CB, SH
Rainy Buttes, Slope County: sec. 10, 20, 33, 34, T. 135 N., R. 98 W.	CB, SH; D; K
School Butte, Hettinger County: sec. 5, 6, 7, 8, T. 136 N., R. 94 W.	CB, SH
Schultz Butte, Stark County: sec. 19, T. 137 N., R. 92 W.	CB, SH
Sentinel Butte, Golden Valley County: sec. 5, 6, 7, 8, 9, T. 139 N., R. 104 W.	SH(?)
Shepard Butte, Hettinger County: sec. 28, T. 135 N., R. 91 W.	CB, SH

Slide Butte, Slope County: sec. 28, 29, T. 134 N., R. 101 W.	A
Straight Butte, Stark and Hettinger Counties: sec. 3, 4, T. 136 N., R. 94 W. and sec. 36, T. 137 N., R. 94 W.	CB, SH
Turtle Valley, Stark County: sec. 21, T. 138 N., R. 98 W.	A, CB, SH
Whetstone Buttes, Adams County: sec. 20, 28, 29, 32, T. 132 N., R. 98 W.	CB, SH
White Butte, Stark County (6): sec. 29, 32, T. 139 N., R. 97 W.	CB, SH
Wolf Butte, Adams County: sec. 23, 24, T. 131 N., R. 97 W.	CB, SH
Youngman's Butte, Stark County: sec. 11, 12, T. 139 N., R. 92 W.	CB, SH

APPENDIX B

DEFINITIONS OF TERMINOLOGY USED

Lithology

Sandstone refers to rock composed mainly of sand-sized particles. Specific interpretive sandstone types used in this report are those of Folk (1965, p. 114). The term "clay" refers to any unconsolidated material composed mainly of clay-sized particles. As used here, mud refers to unconsolidated, fine-grained sedimentary material, consisting of an indefinite mixture of clay, silt, and sand unless the term "mud" is preceded by one of these particle size terms indicating the predominant grain size. Claystone includes any rock composed principally of clay-sized particles (Pettijohn, 1957, p. 341); as used here it is restricted to nonfissile rocks. Siltstone refers to rocks in which silt-sized particles are predominant. As suggested in the AGI Glossary (Howell, 1962, p. 194), the term "mudstone" is used for fine-grained rocks whenever a more definitive name is either not required or not possible. It therefore includes rocks consisting of an indefinite mixture of clay, silt, and sand and in which the predominant textural element is not readily apparent in hand specimen. When used as a broad sedimentary rock category, it includes all fine-grained clastic rocks.

Limestone refers to a crystalline sedimentary rock composed principally of the mineral calcite. Dolostone includes crystalline sedimentary rocks composed principally of the mineral dolomite, as suggested by Shrock (1948, p. 18). Chert includes microcrystalline quartz of various colors. Many kinds of calcareous materials in middle Cenozoic deposits of the Midcontinent have been called caliche by previous workers (Wanless, 1923; Schultz and others, 1955; Lillegraven, 1964 and 1970). As used here, however, the term includes only those beds in which the origin of the secondary calcite is thought to be pedogenic, based on the presence of structures comparable to those of typical caliches personally observed in the southwestern United States and as described from there by Gile (1961) and Reeves (1970).

Bedding

Bedding terminology is that of McKee and Weir (1953) as modified by Ingram (1954):

Massive: No individual beds distinguished

Very Thick Beds: Beds greater than 3 feet thick

Thick Beds: Beds 1 to 3 feet thick

Medium Beds: Beds 4 inches to 1 foot thick

Thin Beds: Beds 1 to 4 inches thick

Very Thin Beds: Beds 0.4 inches to 1 inch thick

Laminae: Beds less than 0.4 inches thick.

The classification of cross-bedding used is that of Allen (1963).

Bedding may be further described as to variability or uniformity of thickness by the following terms (Dunbar and Rodgers, 1963, p. 99, 100): "regular or irregular" and "even or uneven." Regular bedding is that which the thickness of single beds is uniform across the outcrop; irregular bedding is that in which single beds vary in thickness or dissipate laterally. Even bedding is that in which successive beds have nearly the same thickness, and uneven bedding is that in which successive beds have different thicknesses. The bedding character of a given unit may thus be described by selecting the proper size term and one adjective from each of the pairs defined above. For example, a siltstone unit may be said to have medium, irregular, even beds. "Medium, irregular" means that single beds of the unit vary laterally in thickness within the medium size range and "even" means that all beds of the unit are about the same thickness.

Color

The color names used in this report that are accompanied by numerical designations in parentheses are those given in the rock color chart prepared by Goddard and others (1948). The numbers after these color names refer to hue, value, and chroma respectively, as given on this chart. Other color names are general or those given by previous workers and do not necessarily coincide with those on the chart.

Grain Character

Grain-size designations are those of Wentworth (1922); sand grain sizes were determined in the field by visual comparisons of sample grains with a Wentworth sand gage. Sorting was visually estimated in the field; terminology used is that of Folk (1965, p. 103-105). Roundness was determined by visual comparison with the whole-grain roundness chart of Powers (1953).

Mode of Deposition

Terminology for fluvial environments and deposits used in the chapter on Sedimentary History are those of Allen (1965). He distinguished two separate categories of fluvial sediments, those deposited in the channel and those deposited on the floodplain. These roughly correspond to bed-load and wash-load or suspended-load sedimentation types respectively. The names used for the fluvial subenvironments and their associated deposits, as recognized by Allen (1965, p. 128), are as follows:

Environment	Subenvironment	Deposit
Channel	Channel Floor	Channel-lag Deposit
	Channel Bar	Channel-Bar Deposit
	Point Bar	Point-Bar Deposit
Floodplain	Point-Bar Swale	Swale-Fill Deposit
	Abandoned Channel	Channel-Fill Deposit
	Levee	Levee Deposit
	Crevasse (break in levee)	Crevasse-splay Deposit
	Floodbasin (pond)	Floodbasin Deposit
	Floodplain Undifferentiated	Overbank

APPENDIX C

MEASURED-SECTION DESCRIPTIONS

Sections were measured at each major outcrop of middle Cenozoic deposits in North Dakota and a stratigraphic cross-section for these deposits in the state was constructed (Plate 1). The descriptions that follow are presented in descending order. The unit numbers shown in the measured section descriptions are field numbers used to identify samples in later laboratory work; because no samples were collected at covered or concealed intervals they were not assigned numbers. Each clastic unit is described as to general lithologic name (sandstone, claystone, etc.); bedding information; color; grain size, sorting, and roundness; special compositional material or sedimentary structures; and fossil content, in that order. Non-clastic rocks are described in much the same way: general lithologic name; bedding information; color; crystal size and degree of recrystallization if any; special compositional materials or sedimentary structures; and fossil content. An explanation of terminology used is given in Appendix B.

In view of the imprecision of Jacob-staff measurements and the impossibility of showing fractions of feet on a cross-section such as Plate 1, the thicknesses reported for units are given to the nearest foot. These values were determined in the field as follows: if the fraction of a foot was less than six inches, the last even foot was recorded; if the fraction of a foot was six inches or greater, the next even foot was recorded.

The maximum thicknesses of units as shown on Plate 1 are those reported in Appendix C.

SECTION 1, WHITE BUTTE, SLOPE COUNTY. South- and west-facing slopes at the northwestern extremity of White Butte, the easternmost of the Chalky Buttes; about 3 miles east of U.S. 85, about 1 mile west of a section line road that runs along the east side of the Chalky Buttes, and about 7 miles south of Amidon; NE¼SE¼ sec. 25, T. 134 N., R. 101 W., Slope County; section measured August, 1969 (Figures 22, 28, 31, 32).

Unit	Lithology	Thickness (Ft.)	
KILLDEER FORMATION			
10	Silty claystone, clay, and limestone; mostly covered:		14
c	Silty claystone: irregular, uneven, thin beds; pale greenish yellow (10 Y 8/2) both weathered and fresh.	4	
b	Clay: massive; yellowish gray (5 Y 7/2) weathered, pale olive (10 Y 6/2) fresh.	6	
a	Limestone: regular, even, thin to medium beds; pale greenish yellow (10 Y 8/2) weathered, yellowish gray (5 Y 7/2) fresh.	4	
9	Sandstone and silty claystone:		55
e	Calcareous sandstone (Figure 31b): large scale trough (pi) cross-bedding in sets up to 3 feet thick; yellowish gray (5 Y 7/2) weathered and fresh; grains fine to medium, well sorted, subrounded to rounded.	8	
d	Calcareous concretionary sandstone: large scale trough (pi) cross-bedding in sets up to 1 foot thick; pale olive (10 Y 6/2) weathered and fresh; grains medium, well sorted, subrounded to rounded; contains green clay clasts up to 1 inch in diameter and tubular, hollow, vertical calcareous concretions up to 2 inches in diameter (Figures 31a, 32) and oval carbonate concretions up to 1 foot in diameter; very fossiliferous, complete mandible of the rhinoceros _Amphicaenopus_ (?) collected 3 feet below top of this unit; forms major ledge at White Butte.	10	

c	Calcareous sandstone: laminated, large scale trough (pi) cross-bedding; yellowish gray (5 Y 7/2) weathered and fresh; grains fine to medium, well sorted, subrounded to rounded; less resistant to erosion than unit 9d above.	3
b	Silty claystone: massive; yellowish gray (5 Y 7/2) weathered, light olive gray (5 GY 6/1) fresh.	10
a	Noncalcareous sandstone: massive with vague suggestion of large scale trough (pi) cross-bedding; yellowish gray (5 Y 7/2) weathered and fresh; grains fine to medium, well sorted, subrounded to rounded; contains calcareous concretions, some spherical up to 1 foot in diameter and some irregularly shaped up to several feet across.	24
	Covered slope with soft sand at surface in some places.	14
8	Calcareous silty claystone: regular, even, medium to thick beds; grayish orange (10 YR 7/4) to yellowish gray (5 Y 7/2) weathered, very pale orange (10 YR 7/2) fresh.	12
7	Calcareous sandstone; large scale trough (pi) cross-bedding in sets up to 3 feet thick; yellowish gray (5 Y 7/2) to pale olive (10 Y 6/2) weathered and fresh; grains fine, well sorted, subrounded to rounded; a 1-foot thick zone of igneous and claystone pebbles, ½ to 6 inches in diameter, occurs near base of unit.	7

BRULE FORMATION
DICKINSON MEMBER

6	Calcareous, silty claystone: massive; white (N 9) to grayish pink (5 R 8/2) weathered, grayish orange pink (5 YR 7/2) fresh.	15

		FITTERER BED		
5		Sandstone (Figure 22): large scale trough (pi) cross-bedding, some thin sets small-scale climbing ripples; grayish orange pink (5 YR 7/2) to moderate orange pink (10 R 7/4) weathered, yellowish gray (5 Y 7/2) to pale greenish yellow (10 Y 8/2) fresh; grains very fine sand to silt size; disconformable base; blocky weathering habit.		15
		DICKINSON MEMBER		
4		Alternating clay and silty claystone (Figure 28):		11
	d	Silty claystone: massive; yellowish gray (5 Y 7/2) to grayish orange pink (5 YR 7/2) weathered, yellowish gray fresh.	2	
	c	Clay: massive, light greenish gray (5 GY 8/1) weathered, light olive gray (5 Y 6/1) fresh.	5	
	b	Silty claystone: massive, white (N 9) to pale greenish yellow (10 Y 8/2) weathered, grayish orange pink (5 YR 7/2) fresh.	2	
	a	Clay: massive; light greenish gray (5 GY 8/1) weathered, greenish gray (5 GY 6/1) weathered, greenish gray (5 GY 6/1) fresh.	2	
3		Calcareous pitted claystone: regular, even, medium beds; white (N 9) to grayish pink (5 R 8/2) weathered, very pale orange (10 YR 8/2), with grayish orange (10 YR 7/4) clay blebs, fresh; blebs range up to ½ inch in diameter; weathering out of these blebs produces pitted outcrop surfaces.		20

CHADRON FORMATION
SOUTH HEART MEMBER

2	Clay and limestone (Figure 28): clay is massive; moderate greenish yellow (10 Y 7/4) weathered, yellowish gray (5 Y 7/2) fresh. Limestone at top totals 2 feet in thickness; irregular, uneven, thin to medium beds; white (N 9) to yellowish gray (5 Y 7/2) weathered, light greenish gray (5 GY 8/1), with blebs of greenish gray (5 GY 6/1) clay, fresh.	55

CHADRON FORMATION
CHALKY BUTTES MEMBER

1	Sandstone: laminated, irregular, even, medium beds with large-scale trough (pi) cross-bedding; very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) weathered, very pale orange to white (N 9) fresh; grains medium to very coarse, moderately sorted within laminae, subangular to rounded, consisting mainly of quartz, clear feldspar cleavage fragments, and rock fragments, well rounded pebbles and cobbles of various igneous rock types.	12

Total section thickness = 230 feet

The base of the Chalky Buttes Member is not exposed at this locality; measurement was begun at the lowest portion of the outcrop of this unit at the ground surface.

Denson and Gill (1965, Plate 1, Section 5) gave 40 more feet for the section at this locality; however, they did not report the 14 feet of silty claystone, clay, and limestone that cap the section at White Butte. Because they did not give measured section descriptions but only represented their sections graphically, I cannot account for these differences and believe my measurements to be representative of this section.

SECTION 2, CHALKY BUTTES, NORTH (Type section of the Amidon and Chalky Buttes Members of the Brule Formation.) At the head of a deep unnamed gully, on the south slope of the highest butte at the northern tip of the Chalky Buttes; east of U.S. 85, about 4½ miles south of Amidon and about 18 miles north of Bowman; NE¼NE¼ sec. 15, T. 134 N., R. 101 W., Slope County; section measured August, 1969 (Figures 5, 10, 11, 12).

Unit	Lithology	Thickness (Ft.)
CHADRON FORMATION SOUTH HEART MEMBER		
	Rubble: mass of large, slumped blocks of very fine-grained, buff colored sandstone and light gray limestone with chalcedony nodules.	5
6	Clay: massive, grayish orange pink (10 R 8/2) weathered and pale yellowish brown (10 YR 6/2) fresh.	15
CHADRON FORMATION CHALKY BUTTES MEMBER		
5	Sandstone (Figure 12): laminated, irregular, even, medium beds with large-scale trough (pi) cross-bedding; very pale orange (10 YR 8/2) to dark yellowish orange (10 YR 6/6) weathered, very pale orange to white (N 9) to pale greenish yellow (10 Y 8/2) fresh; grains medium to very coarse, moderately sorted within a given horizon, subangular to rounded, consisting mainly of quartz, clear feldspar and rock fragments; well rounded pebbles and cobbles of various igneous rock-types; 1-inch thick zone of iron-oxide staining and limonite nodules characterize disconformable basal contact (Figure 11).	24

CHADRON FORMATION

AMIDON MEMBER

4	Clay and silty claystone (Figure 11): is massive; very pale orange (10 YR 8/2) to light brown (5 YR 5/6) weathered, grayish orange (10 YR 7/4) to pale yellowish brown (10 YR 6/2) fresh. Claystone has irregular, uneven, thick beds; very pale orange (10 YR 8/2) weathered, grayish orange pink (5 YR 7/2) fresh. Silty claystone grades upward and downward into clay forming bulk of unit suggesting silt or mud supply merely fluctuated during deposition of unit; basal contact sharp and marked by color change to purple of what Furman (1970) called analcimolite (Figure 5) below.	16

INTERIOR FORMATION

3	Analcimolite (Furman, 1970; Figure 5): single, irregular, thick beds; at the top, grayish orange (10 YR 7/4) to dark yellowish orange (10 YR 6/6) weathered and fresh, at the base grayish red (5 R 4/2) to dark reddish brown (10 R 3/4) weathered and fresh; bed appears to wedge out toward east across the outcrop (Figure 9) but reappears on the eastern side of the butte where section 2 was measured; in the portion of the outcrop where the analcimolite is missing its stratigraphic position is held by 11 feet of what has elsewhere been called "silicified silty bentonite" by Denson and Gill (1965); this material has irregular, uneven, medium beds, is light greenish gray (5 GY 8/1) weathered and light greenish gray to yellowish gray (5 Y 8/1) fresh.	3

GOLDEN VALLEY FORMATION, UNDIFFERENTIATED

2		Sandstone, silty claystone and clay (Figure 10):		30
	d	Clay: massive; pale greenish yellow (10 Y 8/2) weathered, pale olive (10 Y 6/2) to moderate greenish yellow (10 Y 7/4) fresh.	5	
	c	Silty claystone: massive; white (N 9) to pale yellowish orange (10 YR 8/6) weathered, white to grayish orange (10 YR 7/4) fresh.	5	
	b	Sandstone: large scale trough (pi) cross-bedding; grayish orange (10 YR 7/4) to dark yellowish orange (10 YR 6/6) weathered and fresh; grains fine to medium, moderately sorted, subangular to subrounded; basal contact disconformable; unit wedges out abruptly to the east and west.	10	
	a	Sandstone: large scale trough (pi) cross-bedding; very pale orange (10 YR 8/2) to moderate reddish orange (10 R 6/6) weathered, light brown (5 YR 6/4), grayish orange (10 YR 7/4), or dark yellowish orange (10 YR 6/6) fresh; limonite staining causes darker colors; grains very fine to medium, moderately sorted, subangular to subrounded; top irregular where cut by channel, filled with unit 2b above; base covered.	10	
		Covered slope with a few poor exposures of clay.		15
1		Sandstone (Figure 10): massive with vague suggestion of large scale trough (pi) cross-bedding; grayish orange (10 YR 7/4) to dusky yellow (5 Y 6/4) weathered, dark yellowish orange (10 YR 6/6) fresh; grains very fine to fine, moderately sorted, subangular to rounded; forms a prominent ledge in northern Chalky Buttes and atop Slide and HT or Black Buttes west of U.S. 85; this unit assigned to Golden Valley Formation by Denson (1970).		5

FORT UNION GROUP

Alternating beds of buff siltstone, gray bentonite, dark gray lignitic shale and black lignite (Figure 10).	48
Covered slope: talus and grass	15

Total section thickness = 175 feet

Measurement of section 2 was begun at the base of a deep, unnamed, west-sloping drainage gully.

SECTION 3-A, FITTERER RANCH, NORTH. East-facing slope of low irregular outcrop scarp, west of section line road, about ½ mile north of ranch house and about 12 miles south of South Heart; NE¼SW¼ sec. 7, T. 137 N., R. 97 W., Stark County; section measured August, 1969.

Unit	Lithology	Thickness (Ft.)
BRULE FORMATION DICKINSON MEMBER		
	Rubble: mass of slumped blocks of green-colored, cross-bedded sandstone (Fitterer Bed?); top covered by thick grass.	5
4	Calcareous, pitted-weathering claystone: massive, moderate reddish orange (10 R 6/6) weathered, grayish orange (10 YR 7/4) to very pale orange (10 YR 8/2) fresh; darker fresh color is that of clay clasts, up to 1 inch in diameter, that occur in the claystone and produce a pitted surface where weathered out.	10

CHADRON FORMATION
SOUTH HEART MEMBER

Unit	Lithology	Thickness (Ft.)
3	Clay: massive; pale greenish yellow (10 Y 8/2) weathered, yellowish gray (5 Y 7/2) fresh; forms low, rounded hills or "haystack buttes," very thinly bedded limestone or mushroom-shaped, fibrous aragonite nodules (Figure 16) characterize the top of this unit.	15

CHADRON FORMATION
CHALKY BUTTES MEMBER

Unit	Lithology	Thickness (Ft.)
2	Sandstone: laminated, irregular, uneven, medium to thick beds; white (N 9) to very pale orange (10 YR 8/2) weathered and fresh; grains fine to medium, subrounded to rounded; pebbles and cobbles up to 1½ inches in diameter, consisting	8

of various igneous and metamorphic rock types, occur as thin beds and form a residual-lag deposit where this unit is eroded away; base disconformable, limonitic.

CHADRON FORMATION

AMIDON MEMBER

1 Clay: massive; light greenish gray (5 G 8/1) weathered, light greenish gray (5 GY 8/1) fresh; limonite occurs as nodules, up to 2 inches in maximum diameter, at the contact with unit 2 above and as horizontal streaks of dark yellowish orange (10 YR 6/6) to light brown (5 YR 5/6) discoloration throughout the clay; base of unit marked by a major concentration of limonite nodules, oxidation, and discoloration. 10

The section below unit 1 consists of a thin interval of clay. This material may belong to the Golden Valley Formation if the major limonite zone at the base of unit 1 represents the Interior Formation here or to the Amidon Member of the Chadron if it does not. There is not enough exposure below the limonite zone to determine which unit it belongs to.

Total section thickness = 50 feet

Measurement of section 3-A was begun at the base of a small gully and proceeded west and south.

SECTION 3-B, FITTERER RANCH PROPER (Type section of the Dickinson Member of the Brule Formation.) East- and south-facing slopes of the tallest solitary butte north of the Fitterer Ranch house; west of section line road about 1/8 mile north of ranch house and about 12 miles south of South Heart; NW¼SE¼ sec. 7, T. 137 N., R. 97 W., Stark County; section measured August, 1969 (Figures 18, 19, 23, 25).

Unit	Lithology	Thickness (Ft.)
BRULE FORMATION SCHEFIELD MEMBER		
5	Interbedded siltstone and clay (Figure 25): siltstone has regular, even, medium beds; weathers very pale orange (10 YR 8/2) and is grayish orange (10 YR 7/4) fresh; non-calcareous; contains tubular, vertically oriented calcareous concretions ½ inch in diameter and up to 5 inches long, as well as, spherical and oblong, horizontally oriented, calcareous concretions up to 2 inches in diameter and 4 inches long. Clay occurs as single regular, even thin beds, is moderate reddish orange (10 R 6/6) weathered and pale reddish brown (10 R 5/4) fresh. Alternation of siltstone and clay produced a banded appearance (Figures 19a, 24, 26a).	25
BRULE FORMATION DICKINSON MEMBER		
4	Clay and silty claystone: (Figures 18, 23): clay constituting the bulk of unit is massive; weathers moderate orange pink (5 YR 8/4) and is grayish orange pink (5 YR 7/2) fresh; spherical calcareous concretions up to 1 inch in diameter occur in the clay locally. Silty claystone occurs as irregular, uneven, medium to thick beds; is moderate reddish orange (10 R 6/6) weathered and light brown (5 YR 6/4) fresh.	25

3	Calcareous silty claystone (Skinner's, 1951, "white marker bed"; Figure 19): massive; grayish pink (5 R 8/2) to white (N 9) weathered, white (N 9) fresh; calcareous, especially at top; contains irregular nodules of chert and opal up to 2 feet across.	3
2	Clay, limestone, and claystone: clay occurs at base as a single, very thick irregular bed; moderate orange pink (5 YR 8/4) weathered and pale reddish brown (10 R 5/4) fresh. Next above the clay is a single, irregular, very thin to medium bed of very finely crystalline limestone; grayish orange pink (10 R 8/2) to pale red (10 R 6/2) fresh; contains small clay clasts which weathered out producing a pitted weathering surface. Above the limestone and just below Skinner's (1951) "white marker bed" is a single massive irregular bed of calcareous claystone, grayish orange pink (10 R 8/2) weathered and very pale orange (10 YR 8/2) to moderate reddish orange (10 R 6/6) fresh.	7
1	Claystone: regular, even medium beds; moderate orange pink (10 R 7/4) to pale reddish brown (10 R 5/4) weathered and grayish pink (5 R 8/2) to grayish orange pink (10 R 8/2) fresh; contains small clay clasts which weather out to produce a pitted surface.	9

Total section thickness = 68 feet

Neither the base of the Dickinson Member nor the Fitterer Bed were exposed at this site; measurement was begun at the base of a small gully and continued north and west up the side of a small but prominent butte at this locality.

SECTION 3-C, FITTERER RANCH, SOUTHEAST (Type section of the Schefield Member and the Fitterer Bed of the Dickinson Member of the Brule Formation.) North-facing slope of major scarp southeast of the Fitterer Ranch house; south of section line road, about ½ mile southeast of ranch house, and about 12 miles south of South Heart; SE¼NW¼ sec. 17, T. 137 N., R. 97 W., Stark County; section measured August, 1969 (Figures 20, 21, 26).

Unit	Lithology		Thickness (Ft.)
KILLDEER FORMATION			
7	Sandstone: massive, no cross-bedding apparent; pale greenish yellow (10 Y 8/2) weathered, pale greenish yellow to yellowish gray (5 Y 7/2) fresh; grains fine to medium, moderately sorted, subrounded; contains green clay pebbles up to 1 inch in diameter; caps most buttes in area.		5
6	Calcareous, silty claystone: massive; grayish orange pink (5 YR 7/2) weathered and fresh; contains pale olive (10 Y 6/2), discoid, chert nodules up to 2 feet in diameter; a 1 foot thick resistant ledge, apparently caused by locally high carbonate content, occurs 2 feet below top of unit.		47
BRULE FORMATION			
SCHEFIELD MEMBER			
5	Interbedded silty claystone, siltstone, and clay:		77
c	Silty claystone thick, regular, even beds; very pale orange (10 YR 8/2) weathered, grayish orange pink (5 YR 7/2) fresh; contains vertically oriented, tubular, calcareous concretions, ½ inch in diameter, up to 5 inches long and spherical to oblong concretions, up to 4 inches in diameter; fossil turtle shown in Figure 26 collected 10 feet below top of unit.	67	

b	Silty claystone: massive; moderate reddish orange (10 R 6/6) weathered and fresh; forms a distinct "red zone" in section here.	5
a	Interbedded siltstone, and clay: thin to medium, irregular, even beds; both weather very pale orange (10 YR 8/2), siltstone is grayish orange pink (5 YR 7/2) fresh. Clay is yellowish gray (5 YR 7/2) fresh; unit forms a resistant ledge.	5

BRULE FORMATION

DICKINSON MEMBER

4	Interbedded calcareous, silty claystone and clay: claystone has medium, irregular, uneven beds; moderate reddish orange (10 R 6/6) to light brown (5 YR 6/4) weathered and very pale orange (10 YR 7/4) fresh; calcareous; angular inclusions of pale olive (10 Y 42) to light brown (5 YR 6/4) noncalcareous clay up to 1 inch in diameter (Figure 20); characterized by pitted surfaces where clay inclusions have weathered out. Clay is massive, grayish orange pink (5 YR 7/2) weathered and light brown (5 YR 6/4) fresh.	27

FITTERER BED

3	Sandstone (Figure 21): laminated, medium, irregular, uneven beds and large scale trough (pi) cross-bedding; grains fine to medium, moderately sorted subrounded; base contains green clay pebbles, up to 1 inch in diameter; very fossiliferous. Locally, the Fitterer Bed rests directly on the Chadron Formation (unit 1 below).	7

DICKINSON MEMBER

2	Interbedded calcareous, silty claystone and clay: claystone has medium irregular, uneven beds: moderate orange pink (10 R 7/4) weathered and fresh; contains blebs of pale reddish brown (10 R 5/4), noncalcareous clay, up to 1 inch in diameter, which weather out to give the claystone a pitted surface. Clay is massive, grayish orange pink (10 R 8/2) weathered and grayish pink (5 R 8/2) fresh.	36

CHADRON FORMATION
SOUTH HEART MEMBER

1	Clay: massive, light greenish gray (5 GY 8/1) weathered and fresh; surface littered with fibrous aragonite nodules (similar to those in Figure 16) weathering out of clay.	10
	Covered slope to level ground surface.	5

Total section thickness = 214 feet

Measurement of section 3-C was begun in a narrow, north-sloping gully and proceeded southeast up a prominent point in the outcrop scarp, southeast of the Fitterer Ranch house.

SECTION 4-A, ABANDONED HOUSE SITE PROPER. North- and west-facing slopes of buttes northeast of the Fitterer Ranch, east of section line road, about 1 mile north of an abandoned fieldstone house and out buildings also east of road, and about 9 miles south of South Heart; SE¼NE¼ sec. 29, T. 138 N., R. 97 W., Stark County; section measured August, 1969.

Unit	Lithology	Thickness (Ft.)
BRULE FORMATION		
	DICKINSON MEMBER	
7	Clay and silty claystone: clay is massive, makes up bulk of unit, calcareous. Both clay and claystone are yellowish gray (5 Y 7/2) weathered and light brown (5 YR 6/4) fresh. Silty claystone is restricted to upper 5 feet and has medium, regular, even beds:	16
6	Calcareous, concretionary, silty claystone: massive; yellowish gray (5 Y 7/2) weathered and fresh; characterized by vertical, tubular, calcareous concretions up to 3 inches in diameter and 4½ inches long; similar to unit 3 below but lacks bedding.	6
	FITTERER BED	
5	Sandstone: laminated, thick, irregular, uneven beds with distinct large scale trough (pi) cross-bedding and laminated, medium, irregular, uneven beds lacking cross-bedding; grayish yellow (5 Y 8/4) to pale olive (10 Y 6/2) weathered, yellowish gray (5 Y 8/1) fresh; grains fine to medium, moderately sorted, subangular to rounded; green clay pebbles, up to 2 inches in diameter, occur at base of cross-bedded troughs; contains spherical, calcareous concretions, up to 3 inches in diameter, and irregularities on exposed soles of beds; very fossiliferous (mostly rhinoceros remains); unit 5 is	8

missing in parts of outcrop and unit 6 rests directly on unit 4 locally.

DICKINSON MEMBER

4	Silty claystone: laminated, medium, regular, uneven beds, vague suggestion of small-scale ripple cross-bedding in a few beds; yellowish gray (5 Y 7/2) to grayish orange pink (5 YR 7/2) weathered, yellowish gray (5 Y 7/2) fresh; contains vertical, tubular, calcareous concretions, up to 1 inch in diameter and 4 inches long, and discold calcareous concretions up to 3 inches in diameter.	29
3	Interbedded silty claystone and clay: clay making up bulk of unit is massive; both lithologies weather moderate reddish orange (10 R 6/6) and are grayish orange pink (10 R 8/2) to light brown (5 YR 6/4) fresh; silty claystone occurs at thin, irregular, uneven beds.	21
2	Calcareous silty claystone (Skinner's, 1951, "white marker bed"): massive; grayish pink (5 R 8/2) to white (N 9) weathered, grayish pink to very pale orange (10 R 8/2)fresh.	4
1	Silty claystone: massive; moderate orange pink (10 R 7/4) weathered and fresh; somewhat calcareous near top.	5
	Covered slope to level ground surface below.	15

Total section thickness = 104 feet

Measurement of section 4-A was begun at base of west-facing slope of butte and continued up the slope in an easterly direction.

SECTION 4-B, ABANDONED HOUSE SITE, EAST. North-facing slope of highest butte northwest of Golden Butte (Golden Butte is northeast of the Fitterer Ranch and the highest butte in the vicinity so is the location of antennae for local and police radio station, KDIX); about ½ mile east of measured section 4-A, about 1 mile northwest of Golden Butte and about 9 miles south of South Heart; SW¼NW¼ sec. 28, T. 138 N., R. 97 W., Stark County; section measured August, 1969.

Unit	Lithology	Thickness (Ft.)
KILLDEER FORMATION		
5	Sandstone: massive with vague suggestion of large-scale trough (pi) cross-bedding locally; pale greenish yellow (10 Y 8/2) weathered, yellowish gray (5 Y 7/2) to pale olive (10 Y 6/2) fresh; grains medium, poorly to moderately sorted, subangular to subrounded: contains clasts of green clay, up to 1½ inches in diameter, near base; blue opal occurs as botryoidal encrustations and fracture fillings up to 1/8 inches in thickness; by hand level it was determined that this sandstone is at the same elevation as that on Golden Butte to the southeast and probably corresponds stratigraphically to it.	6
4	Calcareous, silty claystone: massive; grayish orange pink (5 YR 7/2) weathered, light brown (5 YR 6/4) fresh.	14
	Covered slope: thick talus and grass cover.	3
3	Dolostone: massive; pale olive (10 Y 6/2) weathered and fresh.	
	Covered slope: thick talus and grass cover.	15

2	Silty claystone: massive, very pale orange (10 YR 8/2) weathered and grayish orange pink (5 YR 7/2) fresh; contains discoid green chert nodules, up to 1 foot in diameter; similar to unit 4 at section 3-C and unit 4-C at section 7.	5

BRULE FORMATION
DICKINSON MEMBER

	Covered slope: units seen above Fitterer Bed at section 3-C are probably present under this heavily covered slope.	70

	FITTERER BED	
1	Sandstone: laminated, irregular, uneven, medium beds with distinct large-scale trough (pi) cross-bedding; moderate greenish yellow (10 Y 7/4) weathered and pale olive (10 Y 6/2) fresh; grains medium, poorly to moderately sorted, subrounded; clasts of green clay, up to 6 inches in diameter, in base of unit; lower part of unit and the section below covered.	6
	Covered slope: thick grass to level ground surface below.	

Total section thickness = 160 feet

Measurement of section 4-B was begun at base of slope on north side of butte and proceeded up north-facing slope.

SECTION 5-A, LITTLE BADLANDS, WEST (Type section of the South Heart Member of the Chadron Formation.) Units 1 and 2 measured on east-facing slopes of low hills, or "haystack buttes," west of section line road, and units 3 through 8 measured cast of section line road, across area between road and main west-facing scarp of the Little Badlands; about 9 miles northwest of Schefield and 8 miles southwest of South Heart; includes exposures in NE¼SE¼ sec. 22, T. 138 N., R. 98 W., Stark County; section measured September, 1968.

Unit	Lithology	Thickness (Ft.)	
BRULE FORMATION			
DICKINSON MEMBER			
8	Calcareous, silty claystone		10
b	Calcareous, silty claystone: laminar beds with small scale ripple cross-bedding; yellowish gray (5 Y 7/2) weathered, grayish orange pink (5 YR 7/2) fresh; similar to unit 8a below but cross-bedded and loss resistant.	5	
a	Calcareous, silty claystone: laminar beds; very pale orange (10 YR 8/2) weathered and light brown (5 YR 6/4) fresh; forms resistant ledge.	5	
7	Interbedded silty claystone and clay: clay constituting major part of unit is massive, light brown (5 YR 6/4) weathered and fresh; silty claystone occurs as thin, regular even beds and is grayish pink (5 R 8/2) weathered and grayish orange pink (5 YR 7/2) fresh; claystone is somewhat silty in places; lower 5 feet of unit is clay, moderate reddish orange (10 R 6/6) to moderate orange pink (10 R 7/4) weathered and fresh.		35
6	Interbedded silty claystone, clay, and limestone:		10

	d	Silty claystone: massive; moderate reddish orange (10 R 6/6) weathered and fresh.	1	
	c	Clay: massive; moderate orange pink (10 R 7/4) weathered and fresh.	3	
	b	Limestone: massive; grayish pink (5 R 8/2) weathered and fresh; contains blebs, up to 1 inch in diameter, of moderate orange pink (10 R 7/4) clay.	1	
	a	Clay: massive; grayish orange pink (5 YR 7/2) weathered and fresh.	5	
5		Interbedded calcareous, silty claystone and clay: clay constituting bulk of this unit is massive and crumbly; grayish orange pink (5 YR 7/2) weathered and fresh. Silty claystone occurs as thin to medium, irregular, uneven beds which weather grayish yellow (5 Y 8/4) and are grayish orange (10 YR 7/4) fresh. Upper 1 foot of unit consists of grayish orange pink (5 YR 7/2) silty claystone with small-scale ripple cross-bedding; top of unit forms a ledge marking a major break in slope.		15
4		Calcareous silty claystone (Skinner's 1951 "white marked bed"): massive; grayish pink (5 R 8/2) to white (N 9) weathered, grayish pink to very pale orange (10 YR 8/2) fresh.		2
3		Interbedded silty claystone and clay: claystone has medium to thick, irregular, uneven beds; very pale orange (10 YR 8/2) weathered, yellowish gray (5 Y 7/2) fresh. Clay occurs as medium to thick, irregular, uneven beds; yellowish gray (5 Y 7/2) or light brown (5 YR 7/2) or pale olive (10 Y 6/2) fresh. Large clasts of moderate red (5 R 4/6) clay, up to 1 foot across, occur randomly throughout the claystone. Exposure of unit characterized by rugged terrain which appears to be badly slumped in places.		64

CHADRON FORMATION SOUTH HEART MEMBER		
2	Clay and limestone: clay is massive; pale greenish yellow (10 Y 8/2) to yellowish gray (5 Y 7/2) weathered and pale olive (10 Y 6/2) fresh; upon erosion forms low rounded hills or "haystacks" with popcornlike weathering surfaces (Figure 15). Up to 1 foot of limestone occurs at the top of this unit: very thin, irregular, uneven beds; white (N 9) to yellowish (5 Y 7/2) weathered, light greenish gray (5 GY 8/1) fresh; blebs of light olive gray (5 Y 6/1) clay occur randomly throughout the limestone.	15
CHADRON FORMATION CHALKY BUTTES MEMBER		
1	Sandstone: laminated, medium irregular, uneven beds with vague large-scale trough (pi) cross-bedding in places; very pale orange (10 Yr 8/2) weathered, pinkish gray (5 YR 8/1) fresh; grains fine to medium, moderately sorted, subangular to rounded; cobbles of predominately volcanic igneous lithologies occur as thin zones and litter ground or form pebble pavements on eroded slopes.	12

Total section thickness = 173 feet

Measurement began at base of small "haystack butte," west of road.

SECTION 5-B, LITTLE BADLANDS, PROPER. West-facing slope of main badlands scarp; north of old school house; east of section line road, about 9 miles northwest of Schefield and 8 miles southwest of South Heart; SE¼NW¼ sec. 23, T. 138 N., T. 98 W., Stark County; section measured August, 1969.

Unit	Lithology	Thickness (Ft.)	
BRULE FORMATION DICKINSON MEMBER			
5	Calcareous, concretionary, silty claystone; clayey siltstone; and dolomitic limestone:		16
b	Calcareous, concretionary, silty claystone: thin to medium, irregular, uneven beds; grayish orange pink (5 YR 7/2) weathered, yellowish gray (5 Y 7/2) fresh; contains bar-bell, oblong-and-spherically-shaped calcareous up to 3 inches in diameter.	9	
a	Calcareous, concretionary, silty claystone: laminar beds with parting lineations and vague suggestion of ripple cross-bedding; very pale orange (10 YR 8/2) weathered, grayish orange pink (5 YR 7/2) fresh; contains discoid calcareous concretions up to 4 inches in diameter. Upper 6 inches of unit consist of fine-grained dolomitic limestone with thin, regular, even beds; yellowish gray weathered and fresh.	7	
4	Interbedded clay, calcareous, silty claystone, sandstone, and dolomitic limestone:		35
i	Dolomitic limestone: thin, regular, even beds; light greenish gray (5 GY 8/1) weathered and fresh; very fine-grained.	5	
h	Clay: same as unit 4a above.	4	
g	Silty claystone: massive, grayish pink (5 R 8/2) weathered and fresh; somewhat calcareous.	3	

f	Clay: same as unit 4a below.		5
e	Claystone: massive; moderate reddish brown (10 R 4/6) weathered, pale reddish brown (10 R 5/4) fresh; forms a notable red zone.		16
d	Clay: same as unit 4a below.		2
c	Calcareous, silty claystone: massive; very pale orange (10 YR 8/2) to grayish pink (5 R 8/2) fresh; forms a notable white zone.		1

FITTERER BED

b	Sandstone: laminated, irregular, uneven, medium to thick beds with distinct large-scale trough (pi) cross-bedding; yellowish gray (5 Y 7/2) weathered, pale olive (10 Y 6/2) fresh; grains medium, moderately sorted, subrounded; blebs of green clay, up to 3 inches in diameter, occur in lower part; base disconformable; unit not present at principal line of section 5-B but replaced there by clay similar to 4a below; unit 4b described from small exposure 1,000 feet south of principal line of section 5-B.	9	

DICKINSON MEMBER

a	Clay: massive; light brown (5 YR 6/4) weathered, light brown (5 YR 5/6 fresh.	3	
3	Silty claystone; massive; light brown (5 YR 6/4) weathered, light brown or pale reddish brown (10 R 5/4) fresh, darker colors due to clay inclusions, up to 1 inch in diameter; a 6-inch thick, calcareous and resistant ledge occurs 1 foot below top of unit.		4

2	Interbedded silty claystone and clay: clay is massive; yellowish gray (5 Y 7/2) weathered, yellowish gray to pale olive (10 Y 6/2) and light gray (N 7) fresh. Silty claystone has thin to medium, irregular, uneven beds, with small scale ripple cross-bedding locally; very pale orange (10 YR 8/2) to grayish orange pink (5 YR 7/2) to light brown (5 YR 6/4) weathered, light brown to yellowish gray (5 Y 7/2) fresh. Top of unit marked by an 8-inch thick zone of red clay inclusions in a calcareous matrix.	22
1	Calcareous silty claystone (Skinner's 1951 "white marked bed"): massive; grayish pink (5 R 8/2) to white (N 9) weathered, grayish pink to very pale orange (10 R 8/2) fresh.	2

Total section thickness = 79 feet

The description of units at section 5-B starts with Skinner's (1951) "white marker bed"; beds below were studied at better exposures, west of the north-south gravel road which runs through the Little Badlands proper (section 5-A).

SECTION 6, WHITE BUTTE, STARK COUNTY. North- and west-facing slopes at east end of large butte south of section line road; about 9 miles southwest of Dickinson and 4 miles southeast of South Heart; NE¼NW¼ sec. 32, T. 139 N., R. 97 W., Stark County; section measured August, 1969 (Figures 4, 18).

Unit	Lithology	Thickness (Ft.)
CHADRON FORMATION SOUTH HEART MEMBER		
3	Clay (Figure 17): massive; pale greenish yellow (10 Y 8/2) to yellowish gray (5 Y 7/2) weathered and dusky yellow (5 Y 6/4) fresh; irregular masses, up to 6 inches in diameter, of chalcedony occur as float at top of unit.	12
2	"Silicified, silty bentonite" (Denson and Gill, 1965; Figure 18): irregular, uneven, medium to thick beds, with a hint of cross-bedding near base of unit; grayish orange pink (5 YR 7/2) to very light gray (N 8) weathered, light brown (5 YR 6/4) fresh; small clay clasts and spherical siliceous concretions scattered throughout; has a spongy weathering habit probably produced by weathering out of clay clasts.	15
CHADRON FORMATION CHALKY BUTTES MEMBER		
1	Sandstone (Fiture 4): laminated, irregular, uneven, medium to thick beds, not everywhere distinct, some marked by thin zones of pebbles consisting mainly of igneous rock types, others marked by subtle color changes which are probably due to variation in clay matrix content or grain size, vague suggestion of large-scale trough (pi) cross-bedding locally white (N 9) weathered, white to very pale orange (10 YR 8/2) fresh; grains very fine to very coarse, subangular to sub-	47

rounded, although size varies considerably throughout unit, given horizons are moderatley sorted; grains consist mainly of quartz, feldspar, and rock fragments; much clay present as matrix; base is disconformable and sharp where unit rests on the brightly colored Interior and Golden Valley Formations (Figure 4); some limonite staining at base due to reworking of these formations; contact with unit 2 above is gradational.

Total section thickness = 74 feet

Measurement of section 6 was begun just south of road at contact of the Chalky Buttes Member of the Chadron Formation and the Interior Formation and proceeded south and up the north-facing slope of the butte.

SECTION 7, KILLDEER MOUNTAINS (Type section of the Killdeer Formation). East-facing slope of the north-eastern tip of South Mountain or the southern most of the Killdeer Mountains: south of State Highway 22 where it passes between North and South Mountains, about 9½ miles northwest of Killdeer; NE¼NW¼ sec. 15, T. 146 N., R. 96 W., Dunn County; section measured September, 1969 (Figures 27, 29, 30).

Unit	Lithology	Thickness (Ft.)
KILLDEER FORMATION		
4	Siltstone, dolomitic siltstone, silty dolostone: unit consists of various closely related lithologies as follows:	29
e	Silty dolostone: regular, even thin beds; pale greenish yellow (10 Y 8/2) weathered, moderate greenish yellow (10 Y 7/4) fresh.	8
d	Dolostone: regular, even thin beds; moderate greenish yellow (10 Y 7/4) weathered and fresh.	2
c	Siltstone: regular, even very thin to thin beds; grayish orange pink (5 YR 7/2) weathered, light brown (5 YR 6/4) fresh; contains oblong nodules, up to 6 inches long, of pale olive (10 Y 6/2) chert.	6
b	Dolomitic siltstone: massive; yellowish gray (5 Y 7/2) weathered, pale olive (10 & 6/2) fresh.	2
a	Siltstone: massive, dusky yellow (5 Y 6/4) weathered and fresh; has a spongy weathering habit.	11
	Covered slope.	18
3	Siltstone and dolomitic sandstone as follows:	10
c	Siltstone: massive; pale greenish yellow (10 Y 8/2) weathered, moderate greenish	2

		yellow (10 Y 7/4) fresh; forms resistant ledge.		
	b	Siltstone: massive; pale greenish yellow (10 Y 8/2) weathered, yellowish gray (5 Y 7/2) fresh; forms nonresistant slope.	5	
	a	Dolomitic sandstone: regular, uneven medium beds; pale greenish yellow (10 Y 8/2) weathered, grayish yellow (5 Y 8/4) fresh; grains very fine; largely obscurred by talus but forms resistant ledge locally.	3	
		Covered slope: active talus slope.		30
2		Dolostone and siltstone:		6
	b	Dolostone: regular, even, medium beds, moderate greenish yellow (10 Y 7/4) weathered and yellowish gray (5 Y 7/2) fresh; very fine-grained; has spongy surface even when fresh.	4	
	a	Siltstone: massive with a vague suggestion of laminar beds; pale greenish yellow (10 Y 8/2) weathered and moderate greenish yellow (10 Y 7/4) fresh.	2	
1		Calcareous concretionary sandstone: massive to laminated with regular, even, very thin beds, small-scale ripple cross-bedding at some horizons in lower half of unit; yellowish gray (5 Y 7/2) weathered, pale olive (10 Y 6/2) fresh, grains very fine, moderately to well sorted, subangular to subrounded; carbonate content increases toward top such that lithology of upper half of unit is nearly sandy limestone; top half characterized by alternating thin beds of well-cemented sandstone and soft sandstone; well-cemented layers are connected by vertical, tubular, carbonate concretions (Figures 29, 30); this unit forms main ledge in Killdeer Mountains (Figure 27).		65

WHITE RIVER GROUP

Covered slope: characterized by thick vegetation, including trees, and talus, dominated by large blocks of unit 1 which have broken off and fallen apparently due to undercutting of softer underlying beds (Figure 27); this interval includes an undetermined thickness of Killdeer Formation, possibly some Brule Formation, and an unknown thickness of Chadron Formation based on small, poor exposures at the south end of South Mountain.	100

Total section thickness = 258 feet

Measurement of section 7 was begun at the base of the east-facing slope of South Mountain at this locality and proceeded westward up the slope.

APPENDIX D

METHODS USED IN PETROGRAPHIC ANALYSES

Collection of Samples

The first samples studied consisted of representative, fresh samples, collected during the preliminary field reconnaissance study, from the middle of each lithostratigraphic unit at the major outcrops. Thin sections of the major sandstone units were prepared from samples collected during this preliminary study.

During the measurement of stratigraphic sections a more detailed sampling procedure was employed. Three to five fresh samples were collected from each lithostratigraphic unit at a measured section along a horizontal transect at the middle of the unit in the following manner. In the case of major lithologic units (such as those labeled with a number in the measured section descriptions, Appendix C) five samples were obtained; one sample was taken at the line of section and four additional samples were taken at the same horizon. For subdivisions of major units (such as those labeled with a number and a letter in the measured section descriptions, Appendix C) three samples were obtained; one sample was taken at the line of section and two additional samples were taken at the same horizon. In both cases, sample sites were about 15 feet apart; the distance between sample sites was measured in the field by pacing.

Modal Analysis

Thin sections of samples collected during the preliminary field reconnaissance were used in this study. Most of the samples required impregnation prior to mounting. In the modal analyses a total of 300 points (not grains) were identified and counted for each sandstone sample using a mechanical stage set for an interval of 1 mm between points and traverses. Frequencies of occurrence of fourteen lithologic constituents were determined and recorded. From these data the sandstones were classified according to Folk's terminology (1965, p. 114) by means of a special computer program (Stone and Erickson, 1970).

X-ray-Diffraction Analysis

X-ray-diffraction, whole-rock analyses were also made of the major sandstones and mudstones. This study included a qualitative analysis to identify their mineralogy and a semiquantitative study of selected beds in the Dickinson Member at the Little Badlands proper to determine the relative abundances of the major constituents.

The procedures employed for the preparation of samples for these X-ray-diffraction analyses are as follows:

1. Small representative chips totalling about 200 gms were taken from all available field samples of the rock to be tested.

2. These chips were then mixed and crushed to less than 2 to 3 mm with a cast iron mortar and pestle.

3. This material was then ground to less than 20 mesh (0.84 mm) with a porcelain mortar and pestle.

4. A 2-gm split of the sample was then ground for 4 minutes in a Spex 8000 Mixer Mill.

5. An 0.8-gm split of this material was then ground for 5 minutes with a small mullite mortar and pestle and returned to the Spex Mixer Mill until less than 325 mesh (44 microns).

6. The material was then pressed at 10 tons for 30 seconds into a 1 inch pellet backed with bakellite.

A supplementary procedure was employed in the preparation of mudstones suspected to contain montmorillonite. This procedure involved the treatment of the finely ground material from these samples with ethylene glycol in an oven at 55°C overnight; 1 gm of this treated material was then pressed at 5 tons for 30 seconds into an unbacked pellet. Diffraction charts of glycolated and unglycolated samples of the same unit were then compared to determine whether there had been any enhancement of the 17 angstrom montmorillonite peak.

A Philips, high-angle diffractometer, at the Geology Department, University of North Dakota, was used for the X-ray studies. A copper tube operated at 47 Kilovolts and 18.75 milliamps was the X-ray source. Scanning was done at 1° 2θ/min and a Philips, rotating sample holder was employed. Diffraction charts from samples of known mineralogy, as well as the American Society of Testing Materials Powder File and the Fink indices, were consulted for diffraction peak identifications. In the semiquantitative analysis the abundances of minerals were determined by comparison of sample peak heights with those of pure mineral standards X-rayed under similar conditions.

Accuracy and Precision

The compositions of the sandstones, as determined by modal analysis, was not checked by any other method and the accuracy of these identifications cannot be evaluated. Furthermore, these modal analyses were not repeated and the precision of the results cannot be evaluated.

No means of evaluating the accuracy of the general mineralogy or semiquantitative compositions of the sandstones and mudstones, as determined by X-ray diffraction, were employed. These analyses were not repeated and the precision of the X-ray diffraction results cannot be evaluated.

APPENDIX E

THIN SECTION DATA AND ANALYSES

Appendix E consist of the print-out of a computer program for Folk's (1965) sandstone classification developed by Stone and Erickson (1970).

The first set of values shown are point count frequencies for Folk's sandstone constituents. The second set of values gives grouped sub-totals. The third and fourth sets of values express each constituent or category of constituents as a percentage of the total number of grains counted. The final set of values gives the percentage of the framework represented by the three end members used in classification of sandstones on Folk's triangular plot (as in Figure 36).

All abbreviations used in the following computer print-out are as follows:

NMQ	= Folk's non-metamorphic quartz
CH	= chert
MQ	= Folk's metamorphic quartz
MRF	= metamorphic rock fragments
MIC	= mica
FEL	= feldspar
IGRF	= igneous rock fragments
UNST	= unstable minerals
SRF	= sedimentary rock fragments
FECEM	= iron cement
CACEM	= calcite cement
SICEM	= silica cement
POR	= porosity
MATX	= matrix
META	= metamorphic
NON-META	= non-metamorphic
FRMWK	= framework
PERTOT	= percent of the total grains (not points)
FOKFRM	= amount of constituents making up what would be considered framework (as opposed to cement or matrix), according to Folk, for use in calculating percent of the three end members (quartz, metamorphic and igneous) on Folk's (1965) classification triangle
PERFOK (1)	= non-metamorphic elements
PERFOX (2)	= metamorphic elements

PERFOX (3) = igneous elements

The identity and source of samples used in the thin section analyses are given below:

Sample	Unit	Location
1	Chalky Buttes Mbr., Chadron Formation	NE¼NW¼ sec. 32 T. 139 N., R. 97 W., White Butte, Stark County
2	Chalky Buttes Mbr., Chadron Formation	NE¼NW¼ sec. 21, T. 139 N., R. 91 W. Antelope Butte, Stark County
3	Chalky Buttes Mbr., Chadron Formation	NW¼NW¼ sec. 12, T. 139 N., R. 92 W. Youngman's Butte Stark County
4	Fitterer Bed, Dickinson Member, Brule Formation	NW¼NW¼ sec. 17, T. 137 N., R. 97 W., Fitterer Ranch, Stark County
5	Fitterer Bed, Dickinson Member, Brule Formation	NW¼NW¼ sec. 17, T. 137 N., R. 97 W., Fitterer Ranch, Stark County
6	Fitterer Bed, Dickinson Member, Brule Formation	NW¼NW¼ sec. 17, T. 137 N., R. 97 W., Fitterer Ranch, Stark County
7	Killdeer Formation	SE¼NW¼ sec. 17, T. 137 N., R. 97 W., Fitterer Ranch, Stark County
8	Killdeer Formation	SE¼NE¼ sec. 12 T. 136 N., R. 95 W., Black Butte, Hettinger County

9	Killdeer Formation	SE¼NE¼ sec. 12, T. 136 N., R. 95 W., Black Butte, Hettinger County
10, 11, 12[1]	Killdeer Formation	Main, ledge-forming, concretionary sandstone on North Mountain, Killdeer Mountains, Dunn County

[1]These thin sections, prepared and made available for study by Marvin Furman, were used only for general study of the Killdeer sandstone in the Killdeer Mountains; no modal analyses were made of these slides, and therefore no computer print-outs appear for them in this Appendix.

SAMPLE NO. 1

NMQ	123
CH	1
MQ	0
MRF	0
MIC	1
FEL	10
IGRF	89
UNST	6
SRF	1
FECEM	0
CACEM	0
SICEM	0
POR	18
MATX	51
TOTAL NON-META	124
TOTAL META	1
TOTAL IGN	99
TOTAL FRMWK (FOLK)	224
TOTAL CEMENT	0
TOTAL QUARTZ	124
PERTOT NMQ	41.00
PERTOT CH	.33
PERTOT MQ	.00
PERTOT MRF	.00
PERTOT MIC	.33
PERTOT FELD	3.33
PERTOT IGRF	29.67
PERTOT UNST	2.00
PERTOT SRF	.33
PERTOT FECEM	.00
PERTOT CACEM	.00
PERTOT SICEM	.00
PERTOT POR	6.00
PERTOT MATX	17.00
PERTOT NON META	41.33
PERTOT META	.33
PERTOT IGN	33.00
PERTOT FRMWK (FOLK)	74.67
PERTOT CEMENT	.00
PERTOT QUARTZ	41.33
FOKFRM	74.67
PERFOK(1)	55.4
PERFOK(2)	.4
PERFOK(3)	44.2

THIS SAMPLE IS ARKOSE ACCORDING TO FOLK-S CLASSIFICATION

SAMPLE NO. 2

NMQ	114
CH	1
MQ	0
MRF	0
MIC	0
FEL	11
IGRF	54
UNST	1
SRF	0
FECEM	0
CACEM	0
SICEM	36
POR	11
MATX	72
TOTAL NON-META	115
TOTAL META	0
TOTAL IGN	65
TOTAL FRMWK (FOLK)	180
TOTAL CEMENT	36
TOTAL QUARTZ	115
PERTOT NMQ	38.00
PERTOT CH	.33
PERTOT MQ	.00
PERTOT MRF	.00
PERTOT MIC	.00
PERTOT FELD	3.67
PERTOT IGRF	18.00
PERTOT UNST	.33
PERTOT SRF	.00
PERTOT FECEM	.00
PERTOT CACEM	.00
PERTOT SICEM	12.00
PERTOT POR	3.67
PERTOT MATX	24.00
PERTOT NON META	38.33
PERTOT META	.00
PERTOT IGN	21.67
PERTOT FRMWK (FOLK)	60.00
PERTOT CEMENT	12.00
PERTOT QUARTZ	38.33
FOKFRM	60.00
PERFOK(1)	63.9
PERFOK(2)	.0
PERFOK(3)	36.1

THIS SAMPLE IS ARKOSE ACCORDING TO FOLK-S CLASSIFICATION

SAMPLE NO. 3

NMQ	129
CH	1
MQ	0
MRF	0
MIC	0
FEL	21
IGRF	45
UNST	2
SRF	0
FECEM	0
CACEM	0
SICEM	56
POR	11
MATX	35
TOTAL NON-META	130
TOTAL META	0
TOTAL IGN	66
TOTAL FRMWK (FOLK)	196
TOTAL CEMENT	56
TOTAL QUARTZ	130
PERTOT NMQ	43.00
PERTOT CH	.33
PERTOT MQ	.00
PERTOT MRF	.00
PERTOT MIC	.00
PERTOT FELD	7.00
PERTOT IGRF	15.00
PERTOT UNST	.67
PERTOT SRF	.00
PERTOT FECEM	.00
PERTOT CACEM	.00
PERTOT SICEM	18.67
PERTOT POR	3.67
PERTOT MATX	11.67
PERTOT NON META	43.33
PERTOT META	.00
PERTOT IGN	22.00
PERTOT FRMWK (FOLK)	65.33
PERTOT CEMENT	18.67
PERTOT QUARTZ	43.33
FOKFRM	65.33
PERFOK(1)	66.3
PERFOK(2)	.0
PERFOK(3)	33.7

THIS SAMPLE IS ARKOSE ACCORDING TO FOLK-S CLASSIFICATION

SAMPLE NO. 4

NMQ	45
CH	1
MQ	1
MRF	1
MIC	5
FEL	28
IGRF	65
UNST	30
SRF	2
FECEM	1
CACEM	1
SICEM	3
POR	20
MATX	97
TOTAL NON-META	46
TOTAL META	7
TOTAL IGN	93
TOTAL FRMWK (FOLK)	146
TOTAL CEMENT	5
TOTAL QUARTZ	47
PERTOT NMQ	15.00
PERTOT CH	.33
PERTOT MQ	.33
PERTOT MRF	.33
PERTOT MIC	1.67
PERTOT FELD	9.33
PERTOT IGRF	21.67
PERTOT UNST	10.00
PERTOT SRF	.67
PERTOT FECEM	.33
PERTOT CACEM	.33
PERTOT SICEM	1.00
PERTOT POR	6.67
PERTOT MATX	32.33
PERTOT NON META	15.33
PERTOT META	2.33
PERTOT IGN	31.00
PERTOT FRMWK (FOLK)	48.67
PERTOT CEMENT	1.67
PERTOT QUARTZ	15.67
FOKFRM	48.67
PERFOK(1)	31.5
PERFOK(2)	4.8
PERFOK(3)	63.7

THIS SAMPLE IS ARKOSE ACCORDING TO FOLK-S CLASSIFICATION

SAMPLE NO. 5

NMQ	48
CH	1
MQ	1
MRF	0
MIC	0
FEL	10
IGRF	135
UNST	9
SRF	1
FECEM	1
CACEM	1
SICEM	1
POR	19
MATX	73
TOTAL NON-META	49
TOTAL META	1
TOTAL IGN	145
TOTAL FRMWK (FOLK)	195
TOTAL CEMENT	3
TOTAL QUARTZ	50
PERTOT NMQ	16.00
PERTOT CH	.33
PERTOT MQ	.33
PERTOT MRF	.00
PERTOT MIC	.00
PERTOT FELD	3.33
PERTOT IGRF	45.00
PERTOT UNST	3.00
PERTOT SRF	.33
PERTOT FECEM	.33
PERTOT CACEM	.33
PERTOT SICEM	.33
PERTOT POR	6.33
PERTOT MATX	24.33
PERTOT NON META	16.33
PERTOT META	.33
PERTOT IGN	48.33
PERTOT FRMWK (FOLK)	65.00
PERTOT CEMENT	1.00
PERTOT QUARTZ	16.67
FOKFRM	65.00
PERFOK(1)	25.1
PERFOK(2)	.5
PERFOK(3)	74.4

THIS SAMPLE IS ARKOSE ACCORDING TO FOLK-S CLASSIFICATION

SAMPLE NO. 6

NMQ	74
CH	0
MQ	0
MRF	0
MIC	4
FEL	20
IGRF	71
UNST	59
SRF	1
FECEM	1
CACEM	1
SICEM	1
POR	4
MATX	64
TOTAL NON-META	74
TOTAL META	4
TOTAL IGN	91
TOTAL FRMWK (FOLK)	169
TOTAL CEMENT	3
TOTAL QUARTZ	74
PERTOT NMQ	24.67
PERTOT CH	.00
PERTOT MQ	.00
PERTOT MRF	.00
PERTOT MIC	1.33
PERTOT FELD	6.67
PERTOT IGRF	23.67
PERTOT UNST	19.67
PERTOT SRF	.33
PERTOT FECEM	.33
PERTOT CACEM	.33
PERTOT SICEM	.33
PERTOT POR	1.33
PERTOT MATX	21.33
PERTOT NON META	24.67
PERTOT META	1.33
PERTOT IGN	30.33
PERTOT FRMWK (FOLK)	56.33
PERTOT CEMENT	1.00
PERTOT QUARTZ	24.67
FOKFRM	56.33
PERFOK(1)	43.8
PERFOK(2)	2.4
PERFOK(3)	53.8

THIS SAMPLE IS ARKOSE ACCORDING TO FOLK-S CLASSIFICATION

SAMPLE NO. 7

NMQ	68
CH	0
MQ	0
MRF	0
MIC	0
FEL	25
IGRF	64
UNST	68
SRF	0
FECEM	0
CACEM	2
SICEM	1
POR	5
MATX	67
TOTAL NON-META	68
TOTAL META	0
TOTAL IGN	89
TOTAL FRMWK (FOLK)	157
TOTAL CEMENT	3
TOTAL QUARTZ	68
PERTOT NMQ	22.67
PERTOT CH	.00
PERTOT MQ	.00
PERTOT MRF	.00
PERTOT MIC	.00
PERTOT FELD	8.33
PERTOT IGRF	21.33
PERTOT UNST	22.67
PERTOT SRF	.00
PERTOT FECEM	.00
PERTOT CACEM	.67
PERTOT SICEM	.33
PERTOT POR	1.67
PERTOT MATX	22.33
PERTOT NON META	22.67
PERTOT META	.00
PERTOT IGN	29.67
PERTOT FRMWK (FOLK)	52.33
PERTOT CEMENT	1.00
PERTOT QUARTZ	22.67
FOKFRM	52.33
PERFOK(1)	43.3
PERFOK(2)	.0
PERFOK(3)	56.7

THIS SAMPLE IS ARKOSE ACCORDING TO FOLK-S CLASSIFICATION

SAMPLE NO. 8

NMQ	115
CH	1
MQ	0
MRF	0
MIC	1
FEL	21
IGRF	112
UNST	4
SRF	0
FECEM	0
CACEM	0
SICEM	13
POR	20
MATX	10
TOTAL NON-META	116
TOTAL META	1
TOTAL IGN	133
TOTAL FRMWK (FOLK)	250
TOTAL CEMENT	13
TOTAL QUARTZ	116
PERTOT NMQ	38.33
PERTOT CH	.33
PERTOT MQ	.00
PERTOT MRF	.00
PERTOT MIC	.33
PERTOT FELD	7.00
PERTOT IGRF	37.33
PERTOT UNST	1.33
PERTOT SRF	.00
PERTOT FECEM	.00
PERTOT CACEM	.00
PERTOT SICEM	4.33
PERTOT POR	6.67
PERTOT MATX	3.33
PERTOT NON META	38.67
PERTOT META	.33
PERTOT IGN	44.33
PERTOT FRMWK (FOLK)	83.33
PERTOT CEMENT	4.33
PERTOT QUARTZ	38.67
FOKFRM	83.33
PERFOK(1)	46.4
PERFOK(2)	.4
PERFOK(3)	53.2

THIS SAMPLE IS ARKOSE ACCORDING TO FOLK-S CLASSIFICATION

SAMPLE NO. 9

NMQ	85
CH	2
MQ	0
MRF	0
MIC	1
FEL	24
IGRF	107
UNST	5
SRF	0
FECEM	1
CACEM	1
SICEM	63
POR	3
MATX	8
TOTAL NON-META	87
TOTAL META	1
TOTAL IGN	131
TOTAL FRMWK (FOLK)	219
TOTAL CEMENT	65
TOTAL QUARTZ	87
PERTOT NMQ	28.33
PERTOT CH	.67
PERTOT MQ	.00
PERTOT MRF	.00
PERTOT MIC	.33
PERTOT FELD	8.00
PERTOT IGRF	35.67
PERTOT UNST	1.67
PERTOT SRF	.00
PERTOT FECEM	.33
PERTOT CACEM	.33
PERTOT SICEM	21.00
PERTOT POR	1.00
PERTOT MATX	2.67
PERTOT NON META	29.00
PERTOT META	.33
PERTOT IGN	43.67
PERTOT FRMWK (FOLK)	73.00
PERTOT CEMENT	21.67
PERTOT QUARTZ	29.00
FOKFRM	73.00
PERFOK(1)	39.7
PERFOK(2)	.5
PERFOK(3)	59.8

THIS SAMPLE IS ARKOSE ACCORDING TO FOLK-S CLASSIFICATION

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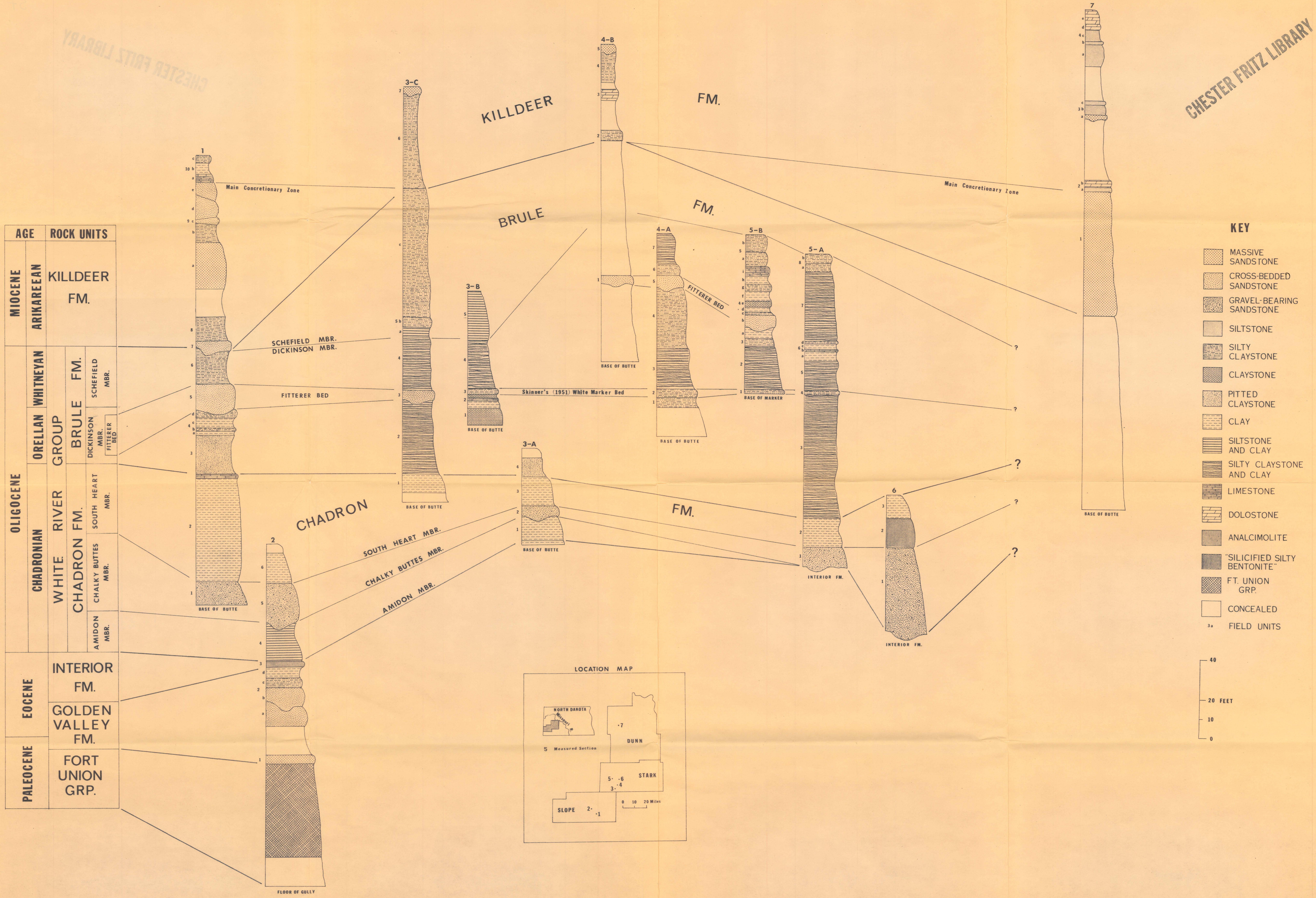

Plate 1 Stratigraphic Cross Section, Middle Cenozoic Deposits, North Dakota