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GEOLOGY OF URANIUM IN THE CHADRON AREA, NEBRASKA AND SOUTH DAKOTA

By

Robert J. Dunham, 1924-

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ABSTRACT

The Chadron area covers 375 square miles about 25 miles southeast of the Black Hills. Recurrent mild tectonic activity and erosion on the Chadron arch, a compound anticlinal uplift of regional extent, exposed 1900 feet of Upper Cretaceous rocks, mostly marine shale containing pyrite and organic matter, and 600 feet of Oligocene and Miocene rocks, mostly terrestrial fine-grained sediment containing volcanic ash. Each Cretaceous formation truncated by the sub-Oligocene unconformity is stained yellow and red, leached, kaolinized, and otherwise altered to depths as great as 55 feet. The composition and profile of the altered material indicate lateritic soil; indirect evidence indicates Eocene(?) age. In a belt through the central part of the area, the Brule formation of Oligocene age is a sequence of bedded gypsum, clay, dolomite, and limestone more than 300 feet thick.

Uranium in Cretaceous shale in 58 samples averages 0.002 percent, ten times the average for the earth's crust. Association with pyrite and organic matter indicates low valency. The uranium probably is syngenetic or nearly so.

Uranium in Eocene(?) soil in 43 samples averages 0.054 percent, ranging up to 1.12 percent. The upper part of the soil is depleted in uranium; enriched masses in the basal part of the soil consist of remnants of bedrock shale and are restricted to the highest reaches of the ancient oxidation-reduction interface. The uranium is probably in the form of a low-valent mineral, perhaps uraninite. Modern weathering of Cretaceous shale is capable of releasing as much as 0.780 ppm uranium to water. Eocene(?) weathering probably caused enrichment of the ancient soil through 1) leaching of Cretaceous shale, 2) downward migration of uranyl complex ions, and 3) reduction by hydrogen sulfide at the water table.

Uranium minerals occur in the basal 25 feet of the gypsum facies of the Brule formation at the two localities where the gypsum is carbonaceous; 16 samples average 0.066 percent uranium and range up to 0.43 percent. Elsewhere uranium in dolomite and limestone in the basal 25 feet of the gypsum facies in 10 samples averages 0.007 percent, ranging up to 0.012 percent. Localization of the uranium at the base of the gypsum facies suggests downward moving waters; indirect evidence that the water from which the gypsum was deposited was highly alkaline suggests that the uranium was leached from volcanic ash in Oligocene time.

INTRODUCTION

LOCATION

The district here termed the Chadron area is on the Great Plains in northwestern Nebraska and southwestern South Dakota, about 25 miles southeast of the Black Hills (fig. 1). The mapped area is an irregular square that includes 375 square miles in Dawes and Sheridan Counties, Nebraska, and Shannon County, South Dakota. The town of Chadron, Nebraska, is in the southwest corner of the area, and the town of Pine Ridge, South Dakota, is in the northeast corner. The southwestern part of the Pine Ridge Sioux Indian Reservation occupies the part of the area in South Dakota.

PURPOSE AND SCOPE OF REPORT

H. A. Tourtelot in August 1953 made a reconnaissance search for uranium in shale in the central Great Plains in the course of the Geological Survey's search for uranium in carbonaceous materials. In the Chadron area, he (1956) found radioactive shale in the Sharon Springs member of the Pierre shale of Late Cretaceous age, and in the Niobrara formation of Late Cretaceous age where the latter unconformably underlies Oligocene tuffaceous rocks. The area was therefore chosen by the Geological Survey as one to be investigated in detail on behalf of the Raw Materials Division of the United States Atomic Energy Commission. Objectives were to investigate the extent and uranium content of known occurrences, and to search for mineable deposits. Detailed study of the associated rocks provided data for interpreting the origin of uranium occurrences.

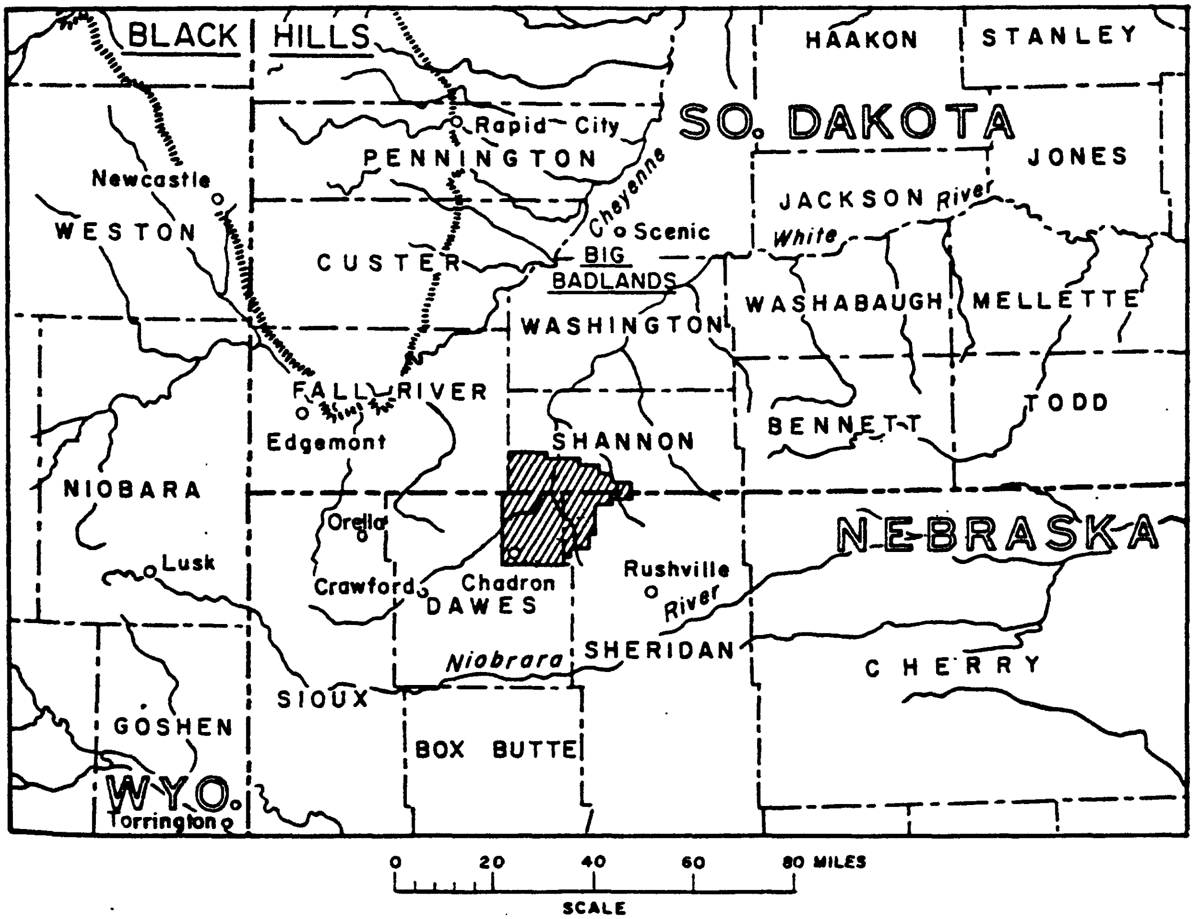

FIGURE 1.--Index map showing location of Chadron area.

PREVIOUS WORK

Before the present investigation in 1954, no detailed geological survey had been made of the Chadron area, but general surveys indicated its broader geologic features. Darton (1899, 1903) made the first geologic map showing the Chadron area, in connection with his report on the underground water resources of western Nebraska. Later Darton (1918) published a structure contour map delineating the Chadron arch by 100-foot contours on the Dakota sandstone of Early Cretaceous age. Lugn (1939) published a more detailed geologic map in his "Classification of the Tertiary System in Nebraska". Members of the State Museum and the Department of Geology of the University of Nebraska have been studying the stratigraphy of the Tertiary strata in northwestern Nebraska since 1933; three unpublished theses deal with parts of the Chadron area. Knoop (1953) and Tychsen (1954) discuss the sedimentary environment of the Chadron and the Brule formations of Oligocene age, and include the southern part of the Chadron area in their maps of the extent of outcrop of the two formations. Moore (1954) reviews Cretaceous stratigraphy in the central part of the Chadron area. The United States Department of Agriculture surveyed the soils of Dawes County, Nebraska (Burn and others, 1917), and Sheridan County, Nebraska (Hayes and others, 1921); the reports include soil maps on the scale of 1 inch equals 1 mile. The distribution of soil types accords with the distribution of rock types to a striking degree in parts of the Chadron area.

Tourtelot (1956) discusses the uranium content and radioactivity of the Sharon Springs member of the Pierre shale and of what is here termed the Eocene(?) soil.

PRESENT WORK

Field work lasted five months in the summer and fall of 1954. Air photographs on the scales of 1:20,000 and 1:31,680 were studied stereoscopically in the field and in the office, and field data were recorded directly on the photographs. The geologic data, drainage, culture, and recovered section corners plotted on the photographs were transferred by means of a vertical sketchmaster to the base, which was compiled from U. S. General Land Office township plats. Aneroid barometer traverses originating at a benchmark established by the U. S. Coast and Geodetic Survey at the Pine Ridge Indian Agency provided a network of 50 readily accessible stations for vertical control. Stratigraphic sections were measured by planetable and alidade or by handlevel and tape.

Laboratory work and interpretation of data lasted eight months in the office in 1955, and a total of thirteen months in 1956-61. The Exploration and Production Research Laboratory of Shell Development Company kindly provided facilities for the later office work.

ACKNOWLEDGEMENTS

Many people helped the investigation; their aid is acknowledged with appreciation and pleasure. Thomas M. Kehn of the U. S.

Geological Survey assisted in the field for two months and collected most of the channel samples of the Sharon Springs member of the Pierre shale. Eugene C. Reed, State Geologist of Nebraska, supplied subsurface information on wells drilled for oil or gas in and near the Chadron area. W. A. Cobban identified fourteen collections of marine molluscs; D. H. Dunkle identified a collection of fish scales; E. B. Leopold extracted and identified the pollen in two collections of uraniferous gypsum; Edward Lewis identified twelve collections of vertebrate fossils; and I. G. Sohn identified two collections of fresh water ostracods; all are members of the Geological Survey. Richard Rezak of Shell Development Company determined the abundance of coccoliths in 9 samples. R. W. Barker of Shell Development Company identified foraminifera in 13 samples. Geological Survey analysts prepared chemical, mineralogic, radiometric, spectrographic, or permeability analyses of more than five hundred samples; the analysts include J. W. Adams, C. Angelo, H. Bivens, Evelyn Cisney, G. Daniels, R. Daywitt, M. Finch, Irving Frost, S. Furman, R. F. Cantnier, J. Gude III, A. E. King, R. Havens, H. Lipp, B. A. McCall, J. McClure, T. Miller, R. Moore, W. F. Outerbridge, J. Rosholt, J. Schuch, D. L. Skinner, A. Sweeney, R. L. Wack, J. Wahlberg, and J. E. Wilson. J. F. Burst and H. F. Young of Shell Development Company supplied supplementary analyses of 2 samples.

I am especially indebted to Professors John Rodgers, M. L. Jensen, J. T. Gregory, and K. M. Waage, of Yale University, who read the manuscript and offered helpful criticism. This report was presented as a thesis in partial fulfillment of the requirements for the degree of doctor of philosophy at Yale University in May 1961. The Director of the Geological Survey for this purpose kindly gave his approval for the report to be placed in open file in advance of its publication. The management of Shell Development Company has been more than gracious in helping the work to completion.

Finally, I am grateful to many former colleagues in the Geological Survey, who gave generously of their time, suggestions, and critical abilities. N. M. Denson, James Gilluly, and H. A. Tourtelot were particularly helpful at different stages of the work.

GEOGRAPHY

The major physiographic feature of the Chadron area is Pine Ridge, the north-facing intricately dissected escarpment that crosses the southern part of the area. To the south is the Dawes Table, which is one of the nearly flat northern reaches of the High Plains division of the Great Plains province; to the north is the White River lowland, which is gently rolling country in the unglaciated part of the Missouri Plateau division of the Great Plains. The Pine Ridge stands about a thousand feet above the White River, which is at an altitude of about 2990 feet in the northern part of the area. Bordeaux Creek, Beaver Creek, and White Clay Creek, all tributaries of the White River, head in Pine Ridge; Slim Butte Creek, Lime Kiln Creek, and Little Beaver Creek, which are also tributaries of the White River, head in the lowlands.

The climate of the area is characterized by low precipitation, high evaporation, and wide range of temperature. Records of the Weather Bureau station at Fort Robinson, near Crawford, Nebraska, give a mean annual precipitation of 16.91 inches. About 48 percent of the precipitation falls during May, June, and July. Evaporation exceeds precipitation, as shown by pedocal soil and vegetation. Mean annual temperature is about 47° F.; the mean for January is 23.1° F., and the mean for July is 71.1° F.; extremes range from -37° F. to 106° F. Pine and other trees flourish on the slopes of Pine Ridge and along the major watercourses; most of the other land is in grass and low bushes such as sage. Stock raising is the chief form of agriculture.

Chadron, the largest town in the area and the county seat of Dawes County, had in 1950 a population of 4,687. The Chicago, Burlington and Quincy Railroad serves the area. Access by automobile is provided by U. S. Routes 19 and 54, and Nebraska Route 59. For further information about geography, see Burn, Davis, Snyder, Hayes, and Kokjer (1917), and Hayes, Wolfanger, Bedell, Britton, Taylor, and Deutsch (1921).

STRATIGRAPHY

GENERAL

The sedimentary rocks at the surface in the Chadron area are about 2,500 feet thick and are divisible into formations well known in other areas. Included are the Belle Fourche shale, the Greenhorn limestone, the Carlile shale, the Niobrara formation, the Pierre shale, all of Late Cretaceous age, the Chadron formation and the Brule formation of Oligocene age, and the Arikaree group of Miocene age. The unconformity at the base of the Chadron formation bevels 1,300 feet of Carlile shale and younger Cretaceous formations, each of which is deeply weathered to fossil soil. Thickness and lithologic character of the outcropping units are shown graphically in a generalized columnar section (fig. 2), which also includes brief descriptions; distribution is shown on Plate 1.

Concealed from view is a section of older rocks comparable in thickness to that exposed at the surface. Four wells penetrated the whole concealed sedimentary section, and found it to be about 2,900 feet thick. Formations represented are the Minnelusa formation and the Opeche formation, which in the Chadron area are of Pennsylvanian and Permian age, the Minnekahta limestone and the Spearfish formation of Permian age, the Sundance formation and the Morrison formation of Jurassic age, the Lakota formation, Fall River formation, Skull Creek shale, Newcastle formation, Mowry shale, and Belle Fourche shale, of Cretaceous age.

SYSTEM	Series	Formation		Section	Thickness (feet)	Character of rocks
TERTIARY	Miocene	Arikaree group	Monroe Creek formation		53 +	Grayish orange siltstone and very fine grain sandstone with thick white ash beds and calcareous concretions, massive, weakly resistant.
			Gering formation		0 - 160	Yellowish gray siltstone and very fine grain sandstone with thin white ash beds, locally conglomeratic, cross-bedded, well-stratified, resistant.
	Oligocene	White River group	Brule formation		195 - 300	Lower part consists of varicolored siltstone, mudstone, and arkosic sandstone; upper part consists of flesh-pink siltstone; grades into gypsum, clay, dolomite, and limestone in central part of area.
			Chadron formation		75 - 115	Greenish gray montmorillonitic claystone overlain by light green silty mudstone and underlain locally by sandstone and red claystone.
	Eocene (?)	Residual soil			0 - 55	Kaolinitic clay mottled red, yellow, white, and purple; contains concretions of iron oxide; grades downward into yellow oxidized rock; developed on Pierre, Niobrara, and Carlile formations.
CRETACEOUS	Upper cretaceous	Pierre shale	upper part		300 +	Gray noncalcareous shale, locally sandy; lower 95 feet contains limestone concretions bearing numerous *Baculites corrugatus*; upper 130 feet contains large isolated *Baculites grandis*.
			middle part	400 feet	900	Gray and brownish gray noncalcareous shale with limestone concretions; lower 75 feet contains numerous sideritic ironstone concretions, many of which are casts of *Baculites gregoryensis*; upper 125 feet are characterized by dark gray montmorillonitic clay with manganese-iron concretions.
			Sharon Springs member		65 - 105	Hard fissile dark gray shale interbedded with bentonite; contains minute pyrite blebs, large limestone concretions, and numerous fragmental fish remains.
		Niobrara formation			300	Chalk or limestone, and calcareous gray shale.
		Carlile shale			300	Orange-weathering silty slightly calcareous gray shale with silty limestone concretions constitutes the lower 140 feet; the middle 60 feet consists of silty shale and shaly crossbedded very fine-grained sandstone; the upper 100 feet consists of dark gray noncalcareous shale containing persistent zones of large limestone concretions.
		Greenhorn ls and Belle Fourche sh			35 +	Dark gray shale overlain by 25 feet of interbedded limestone and calcareous shale.

FIGURE 2.--Generalized columnar section of rocks exposed in Chadron area.

Thickness and lithologic character of the concealed units are described by Baker (1953, p. 87-93) from the Amerada Petroleum Corp., Red Eagle No. 1, sec. 25, T.26N., R.48W., Shannon County, South Dakota.

CRETACEOUS

Belle Fourche Shale and Greenhorn Limestone

Definition

The name Belle Fourche shale was used by Rubey (1930, p. 4) for a 350 to 1,000-foot sequence of black shale and mudstone overlying the Mowry shale in the Black Hills. The name Greenhorn limestone was used by Gilbert (1896, p. 564) for a 25 to 40-foot sequence of thin-bedded limestone and shale underlying the Carlile shale near Pueblo, Colorado.

Description

The only exposure of the Belle Fourche shale and Greenhorn limestone in the Chadron area is in a cutbank on the north side of the White River in sec. 33, T.35N., R.47W. At this place 10 feet of dark gray shale grades upward into 25 feet of light gray limestone. The shale contains thin beds of limestone and calcareous shale in its upper part. The limestone, which occurs in beds a few inches thick, contains thin layers of light gray very calcareous shale and dark gray less calcareous shale.

As seen in the field, shells of Inoceramus labiatus are a prominent part of the limestone. Many shells are broken. In the laboratory, mud-sized particles of lime, in which are scattered fragments of Inoceramus and calcareous globular foraminifera similar to Globigerina, are seen to form the bulk of the limestone. Judging by observations made elsewhere by Richard Rezak of the Shell Development Company, the mud-size particles of lime probably are skeletal parts of unicellular calcareous algae called coccoliths. In this respect, the limestone would resemble chalk or limestone in the Niobrara formation, except for being harder.

The top of the Greenhorn limestone is poorly exposed but appears to grade upward into the slightly calcareous lower part of the Carlile shale.

Age

The Belle Fourche shale and Greenhorn limestone are assigned to the Cenomanian and Turonian stages of the Upper Cretaceous series. (Reeside, 1957).

Carlile Shale

Definition

The name Carlile shale was proposed by Gilbert (1896, p. 565) for a sequence of gray shale near Pueblo, Colorado. The shale there lies above the Greenhorn limestone and below the Timpas limestone, which is a partial equivalent of the Niobrara formation. In the type area, the Carlile shale is about 200 feet thick.

Description

In the Chadron area, the Carlile shale is about 300 feet thick and is divisible into three parts, which were not mapped. Siltstone and sandstone characterize the middle part. Kind of ncretion and sedimentary structure characterize the lower and upper parts. The Carlile shale is exposed along the White River and its tributaries Beaver Creek and Lime Kiln Creek. The lower and middle parts of the formation generally form grassy lowlands. The upper part of the formation is well exposed beneath bluffs formed by chalk on limestone beds in the Niobrara formation. The best exposure of the formation is in sec. 28, T. 35 N., R. 47 W., near where Beaver Creek meets the White River. The following section was measured on the north side of the river.

Section of Carlile Shale,
Sec. 28, T. 35 N., R. 47 W.,
Dawes County, Nebraska

	Feet
Niobrara formation	
Carlile shale:	
Upper part:	
Shale, dark (5Y 5/1), noncalcareous; silt or sand not detected	17
Mudstone, yellowish gray, slightly silty, noncalcareous	5
Septarian concretion zone 1	1.5
Mudstone, yellowish gray, silty, noncalcareous	23
Septarian concretion zone 2	1
Mudstone, yellowish gray, silty, noncalcareous	30
Septarian concretion zone 3	2

Feet

Mudstone, yellowish gray (5Y 7/2), silty, noncalcareous; silt is disseminated in clay, not in laminae......................20

Septarian concretion zone 4.................... 1

Mudstone, brownish gray (5Y 6/1), sandy, silty; sand and silt are abundant and are disseminated in clay........................ 9

Middle part:

Sandstone, brown, very fine grained, and interbedded dark (5Y 4/1) noncalcareous shale; sandstone forms ledges 2 to 6 inches thick, and is finely cross-laminated, exhibits flute casts on under surfaces and ripple marks on upper surfaces; weathers into plates a foot across and a quarter inch thick.......15

Lower part:

Shale, dark (5Y 4/1), noncalcareous, and interlaminated siltstone; siltstone beds are one inch thick, delicately laminated, and constitute 10 percent of interval, some parts having almost 50 percent..........35

Laminated concretion zone; numerous small Scaphites................................. 1

Shale, gray (5Y 4/1), noncalcareous, and interlaminated light brown soft siltstone; siltstone is about 20 percent of interval....20

Shale, gray (5Y 4/1), and interlaminated light brown soft siltstone; largely covered.....................................30

Limestone, fossiliferous; fossils much broken; contains much very fine grained sand and mica; forms resistant beds one-half inch to two inches thick, making topographic bench... 1

Shale, orange (10YR 6/4), slightly calcareous, and interlaminated soft siltstone; largely covered............................57

	Feet
Laminated concretion zone........................	0.5
Shale, orange (10YR 6/4), slightly calcareous, and sparse interlaminated soft siltstone; largely covered....................	35

Greenhorn limestone Total measured 304

The lower part of the Carlile shale is about 140 to 175 feet thick. It consists of black or dark shale and laminae of siltstone. The shale weathers orange, suggesting the presence of oxidizing pyrite or siderite. The shale is slightly calcareous near the top of the Greenhorn limestone. It becomes less calcareous upward and is noncalcareous above the midway mark. Siltstone laminae become more frequent and thicker upward in the sequence. Near the base of the formation, the laminae are less than a millimeter thick and siltstone constitutes less than 10 percent of the rock; near the top of the lower part of the Carlile shale the silt layers are as thick as a half inch and siltstone constitutes almost 50 percent of the rock. These thicker layers are themselves clearly laminated on the scale of fractions of millimeters. The siltstone laminae hardly deserve to be called stone, for the grains are as loosely cemented as though freshly sedimented.

Concretions occur in the lower part of the Carlile shale. Large laminated concretions, 1 x 4 feet, occur as a near continuous layer near the top of the lower part of the Carlile shale. Smaller laminated concretions, 1 x 1.5 feet, occur in the middle of the unit in lesser abundance. A few discontinuous layers of laminated silty limestone a half inch thick, which probably also are concretions, are associated with them. The discontinuous layers contrast with an associated continuous thin bed of broken shells in a matrix of quartzose micaceous very fine-grained sandstone. The concretions in the lower part of the Carlile shale differ from those in the upper part in being laminated with silt. Silt laminae seem to pass from matrix into concretion without interruption, but better exposures are needed to be sure. Veining and cone-in-cone structure are absent. The concretions weather into bold relief, and acquire a tan or brown color suggesting the presence of oxidizing pyrite or siderite. All fossils collected from the lower part of the Carlile shale came from concretions or from the one bed of fossiliferous sandstone. In the concretions, the fossils are concentrated in thin layers parallel to lamination.

The top and bottom of the lower part of the Carlile shale appear to be gradational by interbedding. The top definitely is.

The middle part of the Carlile shale is about 15 to 50 feet thick. It represents the continuation of the upward trend toward greater abundance of siltstone seen in the lower part. It differs from the lower part in having no concretions and in containing some beds of slightly greater grain size. The middle part of the Carlile shale is about 50 percent siltstone or very fine-grained sandstone; the remainder is dark noncalcareous shale. Dark minerals, mica, and fish scales are abundant constituents of the sandstone. Dark grains of carbonaceous matter are present. The middle unit exhibits the same delicate and parallel lamination of material of different grain size that is seen in the lower unit. Exceptions are a few two- to six-inch beds of resistant limey sandstone that are cross-laminated. Change in thickness of beds was not observed. Comparisons of total thickness indicate that the beds do wedge out, although gradually. Weathering produces plates a foot or so across and about a quarter inch thick. The top surface of some of the cross-laminated beds is ripple marked on a scale comparable to the cross-lamination. Cross-laminated beds characteristically contain concentrations of worn small sturdy Inoceramus in their lower one inch. The under surface of some of the cross-laminated beds show small flute casts. The beds having flute casts are not prominently graded, but the under-surface definitely is more sharply defined than the upper surface. The resulting resemblance to graded bedding can be seen in photomicrographs by Rubey (1930, Pl. 4).

The base of the middle part of the Carlile shale is gradational by interbedding. The top is abrupt and irregular. The irregularities seem to be due to burrowing instead of erosion.

The upper part of the Carlile shale is about 110 feet thick. It is black or dark shale that differs markedly from the underlying units in its texture. Instead of the contained silt and sand grains being arranged in layers, they are intimately mixed with clay to make shaly mudstone. The amount of silt and sand decreases upward and the upper 15 feet is practically free of silt and sand grains.

Tan- or brown-weathering septarian concretions occur at several levels in the upper part of the Carlile shale. Fossils were not found in the concretions examined. Four levels can be differentiated at the locality referred to as having the best exposure of the Carlile shale, and at most other exposures. The highest is about 15 feet below the Niobrara formation and the lowest is at the base of the upper part of the Carlile shale. The druse-lined cracks that differentiate septarian concretions from other concretions are better developed in the upper levels than in the lowest one. Some of the cracks are as much as 3 inches wide in places. The cracks, which are mainly radial, are lined with coarsely crystalline calcite of different colors. The calcite of the first layer lining the wall of the crack is commonly darker colored than later layers. From the wall outward, a common sequence is brown, then orange or deep yellow, then light slightly greenish yellow. For each level, the size of the concretions, their height-width ratio, and their frequency are persistent for considerable distances. In the upper levels the concretions are one or two feet wide and somewhat more than half as high. They occur one every few feet along the outcrop and maintain about the same stratigraphic position. In the lowest level, concretions are about the same size, but they occur only one in about 50 feet and their stratigraphic position ranges through an interval of 5 feet. The lower contact of the upper part of the Carlile shale is abrupt, as mentioned; the upper contact appears to be gradational.

Bentonite is absent in the Carlile shale of the Chadron area; Spivey (1940, p. 13) found none in the southern Black Hills, except for a thin bed at one locality. In this respect, the Carlile shale differs from similar black shale in the Graneros formation and Pierre shale, and from the Niobrara formation. Pyrite in the Carlile shale of the Chadron area is sufficiently abundant to cause limonite staining and gypsum crystals. Rubey (1930, p. 8) analyzed two samples from the Black Hills and found 0.1 and 0.2 percent pyrite. The same samples contained 1 and 3 percent organic matter. The sample having the more pyrite had the more organic matter.

Scaphites and *Inoceramus* are fairly abundant in the lower part of the Carlile shale. W. A. Cobban (1955, written communication) identified one collection from the NE 1/4 NW 1/4 sec. 28, T.35N., R.47W., USGS Mesozoic locality D203. It contained:

Scaphites larvaeformis Meek and Hayden

Scaphites praecoquus Cobban

Collignoniceras woolgari (Mantell)

Inoceramus fragilis Hall and Meek

Trigonocallista? sp.

Carbonaceous matter and fish scales occur in sandstone or siltstone beds in the middle part of the Callile shale. The larger scales are an inch across. D. H. Dunkle (written communication, 1955) examined a collection of scales from a bedding plane and says that they "conform in size and all other characteristics to *Ichthyodectes*". *Ichthyodectes* belongs to the order Isopondyli, which includes tarpon, trout, and salmon.

Inoceramus and ammonites occur in the upper part of the Carlile shale. A collection from the SW 1/4 SW 1/4 sec. 12, T. 34 N., R. 47 W., USGS Mesozoic locality D204, was identified by W. A. Cobban (written communication, 1955). It contained:

Inoceramus cf. *I. lamarcki* Parkinson

Prionocyclus wyomingensis Meek

Age

Two of the ammonites collected from the Carlile shale are recognized by Cobban and Reeside (1952) as zonal indices to the upper part of the Turonian stage of the Upper Cretaceous series. *Collignoniceras woolgari* occurs high in the lower part of the Carlile shale of the Chadron area. *Prionocyclus wyomingensis* occurs low in the upper part of the Carlile shale, about 50 feet above *Collignoniceras woolgari*.

Niobrara Formation

Definition

The name Niobrara division, or Niobrara formation, was proposed by Meek and Hayden (1862, p. 419-422) for a sequence of calcareous rocks in the bluffs of the Missouri River near Niobrara, Nebraska. The sequence lies above the Carlile shale and below the Pierre shale, and is about 200 feet thick. It consists of light yellowish and whitish limestone or chalk overlain by lead-gray very calcareous shale or marl that weathers yellow or whitish.

Description

The Niobrara formation in the Chadron area is taken to include the lowest calcareous rocks above the Carlile shale and the highest calcareous rocks below the Pierre shale, both of which are noncalcareous near their contact with the Niobrara formation. The Niobrara formation crops out in the central and northern parts of the Chadron area. The best and most accessible exposures are in sec. 16, T. 35 N., R. 47 W., Shannon County, South Dakota. The more resistant parts of the formation form rough country characterized by wooded intricately dissected bluffs, which border lowlands of Carlile shale. The bluffs tend to retreat by slumping. As a result, blocks of otherwise undisturbed Niobrara formation hundreds of yards across occur 50 feet or more below their original level. Less resistant parts of the formation weather to low slopes characterized by small hummocks. The hummocks owe their existence to the protection from erosion that is afforded by sage bushes.

The thickness of the Niobrara formation is not easily determined; complete exposures are scarce, and the formation is cut by many small faults. Logs from wells in Dawes, Sheridan, Fall River, and Shannon counties indicate that the formation ranges in thickness from 250 to 340 feet. Outcrops in the relatively well exposed area in sec. 16, T. 35 N., R. 47 W., give a total thickness of about 325 feet. The following section was measured:

noncalcareous shale, one is limestone from a concretion. Coccoliths are absent in the shale, and present but recrystallized in the limestone concretion. Rezak examined several samples of noncalcareous shale collected by James Gill and H. A. Tourtelot from a well in Ziebach County, South Dakota, east of the Chadron area, from about the same stratigraphic interval. He found coccoliths to be absent, or scarce and fragmentary.

Upper Part of Pierre Shale

The upper part of the Pierre shale remaining in the Chadron area is about 300 feet thick. It is characterized by concretions different from those in other units. The shale of the upper part of the Pierre shale is light olive gray (5Y 6/1 to 5Y 7/2) and is noncalcareous. A sample X-rayed by J. Gude showed quartz, montmorillonite, illite, and feldspar, listed in order of decreasing abundance. The shale is unlike the lower parts of the Pierre shale in containing feldspar and in lacking kaolinite. In the most southwesterly exposure the shale is rich in disseminated grains of terrigenous sand and silt, some of which are feldspar of medium grain size.

Concretions peculiarly rich in ammonites and other fossils characterize a 40-foot interval about 55 feet above the base of the upper part of the Pierre shale. The concretions are spaced about 30 feet apart laterally and are concentrated at several levels. The concretions are a foot or two in diameter, almost spherical, and variably septarian. They weather white. They consist of dark silty lime plus an amazing concentration of fossils. A single concretion contains as many as 50 fossils, mostly ammonites. The 50 individuals are assorted kinds including various species of Baculites, Scaphites, Inoceramus, Ostrea, and snails. Baculites are particularly numerous. Small and large individuals occur together. These Baculites differ from those found elsewhere in the Pierre shale in the Chadron area in that their aragonite shell and its inherent pearly luster was not destroyed by postdepositional alteration. The arrangement or packing of the fossils within a concretion is puzzling in several ways. The fossils are not in layers nor do they lie parallel to bedding, as would be expected from ordinary sedimentation, and as occurs in the laminated concretions in the Carlile shale. Instead they are jumbled all together. Whether the fossils rest one on the other so as to form a self-supporting framework or rest wholly on mud is a question awaiting further work. In the less fossiliferous ones, fossils appear to rest wholly on mud. Work with the hammer suggests that the fossils are more concentrated in the marginal part of concretions than in the interior. Laboratory work is needed to confirm this observation. The shells show few or no signs of breakage or toothmarks; nor have they been bored by perforating algae or other borers. The living cavities are filled or partly filled with silty fine limestone, not with the sparry calcite that is precipitated chemically in voids.

Concretions also occur in the upper 100 feet of the upper part of the Pierre shale. They are quite different. Each is the lithified filling of the interior of a single large Baculites from which the shell is gone. The molds are calcareous clay that weathers pink, presumably because the clay is sideritic. Most are as large as a man's arm. All belong to one species, Baculites grandis, which is unusual in being larger than any other Baculites found in Cretaceous rocks of the Western Interior region.

Between the two limy concretion intervals in most places the soil contains scattered 2-inch ellipsoidal nodules of phosphate. The nodules consist of a white rind about 1/4-inch thick around a dark gray (N3) interior. Thin, more or less discontinuous layers of white-weathering silty limestone, perhaps concretionary, occur at various levels in the upper part of the Pierre shale. A typical layer consists of lenses about 3 inches thick and 3 feet in diameter. The lenses contain many small clams and snails and but few ammonites, which are small.

The lighter color of the middle and upper parts of the Pierre shale might be taken as a clue to pyrite and organic matter being scarce. Present day weathering produces only a faint brown discoloration, except in the interval that bears siderite concretions. These indications may be deceiving, for Rubey's (1930, p. 8) analyses show gray mudstone from the upper part of the Pierre shale in the Black Hills to contain 1 percent pyrite and 2 percent organic matter.

The abundance of molluscs in the upper part of the Pierre shale, particularly Baculites, has been mentioned. W. A. Cobban (written communication, 1955) identified the following species:

Fossils from the Upper Part of the Pierre Shale

Yoldia evansi (Meek and Hayden)	12, 17, 27
Trigonia (Breviarca) exigua (Meek and Hayden)	8
Breviarca species	17
Inoceramus barabini Morton	6, 17
Inoceramus barabini Morton var. inflatiformis Douglas	11
Inoceramus cf. I. barabina Morton	8
Inoceramus mclearni Douglas	8, 16, 19
Inoceramus sagensis Owen	7, 9, 12, 15, 16, 17, 18, 19
Inoceramus cf. I. sagensis Owen	6
Inoceramus (Endocostea) cf. I. sulcatus Roemer	14
Inoceramus vanuxemi Meek & Hayden	10, 11, 14, 16, 17, 19
Inoceramus aff. I. vanuxemi Meek and Hayden	8
Inoceramus species	13, 21
Ostrea cf. O. inornatus Meek and Hayden	8, 12
Ostrea patina Meek and Hayden	16
Ostrea species	6, 7, 17, 20
Pecten (Syncyclonema) hallii Gabb	7, 8
Pteria linguaeformis (Evans & Shumard)	14, 16, 17
Pteria (Oxytoma) nebrascana (Evans & Shumard)	8
Anomia cf. A. concentrica Meek	16
Anomia cf. A. gryphorhynchus Meek	12
Anomia aff. A. subquadrata Stanton	8
Anomia cf. A. tellinoides Morton	19
Lucina occidentalis Morton	19
Lucina subundata Hall and Meek	16
Lucina species	12
Parmicorbula species	17
Dosinopsis? nebrascensis (Meek and Hayden)	14, 17
Dentalium pauperculum Meek and Hayden	6
Acmaea? parva (Meek and Hayden)	16, 17
Polinices concinna (Hall and Meek)	12, 16
Drepanocheilus evansi Cossman	17
Fusus cheyennensis Whitfield	8
Fusus cf. F. dakotensis Meek and Hayden	18
Pyrifusus aff. P. newberryi (Meek and Hayden)	14
Tornatellaea cf. T. globulosa Wade	17
Cylichna glans-oryza (Whitfield)	8
Eutrephoceras montanense (Meek)	14, 17
Eutrephoceras species	19
Baculites compressus Say (early form)	13, 16, 19
Baculites compressus Say	7
Baculites corrugatus Elias	6, 17
Baculites corrugatus Elias (late form)	8, 11, 12, 13, 14, 15, 16, 19

Baculites cf. B. corrugatus Elias	20
Baculites grandis Hall and Meek	21, 22, 23, 24, 25, 26, 27, 28
Baculites new species	8, 12, 13, 14, 16, 17, 19
Baculites species	9, 10, 18
Solenoceras meekanum (Whitfield)	14, 17
Didymoceras? cheyennense (Meek & Hayden)	14, 15, 17
Didymoceras? species	9
Acanthoscaphites brevis (Meek)	6, 14, 16, 17
Acanthoscaphites quadrangularis (Meek & Hayden)	13
Acanthoscaphites cf. A. quadrangularis (Meek and Hayden)	14, 17
Acanthoscaphites species	7, 10, 19
Placenticeras intercalare Meek	14
Placenticeras meeki Boehm	11, 13
Placenticeras cf. P. meeki Boehm	20

6. D212, SE 1/4 SE 1/4 sec. 5, T. 34 N., R. 48 W., Dawes County, concretions probably 50 to 100 feet above base of upper part.
7. D213, SE 1/4 SE 1/4 sec. 15, T. 35 N., R. 48 W., Shannon County, concretions 50 to 100 feet above base of upper part, 115 feet below lowest occurrence of Baculites grandis.
8. D215, SW 1/4 NW 1/4 sec. 28, T. 34 N., R. 48 W., Dawes County, concretions probably 50 to 100 feet above base of upper part.
9. D216, NW 1/4 NE 1/4 sec. 36, T. 34 N., R. 48 W., Dawes County, concretions probably 50 to 100 feet above base of upper part, possibly higher.
10. D217, NW 1/4 SW 1/4 sec. 19, T. 34 N., R. 47 W., Dawes County, shale in upper part.
11. D218, NE 1/4 NE 1/4 sec. 35, T. 35 N., R. 48 W., Dawes County, concretions 50 to 100 feet above base of upper part.
12. D219, SW 1/4 NE 1/4 sec. 14, T. 35 N., R. 48 W., Shannon County, limestone bed 15 feet above base of upper part.
13. D220, SW 1/4 NW 1/4 sec. 12, T. 35 N., R. 48 W., Shannon County, concretions 55 to 75 feet above base of upper part.
14. D221, south bank of White River, NE 1/4 NE 1/4 sec. 7, T. 34 N., R. 47 W., Dawes County, concretions probably 50 to 100 feet above base of upper part.
15. D222, NW 1/4 NE 1/4 sec. 7, T. 34 N., R. 47 W., Dawes County, concretions probably 50 to 100 feet above base of upper part.
16. D223, SW 1/4 NE 1/4 sec. 23, T. 35 N., R. 48 W., Dawes County, concretions in 8-foot interval probably 50 to 100 feet above base of upper part.

17. D224, SW 1/4 NE 1/4 sec. 23, T. 35 N., R. 48 W., Dawes County, concretions in 20-foot interval lying 17 feet above D223.
18. D225, NW 1/4 NE 1/4 sec. 21, T. 35 N., R. 48 W., Dawes County, shale probably 50 feet higher than D224.
19. D234, NE 1/4 SE 1/4 sec. 36, T. 34 N., R. 49 W., Dawes County, deeply weathered shale probably in lower few hundred feet of upper part.
20. D235, NE 1/4 SE 1/4 sec. 36, T. 34 N., R. 49 W., Dawes County, deeply weathered shale about 50 feet above D234 and 0 to 50 feet below sandstone in upper part.
21. D233, SE 1/4 SW 1/4 sec. 36, T. 35 N., R. 48 W., Dawes County, limestone lens 8 feet below shale bearing large pink internal molds of Baculites grandis high in upper part.
22. D232, SE 1/4 SW 1/4 sec. 36, T. 35 N., R. 48 W., Dawes County, shale high in upper part, 8 feet above D233.
23. D226, SE 1/4 NE 1/4 sec. 29, T. 35 N., R. 48 W., Dawes County, shale high in upper part.
24. D227, NE 1/4 NW 1/4 sec. 18, T. 35 N., R. 48 W., Shannon County, shale high in upper part.
25. D228, roadcut in NW 1/4 NW 1/4 sec. 29, T. 35 N., R. 48 W., Dawes County, shale high in upper part.
26. D229, NW 1/4 NW 1/4 sec. 8, T. 34 N., R. 47 W., Dawes County, shale high in upper part.
27. D230, NE 1/4 SE 1/4 sec. 35, T. 35 N., R. 48 W., Dawes County, shale associated with unfossiliferous concretions high in upper part.
28. D231, NW 1/4 NW 1/4 sec. 1, T. 34 N., R. 48 W., Dawes County, pink limestone concretion high in upper part.

Studies of foraminifera in or near the Chadron area are not available. Coccoliths are scarce in the shale in the Chadron area, according to one sample examined by Richard Rezak (written communication, 1959); they are abundant, but poorly preserved, in one sample of thin clamshell-limestone. Rezak (written communication, 1958) found coccoliths to be abundant farther east, in Ziebach County, South Dakota, where rocks in about the same stratigraphic position (Mobridge member) are slightly calcareous.

The upper surface of the Pierre shale in the Chadron area is an unconformity. Oligocene rocks deposited on the land overlie Pierre shale; record of the withdrawal of the Cretaceous sea from the Chadron area is absent.

Age

W. A. Cobban identified 29 lots of fossils from the Pierre shale of the Chadron area. Of the 15 ammonite zones into which he has subdivided the Pierre shale, 5 ammonite zones are represented in the Chadron area.

The Sharon Springs member, which is nearly barren of fossils useful in dating, yielded one collection of _Baculites_ _haresi_ Reeside and _Baculites_ aff. _B_. _asper_ Morton. Cobban reports "These ammonites have been found in rocks equivalent to the Eagle sandstone of Montana and in the overlying rocks (Claggett shale and equivalent units.)" The Sharon Springs member of the Pierre shale of the reference section overlies the Eagle sandstone of the reference section. Both belong to the early part of the Campanian stage.

The middle part of the Pierre shale yielded from its lower 10 feet many _Baculites_ aff. _B_. _asperformis_ Meek and _Baculites_ aff. _B_. _gregoryensis_ Cobban, of which 3 collections were identified by Cobban. Cobban reports this fauna occurs also in the upper part of the "Rusty Zone" of the Pierre shale along the Front Range in Colorado, beneath the Hygiene sandstone, which contains the Baculites _gregoryensis_ fauna. About 50 feet above the base of the middle part of the Pierre shale occurs _Baculites_ _gregoryensis_ Cobban, associated with

Inoceramus barabini Morton. Cobban reports, "The ammonite is known only from rocks equivalent to the Gregory member of the Pierre shale of the Missouri Valley area in central South Dakota." He considers the Gregory member to be of late Campanian age.

The upper part of the Pierre shale yields fossils at many localities. Collections from 23 were examined by Cobban. Of the collections from the lower concretion zone of the upper part of the Pierre shale, Cobban reports "most of these seem to represent a zone younger than that of typical *Baculites corrugatus* and older than that of typical *Baculites compressus*....This zone, marked by the late form of *B. corrugatus*, characterizes the uppermost part of the Monument Hill bentonitic member of the Pierre shale on the northwest flank of the Black Hills uplift. The lower part of the Monument Hill member contains the typical form of *B. corrugatus*. *Baculites corrugatus* also occurs in the black manganiferous ironstones that are so characteristic of the DeGrey member of the Pierre shale along the Missouri River valley near Chamberlain, South Dakota. Unfortunately the DeGrey specimens are too fragmentary and too few in number for determining which of the two *corrugatus* levels they represent." The DeGrey is considered to be of late Campanian age.

The *Baculites grandis* of the upper 100 feet of the upper part of the Pierre shale is, according to Cobban, "a splendid guide to rocks equivalent to the basal part of the calcareous Mobridge member of the Pierre shale of central South Dakota." He considers *Baculites grandis* to be of early Maestrichtian age.

Section of Niobrara Formation,
Sec. 16, T. 35 N., R. 47 W.,
Shannon County, South Dakota

Sharon Springs member of Pierre shale

Niobrara formation	Feet
Shale, very calcareous, light grayish yellow and grayish orange (5Y 7/2 to 10YR 7/4), fissile, poorly exposed; hard bentonite 0.1 feet thick at top and bottom; contains interbeds of dark gray noncalcareous shale near top	20
Shale, calcareous, darker than above and not so yellow or orange (5Y 6/1); flat oval concretions of pyrite an inch wide and a quarter-inch thick occur a foot below top; a thin white limestone bed occurs 5 feet above base	14
Shale, very calcareous, light colored; contains three thin and very persistent bentonite beds	21
Shale, calcareous, dark	10
Shale as above, largely covered	15
Shale, calcareous, brownish gray; contains layer of *Ostrea congesta* 10 feet above base and three thin beds of bentonite that weather to rusty yellow float; contains several two-foot beds of noncalcareous dark gray (N5) shale	53
Shale, calcareous, dark (5Y 6/1); contains two layers of *Ostrea congesta* and one 0.1-foot bed of bentonite	15
Limestone, argillaceous, light gray (N7); weathers platy rather than shaly as above	15
Limestone, pale orange (10YR 8/2); contains flat pyrite concretions in lower 2 feet	15
Shale, very calcareous, same color; contains 5 layers of *Ostrea congesta*, none thicker than 0.1 foot but all remarkably persistent	29
Shale, calcareous, dark	2

	Feet
Limestone, argillaceous, and very calcareous shale, poorly exposed	80
Limestone, white to pale orange (10YR 8/2); forms cuesta	15
Shale, calcareous, dark, and interbedded limestone	20
Carlile shale	
Total measured	324

On first inspection, the formation appears to be divisible into units useful for outlining structural features. The possibility is suggested by differences in resistance to weathering, which reflects clay content. The 15-foot bluff-forming interval in the lower 35 feet of the formation is prominent in the western part of the area. It contrasts with the less pure rocks above it and brings to mind the distinction made in Colorado and Kansas between the Fort Hays limestone member and the overlying Smokey Hill marl member. Unfortunately the interval is not resistant in the eastern part of the Chadron area. In the eastern part of the area a 60-foot bluff-forming interval occurs in about the middle of the formation. The thinner limestone in this interval is not resistant in the west, although rather pure. Attempts to subdivide the Niobrara formation in the Chadron area were abandoned.

The most abundant rock type in the Niobrara formation is calcareous gray shale, some of which might be called marl. The second most abundant rock type is limestone of the type that might be called chalk. The term chalk is not completely applicable in the Chadron area, for the limestone is not quite as porous, soft, and friable as are typical chalks such as the Austin chalk of Texas. On the other hand, the limestone is appreciably more porous, soft, and friable than ordinary Paleozoic limestone. Porosity probably accounts for the resistance to weathering. Rain sinks in instead of forming rivulets.

The calcareous gray shale or marl is a thinly bedded or platy mixture of clay and calcite. X-ray analysis of 2 samples by J. Gude, and 5 samples by Evelyn Cisney, show the clay to be illite (hydromica) and kaolinite. The samples are from different levels in the middle third of the formation. Illite is more abundant than kaolinite. Montmorillonite is noteworthily absent. In all samples from the overlying Pierre shale, montmorillonite is the most abundant clay mineral. The color of the shale depends on weathering. Slightly weathered samples are brownish; deeply weathered samples are tinged with yellow, orange, or red. Darkness depends on clay content, the darkest samples are the most clayey. Under the hand lens, the calcareous shale is characterized by a peculiar speckling. White calcareous specks stand out against a darker less calcareous matrix. The white specks are flattened spheres a half-millimeter or less in diameter. When powdered and examined at high magnification the white specks are found to consist of remains of the unicellular calcareous algae called coccoliths. Richard Rezak (written communication, 1959) specially treated and examined 2 samples of calcareous shale from the Niobrara formation of the Chadron area and found coccoliths to be abundant in both.

The chalk or limestone consists almost wholly of calcareous hard parts of minute plants and animals. It is fine textured and remarkably pure calcite. Runnels and Dubins (1949) analyzed a chalk or limestone interval in the lower part of the Niobrara formation. Across Kansas, they found the interval to be 88 to 98 percent pure calcium carbonate. In the Chadron area, calcareous foraminifera and more or less recrystallized fragments of Inoceramus make up less than a third of the rock. The mud-sized remainder is largely coccolith debris, according to analysis of one sample by Rezak (written communication, 1959).

Coccolith Distribution*

Sample No.	Location	Abundance
D239-3	Niobrara formation, probably in the lower third. Sample is gray, very calcareous shale. Sec. 30, T. 35 N., R. 46 W., Sheridan Co., Nebraska.	Abundant
D6-9	Niobrara formation, about 175 feet below Pierre shale. Sample is chalk or limestone. Sec. 16, T. 35 N., R. 47 W., Shannon County, South Dakota.	Abundant
D5-3	Niobrara formation, 20 feet below Pierre shale, about 280 feet above Carlile shale. Sample is gray very calcareous shale. Sec. 16, T. 35 N., R. 47 W., Shannon County, South Dakota.	Abundant
D3-9a	Pierre shale, Sharon Springs member, 10 feet above concretion zone that is above bentonite zone, and 80 feet above top Niobrara formation. Sample is black noncalcareous shale. Sec. 17, T. 35 N., R. 47 W., Shannon County, South Dakota.	Rare
D252	Pierre shale, middle part, limestone concretion zone above the ferruginous concretion zone that may be the Gregory shale. Sample is gray noncalcareous shale. Sec. 31, T. 35 N., R. 47 W., Dawes County, Nebraska.	None

Sample No.	Location	Abundance
D54-R	Pierre shale, limestone concretion zone near top of middle part. Sample is fragment of limestone concretion.	Recrystallized
D66-R	Pierre shale, upper part, near base and 30 feet below *Baculites compresus* zone. Sample is thin clam shell-limestone. Sec. 14, T. 35 N., R. 43 W., Shannon County, South Dakota.	Abundant but badly recrystallized
D22	Pierre shale, upper part, between *Baculites compressus* zone and *Baculites grandis* zone. Sample is light gray noncalcareous shale. Sec. 20, T. 35 N., R. 48 W., Dawes County, Nebraska.	Rare

* Coccolith abundance was kindly determined by Richard Rezak of the Shell Development Company.

At Yankton, South Dakota, Rezak (written communication, 1958) found about 70 percent of one sample of the Niobrara chalk to be coccoliths. Black (1953, p. 86) found the average coccolith percent of Cretaceous chalk in England to be about 60 percent, some samples being richer.

Like the Greenhorn limestone, the limestone in the Niobrara formation is texturally equivalent to shale, not to sandstone. The chalk, or limestone, is evenly bedded on the scale of a few inches to a few feet. It weathers white except for red and orange stains near pyrite concretions.

Thin layers of bentonite are numerous in the formation, particularly in the more clayey interval near the top. In the upper 50 feet of the formation, 17 layers occur, counting only those thicker than 0.1 foot. They are cream colored where fresh, and weather to various shades of orange and red. Their thickness ranges from 0.1 to 0.8 foot. They thicken and become more numerous upward, toward the thick bentonite beds in the Sharon Springs member of the Pierre shale. Some layers are minutely laminated. In spite of being thin, layers persist for at least 300 yards and probably much farther.

Concretions of silty limestone occur sparsely and erratically in the upper part of the formation in the northern part of the area, for example in sec. 3, T. 35 N., R. 46 W. The largest are about 3 feet in diameter. They occur a few tens of feet apart laterally. Septarian veins and fossils were absent in those broken to expose the interior. The concretions are noticeably more silty than their matrix.

Pyrite, organic matter, uranium and other trace metals, are rather abundant in the Niobrara formation. Disc-shaped pyrite concretions about an inch in diameter are numerous at many levels in the more clayey parts. The concretions are rough surfaced, due to outward-projecting crystals, and zoned. The inner part is finely crystalline and the outer part is coarsely crystalline. The abundance of otherwise undetected pyrite in the formation is indicated by weathering colors and gypsum crystals, and by spectrographic analysis. The element iron occurs in calcareous shale in amounts ranging from about 1 percent to about 5 percent, much of it presumably in the form of pyrite. Rubey (1930, p. 8) analyzed a sample from the Black Hills and found almost 2 percent pyrite. He found 6 percent organic matter in the same sample. Hunt and Jamieson (1956, p. 436) found more organic matter in calcareous shale in the Niobrara formation than in any other shale in

Wyoming. LeRoy and Schieltz (1958, p. 2449) report "light oil stains and strong petroliferous odors" in Ostrea congesta layers in Colorado. Uranium and other trace metals in the formation will be discussed in a separate section.

Fossils abundant in the Niobrara formation of the Chadron area, other than the rock-forming coccoliths, are foraminifera, clams, mosasaurs, and fish. Loetterle (1937, p. 67) examined samples from the Chadron area representing 110 feet of the Niobrara formation. He found all the foraminifera to belong to three calcareous species. The more abundant were Globigerina cretacea d'Orbigny, and Gümbelina globulosa (Ehrenberg). Scattered Ostrea congesta and unidentified species of Inoceramus form thin ledges. W. A. Cobban (1955, written communication) identified the specimens. Most of the Ostrea and Inoceramus are rather small and thick shelled. Vertebrate bones occur at several places in the more clayey beds in the upper part of the formation. Articulated skeletons of bony fish and of mosasaurs are rather common. Edward Lewis confirmed the identification of several specimens. The size is remarkable. One mosasaur skeleton in sec. 20, T. 35 N., R. 47 W., measured 15 feet and has teeth more than an inch long. Mosasaur vertebrae elsewhere in the area are commonly more than an inch in diameter. The largest fish skeleton found has vertebrae an inch in diameter and parallel curving bones two feet long and a quarter inch thick. Articulated skeletons of small fish were not found, although their teeth occur in the residue left after dissolving samples in hydrochloric acid. Scaphites and Baculites are absent or undiscovered in the Niobrara formation of the Chadron area. The same is true in the Black Hills, where the rocks are similar except for lacking pure chalk or limestone (Cobban, 1951, p. 2192).

Loetterle (1937) studied the foraminifera in many samples of the Niobrara formation from Kansas, Nebraska, and South Dakota. For the region as a whole, he found significant differences in foraminifera from different levels. The thin lower part of the Niobrara formation, which he calls Fort Hays limestone, contains many genera, both calcareous and arenaceous. The thick middle part of the Niobrara formation, which he calls the main portion of the Smokey Hill chalk, contains only the two calcareous species Globigerina cretacea and Gümbelina globulosa in most places. The thin upper part of the Niobrara formation, which he calls the upper chalky zone of the Smoky Hill chalk, contains a greater number of species. Arenaceous foraminifera appear in the basal part of the overlying Pierre shale, completing the cycle. A similar upward change in the ratio of arenaceous to calcareous foraminifer, and in number of genera, was found by Fox (1954) in Wyoming.

On the basis of field evidence, the Niobrara formation grades into the overlying and underlying formations. No signs of unconformity were seen, but exposures of the top are poor. The best exposure is in the SE 1/4 sec. 30, T. 35 N., R. 47 W., in a gulley. Near the top and the base the formation consists of shale, as do the formations on the other side of the contacts. Toward the contacts the shale of the Niobrara formation becomes darker and less calcareous.

Interbeds of noncalcareous shale occur in an interval of a few feet at the contact. For want of more practical criteria, the Niobrara formation is defined to include all the shale that effervesces with 10 percent hydrochloric acid.

The field evidence could be deceiving. In areas where the fossils have been better studied, other workers infer that the top of the Niobrara formation is an unconformity. Reeside (1957, p. 528) reports the absence in the eastern part of the Western Interior region of fossils known from the Telegraph Creek formation and Eagle sandstone of the western part of the Western Interior region. He infers that these fossils are absent because of nondeposition.

Age

The Niobrara formation is ordinarily assigned to the Upper Cretaceous series, and to the undifferentiated Coniacian and Santonian stages. No new evidence came from the present study.

Pierre Shale

Definition

The name Fort Pierre group, subsequently shortened to Pierre shale, was proposed by Meek and Hayden (1862, p. 419-424) for a sequence of dark shale in South Dakota. The shale lies above the Niobrara formation and below the Fox Hills formation; a thickness of about 700 feet remains in the type area.

General Description

The Pierre shale remaining in the Chadron area is more than 1,300 feet thick. The thickness eroded away before Oligocene time is unknown. About 100 miles to the southwest, in central Banner County, Nebraska, the Pierre shale is more than 4,000 feet thick (Reed, 1952, p. 78). The Pierre shale consists of dark shale that contains several lithologic zones characterized by bentonite beds, concretions, or differences in kind of shale. The Pierre shale is sufficiently thick to require subdivision; otherwise structural features cannot be adequately mapped. The lower part of the Pierre shale forms a distinctive, usually resistant, unit that is recognizable throughout a large part of the Great Plains. Elias (1931) separated this unit from the overlying shale beds and called it the Sharon Springs member. Elias and others also have proposed subdivisions of the remainder of the Pierre shale but these subdivisions, although useful elsewhere, are not applicable in the Chadron area. The remainder of the Pierre shale is therefore subdivided into two mapped informal units: the middle part of the Pierre shale, and the upper part of the Pierre shale. Age assignment can best be discussed after the three subdivisions are described.

Sharon Springs Shale Member of the Pierre Shale

The Sharon Springs member weathers to form a low unvegetated scarp that rises above the less resistant upper beds of the Niobrara formation and is a prominent topographic feature in the northern part of the Chadron area. The thickness of the Sharon Springs member ranges from 105 feet in the western part of its outcrop to 65 feet in the eastern part. From bottom to top the member can be subdivided into the lower shale zone, the bentonite zone, the concretion zone, and the upper shale zone. Subdivision helped in charting the distribution of uranium, but the member can be described more conveniently as a whole. The section at an easily accessible exposure on the promontory west of the road in sec. 16 and 17, T. 35 N., R. 47 W., follows:

Section of Sharon Springs Member of Pierre Shale,
Sec. 16 and 17, T. 35 N., R. 47 W.,
Shannon County, South Dakota

	Feet
Middle part of Pierre shale	
Sharon Springs member:	
Shale, noncalcareous, gray (5Y 6/1) to dark gray (N3), strikingly fissile; fish scales abundant; contains 5 thin beds of bentonite, none thicker than 0.5 feet	21
Shale, as above; characterized by white-weathering limestone concretions, averaging 6 feet by 1.5 feet, which occur at four levels; lower part of unit exhibits rusty boxworks measuring 2 to 4 feet on a side; contains 16 thin beds of bentonite	21
Shale and bentonite; contains 10 beds of bentonite thicker than 0.3 feet, aggregating 8.8 feet; a foot from the base is the Ardmore bentonite bed, which is 3.2 feet thick	18
Shale, as above; contains 7 thin beds of bentonite, none thicker than 0.6 foot	26
Niobrara Formation	
Total measured	86

Shale, bentonite, and concretions make up the Sharon Springs member. The shale closely resembles the better known Chattanooga black shale of Late Devonian age. Where fresh, the shale is black or dark (N3), hard, and tough. Where weathered, its black or dark color remains in some beds but changes to silvery gray (similar to that of the siliceous Mowry shale of the Black Hills) in others. Weathered shale splits into sharp-edged sheets several inches wide and a fraction of a millimeter thick, which snap when broken. X-ray analyses by Gude show the most abundant mineral to be quartz. Judging by the irregularly indented shape of some particles, part of the quartz probably grew in the rock. Montmorillonite is second most abundant. Illite and kaolinite make up most of the remainder, except for pyrite and organic matter. Crystals and small concretions of pyrite are more numerous in the Sharon Springs member than in any other unit in the area. Abundant pyrite is further indicated at the outcrop by limonite stains and crusts, gypsum crystals, and powders and hard masses of the yellow sulphate mineral jarosite. Jarosite, where deposited in intersecting fissures, commonly joins with limonite to form boxworks that weather to have a relief of several inches. Spectrochemical analyses of three samples of Sharon Springs black shale from South Dakota, reported by Tourtelot (1956, p. 76), show iron to be in the range of about 1 to about 5 percent. Much of the iron is probably in the form of pyrite. Organic matter is a sizable contributor to the bulk of the shale. Rubey (1930, p. 8) analyzed a sample of similar black shale from the lower part of the Pierre shale in the Black Hills and found 8 percent organic matter. A 10-foot bed in the middle of the member in sec. 7, T. 35 N., R. 46 W., now consists of brick-red harsh-textured shale and reddish brown scoriaceous material having a metallic luster. The resemblance of this outcrop to the clinker formed where coal has burned underground (Brown, et al., 1954, p. 166) indicates that the Sharon Springs shale burned on the outcrop in the past. Small areas of burned shale in the Sharon Springs member are known in other areas also; for example, near the junction of the White River and the Missouri River in Lyman County, South Dakota (Gries and Rothrock, 1941, p. 10). Two samples from sec. 8, T. 35 N., R. 46 W., near the burned area and from the same interval, were analyzed for oil by Irving May (written communication, 1955). He found 2.8 gallons of oil per ton in one and 1.0 gallon of oil per ton in the other.

Part of the organic matter is large enough to recognize as fish debris and plant debris. Under the microscope, much disseminated organic matter can be recognized. Leaching with hydrofluoric acid reveals small capsule and sack-like masses of soft flexible organic matter. Some are vaguely chambered. They probably are the remains of arenaceous and chitinous foraminifer, or other protozoans. The size is right for foraminifera such as *Ammobaculites*. Others are ellipsoidal. They may be the remains of slime such as that surrounding modern faecal pellets. H. A. Tourtelot (oral communication, 1959) has observed abundant faecal pellets in specially prepared thin sections of Pierre shale.

Traces of uranium occur in the Sharon Springs member, and in the Niobrara formation and other Cretaceous shale of the Chadron area. Their distribution is dealt with in a separate section.

Bentonite layers occur throughout the Sharon Springs member. They are sufficiently frequent and thick to characterize a lithologic zone about 15 feet thick. The bentonite was X-rayed and consists of montmorillonite. Near the base of the zone one bentonite bed maintains a thickness of about 3 feet throughout the Chadron area. This bed is called the Ardmore bentonite. It is thought to be an extension of the bed strip mined near Ardmore, Fall River County, South Dakota, and elsewhere (Spivey, 1940). Studies by Spivey show that the Ardmore bentonite is valuable not only for its thickness but because it has a greater capacity to carry exchangeable bases than any of the other Cretaceous bentonites he analyzed. Bentonite layers are not restricted to the bentonite zone. Counting only those layers thicker than 0.1 foot gives as many as 40 layers in the Sharon Springs member. Counting thinner layers would give a total measured in hundreds. Bentonite color ranges from off-white (10Y 8/2) or gray (N4) to orange (5YR 5/6 to 10YR 8/6), being orange where weathered. The color probably reflects the oxidation state of associated iron. In fresh material, pyrite occurs in small cubes and in nodules as large as two inches across. Pyrite is absent in the weathered material; particles of limonite are found instead.

The outstanding sedimentary structure visible in the field is the evenly parallel lamination. Laminae of bentonite occur in shale, and laminae of shale occur in bentonite. Moreover, the components of shale, such as fish scale concentrations, occur in laminae; probably the striking fissility developed by weathering reflects laminae too fine or too subtle to be seen with the hand lens. Even the thick seemingly massive bentonite beds contain nonclay minerals arranged in repeated layers parallel to the bedding. Dengo (1946, p. 23) observed this to be true of bentonite on a microscopic scale.

Concretions that weather into bold relief or to a litter of white limestone characterize a zone about 30 feet thick in the Sharon Springs member. Some of the concretions are larger than those in any other unit in the Chadron area. A typical large concretion is 6 feet wide and 1.5 feet high. Most are several feet wide and half as high. They occur in crude layers and are spaced about 20 feet apart. Most are roughly circular in plan view; those that tend to be elongate have their long dimension roughly parallel throughout an exposure. Laminae in the matrix do not pass through them. They consist of dark gray limestone that weathers light gray. Some contain plant fragments and bones. Because of their size and hardness, not many were searched for fossils. The weathered surface is harsh and gritty from the presence of silt-sized particles of quartz. Some smell of oil when freshly broken. Some are veined to some degree with drusy calcite of different colors. The sequence of drusy precipitation, from older to younger, is brown calcite, yellow calcite, then white or clear calcite. Cavities remain where the druse failed to fill the fissure. A septarian concretion in the C. SE 1/4 sec. 13, T. 35 N., R. 46 W., encloses a log. The log is oriented east-west. The concretion is 10 feet long, 1.4 feet wide, and 1.0 foot high and exhibits numerous veins 3 inches wide, which cut the log. The wood of the log is brown, extremely light in weight and crumbly, and is coarse textured. On the surface of the log are imprints that resemble the phosphatic brachiopod Lingula. Inside are holes suggesting that the wood was worm-eaten.

A further feature of interest about the concretions is that they are typically associated with lenses of limy bentonite or very limy shale exhibiting cone-in-cone structure. The cone-in-cone lens underlies the concretion, but may be separated from it by a fraction of an inch of shale, and has about twice the lateral extent of the concretion. The part of the cone-in-cone lens that extends beyond the concretion is somewhat thicker than the part beneath the concretion, 0.4 foot versus 0.2 foot. Some concretions are not associated with such lenses, although they too exhibit marginal cone-in-cone structure. In this case, the cone-in-cone structure occurs on the upper and lower surface of the concretion. These relationships indicate that the cone-in-cone structure and probably the concretionary calcite itself formed after deposition of the overlying beds, assuming with Pettijohn (1957, p. 210) that cone-in-cone structure is a pressure phenomenon. Limy bentonite beds exhibiting cone-in-cone structure may occur not associated with concretions.

The upper few feet of the member contains peculiar small concretions resembling nested egg shells. Where weathered, they are earthy and exhibit delicately concentric brittle shells, each slightly separated from the next, but joined by delicate cross-linking veins. Where fresh they consist of light gray silty limestone veined and shelled with fibrous gypsum.

Larger fossils in the Sharon Springs member include fish, land plants, mosasaurs, and one large shark. Molluscs are scarce. W. A. Cobban (written communication, 1955) identified Baculites haresi Reeside and Baculites aff. B. asper Morton in a collection (USGS Mesozoic locality D207) from about 30 feet below the top of the member in the SE 1/4 NE 1/4 sec. 5, T. 35 N., R. 46 W., Shannon County.

One collection of hard parts from small fish was examined by David Dunkle (written communication, 1955). He recognized vertebrae, skull bones, and scales of teleost fish. Land plant remains are mostly woody matter showing cell structure. Leaves were not found. Edward Lewis (written communication, 1955) confirmed the identification of several mosasaurs. The skeletal parts of mosasaurs are still joined together, but those of fish are separated.

Microfossils in 13 samples from a complete measured section in sec. 26, T. 36 N., R. 48 W., were kindly examined by R. W. Barker of Shell Development Company. (An interval of 14 feet in the bentonite zone was not sampled.) He found most of the fossiliferous samples to contain a sparse and wholly arenaceous assemblage of foraminifera. Barker's (written communication, 1959) results follow:

Microfossils in Sharon Springs Member
Exposed in Sec. 26, T. 36 N., R. 48 W.,
Shannon County, South Dakota*

Sample No.		Interval below top of member feet
K74-1	*Globigerina* species, somewhat rolled. cf. *Eponides*, large form, badly rolled. *Trochammina* species, crushed.	0-5
K74-2	*Trochammina* species, sparse. *Cibicides* cf. *beaumontensis* (d'Orbigny)	5-10
K74-3	Practically no fauna. cf. *Bathysiphon* species. *Haplophragmoides* species, badly crushed.	10-15
K74-4	As above but poorer.	15-20
K74-5	Practically no fauna. *Haplophragmoides* cf. *excavata*. Cushman and Waters, badly crushed, test white.	20-25
K74-6	No fauna.	25-29
K74-7	*Haplophragmoides* cf. *excavata*. One very worn calcareous foraminifera, indeterminate. Swampy, brackish?	29-34
K74-8	No fauna, much carbonaceous matter.	34-38
K74-9	No fauna, more carbonaceous matter.	38-43
K74-10	No fauna, very small residue.	57-63
K74-11	No fauna, negligible residue, highly carbonaceous.	63-69
K74-12	*Haplophragmoides* cf. *excavata*, cf. *Bathysiphon* species. Other finely agglutinated fragments indeterminate, carbonaceous matter (plants?).	69-77
K74-13	*Globigerina* species, fish teeth, phosphate (?).	77-85

* Microfossils were kindly identified by R. Wright Barker of Shell Development Company. Samples were contaminated in the laboratory with Tertiary Claiborne foraminifera, which could be recognized as foreign by their reddish brown tinge and by the fact that the species are unknown in Cretaceous rocks.

The most abundant genera is *Haplophragmoides*. *Trochammina* and *Bathysiphon* are the other relatively abundant genera. Barker recognized most of the identifiable *Haplophragmoides* to be akin to *H. excavata*, which he considers indicative of fresh to brackish water. Barker finds *Haplophragmoides excavata* in lower Eocene rocks west of Lake Maracaibo that are generally considered to have been deposited in brackish to fresh waters ~~(Miller and others, 1958, p. 609)~~. It is interesting that *Globigerina* occurs in the sample at the base of the section and in the sample at the top of the section. Calcareous bottom dwellers occur in the upper two samples. These things, plus the abundance of carbonaceous matter he found in the middle samples, suggest that the Sharon Springs member was deposited during a temporary freshening of the water.

In Colorado, LeRoy and Schieltz (1958, p. 2451) found almost all of the foraminifera of the Sharon Springs member to be arenaceous, mostly *Haplophragmoides*, and *Bathysiphon*. Loetterle (1937, p. 14) found another arenaceous foraminifera, *Ammodiscus*, to characterize the basal black carbonaceous 100 feet of the Pierre shale in eastern South Dakota and northern Nebraska. Rezak (written communication, 1959) looked for coccoliths in one sample from near the upper contact in the Chadron area, and found them to be scarce.

Several samples were disaggregated and leached with concentrated hydrochloric acid, followed by ammonium hydroxide, then hydrofluoric acid. The residue contained a considerable amount of chitin. The chitin is white in transmitted light and clear, except for contained specks of pyrite and other minerals. It is slightly birefringent. Most of the pieces are too small to guess at the shape of the original skeleton. The few larger pieces suggest small arthropods. They are unornamented and characteristically folded. Crustaceans, or perhaps insects, seem likely possibilities. One piece resembles the back covering of a shrimp or crawfish, but is only a millimeter long. Another piece resembles the leg of a shrimp, even to the peculiar wrinkles at the joint. Another shows a ridge resembling that along the back of a shrimp, near the head. The larger pieces of chitin are thought not to be fish remains, because chitinous scales resist folding and these characteristically are tightly folded.

The lower contact of the Sharon Springs member appears to be gradational by interbedding, as discussed in the section on the Niobrara formation. The upper contact is nowhere well exposed, but in trenches it appears to be progressively gradational through an interval of several feet.

Middle Part of Pierre Shale

The parts of the Pierre shale above the Sharon Springs member weather to low rolling hills covered with grassy soil. Distribution and character were inferred from infrequent small exposures and from lithologic differences that show through the soil. The thicknesses given are mainly from one complete measured section and, for some of the intervals, are little better than estimates, due to the fewness of reliable dip measurements. The best exposures, and the place the complete section was measured, extend from the SE 1/4 sec. 18, T. 35 N., R. 47 W., to the C. sec. 11, T. 35 N., R. 48 W., then from the SE 1/4 sec. 15 to the NW 1/4 sec. 21, T. 35 N., R. 48 W. The following section includes the middle and upper parts of the Pierre shale:

Partial Section of Pierre Shale,
Sec. 18, T. 35 N., R. 47 W., and Secs. 11, 15, and 21,
T. 35 N., R. 48 W., Shannon County, South Dakota

Pierre shale

Upper part:	Feet
Mudstone, light brownish gray (5Y 7/2), noncalcareous; poorly exposed; soil contains fragments of light gray limestone concretions and, in upper part, large orange- or pink-weathering internal molds of *Baculites grandis*..................................	130+
Shale, dark gray (N3 moist), noncalcareous; poorly exposed; surface littered with 2-inch phosphate nodules having a 1/4-inch white rind; scattered very hard limestone concretions having bluish metallic stains.......	25
Mudstone, poorly exposed.................................	50
Mudstone characterized by concretions unusually rich in fossils, particularly *Baculites* and *Scaphites*...	40
Mudstone, pale yellowish brown (10YR 6/2), noncalcareous; 15 feet above base is 2-foot bed of fossiliferous limestone rich in clams (USGS locality D219)....................................	55
Middle part:	
Mudstone, bentonitic, light gray (N6) to darker gray, noncalcareous; forms gumbo crust, which does not support vegetation; contains discontinuous thin lenses of fibrous calcite or aragonite; color-banded on scale of 10 feet or so; contains persistent 1-foot zone of small black manganese-iron concretions near middle; lower part poorly exposed.....................	125

	Feet
Mudstone, poorly exposed; soil contains angular fragments of white-weathering limestone concretions that are medium gray (N5) and very hard when fresh; near middle is zone of unknown thickness of siderite concretions; limestone concretions in lower few tens of feet weather red and brown, indicating that they are sideritic; a 10-foot bed of dark gumbo soil occurs about 100 feet below top..	700
Mudstone, olive gray (5Y 5/2), poorly exposed, characterized by abundant siderite concretions.......	75

Sharon Springs member of Pierre shale

Total measured	1210

The middle and upper parts of the Pierre shale differ from other Cretaceous shale in their texture. Lamination is scarce or absent above the Sharon Springs member. Silt and montmorillonite occur, but instead of forming laminae and thin beds they are intimately mixed with other material. Silty clay appears instead of siltstone and clay, producing mudstone[1] instead of shale, as the term is strictly defined.

The middle part of the Pierre shale is about 900 feet thick. Three smaller subdivisions could be mapped if necessary. The lower 75 feet consists of soft olive gray (5Y 5/2) shale characterized by numerous siderite concretions. Although X-ray analysis was not done,

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[1] Because of the lack of a suitable term to apply to the whole of the mud-sized fine-grained terrigenous rocks of the Cretaceous, the term shale will occasionally be used in the loose sense. Context should make clear the meaning intended. The convenience gained seems worth the possibility of confusion.

the shale probably contains montmorillonite. Its soil swells and contracts to form shrinkage cracks 3 inches in diameter. The siderite concretions are about a foot wide and are dark brown (10YR 4/2), where fresh. Upon weathering, they disintegrate to a debris of 1/4-inch to 1-inch angular fragments that are metallic reddish brown (5YR 2/1) limonite. The limonite debris resists further weathering and accumulates at the surface of the soil to make a nearly continuous rubbly layer. Its presence gives the outcrop a reddish gray cast. When viewed from a distance the reddish gray contrasts sharply with the black or silvery gray of the underlying Sharon Springs member and appears to mark an abrupt contact. At close range the contact is seen to be gradational through an interval of several feet. Associated with the angular fragments are limonite internal molds of small Baculites. Their abundance in the debris can be envisioned from the fact that a handful of fairly well preserved specimens can be collected in a few minutes at almost any place the debris has formed a continuous layer.

The middle 700 feet of the middle part of the Pierre shale consists of light olive gray noncalcareous shale characterized by white-weathering lime concretions. One X-ray analysis of the shale by J. Gude shows quartz to be the most abundant mineral; the remainder consists of an undifferentiated mixture of montmorillonite, kaolinite, and illite. Fresh concretions, which are seen rarely, consist of very hard medium gray (N5) limestone. The concretions probably are abundant and widely distributed in the interval, because angular white fragments of limestone occur at most places in the soil. The white-weathering concretions in the lower few tens of feet are associated with calcareous concretions that weather brown or red, presumably from contained siderite. One zone of sideritic limestone concretions occurs in the middle of the unit. A 10-foot bed of dark swelling clay, similar to that described below, occurs about 100 feet below the top of the unit.

The upper 125 feet of the middle part of the Pierre shale forms a banded landscape unlike most of the outcrop of the Pierre shale. The bands are barren of vegetation and consist of massive beds of swelling clay. The beds are 10 to 20 feet thick and probably are unusually rich in montmorillonite. Some beds are light gray (N6), some are dark. When wet, the clay is very sticky and plastic and swells to produce a minutely irregular surface. Upon drying, the irregularly swollen surface layer becomes hard and yet more irregular. The surface crust rather resembles a layer of popped corn, and these beds are sometimes referred to as popcorn beds or gumbo. Long drying causes the underlying clay to shrink away from the crust, leaving a space several inches high that is floored with a powder of dried clay. Discontinuous layers of fibrous brown calcite or aragonite a fraction of an inch thick occur in the montmorillonitic clay. The fibers are arranged perpendicular to bedding. Some enclose white clay, which suggests they may have grown in the sediment.

A massive bed of montmorillonite-rich clay seems very different from a zone of interbedded bentonite and shale, such as was described from the Sharon Springs member. Yet the difference may only reflect a different arrangement of constituents. If the discrete bentonitic beds and shale beds of the Sharon Springs bentonite zone had been thoroughly mixed by worms or other burrowers before lithification, the result might well have been a massive bed of montmorillonite-rich clay resembling those in the middle part of the Pierre shale. This possibility throws doubt on the validity of using bentonite beds to correlate between burrowed sequences and laminated sequences.

Near the middle of the upper 125 feet of the middle part of the Pierre shale occurs a 1-foot zone rich in heavy black pellets and small concretions. A sample was analyzed by A. E. King. He found large amounts of manganese (9.64 percent) and iron plus some silicates. The manganese mineral has not been identified. Iron-manganese carbonate concretions, which are richer in manganese and are more abundant than in the Chadron area, occur in the Oacoma lithologic zone of the Sully or DeGrey member of the Pierre shale in the lower Missouri River valley in South Dakota. They have been studied by Gries and Rothrock (1941), as a possible source of low-grade manganese ore.

Molluscs, particularly Baculites, are abundant in concretions in the lower 75 feet of the middle part of the Pierre shale. A limestone bed probably in the upper few hundred feet of the middle part of the Pierre shale, but possibly in the lower few tens of feet of the upper part of the Pierre shale, yielded one collection of clams. W. A. Cobban (written communication, 1955) identified the following species from the middle part of the Pierre shale. The large numbers (D207, etc.) in this and the next list of localities are the numbers in the United States Geological Survey Mesozoic invertebrate collection.

Fossils from the Middle Part
of the Pierre Shale

	4
Inoceramus barabini Morton	5
Inoceramus cf. *I. barabini* Morton	5
Inoceramus aff. *I. vanuxemi* Meek and Hayden	2
Inoceramus species	5
Parmicorbula? species	1,3
Baculites aff. *B. asperiformis* Meek	1,3
Baculites aff. *B. gregoryensis* Cobban	4
Baculites gregoryensis Cobban	

1. D211, NW 1/4 SW 1/4 sec. 16, T. 35 N., R. 47 W., Shannon County, concretions 0 to 3 feet above base of middle part.
2. D210, NE 1/4 NE 1/4 sec. 12, T. 35 N., R. 48 W., Shannon County, concretions 0 to 10 feet above base of middle part.
3. D209, SW 1/4 NW 1/4 sec. 32, T. 35 N., R. 47 W., Dawes County, concretions 0 to 10 feet above base of middle part.
4. D208, NE 1/4 SE 1/4 sec. 12, T. 35 N., R. 46 W., Shannon County, concretions about 50 feet above base of middle part.
5. D214, NE 1/4 SW 1/4 sec. 34, T. 34 N., R. 48 W., Dawes County, limestone bed probably in upper few hundred feet of middle part, but possibly in lower few tens of feet of upper part.

Gray calcareous shale in the middle part of the Pierre shale in a well in sec. 1. T. 33 N., R. 50 W., yielded an assortment of calcareous and arenaceous foraminifera to Loetterle (1937, p. 67). Fox (written communication, 1955). examined the foraminifera in a sample of Gregory marl overlying the Sharon Springs member collected in South Dakota by Roy Kepferle. Fox found 16 genera; calcareous plankton are represented by *Globigerina*, arenaceous bottom-dwellers by *Haplophragmoides*. Rezak (written communication, 1958) searched for coccoliths in two samples from the Chadron area. One sample is

The fossils thus indicate that the upper part of the Pierre shale is of late Campanian and early Maestrichtian age; the middle part is of late Campanian age; the Sharon Springs member is perhaps of early Campanian age.

EOCENE(?)

Rocks deposited during latest Cretaceous, Paleocene, Eocene, and earliest Oligocene time are absent in the Chadron area. Oligocene rocks rest unconformably on folded Pierre shale, Niobrara formation, and Carlile shale (fig. 3). Although evidence of sedimentation is lacking, the Chadron area holds a record of some of the things that happened during part of this time. The Pierre shale, Niobrara formation, and Carlile shale are strikingly altered for as much as 55 feet below their contact with Oligocene rocks (fig. 4). The altered material is here interpreted as an ancient lateritic soil formed under a hot wet climate in Eocene(?) time. The several kinds of evidence supporting the interpretation are developed under separate headings below. Reasons for assigning the ancient soil questionably to Eocene time are discussed after the section on origin, for the age assignment depends on inferences based on evidence not related to age.

Because the altered material is thin and because the Cretaceous formations can be recognized in spite of their alteration, the altered material was not separately mapped. The outcrop belt of the altered material is bounded at the top by the mapped base of the White River group. Where the map shows nearby localities sampled for uranium, the sampled localities mark the base of the altered zone. Good exposures are easily accessible in the bluffs on the north side of Little Beaver Creek in the north-central part of the area. The ancient soil tends to resist weathering and to be free of vegetation.

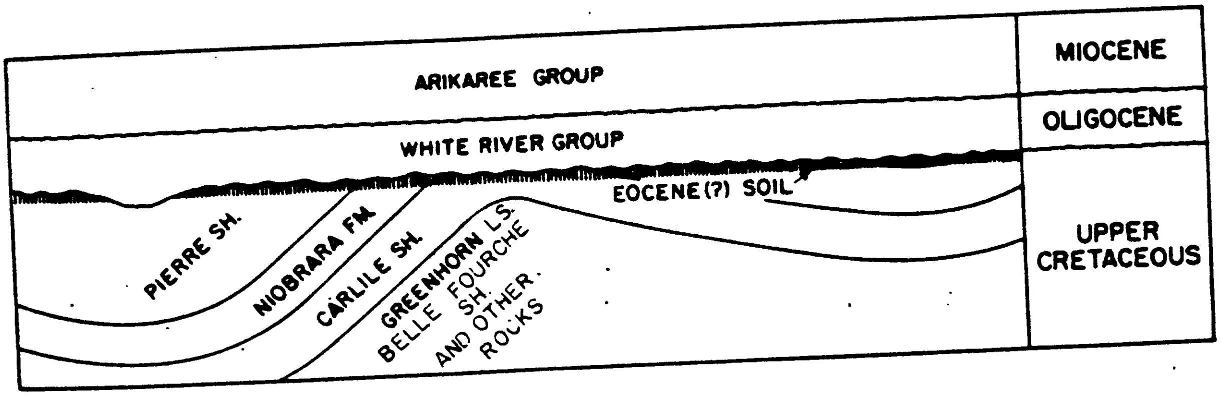


FIGURE 3.--Diagrammatic cross-section showing relationship of Eocene(?) soil to contiguous formations.

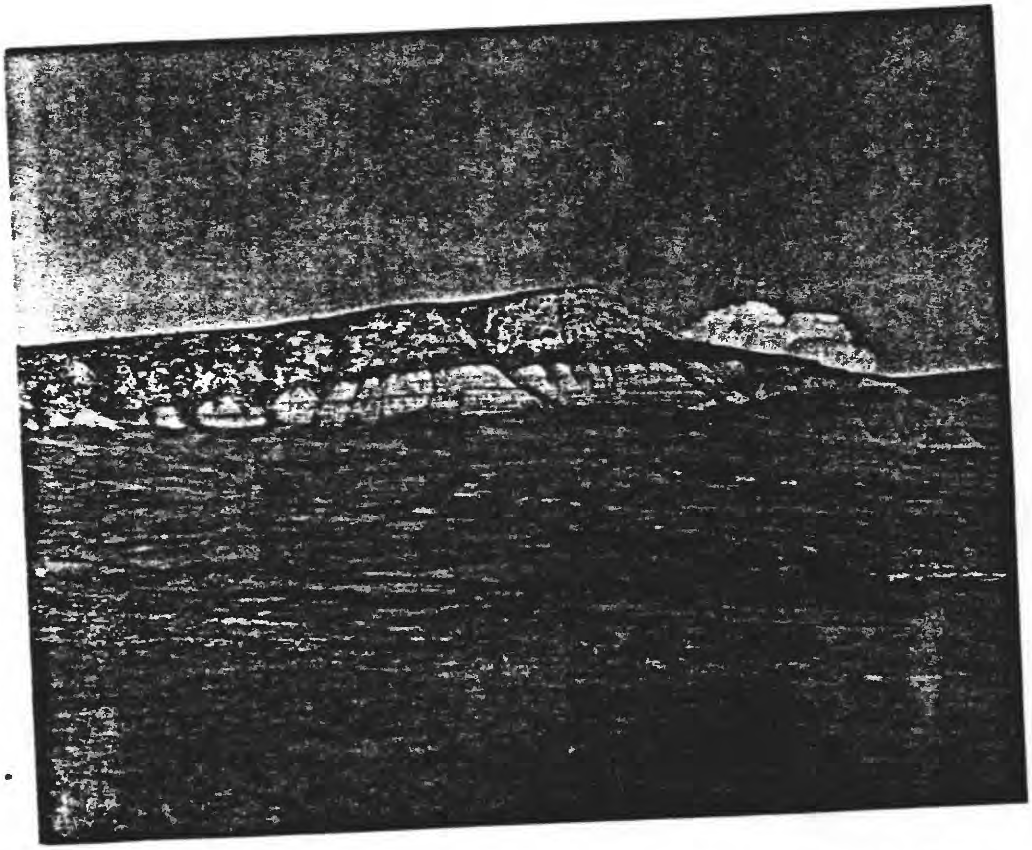


FIGURE 4.--Eocene(?) soil 55 feet thick underlain by dark calcareous shale of the Niobrara formation and overlain by White River group and then by upland silt, near locality 42, sec. 29, T.36N., R.46W., Shannon County, South Dakota.

Profile

The altered material in the Chadron area can be divided into three zones (fig. 5). At the top is the transformed zone. It is discolored, kaolinized, leached of calcite, impregnated with iron oxides, and structurally transformed. In the middle is the oxidized zone, It retains original structure and calcite, but is impregnated with iron oxides and discolored. At the base is the arbitrarily defined boundary zone. It represents the interval in which oxidized material and bedrock complexly interpenetrate with each other, and where the uranium discussed in a separate section is concentrated.

Profile on Calcareous Shale

The altered material developed on calcareous shale of the Niobrara formation is widespread and shows most clearly the three zones. It can be used as a standard with which to compare variant types. A typical measured section follows:

Section of altered material on calcareous shale
of the Niobrara formation in sec. 14, T. 35 N., R. 45 W.,
Shannon County, South Dakota

	Feet
Chadron formation:	
Mudstone, gray, rich in silt and containing nodular lenses of lime	5+
Altered material:	
Transformed zone	
Claystone, noncalcareous, mottled; color is orange-red mottled with white, red, purple, and yellow; no bedding	

FIGURE 5.--Eocene(?) soil 18 feet thick underlain by dark calcareous shale of the Niobrara formation and overlain by Chadron formation. Dark remnants in lower part of soil mark the boundary zone; light material showing bedding is the oxidized zone; dark material beneath the grass line is the transformed zone. Locality 37, sec. 30, T.35N., R.46W., Sheridan County, Nebraska.

or joints remain; hard and brittle, but talc-smooth; limonite concretions abundant.	3
Claystone, noncalcareous, orange (10YR 7/4); similar to above but has fewer concretions and is faintly bedded	4
Oxidized zone	
Shale, calcareous, bright yellow (5Y 8/4), has but few concretions.	13
Boundary zone	
Shale, calcareous. Remnants of gray bedrock as much as 2 feet wide enclosed in yellow shale.	3
Niobrara formation	
Total thickness of altered material.	23

Transformed Zone

The transformed zone commonly is 4 to 9 feet thick. The maximum thickness of 13 feet was observed at locality 47, sec. 27, T. 36 N., R. 47 W. Where Oligocene channel sandstone occurs, the transformed zone is locally absent. The transformed zone consists of kaolinitic claystone colored orange (10YR 8/6 to 10YR 8/4), white (N8 and N7), red (5R 4/6), and rarely purple (5P 4/2). Orange is the most prominent color. At places where the altered zone seems to have been least affected by pre-Oligocene erosion, the upper part of the transformed zone is white and the lower part is red, white, and orange. The mixed colors of the lower part are brilliantly ringed, streaked, and mottled, commonly in a small-scale crudely reticulate pattern. The brilliantly mottled claystone passes downward into less brilliantly mottled and more orange claystone or into solid orange claystone of a less intense color. At places where the upper part of the remaining transformed zone contains no white, the absence of white probably is due to pre-Oligocene erosion.

The claystone is compact, cohesive, and tough. When dry it is hard and smooth; when wet it is soft, slick, and smears readily. R. F. Gantnier (written communication, 1955) determined the vertical permeability to air and the effective porosity of two dry samples. The air permeability of both samples is less than 0.1 millidarcy, the minimum sensitivity of the instrument used. The effective porosity of the dry sample from the upper strongly kaolinized part of the zone is 19.1 percent. The effective porosity of the dry sample from the lower part of the zone is 22.7 percent. For comparison, a dry sample of unweathered calcareous shale close beneath the boundary zone has an air permeability of 1.0 millidarcy (at least 10 times that of the transformed zone) and an effective porosity of 36.1 percent. Gantnier noted for the three samples that "the high porosities and low permeabilities probably are the result of capillary openings," which indicated to him that "the 'true effective porosity' is fairly close to zero in all three samples."

Shaly bedding and joints are absent. Original structure is so completely destroyed that the planar orientation seen in thin section in shale is gone. Thin sections of orange samples show the claystone to be homogeneous except for dots and streaks of limonite. In many places the claystone shows on calcareous shale and on noncalcareous shale what might be called kneaded structure. Kneaded claystone is characterized by curving or even swirling faint lineation formed by slight differences in color or in resistance to present-day erosion. Kneaded claystone produces peculiar outcrops characterized by steep slopes that are minutely castellated and at some places tunneled (fig. 6). A different secondary structure occurs at locality 28, sec. 21, T. 34 N., R. 47 W. The upper few feet of the transformed zone is near-white kaolinite lacking limonite concretions, which seems at first inspection to have retained its shaly bedding. The structure probably is not shaly bedding, because it overlies greatly altered claystone. Platy structure (Nikiforoff, 1937, p. 311-312), which may be the more appropriate term, is well known from the upper part of some present-day soils. Slump structure, suggesting plastic deformation before deposition of Oligocene sediment, occurs at locality 28, sec. 21, T. 34 N., R. 47 W.

X-ray analyses by Evelyn Cisney show that the most abundant clay mineral is kaolinite, whereas the most abundant clay mineral in the underlying oxidized zone and in unweathered shale is illite. Concretions of limonite and hematite are numerous in the transformed zone, especially in the lower part. They are locally intergrown with a manganese hydroxide mineral identified by Evelyn Cisney as lithiophorite. Some of the concretions are small enough to be called pellets and are concentrically shelled. Others are larger, rather extensive, irregularly lenticular, and oriented parallel to the weathering horizons. Others are tubular and oriented perpendicular to the weathering horizons. They occur in the profile on both calcareous shale and noncalcareous shale. The tubular concretions superficially resemble articulated crinoid ossicles (fig. 7); they are, however, restricted to the transformed zone and occur in

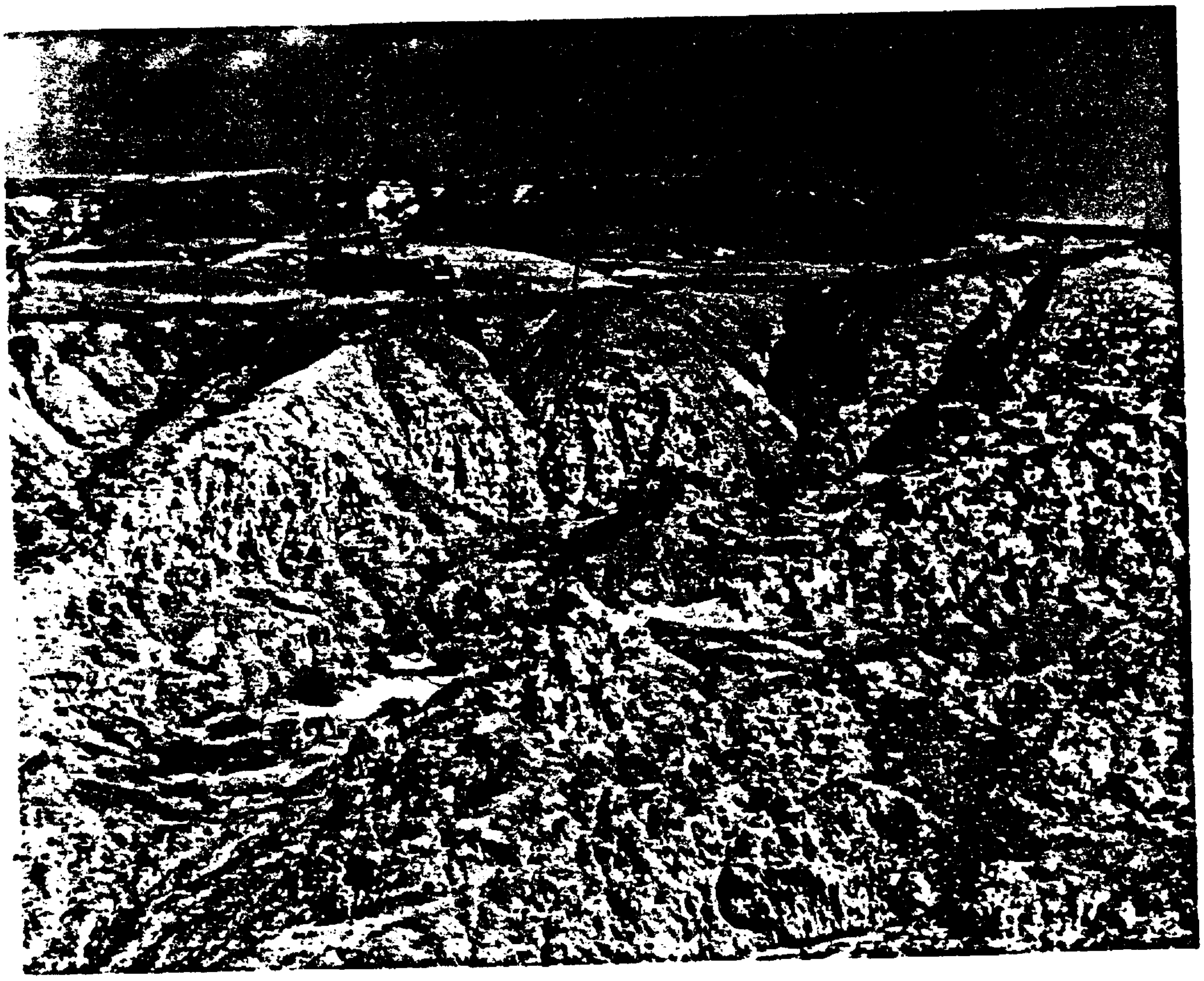


FIGURE 6.--Castellated and tunneled weathering forms in kneaded clay in the transformed zone developed on Carlile shale in the SE 1/4 sec. 16, T.34N., R.47W., Dawes County, Nebraska.

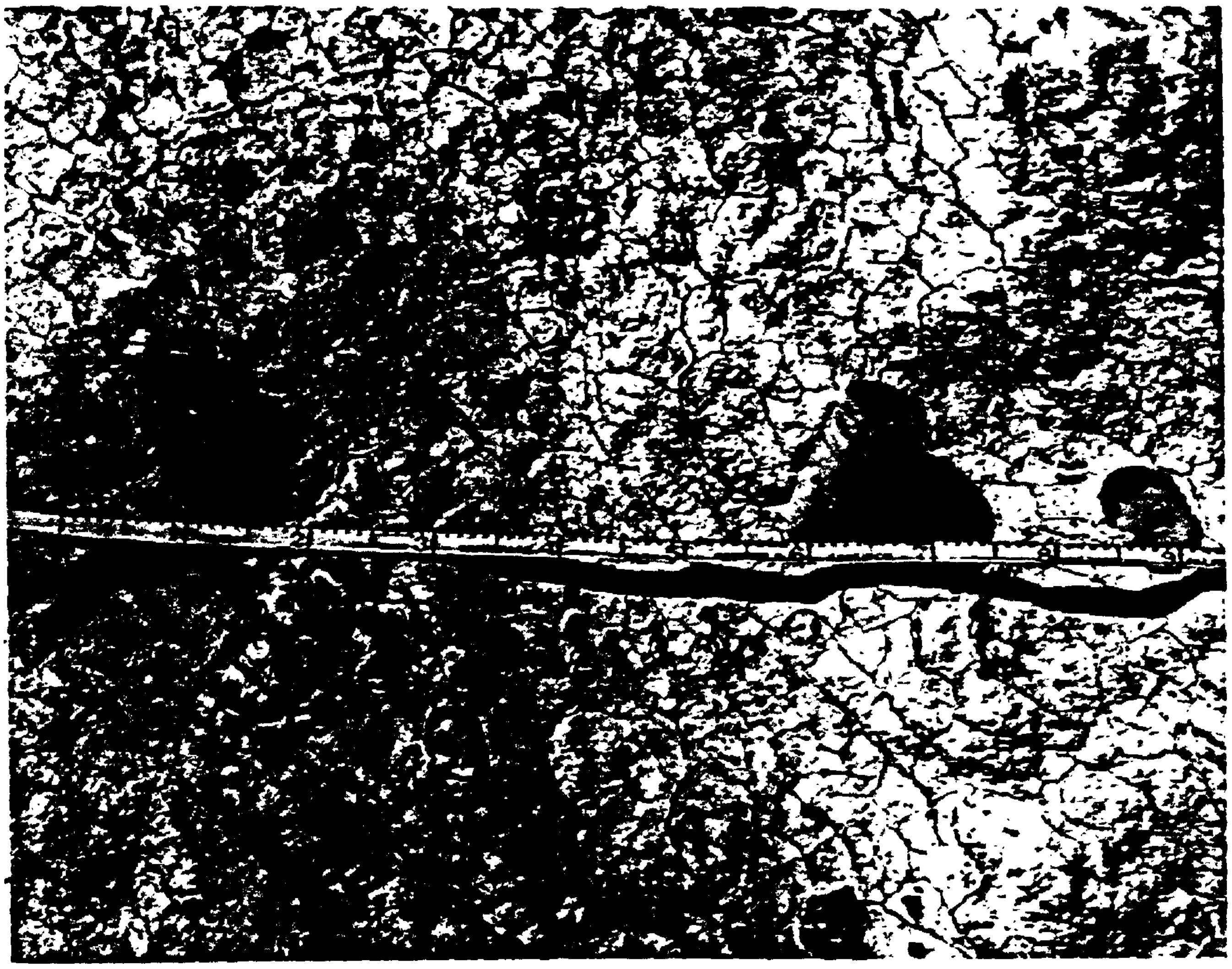


FIGURE 7.--Limonite concretions resembling articulated crinoid ossicles in the transformed zone developed on the Sharon Springs member of the Pierre shale in the NW 1/4 sec. 16, T.34N., R.47W., Dawes County, Nebraska.

identical form in the profile on several formations. Their orientation and shape suggest precipitation around roots.

Curious white (N9) concretions occur in the upper part of the transformed zone at a few places, for example locality 28, sec. 11, T. 34 N., R. 47 W. (figs. 8 and 9). The white concretions are subspherical, hard, brittle, and porous. Broken pieces are smooth to the touch, resembling talc. As shown by Figures 13 and 14, they are intimately associated with limonite and hematite concretions and occur in claystone having diffusion bands of limonite and hematite. X-ray analysis shows that the white concretions are either kaolinite or a mixture of kaolinite and alunite. W. F. Outerbridge reports that the X-ray pattern matches the standard for kaolinite and the standard for alunite. Evelyn Cisney reports only kaolinite in two runs, the second one heated. George Ashby and R. L. Wack report a mixture of alunite and kaolinite, after examining X-ray patterns and thin sections. Because the analysts examined different parts of one sample, it is likely that the ratio of kaolinite to alunite changes erratically and abruptly. One piece was analyzed for sulfate by H. F. Young of the Shell Development Company. He found 19.5 percent of the heated dry weight of the sample to be sulfate. Such a percentage would occur in a pure three-to-one mixture of kaolinite and alunite. The overlying claystone resembles the concretions in the field. Its clay size minerals consist of kaolinite and quartz according to Ashby, or kaolinite and hydromica (illite) according to Cisney. The claystone that is the matrix of the concretions is kaolinite and hydromica (illite) according to Cisney. Judging by the abundance of kaolinite in the associated material, kaolinite is probably more abundant than alunite in all the concretions.

FIGURE 8.--Concretions of iron oxide and of kaolinite-alunite weathering out of the transformed zone developed on calcareous shale of the Niobrara formation on spur at locality 28, sec. 21, T.34N., R.47W., Dawes County, Nebraska.

FIGURE 9.--Fresh exposure of kaolinite-alunite concretions in the transformed zone at the locality shown in Figure 8. Note diffusion banding in iron oxides at point of hammer.

The alunite was formed prior to Oligocene time, as demonstrated at locality 26, sec. 11, T. 34 N., R. 47 W., where kaolinite-alunite occurs as rounded pebbles in the basal Oligocene sandstone and as unbroken concretions a few feet below the unconformity. The kaolinite-alunite pebbles are associated with other pebbles of the same size, which consist of limonite, iron-manganese oxide, red clay, fragments of Cretaceous fossil bones, and phosphate nodules. All but the last two constituents also occur in place, directly beneath the unconformity. The bones and phosphate nodules were probably derived from the Pierre shale.

The present top of the transformed zone is knife-blade sharp in places where the overlying Oligocene rocks are sandstone or conglomerate. The top is poorly defined in the many places where the overlying Oligocene rocks are red or mottled claystone, which consists in part of reworked altered material. An aid in recognizing the contact is the presence in Oligocene rocks of sand grains, and lag concentrate of limonite concretions. Also, undisturbed altered material commonly is orange, but reworked altered material nowhere is orange. The base of the transformed zone is a sharp contact between orange above and yellow below, when seen from a distance. At close range the contact is less sharp, due to alteration gradually decreasing downward. Calcite in enough abundance to effervesce vigorously with 10 percent hydrochloric acid is absent above the contact and present below the contact. On this basis, the base of the transformed zone is gradational through an interval of about half a foot.

Oxidized Zone

The oxidized zone consists of discolored calcareous shale. Its thickness is commonly about 20 feet. The maximum thickness is 45 feet, observed at locality 42, sec. 29, T. 36 N., R. 46 W. Erosion prior to deposition of Oligocene rocks locally removed the upper part of the zone in the Chadron area. Outside the Chadron area, erosion removed the whole of the altered material beneath Oligocene channel sandstones near Scenic in the Big Badlands of South Dakota, according to Wanless (1923, p. 193-202) and Clark (1937, p. 277-280), and at a place four miles west of Orella, Sioux County, Nebraska.

Yellow (5Y 7/2 to 10YR 8/4) is the characteristic color of the oxidized zone. Except for being lighter toward the base, the color is rather uniform and contrasts sharply with the gray (5Y 6/1 to N5) of unweathered calcareous shale. Prominent concretions of limonite occur locally in the upper part of the oxidized zone. Microscopic particles of limonite are abundant in all samples. Destruction of organic matter and pyrite and the accompanying formation of limonite probably caused the discoloration. Shaly bedding is as prominent in the oxidized zone as in the bedrock, and joints and some bedding planes are more prominent.

Boundary Zone

Recognition of a boundary zone would be unnecessary if the contact between gray shale of the bedrock and yellow shale of the oxidized zone were regular. The contact is not regular, although it is knife-blade sharp in calcareous shale. Remnants of gray shale isolated in yellow shale occur several feet above the top of the bedrock. Pinnacles of gray shale extend several feet upward between pockets of yellow oxidized shale. The boundary zone is therefore defined to include the interval of interpenetration. Its thickness is rarely less than two feet, and reaches a maximum of nine feet at locality 28, sec. 21, T. 34 N., R. 47 W. The unique feature of the boundary zone is the occurrence of concentrations of uranium. Further description of the boundary zone is unnecessary, for the oxidized parts are similar to the overlying oxidized zone and the unoxidized parts are similar to the underlying bedrock.

Profile on Noncalcareous Shale

The altered material on most noncalcareous shale is superficially indistinguishable from that on calcareous shale. Closer inspection reveals differences. The absence of lime in the bedrock makes the distinction between transformed and oxidized zones less distinct, and there is considerable difference between different kinds of noncalcareous shale. Two measured sections will illustrate.

Section of altered material on upper part of Pierre shale in sec. 7, T. 34 N., R. 47 W., Dawes County, Nebraska

	Feet
Chadron formation:	
Claystone, gray, slightly silty, slightly calcareous; outcrop abundantly littered with agate, silicified wood and bone, botryoidal translucent blue chert, and 2-inch lenses of white silicified limestone.	15+

Altered material:

Transformed zone:

Claystone, light greenish gray (5GY 8/1), structureless.	3
Claystone, as above but red.	2
Claystone, as above but light greenish gray, and has suggestion of bedding. All three claystones are cross-cut by the Chadron formation	1

Oxidized zone:

Shale, noncalcareous, light yellow-gray (5Y 7/2) streaked by dark yellow-orange along some bedding planes and joints.	21
Shale as above; contains two discontinuous thin limestones, probably concretionary, which are stained and partially replaced by limonite and hematite	16

Boundary zone:

Shale as above except for color; part is gray (5Y 5/1) similar to underlying bedrock and part is yellow-gray (5Y 7/2) similar to oxidized zone; the gray shale forms disconnected masses in the yellow-gray shale, some as much as 5 feet high. Concretionary cone-in-cone lenses of limestone are partially altered to dark yellow and bright red by iron oxides, some of which is metallic. Yellow-orange discoloration also forms rectangles 2 to 4 feet on a side, parallel to bedding and joints. Unit contains bright red molds of <u>Baculites grandis</u>.	10

Upper part of Pierre shale:

Shale, gray, noncalcareous. Contains limestone concretions that are stained red and yellow down to about 15 feet below the boundary zone and are unstained below that level	57
Total thickness of altered material	53

Section of altered material on Sharon Springs member of Pierre shale in sec. 24, T. 35 N., R. 46 W., Shannon County, South Dakota

	Feet
Chadron formation:	
Sandstone, calcareous, fine-grained, littered with rough plates of opaque chert	15+
Altered material:	
Transformed zone:	
Claystone, noncalcareous, slightly greenish and bluish near-white, 5Y 7/2 being predominant, sparsely streaked with red; talc-smooth; soft when damp, hard when dry; resembles thick solid white claystone on Sharon Springs bentonite zone west of village of White Clay; contains scattered metallic limonite concretions, which are abundant compared to exposures at White Clay	16.5
Oxidized zone:	
Claystone as above, but with no concretions	3.5
Claystone, pale red (5R 6/2).	4
Claystone, pale greenish-white streaked along bedding and joints with yellow.	1.5
Claystone, dark yellow-orange (10YR 6/1); contains hard concretions of purple to brown limonite; suspect this was bentonite bed.	0.2
Claystone, slightly bluish white near N7.	0.4
Boundary zone:	
Shale, black, brown (10YR 6/2), bluish and greenish near-white; fish scales preserved in black and brown shale; nearly disconnected masses of black and brown shale a few feet long are separated from each other by light colored shale; contacts are not sharp. . . .	1.5
Sharon Springs member of Pierre shale:	
Shale, black, belonging to concretion zone.	13+
Total thickness of altered material. .	27.6

Transformed Zone

Considerable variation characterizes the transformed zone developed on noncalcareous shale. Except for the Sharon Springs member, in most places noncalcareous shale lacks a well-defined transformed zone, perhaps because of pre-Oligocene erosion. A well-defined transformed zone does occur at two places on the Carlile shale. One is in secs. 15 and 16, T. 34 N., R. 47 W., where a 6- to 25-foot transformed zone exhibiting kneaded and platy structure similar to that on calcareous shale occurs. White-mottled kaolinite and buckshot-size concretions of limonite are especially prominent in this area. Weathered slopes are mantled with a lag gravel of limonite concretions. The other place is in a gulley in the NE 1/4 sec. 7, T. 34 N., R. 47 W. Here greenish-gray montmorillonitic Oligocene claystone truncates a foot or two of red clay which grades downward into oxidized yellow (5Y 7/2) Carlile shale.

The transformed zone developed on the noncalcareous shale of the Sharon Springs member is thicker than any other and is almost wholly white or near white (5Y 6/1 to 5Y 7/2) talc-smooth claystone. The maximum thickness of white claystone is 20 feet, which occurs in sec. 36, T. 35 N., R. 46 W. Except for scattered concretions, iron oxide is seemingly absent. The white claystone consists largely of kaolin whereas the underlying orange, red, and near-white material of the oxidized zone consists largely of montmorillonite, according to X-ray analysis by A. J. Gude III. As much as 10 feet of claystone that is mottled and streaked with purple, red, and yellow underlies the white claystone some places. It is kaolinitic in part and contains numerous specks and concretions of iron oxide. The white claystone is fissile. This structure may be relict shaly bedding, in which case the soft claystone probably should be called shale, but more probably is platy structure such as occurs in the transformed zone developed on calcareous shale.

The transformed zone on the siderite-rich part of the Pierre shale is dark red (5R 6/4) and grades imperceptibly into the red oxidized zone, according to observations at the few poor exposures available. On other parts of the Pierre shale the transformed zone was not observed.

Oxidized Zone

The oxidized zone on noncalcareous shale is commonly about 25 feet thick, ranging from almost 10 feet to 37 feet. Yellow (5Y 7/2 to 10YR 8/4) shale, similar to that of the oxidized zone on calcareous shale, characterizes the oxidized zone on the whole of the Carlile shale and on parts of the Pierre shale. The oxidized zone on other parts of the Pierre shale is red and greenish near-white. Pale red (5R 6/2) characterizes the oxidized zone developed on the upper 100 feet of the upper part of the Pierre shale. Pale red (5R 6/2), orange (10YR 6/1), and near-white occur in the Sharon Springs shale were X-rayed. They resemble the bedrock, except for a sample of brown shale that contained more kaolinite than montmorillonite, according to J. Gude. Dark red

5R 4/6) characterizes the oxidized zone on the siderite-rich lower 75 feet of the middle part of the Pierre shale.

Limonite concretions large enough to be visible in the field are generally absent or scarce in the lower part of the oxidized zone on calcareous shale. They are absent in the dark red phase of the oxidized zone on noncalcareous shale, although microscopic specks of hematite are abundant. In contrast, small spherical limonite concretions having a warty surface and concentric shells are abundant in yellow shale in the upper part of the oxidized zone on the middle part of the Carlile shale exposed in sec. 13, T. 34 N., R. 47 W. From published descriptions, the warty concretions seem to resemble the buckshot and pisolith concretions in soils of Panama (Joffee, 1949, p. 466) and the so-called bean ore or hail ore of the Celebes (Mohr, 1944, p. 374), although those in the Chadron area are not abundant enough to warrant the name ore.

Limestone concretions in both the Carlile shale and the Pierre shale have altered to limonite and hematite in the oxidized zone. Limonite and hematite pseudomorphs of limestone concretions, concretionary lenses, and calcareous fossils occur in yellow shale down to a few feet above bedrock in the Pierre shale in sec. 31, T. 34 N., R. 47 W. The nearer the pseudomorphs are to the top of the profile, the redder and more compact they are. Some of the concretions are capped by splotchily irregular flattish downward-curving concretions of brittle white kaolinite-alunite, which also occurs sparsely as small concretions that are similar to but less well defined than those described in the transformed zone, and as fillings in cracks in septarian concretions. Kaolinite-alunite is rare in the oxidized zone, and occurs only on noncalcareous shale.

Boundary Zone

The boundary zone on noncalcareous shale is ordinarily several feet thick. It differs from the boundary zone on calcareous shale in that the contact of oxidized against unoxidized material is gradational instead of knife-blade sharp. In the Sharon Springs member of the Pierre shale the contact is so gradual that the boundary zone itself is barely recognizable, but in other parts of the Pierre shale, and in the Carlile shale, the contact is gradational through only about six inches. Concentrations of uranium characterize the boundary zone in noncalcareous shale as in calcareous shale. There would be some justification for extending the boundary zone below the base of oxidized shale, for limestone concretions in what is considered bedrock are discolored to a depth of as much as 20 feet at some exposures of non-calcareous shale.

Profile on Chalk or Limestone

Vertical changes can be made out in the altered material developed on chalk or limestone, but well-defined zones are absent. On the highlands in the center of the mapped area, near the junction of Beaver Creek with White River, the whitish middle chalk or limestone of the Niobrara formation is sparsely spotted and streaked along joints with pale orange (10YR 8/6) to bright red (5R 4/6) through an interval of 15 to 30 feet. Between this light-colored limestone and the Oligocene greenish-gray claystone above is a foot or two of brown (5YR 4/4) claystone. The upper chalk of the Niobrara formation is similarly stained throughout its 50-foot thickness at the west end of the bluff in sec. 30, T. 36 N., R. 46 W., and is also overlain by a few inches of brown clay that lies beneath Oligocene rocks. The brown clay probably represents the transformed zone; the stained chalk probably represents a weakly developed zone of oxidation. A boundary zone could not be recognized. Present-day weathering gives weak yellow, red, and orange colors to the limestone of the Niobrara formation, and its effects are not easy to differentiate from those of ancient weathering.

The concentrations of uranium that characterize the boundary zone in shale were found nowhere in the altered material developed on chalk.

Vertical Variation in Chemical Composition

Considerably more laboratory work needs to be done on the chemical composition of the altered material in the Chadron area. That reported here provides little more than reconnaissance knowledge, gathered in course of investigating uranium occurrences. Most of the analyses come from altered material on calcareous shale in the Niobrara formation. Although incomplete, knowledge about chemical composition provides grounds for inferring chemical conditions during alteration.

$CaCO_3$, Fe_2O_3, Fe_2O_3/FeO

Field observations tell several things about qualitative chemical composition. Reactions with hydrochloric acid show that calcium carbonate is practically absent in the transformed zone. Yellow and red colors show that much of the iron is three-valent. Abundance of limonite concretions indicates that iron is more abundant in most of the altered material than in the bedrock. The white color and relative scarcity of concretions in the upper or bleached part of the transformed zone suggest that iron is deficient in this part of the profile.

Two series of incomplete chemical analyses offer support. A series of 27 channel samples (USGS serial numbers 213429-213449) through the soil and underlying Niobrara formation were collected at locality 42, sec. 29, T. 36 N., R. 46 W. The section includes 6 feet of orange weakly mottled transformed zone in 1 sample, 46 feet of yellow oxidized zone in 13 samples, 3 feet of boundary zone in 2 samples, and 40 feet of gray bedrock in 11 samples. The samples were analyzed by R. Daywitt, T. Miller, J. McClure, and J. Schuch for calcium carbonate. They found that calcium carbonate in the bedrock averages 24.4 percent; the boundary zone 18.1 percent; the oxidized zone 17.2 percent; and the transformed zone 1.8 percent. Details are shown in Figure 10. The gradual upward decrease in average percentage of calcium carbonate in the oxidized zone probably is due to original difference in the bedrock, not to alteration, unlike the abrupt upward decrease at the base of the transformed zone.

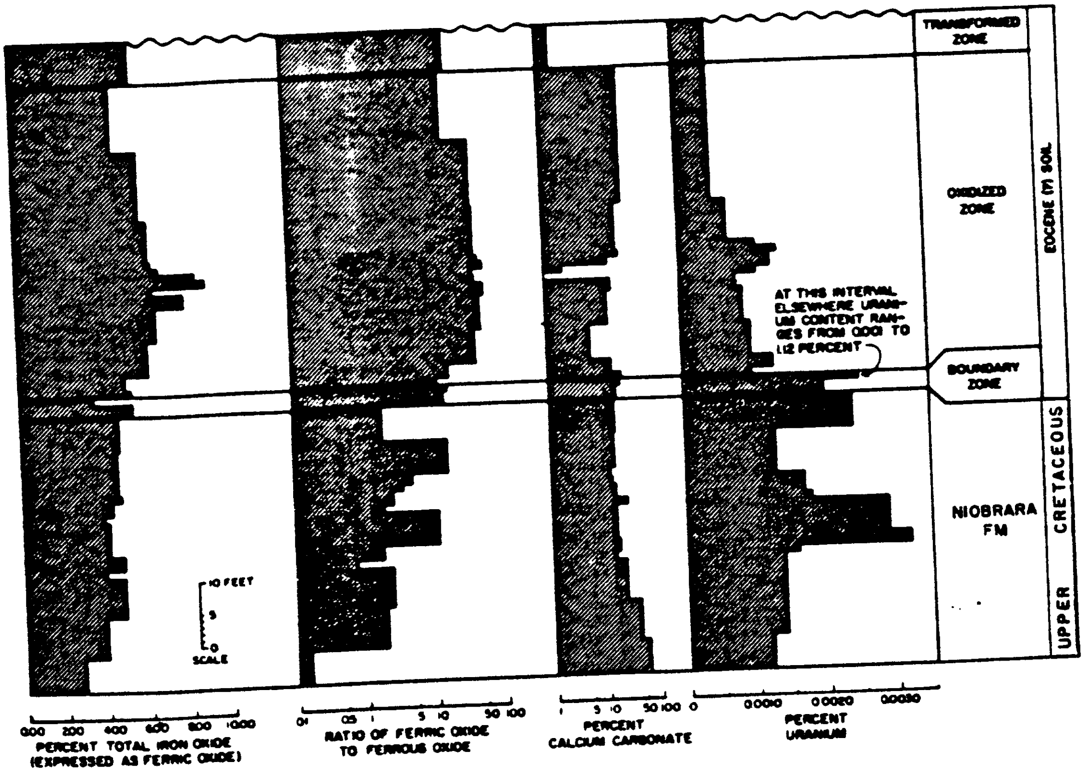


FIGURE 10.--Bar graphs showing vertical variation in abundance of iron oxide, calcium carbonate, and uranium in Eocene(?) soil and Niobrara calcareous shale bedrock, locality 42, sec. 29, T.36N., R.46W., Shannon County, South Dakota.

Splits of the same samples then were analyzed for Fe_2O_3 and FeO by S. Furman, J. Wilson, and H. Bivens. Their results show that the ratio Fe_2O_3/FeO for the bedrock averages 4.4, for the boundary zone 16.7, for the oxidized zone 43.6, and for the transformed zone 21.8. Details are shown in Figure 10. Analysis for FeO is difficult, for two-valent iron readily oxidizes in the laboratory. Furthermore, recent weathering affects the ratio in bedrock. The samples came from a bluff, which appears to be considerably less weathered at the base than at the top. Recent weathering probably accounts for the gradual upward increase of the Fe_2O_3/FeO ratio within the bedrock; without analysis of samples from a drill hole, it is impossible to be sure.

Iron occurs as pyrite in the bedrock and as limonite and hematite in the soil. By measuring the amount of ferric oxide in samples that have been completely oxidized in the laboratory, it is possible to determine the degree of iron enrichment in the altered material. Furman, Wilson, and Bivens found that iron, expressed as Fe_2O_3, in the bedrock averages 4.2 percent, the boundary zone 4.5, the oxidized zone 6.6, and the transformed zone 5.7. Details are shown in Figure 10. Judging by the abundance of concretions in the middle of the oxidized zone at this locality, the maximum in iron oxide in the middle of the oxidized zone probably is due to alteration. The gradual upward increase in the bedrock probably is an original difference, judging by the distribution of pyrite concretions. The decrease in abundance of iron in the one sample of the transformed zone probably is part of a pattern that is seen better where the transformed zone was sampled in detail.

Deficiency of iron in the upper part of the transformed zone is shown by a series of 5 samples from locality 28, sec. 21, T. 34 N., R. 47 W. There the transformed zone on the Niobrara formation is white platy claystone in the upper 2.5 feet, white nonplaty claystone for 1.7 feet, brilliantly mottled orange, white, and red claystone for 3.0 feet, then less brilliantly mottled claystone for 2.9 feet. The upper part of the oxidized zone is represented by 3.0 feet of yellow calcareous shale. The lower part of the oxidized zone and the underlying bedrock are exposed but were not sampled for these analyses. Large grab samples (serial numbers 230107-230112) from each measured unit were analyzed by D. L. Skinner. Limonite concretions are abundant in the 3.0-foot brilliantly mottled unit. Concretions were picked out of the samples and discarded. As shown in Table 1, Skinner found that the white claystone from the upper two units contains only half as much iron as the mottled claystone and the upper part of the oxidized zone. Had the concretions in the 3.0-foot brilliantly mottled unit been included, the contrast would have been several times greater.

No analyses are available for the altered material on noncalcareous shale. Judging by the deep red color and by the abundance of hematite specks, that on the siderite-rich lower 75 feet of the middle part of the Pierre shale probably would contain considerably more Fe_2O_3 than the 5 percent or so in the analyzed altered material on calcareous shale.

Table 1.--Ferric oxide, alumina, and silica in Eocene(?) soil on calcareous shale of the Niobrara formation, locality 28, sec. 21, T. 34 N., R. 47 W., Dawes Co., Nebraska.

	Thickness (feet)	Total Fe as Fe_2O_3	Al_2O_3	SiO_2	Remainder (includes $CaCO_3$)	Serial Number
Transformed zone	2.5	2.0	24.8	56.5	16.7	230107
	1.7	2.3	27.1	56.6	14.1	230108
	3.0	4.7	20.6	61.3	13.4	230110
	2.9	5.2	19.0	56.8	19.0	230111
Oxidized zone	3.0*	5.0	11.4	33.0	50.6	230112

* Chalky bed

	Thickness (feet)	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3	Serial Number
Transformed zone	2.5	2.28	28.25	12.46	230107
	1.7	2.08	24.56	11.78	230108
	3.0	2.97	13.04	4.38	230110
	2.9	2.99	10.92	3.65	230111
Oxidized zone	3.0	2.89	6.60	2.28	230112

Alumina and Silica

Skinner analyzed the same samples for alumina and silica, as shown in Table 1. The white claystone in the upper part of the transformed zone is about one-fourth alumina whereas the mottled claystone in the lower part of the transformed zone is about one-fifth alumina. Silica is somewhat less abundant in the upper part of the transformed zone than in the lower part of the transformed zone. Comparing the upper part of the oxidized zone with the other units is difficult because of the presence of calcite, and because there is only one sample. No samples of bedrock were analyzed at locality 28.

The other series of samples, from locality 42, were analyzed spectrographically by R. Havens. They allow comparison of oxidized and unoxidized calcareous shale. Aluminum is more abundant in the oxidized zone than in the bedrock, and yet more abundant in the transformed zone. Silicon is more abundant in the oxidized zone than in the bedrock. No difference can be seen between the oxidized zone and the transformed zone, both being in the undifferentiated range of tens of percent. There is only one sample here for the transformed zone. The abundance of aluminum is one unit of measurement less than the abundance of silicon in the oxidized zone and bedrock, but is the same as silicon in the transformed zone. Allowing for the lack of precision in the semiquantitative method, the analyses suggest a concentration of aluminum relative to silicon in the transformed zone. If the risk is not too great, the incomplete information from the two localities can be combined. When combined, the evidence suggests that alumina or aluminum is enriched in the altered material and enriched most in the highest part; and that silica or silicon is enriched in the altered material but enriched most somewhere beneath the level of greatest alumina or aluminum. Part of the enrichment is due merely to calcium carbonate being removed, but part may be due to migration of alumina and silica.

To see the difference between silica, alumina, and ferric oxide in the upper part of the profile, ratios are more instructive than percentages. Variations in amount of calcium carbonate then do not obscure the patterns. The ratios in the lower part of Table 1 show that, compared to alumina, silica is considerably less abundant in the upper bleached part of the transformed zone than in the lower mottled part of the transformed zone, and is slightly more abundant in the lower part of the transformed zone than in the upper part of the oxidized zone. Compared to iron, alumina is markedly more abundant in the upper part of the transformed zone than in the lower part of the transformed zone. Expressed in another way, iron and silica decrease as alumina increases. This trend would culminate in bauxite.

Splits of the samples analyzed by Skinner from locality 28, plus samples of the lower part of the oxidized zone, the boundary zone, and the bedrock at locality 28, were X-rayed by Evelyn Cisney. She found the brilliantly mottled claystone and overlying units to consist of kaolinite and lesser hydromica (illite), and the weakly mottled claystone to consist of hydromica (illite) and lesser kaolinite. The clay minerals of the lowest part of the transformed zone resemble those in the oxidized zone, the boundary zone, and the bedrock. The highest part of the transformed zone probably is richest in kaolinite, judging by a sample analyzed by George Ashby, which contained kaolinite and no illite. The analyzed kaolinite-alunite concretions referred to earlier come from the brilliantly mottled claystone at this locality.

Selenium, Arsenic, Uranium, and Other Trace Metals

Selenium and arsenic were not analyzed during this investigation, but their distribution is known. Moxon, Olson, and Searight (1939, p. 34) report analyses for selenium from the Niobrara formation at one locality in the Chadron area, and Moxon, Searight, Olson, and Sisson (1944, p. 72) report analyses for arsenic from the same samples. The locality was identified from their photograph as the knoll on the north side of the road in the SW 1/4 sec. 35, T. 36 N., R. 46 W. Their analyses are given below:

Unit Sampled: Present Terminology	Unit Sampled: Terminology of Moxon et al	Feet	Selenium (ppm)	Arsenic (ppm)
White River group	gray bed	8 1/2-18 1/2	0.7	30.0
	red bed	4 - 8 1/2	3.5	22.0
Transformed zone	mixed Niobrara and red beds	0 - 4	1.5	
Oxidized zone	yellow Niobrara	20-25	11.6	9.0
	yellow Niobrara	10-20	7.0	45.0
	yellow Niobrara	0-10	7.3	0.2
Unweathered material	Niobrara	10-20	8.3	18.6

Compared to bedrock, selenium is notably deficient in the transformed zone, but arsenic is not. The above authors (1944, p. 80) say, "The loss of selenium from the parent material in the soilformation processes is very great. . . . The loss of arsenic, on the other hand, is much less, indeed it may be very slight."

The spotty enrichment of uranium in the upper part of the boundary zone is discussed in detail in a later section. Here it is worth mention that uranium is generally less abundant in the transformed zone and oxidized zone than in the bedrock. The difference is small but apparent in every suite of samples. For example, at locality 42 (fig. 10) the element uranium is less than 0.001 percent in the altered material and more than 0.001 percent in the bedrock.

The samples from locality 42 that were analyzed spectrographically by R. Havens contain traces of metals other than iron. The semiquantitative method allows rather large differences in abundance to be recognized. By using the median values for the group of samples from bedrock and for the group of samples from the oxidized zone, and the single value for the transformed zone, it is possible to compare intervals. The boundary zone is discussed in the section on uranium.

Nine elements varied from zone to zone sufficiently to be detected by the semiquantitative method (fig. 11); elements whose variation was through only two bracketed values are not considered, for the ranges represented by bracketed values may overlap. Lanthanum, yttrium, manganese, gallium, lead, and ytterbium were concentrated in the weathered rocks, as well as aluminum and silicon. Calcium was depleted as would be expected from the previous analyses for calcium carbonate. The enrichment of aluminum and silicon in the soil has already been discussed. How much of the enrichment is due to original differences, simple loss of calcite, or actual migration, must await

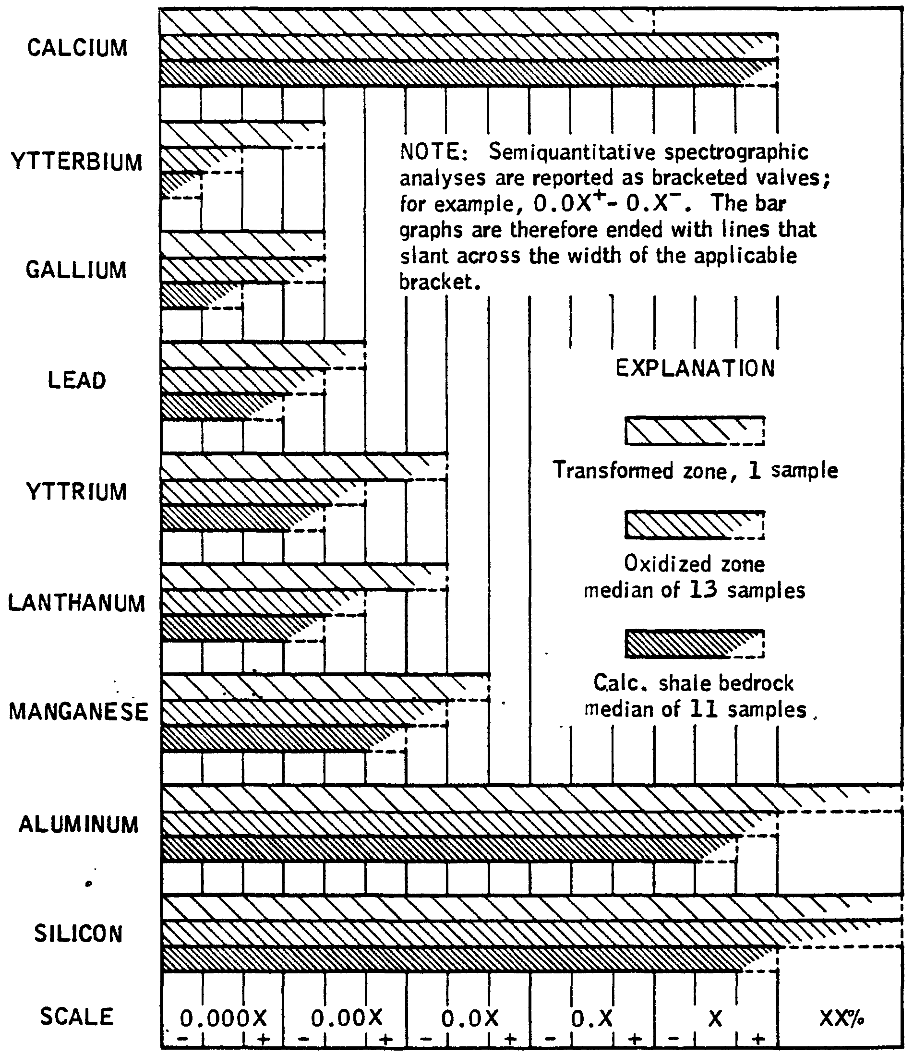


FIGURE 11.--Bar graphs showing vertical variation in abundance of various elements in Eocene(?) soil and Niobrara calcareous shale bedrock, locality 42, sec. 29, T.36N., R.46W., Shannon County, South Dakota.

ther study. It is noteworthy that depletion of calcium and enrichment of lanthanum, yttrium, manganese, and gallium, plus aluminum and iron could be predicted to result from weathering by knowledge of ionic radius and charge (Rankama and Sahama, 1950, p. 238.)

Origin

The following interpretation of the origin and age of the altered material underlying the Chadron formation is not new. Except for adding more details about origin and attempting to be more precise about age, the present interpretation is remarkably similar to that advanced by Wanless in 1923 for 70 feet of similar altered material ("Interior formation") in the Big Badlands of South Dakota, where many of the dvantages the Chadron area affords are absent.

Ancient Soil

Reasons for concluding that the altered material is an ancient soil are three:

(1) The altered material resembles soil in profile. It is leached, oxidized, and kaolinized, and the degree of alteration decreases downward. Differences in color, texture, and other properties visible in the field allow the profile to be divided into zones. The sequence of zones is comparable to that in ancient soil; for example, the zones in the Chadron area described as transformed, oxidized, boundary, and bedrock compare in sequence with the zones in gumbotil described as "thoroughly decomposed chemically," "oxidized and leached of carbonates,"

oxidized but containing primary carbonates," and "unoxidized and unleached" by Leighton and MacClintock (1930).

(2) The altered material resembles soil in stratigraphic position. Its base conforms to the land surface represented by the sub-Oligocene unconformity, and its base cross-cuts formation boundaries in the underlying Cretaceous rocks.

(3) Alteration occurred before deposition of Oligocene sediment. Rounded pebbles derived from the upper part of the altered material occur as pebbles in Oligocene channel sandstone, and the upper part of the altered material is absent beneath Oligocene channel sandstone.

Alteration after Burial

Before attempting further interpretation of the ancient soil, one problem must be dealt with. If the ancient soil is now much as it was before burial, it can be interpreted in terms of modern soils with some confidence. If Oligocene and later groundwater deeply changed the soil after it was buried, further interpretation would be difficult or impossible.

Deep alteration by groundwater seems not to have happened. Definite evidence of alteration by Oligocene and later groundwaters was found at one locality in the Chadron area. At locality 31, sec. 36, T. 34 N., R. 49 W., the basal Oligocene rocks are quartzose, well-sorted sandstone and conglomerate channel-fill that is porous and permeable. The channel is cut into the yellow oxidized zone on Pierre shale. Near the contact the shale is lighter than below and contains a yellow powder identified by R. L. Wack as jarosite, plus gypsum. The bleaching and mineralization extend less than one inch into the oxidized zone, and a lesser distance into the Oligocene rocks. The exposure is not fresh; the jarosite and gypsum most likely are modern alteration products of pyrite.

Nowhere else in the Chadron area were any signs of groundwater alteration seen. Near Orella, Sioux County, Nebraska, an Oligocene channel sandstone rests unconformably on the red oxidized zone developed on Pierre shale, and, at the bottom of the channel, on unoxidized greenish-gray Pierre shale bedrock (fig. 12). The red shale and the greenish-gray shale there show unmistakable signs of alteration by Oligocene or later ground water. Both are bleached white or greenish-white for about 1 inches below the unconformity. Large cubes of pyrite cement the basal few inches of sandstone above the unconformity. The sandstone contains several boulders of originally red clay, and shale, probably eroded from nearby banks of the ancient river. The boulders are also bleached. Large boulders are bleached to a depth of several inches but their center is still completely red. Bleaching extends as far inward on the bottom and sides of the boulders as on the top. Small boulders are completely bleached; even the center is greenish-white claystone or shale. Channel sandstone in the Big Badlands, South Dakota, exhibits similar bleaching and pyrite cementation according to Clark (1937, p. 273-276). These facts indicate that Oligocene and later ground water altered the ancient soil and its bedrock where the transformed zone is absent and the overlying rocks are permeable, but the alteration extended only inches downward from the permeable rocks.

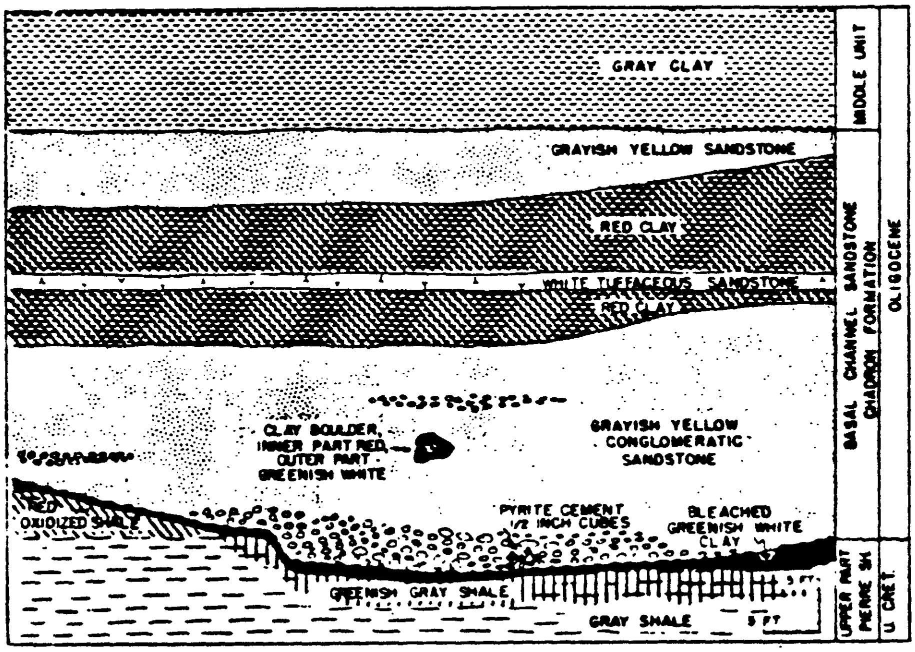


FIGURE 12.--Sketch of oxidized Cretaceous shale truncated beneath Oligocene channel sandstone, partly bleached to greenish white clay, SW 1/4 sec. 36, T.34N., R.54W., 4 miles west of Orella, Sioux County, Nebraska.

Not only is the groundwater alteration of the ancient soil superficial, it is recognizably distinct from alteration due to soil-making. Soil-making involved water that was oxidizing and acid. The ground water evidently was reducing and nonacid. Red color is bleached when ferric iron is reduced to non-red ferrous iron and then removed, according to Keller (1929, 1953). The inference that Oligocene and later ground water were reducing is confirmed by the presence of pyrite. Judging by the calcite cement in the sandstone, the ground water was neutral or alkaline. The fact that the iron sulfide crystallized as pyrite instead of marcasite is in accord (Edwards and Baker, 1951).

Pedologic Classification

The ancient soil in the Chadron area is a zonal soil; that is, it reflects the influence of ancient climate and vegetation. Interpreting the ancient climate and type of vegetation becomes possible when the soil is classified.

Loss of lime shows that the ancient soil belongs to the pedalfer order. Red and yellow colors, limonite concretions, enrichment in iron, slight enrichment in alumina, kaolinization, relatively poor vertical differentiation, and great thickness show that the ancient soil belongs to the lateritic soil suborder, as defined by the U. S. Department of Agriculture (~~Thorp and~~ Baldwin and others, 1938). Further subdivision is less certain. The lateritic soil suborder contains five great soil groups in the United States and territories: yellow podzolic (lateritic) soils, red podzolic (lateritic) soils, the two of which are commonly referred to as undifferentiated yellow and red podzolic (lateritic) soils or simply as red and yellow soils, yellowish-brown lateritic soils, reddish brown lateritic soils, and laterite soils. Bleaching and loss of iron from the upper part of the transformed zone, plus color mottling, compact clayey texture, and relative abundance of silica, indicate that the ancient soil belongs to the undifferentiated yellow and red podzolic (lateritic) groups.

Implications as to Climate and Vegetation

The present distribution of pedalfer and pedocal soils conforms broadly to the distribution of wet and dry climates. Pedalfer soils occur where precipitation exceeds evaporation and transpiration, where trees are the dominant plants. Within the pedalfer group, kind of soil conforms broadly to temperature. Lateritic soils are common in the tropics and extend into warm-temperature regions. Baldwin, Kellogg, and Thorp (1938, p. 263) relate lateritic soils to "forested warm-temperate and tropical regions."

According to descriptions given by Robinson (1936), soils similar to that in the Chadron area occur today from the equator to about 35° latitude, in Brazil, Cuba, southeastern United States, Tanganyika, southern Nigeria, southern China, southern India, Ceylon, and Indo-China. Near the equator, lateritic soil is associated with laterite and bauxite.

Various climatic classifications of soils agree in placing the Chadron area type of lateritic soil in climates that are hot and wet.

Vilensky (in Jenny, 1941, p. 186) plots type of soil against moisture and against temperature. What he terms "podsolized yellow soils" occur in his subtropic (54 to 68° F) temperature zone and in his humid (more than 1.75 precipitation-evaporation ratio) moisture zone. What he terms "podzolized red soils" differ in being in the tropic (more than 68° F) temperature zone, but are also in the humid zone. Thornthwaite (in Jenny, 1941, p. 186) plots type of soil against "temperature efficiency or TE index" and against "precipitation effectiveness or PE index." His more sophisticated concepts allow better for seasonal differences. What Thornthwaite terms "red and yellow earths" occur between TE index 128 and 64. For comparison, the poleward limit of tundra has a TE index of 0 and the poleward limit of tropical rain forest and savanna has a TE index of 128. The lateral sequence goes from snow and ice to muskeg to podsols to gray-brown earths to red and yellow earths to laterites. On the precipitation axis, red and yellow earths occur in the zone having a PE index greater than 64, the lateral sequence going from gray earths, to chestnut earths, to black earths, to prairie earths, to red and yellow earths.

It thus appears that the ancient soil records a time when the Chadron area was hot and wet and therefore forested.

The meaning of specific numbers for the ancient climate in the Chadron area is open to question. There is no assurance that a modern soil is as modern as the climate measured at the same place. Climatic measurements go back a few tens or hundreds of years. Mature soil is not made in so short a time. The fact that red and yellow soil occurs as far north as the southeastern United States and southern China, where the present climate is considerable cooler than equatorial, raises the question of whether modern red and yellow soil carries the imprint of more than one climate. Joffee (1949, p. 506) considers the red and yellow soil of the southeastern United States to be a prime example of soil formed in an earlier more tropic climate. Mohr and Van Baren (1954, p. 356-361) conclude that many lateritic soils and laterites at the present surface of the ground are products of earlier climates. He notes several kinds of evidence. For example, laterite and lateritic soil occur at the surface in Australia and Africa in regions that are now too dry for leaching to occur. In Indonesia lateritic soil occurs mostly on Miocene rocks and pre-Tertiary rocks and none occurs on Quaternary rocks. The relatively shallow weathering of Pleistocene augite-andesite in the British West Indies contrasts strikingly with the thick lateritic soil on older rocks. These things indicate that the making of thick lateritic soil requires geologic intervals of time. Pleistocene and Recent fluctuations of climate indicate that climate does not necessarily remain constant for geologic intervals of time. The present climate seems to be merely a glimpse at a succession of climates that one after the other acted to make modern soil as it now appears. Interpretation of soil in terms of degrees of temperature and inches of rainfall is therefore suspect.

The conclusion remains that the climate in the Chadron area became as hot and wet during the making of the ancient soil as the southeastern part of the United States became during the making of its modern soil. When hot and wet, the Chadron area was most probably forested.

Topography and Ground Water

No signs of mountains or hills can be seen in the ancient soil, in spite of the crustal movements known to have occurred after deposition of the Pierre shale and before deposition of Oligocene rocks. The nearly uniform thickness of the soil and the nearly uniform thickness of the overlying Oligocene claystone in the Chadron and nearby areas indicate that the soil was made on a plain. Had the Oligocene rocks been laid down on a surface of great relief, such as described in eastern Wyoming by Denson and Botinelly (1949), the Chadron formation would range in thickness from a knife edge to hundreds of feet. Mountains or hills due to non-catastrophic local uplift seem unlikely on theoretical grounds, in view of how easily shale and limestone are eroded in hot wet regions.

River courses eroded into the soil and filled with Oligocene sandstone and gravels show that at the end of soil making the plain sloped generally eastward, steeply enough for rivers crossing it to transport cobbles of crystalline rocks from distant mountains. Without evidence to the contrary, it seems reasonable to assume that the plain also sloped generally eastward during soil making.

Groundwater zones can be recognized in the ancient soil. Limonite and hematite in the oxidized zone and transformed zone show where iron was oxidized and where ferric hydroxide gels were more or less dried out. Oxidation suggests the presence of air, and drying out ordinarily requires air; therefore, the oxidized zone and transformed zone record the ancient vadose zone and the bedrock records the ancient phreatic zone.

The boundary zone apparently records the water table, or at least its lowest stand. Modern water tables are sometimes illustrated as planes, but in detail they are far from plane. Capillary forces draw water up into fine pores, causing the water table to be a zone of appreciable thickness. Water rises higher in the narrow tortuous passageways provided by pores in solid rock than it does along the passageways provided by joints. Meinzer (1942, p. 394) describes the zone under the term capillary fringe. The irregularly interpenetrating oxidized and unoxidized material characterizing the boundary zone is much like a fringe. In the boundary zone gray shale occurs in spaces between joints and bedding planes, whereas yellow shale occurs adjacent to joints and bedding planes; thus the boundary zone probably does correspond to the ancient water-table zone.

Ground-water tables beneath plains lie above river level in wet climates and closely parallel the surface of the plain. The nearly uniform thickness of the ancient soil indicates a rather even water table. It also indicates that at times the level of permanent rivers lay more than 55 feet below the surface of the plain. The plain apparently was an incised or upland plain; the plain probably was fairly well drained, for great quantities of calcium carbonate and other substances were leached from the rock and removed in solution. Mohr and Van Baren (1954, ~~(1955,~~ p. 362) report~~s~~ that good drainage is essential for leaching; and zonal soils are well drained.

Age

The age of ancient soil can be an ambiguous concept. Here age is conceived of as the time when lateritic weathering produced the transformed zone of the existing ancient soil.

The age assignment of the ancient soil in the Chadron area is less precise or less certain than that of any other exposed unit. Prospects for improvement are poor. The soil contains no fossils useful for dating. The overlying rocks are tens of millions of years younger than the underlying rocks; superposition in the Chadron area shows only that the soil was made during the interval of time that includes Cretaceous, Paleocene, Eocene and Oligocene.

Assigning the soil to this interval is fairly certain. The interval is, however, so wide that a less certain but more precise assignment seems worth attempting. To outline the approach, superposition in nearby areas narrows the interval to Paleocene and Eocene time. Three lines of indirect evidence then independently suggest, but do not prove, Eocene time. The indirect evidence suggests also that Early Eocene is more probable than other parts of Eocene time. The uncertainty inherent in using such indirect evidence deserves emphasis; it is symbolized by the query in the assignment to Eocene(?) time.

Superposition in the Chadron and Adjacent Areas

The youngest fossiliferous rocks underlying the soil in the Chadron area contain _Baculites grandis_, which is Cobban and Reeside's (1952) suggested zonal index for the Mobridge member of the Pierre shale of the reference section (Maestrichtian). The oldest fossiliferous rocks overlying the soil contain brontotheres of Early, but not earliest, Oligocene age.

Fortunately, the ancient soil of the Chadron area is not restricted to the Chadron area. Nearly continuous exposures allow the soil to be traced northeastward into the Big Badlands of South Dakota and southwestward into the Crawford area of northwestern Nebraska. Schultz and Stout (1955), who describe the ancient soil in the Crawford area, report that the soil occurs also in the Torrington-Goshen Hole area of eastern Wyoming. They note that in the Torrington-Goshen Hole area the soil is on the Lance formation and that reworked soil occurs in the overlying Yoder formation. The Lance formation is of latest Cretaceous age. The Yoder formation contains numerous vertebrate fossils, which Schlaikjer (1935, p. 71-75) reports to be distinctly transitional between Duchesne (Eocene or Oligocene) age and early Chadron (Oligocene) age, and assigns to Oligocene age. Superposition in the Torrington-Goshen Hole area thus narrows the interval to Paleocene and Eocene time.

Superposition in North Dakota and Saskatchewan

That bright-colored material in the Chadron area can be traced northeastward and southwestward along the outcrop of the sub-Oligocene unconformity for long distances is significant, for it provides grounds for assuming that similar bright-colored material beneath the sub-Oligocene unconformity elsewhere in the northern Great Plains was once continuous with the bright-colored material in the Chadron area. Modern lateritic soils blanket large regions; it is reasonable to expect ancient lateritic soils to do the same. If the assumption is valid, North Dakota and Saskatchewan furnish evidence bearing on the age of the ancient soil in the Chadron area. In both places bright-colored material beneath the sub-Oligocene unconformity can be dated with greater precision than is possible in the Chadron area.

In western North Dakota bright-colored material occurs extensively in the 75-foot Golden Valley formation, which conformably overlies Paleocene rocks, unconformably underlies Oligocene rocks, and contains Eocene fossils. According to Brown (1952, p. 91), the bright-colored material was deposited in Early Eocene (Wasatch) time. The Golden Valley formation contains white kaolinitic clay of ceramic grade, which is mottled and stained with bright yellow orange or reddish orange. The orange mottled material is sufficiently distinct to warrant the name marker bed, and sufficiently extensive to be useful to Benson in his mapping of the regional structure of western North Dakota. The bright color of the Golden Valley formation was not attributed to lateritic weathering in the brief accounts published by Benson and Laird (1947), Benson (1949), and Brown (1952, p. 89-90). Even so, the striking resemblance of the bright-colored material in the Golden Valley formation to the bright-colored material in the ancient soil of the Chadron area suggests that the bright colors in the two areas were made by the same processes. In particular, the fact that orange mottles occur in the ancient soil of the Chadron area and in the Golden Valley formation seems unlikely to be mere coincidence. The mottling and the hue of the mottles both point to alteration of previously deposited sediment. Color-mottling is something that happens after deposition, for color boundaries are not accompanied by differences in texture allowing other descriptive names to be used. Weathering is of course not the only thing that produces color-mottling, but weathering does seem to be the only common geological cause for orange mottles.

A little evidence suggests that even if the orange were not in the form of mottles, the hue itself would still indicate that the Golden Valley formation was modified by soil making. Although orange is a weathering color, the question might arise as to whether the weathering happened at the place of deposition or elsewhere--red soil can be eroded and redeposited as redbeds, and it might seem that orange soil can too. Judging by the Chadron area, erosion and redeposition of orange soil causes it to turn red or otherwise lose its orange color; orange is absent above the sub-Oligocene unconformity everywhere in the Chadron area, although in many parts of the area the lowest Oligocene rocks are made largely of red, white, or purple reworked soil.

In southwestern Saskatchewan, bright-colored material in the Ravenscrag formation conformably overlies Paleocene rocks and unconformably underlies very early Oligocene rocks. The bright-colored material constitutes the upper part of the Ravenscrag formation, which Russell (1953, p. 106-109) describes and correlates in part with late Paleocene formations. Three described features seem to bear on the origin of the bright color. One is the presence of "kaolinized clays," which suggests lateritic weathering. Another is the vertical sequence of colors in the Ravenscrag formation from "sombre and gray" below, through bright yellow," to "purple" above, which can be duplicated in the ancient soil of the Chadron area and suggests a soil profile. The third is Russell's description of relationships at the base of the bright-colored zone:

> "Although the change in predominant color appears very sharp from a distance it is not always readily located on the outcrop. It is also known that this color change does not follow a precise stratigraphic level but may vary upward or downward from place to place."

The hue of the color, the lack of sharpness of the boundary, and the fact that the color change cuts across planes of deposition also suggest ancient weathering.

If the bright-colored material in North Dakota and Saskatchewan reflects the same episode of lateritic weathering that produced the soil in the Chadron area, which seems likely but far from proved, then the Paleocene-Eocene age assignment can be narrowed to Eocene.

Lateritic Weathering in Distant Areas

A second line of approach seems to shed light on the age of the ancient soil in the Chadron area. Intensive lateritic weathering requires a rather special set of conditions. Among others, sedimentation must practically cease, the land must be well-drained, and the climate must be hot and wet. The requirements, whatever they are in detail, are satisfied beyond doubt where lateritic soil, laterite, or bauxite are known to occur. These end results of lateritic weathering are extraordinarily common in rocks of Eocene age, and particularly in rocks of Early Eocene age.

Bauxite in the United States and the World

In discussing the origin of bauxite and other aluminum ore formed by lateritic weathering, Allen (1952, p. 685) reports the age of deposits in ten states in the United States. He assigns the deposits to Eocene time in six of the ten, and to Late Cretaceous, Paleocene, or Oligocene time in none.

> "The gibbsite of Georgia, Alabama, Virginia, and Arkansas was probably formed during the Eocene epoch. Gibbsite was formed in California during the Eocene; at Castle Rock, Washington, during the Eocene...One occurrence of diaspore in the Cle Elum iron deposit, Kittitas County, Washington, is of Eocene age...and the boehmite of Arkansas, Washington, and California was probably formed during the Eocene epoch."

Lateritic weathering during Eocene time was not restricted to the United States. According to Harder's (1949) summary of the world distribution of bauxite and the stratigraphic relationships of the deposits, Early Eocene time was unusually favorable for lateritic weathering. Harder (1949, p. 891) reports:

> "Lower Eocene bedded bauxites...They comprise the bauxites of the Istrian peninsula, Dalmatia, Herzegovina, and southern Montenegro along the Adriatic Coast in Yugoslavia, those of the Barcelona region in northeastern Spain, the Jammu deposits of Kashmir in northwestern India, and the important belt of bedded bauxite deposits in the United States extending from central and southern Georgia through southeastern Alabama and northeastern Mississippi to central Arkansas."

Redeposited Lateritic Soil in the Rocky Mountains

Thanks to Van Houten's (1948) penetrating analysis of red-banded early Cenozoic rocks in the Rocky Mountains, lateritic soil can be recognized even after it has been redeposited, as long as it keeps its red color. Van Houten marshals persuasive evidence that the redbeds he dealt with owe their color to lateritic weathering. He interpreted the redbeds as being red soil made by lateritic weathering in uplands and redeposited where it could retain its red color. Reworked red soil cannot be deposited until after lateritic weathering has begun on the uplands, but may continue as long as any red soil remains on the uplands.

Van Houten (1948, p. 2085) summarized the age of redbeds in the Rocky Mountains. The interesting thing about the distribution of redbeds in the Rocky Mountains is the predominance of Lower Eocene redbeds. Lower Eocene redbeds occur in ten parts of the Rocky Mountains; whereas Upper Cretaceous redbeds occur in one, Paleocene redbeds occur in four, Middle Eocene redbeds occur in three, and Upper Eocene redbeds occur in two. That redbeds of Early Eocene age are so extensive in the Rocky Mountains thus seems to be part of the larger pattern in which bauxite of Early Eocene age is unusually extensive in the United States and the world.

Implication

The abundance of Early Eocene bauxite in the southeastern United States, and of Early Eocene redeposited lateritic soil in the Rocky Mountains, indicate that something about Early Eocene time greatly favored lateritic weathering, and therefore suggests that the lateritic soil in the Chadron area is likely to be of Eocene age, more precisely, of Early Eocene age.

Soils can be thought of as having geographic facies. The lateritic soil that now occurs in the southeastern United States is, in this sense, a northern facies of the bauxite and laterite in Jamaica and Cuba. Ancient soils can be expected to show similar facies patterns. Such a pattern apparently existed in Early Eocene time in Europe. On the north side of the Mediterranean is bauxite of Early Eocene age. To the north, near Paris, Gignoux (1955, p. 477) describes plastic clay that is "completely decalcified so that no fossils are found" between Montian (Paleocene) marine beds and Ypresian (Eocene) marine beds. The plastic clay truncates underlying beds and grades laterally into near-shore rocks bearing lignite and marine shells. The plastic clay in the Paris area is used for pottery where it is white, which indicates kaolinite. In central Europe, the clay is red and rich in ferruginous concretions. The clay is evidently lateritic soil.

On this basis, the well-dated Arkansas bauxite probably had a northern lateritic soil facies during Early Eocene time. The ancient soil in the Chadron area is a likely candidate, although subsequent erosion has removed all hope of tracing one into the other. The fact remains that there is one extensive level of bauxite in Arkansas and adjacent areas and one extensive level of lateritic soil in the Chadron and adjacent areas. Chances are that the two are of the same age.

Requirements as to Drainage and Climate

A third line of approach to the question of age concerns drainage and climate. Two of the stringent requirements for the development of extensive thick lateritic soil on plains are good drainage and wet climate. Paleocene time seems not to have met the first requirement in the Great Plains; Late Eocene and possibly Middle Eocene time seem not to have met the second requirement.

To elucidate, thick sequences of Paleocene rocks in the Great Plains are wholly drab, for example, the thousands of feet of Fort Union formation west and north of the Chadron area. The sea is known to have lain in the Dakotas during Paleocene time. As Brown (1952, p. 92) says, "the interfingering of brackish water tongues of the Cannonball formation with coal seams of the early Fort Union in the valley of the little Missouri River, shows that the coal-forming swamps, pools, or lakes, were practically at sea level but at varying distances inland from the sea." The frequency and thickness of coal beds in the Fort Union formation shows that the water table was generally near the surface of the ground. Bryson (1949) remarks that individual coal beds in lower Tertiary rocks in the Great Plains can be traced across hundreds of square miles, as compared with the few miles of outcrop along which coal beds can be traced in Upper Cretaceous rocks west of the Rocky Mountain front. This fact plus the absence or scarcity of coarse grains in the Fort Union formation indicate that the coastal plain sloped very gently, and hence was low-lying for great distances. In such a situation, lateritic weathering is unlikely.

Lateritic weathering ends when precipitation fails to exceed evaporation (and transpiration) by a goodly amount. Assuming that Eocene climate in the Chadron area was not greatly different from that elsewhere in the general region, evidence from the west bears on the Chadron area.

Thanks to work by Bradley (1931), Dane (1954), and Picard (1955) on the Green River lakes of Utah, Colorado, and Wyoming, much is known about the wetness of Eocene climate. In Middle Eocene time, when the oil shale of the Green River formation was deposited, Gosiute Lake occupied a large area in Wyoming, Colorado, and Utah. Because the size of the Middle Eocene lake remained fairly constant for a long time, and for other reasons, Bradley infers that evaporation and precipitation were roughly balanced over the area drained by the lake. Before Middle Eocene time, the climate was definitely wet, as indicated by expansion of the lake. The Middle Eocene rocks studied by Bradley are underlain in Utah by a black shale facies deposited during slow expansion of the lake, which Picard (1955, p. 87) tentatively dates as lower Eocene (Wasatch). After Middle Eocene time, the Green River lakes shrank and produced abundant evaporite minerals. Dane (1954) reports that the saline facies is more than 900 feet thick in Utah. He and Picard (1955) agree that the saline facies is contemporaneous with the lower part of the Uinta formation of Late Eocene age. Judging by the Green River lakes, the regional climate was generally wet in Early Eocene time, generally dry in Late Eocene time, and variably and about equally wet and dry in Middle Eocene time.

Evidence from the Green River lakes thus suggests that Late Eocene time and probably Middle Eocene time were too dry for lateritic weathering.

Possibility of Non-regional Lateritic Weathering

The preceding discussion is based on the inference that the lateritic weathering recorded in the Chadron area was regional. The inference needs to be specifically examined. Crustal uplift of the Chadron arch occurred during the interval in question. Crustal uplift could conceivably produce a well-drained highland having an independent climate and mantled with lateritic soil--an island of lateritic weathering. In such a situation evidence from outside the Chadron area would be irrelevant.

Two things indicate against this "lateritic island" possibility.

(1) Evidence discussed in the section on topography indicates that the Chadron area was a plain during the making of the ancient soil. Had the rate of uplift exceeded the rate of erosion of shale and limestone so as to produce an upland, the upland and its original soil were removed before the existing ancient soil was produced.

(2) The ancient soil in the Crawford area and Big Badlands, where there is no Chadron arch, is continuous with the ancient soil in the Chadron area, and is indistinguishable from it where both are developed on the same kind of bedrock.

Conclusions as to Age

The ancient soil is almost certainly of Paleocene and/or Eocene age, as shown by superposition in the Chadron and adjacent areas. Evidence from North Dakota and Saskatchewan suggests Eocene age. Evidence from lateritic weathering in distant areas also suggests Eocene age, and, more precisely, Early Eocene age. Considerations of drainage and wetness are in accord with the other suggestive evidence. Despite the concurrence of the available lines of evidence, the uncertainty inherent in each of the individual lines rules against conclusive age assignment. The ancient soil is therefore assigned to Eocene(?) time.

OLIGOCENE

White River Group

The name White River group was proposed by Meek and Hayden (1858, p. 119, p. 113; 1862, p. 433-434) for "white and light drab clays with some sandstone beds and local layers of limestone" exposed as badlands along the White and other rivers. Darton (1899, p. 755-759) subdivided the group into two formations, the Chadron below and the Brule above. In the present study these subdivisions were mapped in the central and western parts of the area. Had time permitted, subdivision could have been carried further.

Chadron Formation

Definition and Typical Section

Darton did not formally designate a type locality for the Chadron formation; but in 1931 (personal communication cited in Wilmarth, 1938, p. 392) he stated that he named the formation for exposures at Chadron, Nebraska. His (1903, p. 40) description and illustration of the section at Chadron apparently are based on imperfect water well records, and do not adequately define the formation. The concept in Darton's mind can be inferred, however, by his placement of boundaries in other areas, for example in Goshen Hole and Platte Valley (1905, p. 172-173) and in the Big Badlands (1905, p. 43, Pl. XLV), and by his general description of the formation (1903, p. 18).

The following measured section seems to accord with Darton's concept of the Chadron formation. The section typifies the Chadron formation in the Chadron area, as well as one locality can represent variable rocks.

Section of Chadron Formation
NE cor. sec. 32, T. 34 N., R. 48 W.
4 miles north of Chadron, Dawes County, Nebraska

	Feet
Brule formation:	
Dolomite, white (N9), laminated with clay, rich in ostracods; persistent toward north where it is overlain by bedded gypsum and laminated clay; disappears toward south.	
Chadron formation:	
Pellet mudstone part:	
Mudstone, pale greenish yellow near 10Y 8/2, very silty, calcareous, massive; visible pellets are mostly 1/4 to 1/16 inch and round; lower half contains two concentrations of calcite cement in form of lumpy lacework or lime pans a foot or so thick; the upper lacework zone is faintly mottled with pink.	24
Lime pan (caliche); differs from lumpy lacework above in being solid, more resistant, and more persistent, but it, too, swells and thins, up to 3 feet and down to 1 foot; visible pellets present but scarce.	2
Mudstone, pale greenish yellow near 10Y 8/2, less silty and more clayey than above, calcareous, pelleted, massive; lower half tends more toward pale brown than toward pale green, as seen from a distance; teeth and bone fragments identified by Lewis as Early Oligocene brontothere	24
Lime pan, as above but pellets make up more than half of rock	2

Mudstone, pale greenish yellow near 10Y 8/2, silty, calcarecus, pelleted, massive; grades into claystone below 13

Total thickness of pellet mudstone 65

Green claystone part:

Claystone, very pale olive near 10Y 7/2, massive, deep shrinkage cracks; chalcedony is abundant; brown, black, and opaque white plates associated with bones at base, rough-surfaced translucent rose and gray hollow masses up to 1 foot across in lower 3 feet, same in upper part but not hollow and only half inch in diameter. 9

Claystone, pale olive near 10Y 6/2, massive, deep shrinkage cracks; chalcedony is medium-sized rough-surfaced type and is translucent light gray or light bluish gray 6

Total thickness of green claystone 15

Sandstone-red claystone part:

Red claystone, mottled pale red (10R 6/2) and pale olive near 10Y 6/2; upper part mostly green, lower part mostly red and sandy; gradational above and below 10

Sandstone, near white but streaked with red and drab in upper clayey part, quartzose, fine-grained, calcareous, cross-bedded; lenses of mostly vein quartz conglomerate at base 5

Total thickness of sandstone-red claystone . . . 15

Eocene(?) soil

Oxidized zone on upper part of Pierre shale

Total thickness of Chadron formation 95

General Description

The Chadron formation ranges in thickness from 75 to 110 feet. It consists of mudstone, claystone, and lesser sandstone and conglomerate. Its outcrop belt, including the lower part of what is mapped as undifferentiated White River group, forms a crude horseshoe closed in the country west of White Clay, and extending on the south along the south side of White River, and on the north along the southern slope of Slim Buttes. Erosion produces unvegetated badlands in which gentle and smoothly rounded slopes grade upward into steep and intricately dissected bluffs.

The formation differs in composition from place to place in the Chadron area, although not to the degree that will be seen in the Brule formation. In most of the area, the Chadron formation consists of two parts, a lower green claystone and an upper green, or green and pink, pellet mudstone. This is not the case in a belt trending eastward and northeastward through the center of the area. There the green claystone is underlain by a complex assemblage of conglomerate, white sandstone, red sandstone, and red claystone, which will be referred to as the sandstone-red claystone, or basal part of the Chadron formation (fig. 13).

The base of the formation is an angular unconformity representing a considerable hiatus. The top is marked by the upper limit of pellet mudstone and/or lime pans.

Sandstone-Red Claystone

The thickness of the sandstone-red claystone part of the Chadron formation ranges from a wedge-edge to 21 feet. Its distribution, shown in figure 13, is limited to a belt about 3 miles wide and more than 14

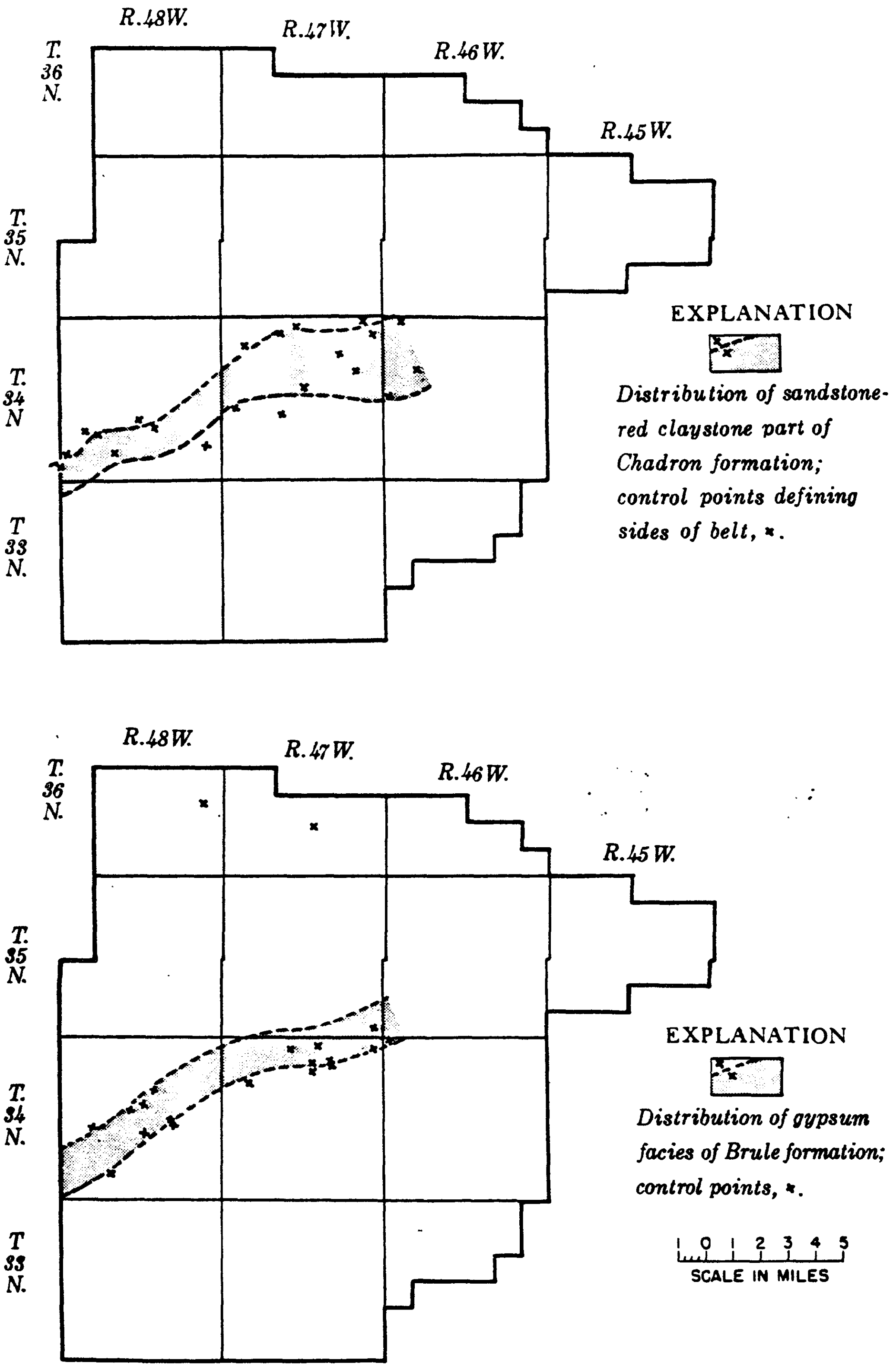


FIGURE 13.--Maps showing distribution of the sandstone-red claystone part of Chadron formation and of the gypsum facies of the Brule formation.

miles long trending about N 70° E through the central and western parts of the area. In the west, where thickest and coarsest, it consists of a lower white conglomeratic sandstone and an upper red claystone; toward the east and toward the sides of the belt the white sandstone and the red claystone merge together. The upper contact is gradational.

Lithology.--The white sandstone is calcareous, poorly sorted, quartzose to feldspathic, cross-bedded, and conglomeratic (fig. 14). Grain size averages medium grade and roughly decreases upward. Cross-bedding is on the scale of feet and cross-beds dip at about 20 degrees. At the NE cor. SW 1/4 sec. 31, T. 34 N., R. 48 W., where white sandstone is 10 feet thick and contains about 20 percent conglomerate fraction, about 80 percent of the conglomerate is white vein quartz and feldspar of granule and pebble size. The remainder of the conglomerate fraction is mostly white vein quartz and other siliceous rock of cobble size. The calcite cement there takes the form of clustered sand crystals in the finer interbeds.

The red claystone is moderate orange pink (10 R 7/4) to grayish pink (5 R 8/2), and is mottled with greenish white and grayish yellow. The claystone is sandy and locally conglomeratic. Part of the sand and conglomerate fraction is similar to that in the white sandstone; part consists of re-deposited Eocene(?) soil. For example, in the CN 1/2 sec. 29, T. 34 N., the basal 11 feet of the formation is red sandy claystone that contains lenses of vein-quartz pebbles in a matrix that consists largely of small pebbles of red and light greenish gray shale and clay. The shale and clay pebbles are well-defined and

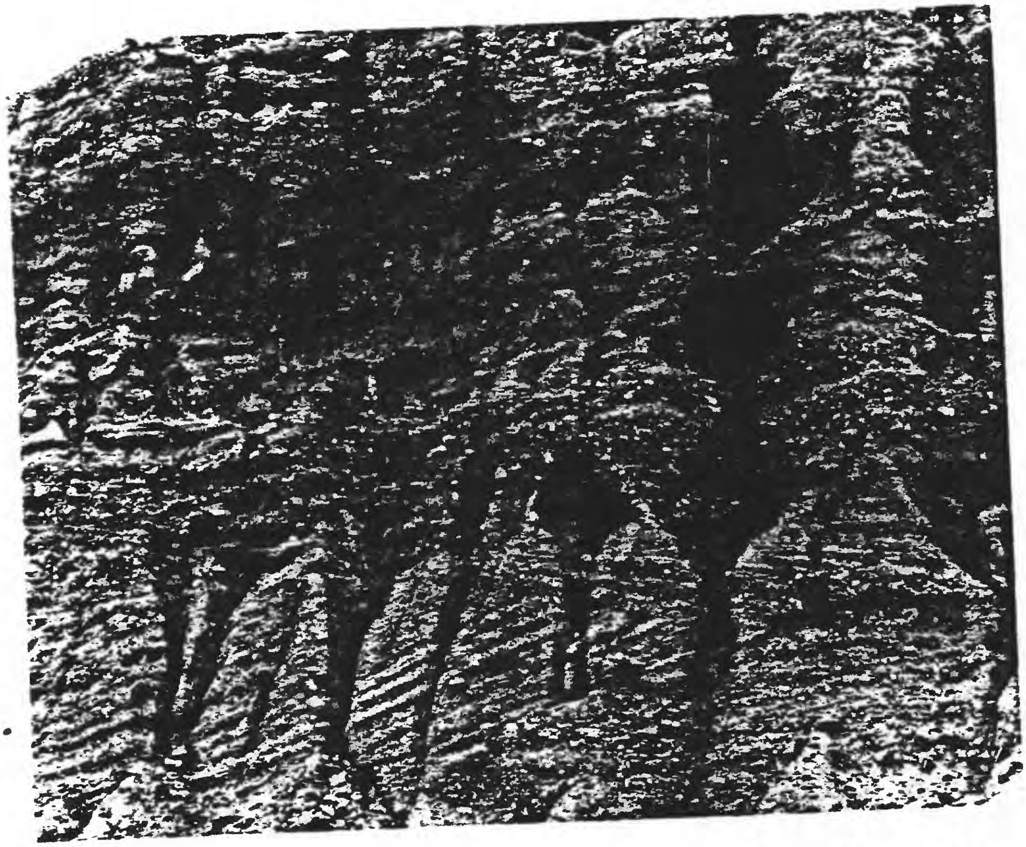


FIGURE 14.--Conglomeratic white sandstone at base of Chadron formation, NE cor. SW 1/4 sec. 31, T.34N., R.48W., Dawes County, Nebraska.

crete in the lower part of the unit but become indistinct mottles upward. Similar gradation can be seen between well-defined pebbles of white kaolinte-alunite and irregular mottles of white kaolinite in the SE 1/4 NW 1/4 sec. 11, T. 34 N., R. 47 W., where pebbles of limonite concretions from the Eocene(?) soil are abundant. Clusters of medium to coarsely crystalline gypsum crystals loosely joined together in masses an inch or so in diameter make up 20 to 30 percent of the red claystone at many places in the eastern part of the belt; for example, in the SW cor. sec. 12, T. 34 N., R. 47 W. Purple (5 P 6/2) is a common color in the vicinity of this locality.

Lateral Variation.--From west to east, along the length of the belt of occurrence of the sandstone-red claystone (fig. 13), several changes occur. The belt widens; there is a decrease in thickness, in abundance of quartz pebbles, and in size and abundance of quartz sand; and there is an increase in clay, red color, and gypsum. The 21 feet of conglomeratic white sand and red claystone at the western end of the belt becomes 10 feet of red clayey sandstone and sandy claystone in the NW 1/4 SE 1/4 sec. 10, T. 34 N., R. 47 W., which in turn becomes 3 feet of sandy red claystone at the eastern end of the belt. Eastward beyond the belt shown on Figure 13, the sandstone-red claystone unit apparently disappears, and green claystone and bedded chert at the base of the White River group in the SW 1/4 sec. 5, T. 34 N., R. 46 W., seem to take its place. Exposures still farther east are described in the section on the undifferentiated White River group.

From the center of the belt toward its sides, the sandstone-red claystone also becomes less sandy. For three examples, going toward the north side of the belt across sec. 29, T. 34 N., R. 48 W., white sandstone becomes red; and going toward the north side of the belt across the NW 1/4 SE 1/4 sec. 10, T. 34 N., R. 47 W., red clayey sandstone becomes red sandy claystone, and in the SE 1/4 NW 1/4 sec. 11, T. 34 N., R. 47 W., the red sandy claystone in turn grades northward into red sand-free claystone containing about 20 percent gypsum, and then disappears. Similar relationships are seen when the sandstone-red claystone is traced from sec. 10 toward the southern side of the belt; at the most southern exposure, in the SW cor. sec. 18, T. 34 N., R. 46 W., the unit consists of 3 feet of red sand-free claystone.

The eastward and sideward lateral sequences thus resemble the upward vertical sequence.

Green Claystone

The thickness of the green claystone ranges from 15 to 40 feet. Its upper and lower contacts are gradational. Although not the thickest of the three divisions of the formation, the green claystone is markedly uniform and extensive and is what is usually implied by the expression "typical Chadron." It consists of drab greenish gray claystone that produces deeply weathered hummocky slopes convex upward and commonly bare of vegetation. The rounded hummocks on the green claystone contrast sharply with the intricately dissected angular bluffs on the overlying pellet mudstone and on the Brule formation.

Gross Lithology.--The color of the green claystone is drab greenish gray near 10Y 6/2, 10Y 7/2, 5Y 6/2, and 5Y 7/2 at different localities. The green tint is best seen from a distance or on fresh exposures. When wetted, the claystone swells and becomes plastic mud; when dried, it shrinks and cracks deeply. The unusually deep shrinkage cracks suggest that the clay mineral is montmorillonite. Two samples were X-rayed by A. J. Gude, III, (written communication, 1955) who found montmorillonite and quartz to be abundant in both; in addition, one contains minor albite and illite and the other contains a trace of andesine(?). Part of the quartz and feldspar is of silt and sand size.

The claystone is commonly massive from bottom to top. Slight differences in color or weathering allow two or three poorly defined beds to be made out at some places, particularly when viewed from a distance. Their tops and bottoms are remarkably parallel. The scarce grains of silt and sand in the green claystone are scattered through the clay instead of being concentrated in layers.

Varnished Pebbles.--The lower part of the green claystone contains pebbles. The pebbles are well-rounded to subangular and range in size from about four inches to a quarter-inch. At most places, for example east of the road in the NE 1/4 sec. 7, T. 34 N., R. 47 W., the pebbles consist of quartz, quartzite, chert, silicified wood and bone, and various unidentified siliceous rocks having the texture of igneous or metamorphic rocks but lacking feldspar and composed wholly of material harder than steel. Although feldspar and limestone pebbles were carefully searched for, none was found. At a few places, for example, in the NW 1/4 sec. 19, T. 35 N., R. 45 W., rounded limonite pebbles are similar except for rounding and color to limonite concretions in the Eocene(?) soil. The interior of the pebbles is darker and more compact than the limonite in the Eocene(?) soil; some pebbles are almost black and are mixtures of iron and manganese oxides. They occur mainly at the base of the green claystone.

The pebbles, limonite ones as well as siliceous ones, look as though they had been carefully smoothed, then dipped in tan, brown, or black varnish. Deep recesses are as glossy as the rest of the surface, indicating chemical polish. Freshly broken surfaces show in cross section a dark rind or patina that is barely perceptible except where it penetrates deeply along cracks and crystal boundaries. The presence of a patina again indicates chemical action; hence the pebbles in the green claystone are here referred to as varnished pebbles.

The varnished pebbles occur isolated or in poorly defined pockets, except for a discontinuous layer resting on the unconformity. A representative pocket of pebbles, such as one of those in the SE 1/4 SW 1/4 sec. 19, T. 34 N., R. 47 W. (fig. 15) is a foot thick, three feet wide, and roughly circular in plan view. Digging shows that the pebbles in a pocket are unsorted. They are not bedded nor arranged with their long axis in the horizontal plane. They do not touch one another but are isolated by clay, which supports their weight. The margins of the pocket are poorly defined. The varnished pebbles are <u>not</u> associated with large amounts of sand. Although green claystone

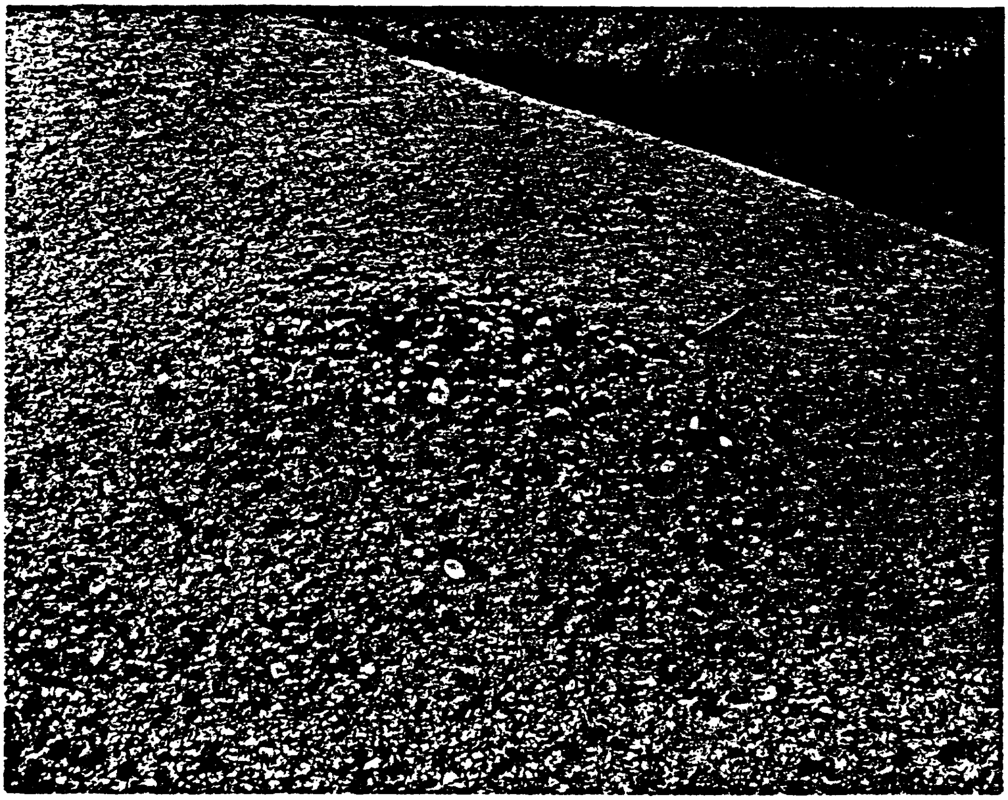


FIGURE 15.--Pocket of varnished pebbles in the green claystone part of the Chadron formation, SE 1/4 SW 1/4 sec. 19, T.34N., R.47W., Dawes County, Nebraska.

containing varnished pebbles may be slightly richer in disseminated sand than drab claystone without varnished pebbles, the difference is not great.

Secondary Limestone.--Thin, discontinuous lenses of limestone occur at some places in the green claystone, particularly near its base in places where the sandstone-red claystone is absent. Lenses of similar thinness and discontinuity in the Big Badlands and Crawford area have long been referred to as fresh water limestones or algal limestones. Those in the Chadron area probably are not of freshwater or algal origin. They differ from bedded limestone in the Chadron area in three ways: they are not laminated or layered; they do not contain ostracods or other fossils; and they are markedly erratic in thickness. A sample was taken from a 3-foot zone containing irregular lenses of limestone, each a few feet long and about an inch thick, in the NE 1/4 sec. 23, T. 34 N., R. 48 W., and examined under the microscope. It is limestone in the chemical or mineralogic sense, for mud-size calcite crystals make up more than 50 percent of the rock. Crystal size is roughly 3 microns. The calcite is, however, merely an interstitial filling between loosely fitting shards of volcanic glass that rest one on the other. The points of the shards are sharp and unrounded. It does not contain any microscopic fossils, nor any known structures made by calcareous algae and seems to be the result of cementation of ash.

<u>Gypsum Clusters and Chalcedony Concretions</u>.--Gypsum clusters similar to those in the underlying red claystone occur throughout 15 feet of green claystone in the SW cor. sec. 12, T. 34 N., R. 47 W. An average cluster is about one inch in diameter and is made of friable equidimensional medium crystalline gypsum. Although friable, most of the clusters have a harshness indicating that they are thinly coated with chalcedony. Some clusters are partially replaced by chalcedony to a depth of several millimeters. Associated with the gypsum clusters are rough-surfaced hollow or solid concretions of gray translucent chalcedony. The surface of the chalcedony concretions is of about the same scale of roughness as the surface of gypsum clusters. Whole concretions are of about the same size as gypsum clusters, and the hollow ones resemble the result of dissolving the gypsum in a partially replaced gypsum cluster. One seemingly pure chalcedony concretion from this locality was examined under high magnification and found to contain relics of unreplaced gypsum crystals. The chalcedony grows in the form of expanding arcs making a rosette pattern which is centered in the interior of gypsum crystals. Relict gypsum showing cleavage occurs where rosettes fail to meet, and occurs also between the arcs of individual rosettes. It is evident that the chalcedony has replaced gypsum, and that the rough-surfaced chalcedony at this locality is pseudomorphic after gypsum clusters. The idea that rough-surfaced chalcedony is a replacement of gypsum is not new, for similar concretions in the Chadron formation in the Big Badlands were so interpreted by Honess (1923) and Wanless (1923, p. 207-208). They also recognized

chalcedony pseudomorphs of barite. A few tabular concretions in the Chadron area may represent original barite, but identification is uncertain.

Rough-surfaced chalcedony concretions similar in shape and size to those in sec. 12 are abundant in the green claystone elsewhere in the Chadron area, weathering out to produce a lag gravel at many places. The largest concretions attain a diameter of a foot and are generally hollow. At most places, rough-surfaced chalcedony concretions occur as float and the existence of stratigraphic control cannot be determined. In the NW 1/4 of sec. 33, T. 34 N., R. 48 W., two outcrop bands of concretion-rich claystone are clearly separated by an outcrop band of concretion-free claystone. Curvature of the outcrop bands indicates that the bands are parallel to bedding. This seems acceptable evidence of stratigraphic control.

<u>Lateral Variation</u>.--The distribution of varnished pebbles in the green claystone roughly follows the distribution of sandstone-red claystone. A traverse perpendicular to the sandstone-red claystone belt, for example from sec. 25, T. 34 N., R. 48 W., to sec. 32, T. 34 N., R. 47 W., shows the abundance of pebbles to decrease with distance from the edge of the sandstone-red claystone. The thickness of the interval containing pebbles also decreases away from the edge of the sandstone-red claystone, from 20 feet to less than one foot. Pebbles are scarce or absent in the green claystone directly overlying the sandstone-red claystone. Some occur at the base of red claystone where

..d claystone is the basal part of the Chadron formation, but, generally speaking, varnished pebbles are much less abundant in the center of the belt than near its flanks.

Pellet Mudstone

The thickness of the pellet mudstone of the Chadron formation ranges from 55 to 70 feet. It erodes to badlands. Slopes on the upper part of the pellet mudstone are as steep and intricately dissected as those on the Brule formation; slopes on the lower part gradually merge with the gentle slopes on the green claystone. The gradation seen in the topography may be seen also in bulk composition.

Gross Lithology.--At most places the pellet mudstone is pale green near 10Y 8/2, 5Y 8/1, or 5Y 7/2, which shows best from a distance. At other places, the pellet mudstone is either pale pink (5YR 7/2) or is color-banded in various shades of green, pink, and brown similar to those in the Brule formation. Except for vague parallel beds delineated by slight differences in color or in clay content, the pellet mudstone is massive.

The pellet mudstone consists of a calcareous mixture of silt and clay, which is richer in silt than the underlying green claystone, and richer in clay than the overlying siltstone of the Brule formation. A sample from the upper part of the unit was disaggregated in water and found to contain about 70 percent silt. The ratio of silt to clay and the content of calcareous matter increases upward. Shrinkage cracks, which apparently reflect amount or kind of clay, are about a quarter of an inch deep and are spaced every inch and a half or so in the lower part of the pellet mudstone, but are less than a sixteenth of an inch deep and spaced less than an inch apart in the upper part.

Examination of the sample mentioned at high magnification revealed that the medium and coarse silt consists of quartz, feldspar, and volcanic glass. Many of the recognizable grains are angular, some are subrounded, and a few are well rounded and frosted. Part of the clay occurs as an unabraded alteration product on the rims of volcanic glass; part occurs as bundled sheaths that seem too delicate to have withstood transportation. One sample was X-rayed by A. J. Gude, III (written communication, 1955), who found quartz abundant, mixed montmorillonite-illite-kaolinite present, and andesine minor.

Pellets.--The pellets giving the pellet mudstone its name are clay-coated structureless aggregates of mudstone that are harder, darker, and less calcareous than their matrix. Most are equidimensional, subround to subangular, and 1/16 to 1/4-inch in diameter; extremes range from round to cubic, and from 25 microns, or possibly less, to about an inch. Sorting is so poor that all extremes may occur in a single sample. The few samples examined under the microscope show the pellets to be made of silt-size quartz, feldspar, and volcanic glass, plus a much lesser amount of clay.

Cohesiveness ranges widely. At some levels the pellets crush easily in the fingers; at other levels they break only under the

-er. Acid treatment shows that cohesiveness is not due to calcite cement; the microscope indicates that it is due partly or wholly to interstitial chalcedony. The clay coating, which is lustrous, attains a thickness of 30 microns on a 2-millimeter hard pellet, but is thinner on smaller pellets and on less cohesive pellets. The pellets at any one level closely resemble their matrix and each other in size of contained silt and in hue.

Lime Lumps and Lime Pans.--Concentrations of lime cement take two forms. The less common form is a poorly defined lump a few inches in diameter that is slightly more resistant to weathering than its matrix. If better defined, such lumps would be concretions. The calcite cement is microcrystalline, the crystals averaging about 3 microns in diameter. The other constituents of the lumps are no different from those in the pellet mudstone between the lumps. The lumps are close set and occur in thick zones.

The second form may be called a lime pan. Lime pans are white layers of pellet mudstone a few feet thick that are more or less solidly impregnated with calcite cement similar to that in lumps (fig. 16). Top and bottom are irregular, so that thickness changes erratically and abruptly. The bottom is commonly more irregular than the top. At some localities, for example in the NW 1/4 sec. 2, T. 34 N., R. 46 W., or in NE 1/4 SW 1/4 sec. 31, T. 34 N., R. 47 W., the bottom of lime pans shows a fringe of vertical veins extending several feet down from the rest of the pan.

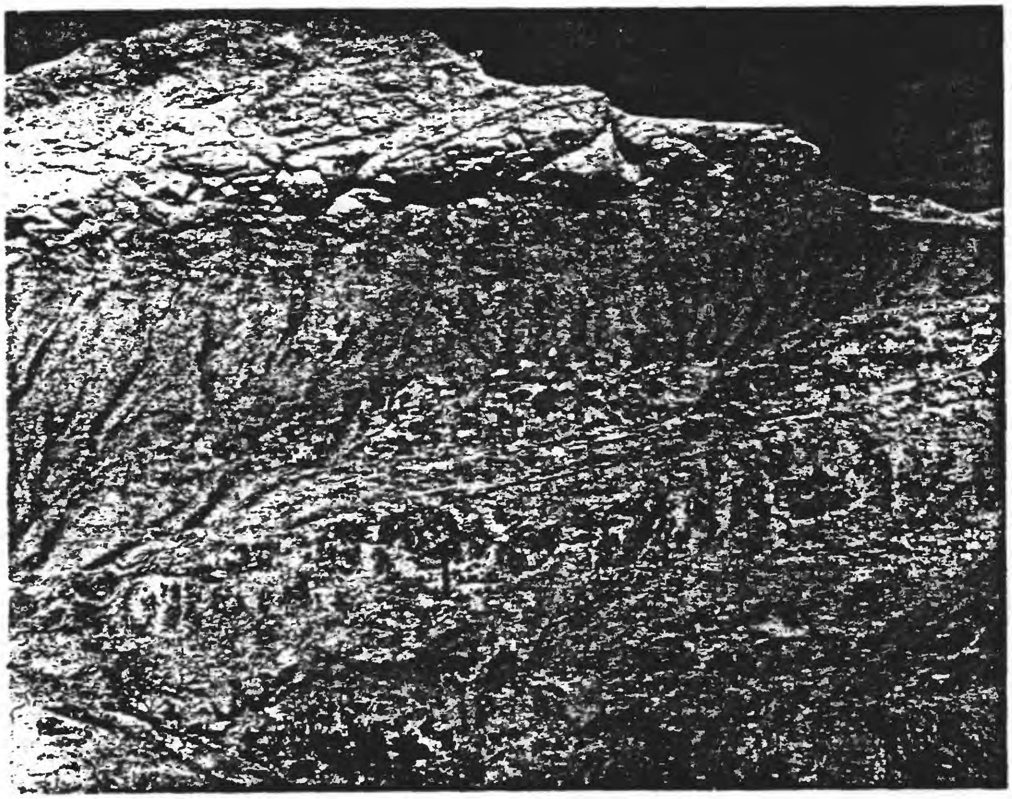


FIGURE 16.--Lime pans in pellet mudstone part of Chadron formation, SW 1/4 NE 1/4 sec. 20, T.34N., R.47W., Dawes County, Nebraska.

Lime pans are further characterized by their lateral variability. Solid pans grade laterally into less resistant lumpy laceworks, consisting of interconnected veins, stringers, lumps, and nondescript masses. A 2-foot solid lime pan that forms a resistant ledge may grade laterally into lumpy lacework, then disappear, then reappear again, or else grade laterally into a less solid but still uniform lime pan that makes only a slight break in slope. Despite the small-scale irregularities, some lime pans, particularly the one at or near the top of the formation, are persistent, maintaining the same level for miles of outcrop.

What are here termed lime pans may correspond in part to the Purplish white layers used by Schultz and Stout (1955) as key beds for subdividing the White River group in the Crawford area. Unlike Purplish white layers, lime pans in the Chadron area do not locally consist of gypsum, nor are they characteristically tinged with purple.

Lateral Variation.--Slight differences in the pellet mudstone crudely delineate a belt trending eastward and northeastward through the central and western parts of the area. The belt parallels the belt delineated by the sandstone-red claystone, but more nearly coincides with a similar belt delineated by the gypsum facies of the Brule formation (fig. 13). Near the center of the belt, for example in the SE 1/4 NE 1/4 SE 1/4 sec. 21, T. 34 N., R. 48 W., or in the NE 1/4 NW 1/4 sec. 6, T. 34 N., R. 46 W., lime is scarce and is not concentrated in pans or lumps, the mudstone is relatively rich in clay, visible pellets are few, and none of the mudstone is pink. South of the belt, for example in the NE 1/4 SW 1/4 sec. 31, T. 34 N., R. 47 W., or in the

NW 1/4 sec. 2, T. 34 N., R. 46 W., lime is abundant and is concentrated in the form of lumps as well as pans, pellets are abundant, and more of the rock is pink than is green.

Fossils and Age

Fossils are scarce in the Chadron formation. The scarcity is particularly striking in comparison to the abundance of titanotheres in the sandstone bodies in the green part of the Chadron formation in the Big Badlands.

Teeth and a few bones from the one fossil found in the pellet mudstone (mentioned in the description of the section given to typify the formation) were identified by Edward Lewis. He (written communication, 1955) writes, "Tooth and bone fragments of a brontothere; definitely from Chadron fm., early Oligocene age." Brontotheres are kinds of titanotheres (Romer, 1945, p. 431).

Similarly large and massive bones thought to be titanotheres occur in the green claystone. At some places, for example in the NW 1/4 sec. 33, T. 34 N., R. 48 W., massive bones occur in small areas in enough abundance to indicate that the bodies of more than one individual were buried together. None were collected for identification, but their great size and their similarity to the identified specimen from the pellet mudstone indicate that they are some kind of titanothere. It is interesting that no small bones were found in the green claystone and that none of the large bones have sharp edges or delicate projections, such as are seen on bones of buffalo in Pleistocene or Recent alluvium.

The few fossils found in the sandstone-red claystone are rounded and worn and are too poorly preserved to be identified (Edward Lewis, written communication, 1955).

Thanks to the Early Oligocene assignment of the titanothere from the lime pan zone of the pellet mudstone, the Chadron formation in the Chadron area can be said to be about the same age as the Chadron formation in the Big Badlands. Following convention, the whole of the Chadron formation is here assigned to Early Oligocene time. One reservation is necessary; the lack of identifiable fossils from the sandstone-red claystone leaves open the possibility that deposition could have begun in Eocene time.

Brule Formation

Definition

The name Brule formation was introduced by Darton (1899, p. 755-759) for a 320 to 600-foot sequence in Nebraska consisting "mainly of a hard, sandy clay, of pale-pink color" lying between the Chadron formation below and the Gering formation above.

General Description

In the Chadron area, the Brule formation ranges from 195 to more than 300 feet thick. It consists of siltstone, mudstone, sandstone, which erode to badlands, plus gypsum, dolomite, and limestone, claystone, and laminated clay, which erode to grassy hills. The two groups of rock types are laterally segregated; gypsum and associated rock are restricted to a narrow belt trending about N 70° E through the western and the central parts of the Chadron area. The Brule formation in this central belt is here called the gypsum facies, the remainder being the clastic facies.

The base of the formation is marked in the gypsum facies by the base of bedded dolomite or gypsum, or by the top of pellet mudstone, whichever is lower, it is marked in the clastic facies by the top of lime pans. The top of the formation is an erosional unconformity.

Gypsum Facies

Gypsum and clay and scarcer dolomite and limestone crop out on the south side of White River in a belt of isolated hills trending about N 70° E through the center of the Chadron area (figure 13). The hills are fairly steep sided and well vegetated with grass. The belt of hills has about the same trend as the belt of sandstone-red claystone at the base of the Chadron formation, and, except for being offset a mile or so to the north, about the same geographic position. The belt of hills extends from sec. 31, T. 35 N., R. 46 W., to sec. 21, T. 34 N., R. 48 W., and is inferred to have extended on across Bordeaux Creek to sec. 29, T. 34 N., R. 48 W. It is about a mile wide and 12 miles long. The original thickness of the gypsum facies is unknown, but a thickness of about 300 feet remains on Isinglass Hill southeast of the juncture of Bordeaux Creek and White River. The measurement includes a poorly exposed interval whose thickness was estimated to be 120 feet, as seen in the following measured section. The 115 feet measured above the questionable interval and the 65 feet measured below are, however, fairly definite.

Partial section of gypsum facies of Brule formation
Southwest side Isinglass Hill, Secs. 15 and 22,
T. 34 N., R. 48 W., Dawes County, Nebraska

	Feet
Gypsum facies of Brule formation	
Gypsum, light yellowish gray (5Y 8/1), slightly calcareous, medium to coarsely crystalline, thin-bedded; this and following 6 beds measured in C SW 1/4 sec. 15, but sequence also exposed in C NE 1/4 sec. 22 near Isinglass bench mark	3
Clay and gypsum interlaminated, light yellowish gray (5Y 8/1), largely covered; soil is very deep and friable and is rich in silt-size gypsum crystals and plates of gray chalcedony	8
Gypsum, as above	2

Clay and gypsum interlaminated, as above except soil also contains tabular masses of satinspar . .	23
Gypsum, grayish pink, slightly calcareous, medium to coarsely crystalline, thin bedded to millimeter-laminated; contains satinspar in beds (beef) and veins; satinspar has fibers as much as 2 inches long; wavy bedding in upper part	6
Clay and gypsum interlaminated, light yellowish gray; largely covered, soil as in upper beds . . .	7
Gypsum, pink to red, coarsely crystalline, laminated to thin bedded, wavy bedded; contains satinspar partially replaced by chalcedony, and coarse irregular masses of selenite; crystals on upper surface extremely coarse and apparently grew upward during weathering; bed is persistent and distinctive	6
Clay and gypsum interlaminated, as above, this and following 9 beds measured in NE 1/4 NW 1/4 sec. 22	25
Gypsum, light yellowish gray mottled with pink, very coarsely crystalline (1/16-inch crystals), thin bedded, porous and light weight; is least porous in freshest samples	4
Clay, very light brownish gray, largely covered . .	5
Gypsum, light yellowish gray mottled with pink, coarsely crystalline, thin bedded; capped by quarter-inch plate of pink chalcedony	2,7
Dolomite, calcitic white-weathering, microscopically crystalline, massive	0.3
Clay, light yellowish gray, largely covered . . .	11
Gypsum, slightly to strongly calcareous, medium to coarsely crystalline, thin bedded; upper inch replaced by chalcedony	4
Clay, olive gray, largely covered	8
Covered, soil indicates interlaminated clay and gypsum; thickness estimated on assumption that beds dip 7° toward N 20° E in SE 1/4 NW 1/4 sec. 22	120

Clay and gypsum interlaminated, light yellowish gray; sand size crystals in gypsum laminae; this and following beds measured on scarp and gulley in C SW 1/4 sec. 22 30

Gypsum, light greenish yellow near 10Y 8/2, calcareous, coarsely crystalline, thin bedded with layers ranging from an inch to a quarter inch and extraordinarily persistent, porous; veined with satinspar partially replaced by chalcedony 2

Gypsum and clay interlaminated, light greenish yellow near 10Y 8/2; gypsum crystals are sand size and not cemented together 7

Dolomite, limestone, gypsum, and clay interbedded, light yellowish gray to white; considerable replacement; limestone and clay are impregnated with selenite in the fashion of sand-calcite crystals; crystals are cubic feet in size and free of impurities in spaces an inch across; generally laminated to thin bedded; dolomite and limestone are microcrystalline; clay is dolomitic and delicately laminated; uranium is concentrated in the dolomite and limestone beds 13

Clayey dolomite, pale olive gray (10Y 6/2) to greenish white (5GY 9/1), lamination greatly resembles shale in the field 13

Total exposed thickness of gypsum facies of Brule formation 300

Chadron Formation

Pellet mudstone, yellowish gray (5Y 8/1 to 5Y 7/2), calcareous; differs from overlying clay in being pelleted, silty, massive, and in weathering to a rough cracked surface; grades toward underlying green claystone through 30 feet.

The outstanding sedimentary structure in the gypsum facies is lamination and parallel bedding (Figure 17). Except in the basal part of the gypsum facies, where onlap can be seen, resistant beds are remarkably

FIGURE 17.--Laminated gypsum and dolomite, basal part of gypsum facies of Brule formation, SE 1/4 sec. 3, T.34N., R.47W., Dawes County, Nebraska.

persistent. Millimeter lamination or thin bedding characterize most of the sequence. Lamination is easily seen in gypsum, dolomite, and limestone where they are resistant, but can be seen in clayey parts of the sequence only in fresh exposures. Fresh natural exposures of non-resistant beds are much scarcer in the gypsum facies than in the clastic facies, as the clay in the gypsum facies weathers to extraordinarily deep crumbly soil.

Because the present investigation is concerned with uranium, which in Oligocene rocks is concentrated beneath considerable gypsum, the gypsum facies was mapped to exclude possible areas of thin gypsum.

Gypsum.--The gypsum beds that are free of clay tend to resist weathering and form ledges that from a distance are easily mistaken for sandstone. Their resistance apparently is related to porosity, for weathered samples of bedded gypsum are crumbly and much lighter than crystals of equal size. Where much rain is absorbed, run-off is of course lessened. The resistant beds range in thickness from 2 to 8 feet. Most are laminated by differences in crystal size or by clay partings. Bedding planes are spaced from a sixty-fourth of an inch to several feet apart, as determined by differences in weathering. They are remarkably parallel to each other. Except near the base of the facies locally, where resistant beds of gypsum grade into gypsum-rich claystone, individual gypsum beds generally persist.

In hand specimen, the gypsum beds are light yellow-gray, except for a few that are pink. Near the surface, the gypsum is granular and readily breaks into sand-size crystals. The granularity and attendant porosity result in part from solution due to modern weathering, for weathered faces are less compact than the interior of beds. Crystal size ges from very fine to very coarse. The coarsest crystals are in the most porous samples, which suggests recrystallization.

The two gypsum beds that at different places are the lowest resistant bed in the gypsum facies in sec. 3, T. 34 N., R. 47 W., near the inferred center of the gypsum belt, contain enough macerated plant fragments to be called carbonaceous. Plant fragments occur there also in the immediately underlying claystone. Concentrations of uranium minerals, discussed in a separate section, are associated with the carbonaceous material

A grab sample of a 3-foot bed in the SE 1/4 NW 1/4 sec. 3, T. 34 N., R. 47 W., was analyzed by Irving Frost of the Denver laboratory of the Geological Survey, with results as follows:

Lime (CaO)	30.74 percent
Sulfur trioxide (SO_3)	44.06
Water driven off at 60° C	0.61
Water driven off at 300° C	19.27
Chloride (Cl^-)	0.10
Sesquioxide (principally Fe_2O_3)	0.50
Silica (SiO_2)	1.10
Total	96.38

This analysis gives an apparent equivalent of 94.5 percent gypsum, which is of commercial purity. Less pure beds contain more silica. The same sample was X-rayed by J. F. Burst (oral communication, 1959), who found the mineralogic composition to be gypsum and dolomite.

Three samples of resistant gypsum were examined at high magnification. Two are peculiar in containing carbonaceous matter, opaque inclusions, and uranium minerals. They are discussed in another section.

The other is from a 3-foot bed of laminated gypsum 20 feet above, the base of the gypsum facies in the C. W 1/2 sec. 3, T. 34 N., R. 47 W. Crystal size ranges from about 10 microns in one of the three layers in the thin section to about 0.1 mm in the coarsest layer. Boundaries between layers are fairly sharp. The fine layer appears to have smoothed out irregularities left by deposition of the coarse layer. Crystals are roughly shaped like axe-heads or double wedges, the long axis tending to lie parallel to bedding.

The outstanding feature revealed by high magnification is that considerable corrosion-compaction has occurred. The crystals are in such close contact that little open space remains, and they form a mosaic. Mosaic texture can result from enlargement of crystals after deposition or from corrosion and compaction. Corrosion seems to be the answer here, for crystals interpenetrate each other in a complex and irregular fashion. Pressure played a part, for some crystals have conformed to available space by slippage along cleavage planes, thus forming miniature stair-step faults.

The calcite that makes some gypsum beds calcareous is visible in the thin section as seams of minute crystals, 1 to 3 microns in diameter, following the contacts between gypsum crystals. Some of the crystals may be dolomite, as X-ray analysis showed that the carbonate in another sample is dolomite. Many of the larger gypsum crystals contain inclusions. Some are calcite or dolomite, some are a fluid having an index of refraction greatly different from gypsum. As the chemical analysis shows 0.1 percent chloride, the fluid inclusions may be brine.

Clay.--The gypsum-rich clay that makes up the bulk of the gypsum facies is light yellowish gray to light greenish yellow. The clay is laminated, and if it were not so soft might be called shale. It is rarely well exposed, but the soil over it is rich in tiny crystals of gypsum, and fresh exposures show that the gypsum crystals occur as laminae. Most of the gypsum laminae are only one or a few crystals thick; some are an inch or so thick. The gypsum crystals in the laminae range from silt size to sand size, being smallest in the the thinnest laminae, and are not detectably joined together.

A sample of clay from 33 to 73 feet above the base of the Brule formation near the center of the gypsum belt in the SW 1/4 sec. 3, T. 34 N., R. 47 W., and a sample of clay from 0 to 20 feet above the base Brule formation in the same area were X-rayed by A. J. Gude III (written communication, 1955). He reports the first to consist of montmorillonite, calcite, and quartz, and the second to consist of quartz, mixed montmorillonite and illite, and andesine, both quartz and the mixed clay being abundant. More work needs to be done on clay mineralogy.

Dolomite and Limestone.--Resistant beds of generally unfossiliferous white-weathering dolomite or limestone mark a distinctive zone, which in most places forms the basal part of the gypsum facies, and extends a mile or so beyond the gypsum facies as mapped. Uranium in the dolomite or limestone of this basal zone is discussed in a later section. The dolomite or limestone is remarkably thin bedded and parallel bedded. Many beds are laminated on the scale of fractions of a millimeter, and few are without bedding planes for as much as one foot.

Degree of effervescence with dilute hydrochloric acid proved unreliable for differentiating dolomite from calcite in the field. Encrustations of secondary calcite, which cause vigorous effervescence, and impregnations of secondary gypsum and silica, which hinder effervescence, are both present. Of two samples analyzed by the carbon dioxide generation method by R. F. Gantnier (written communication, 1955), one contains 95 percent dolomite and 1 percent calcite, and the other 98.8 percent calcite and no dolomite.

Four samples from the dolomite or limestone zone were examined under the microscope. All consist mostly of dolomite; etched surfaces indicate that calcite makes up less than a fourth of the rock. Crystals are a few microns in diameter. Some of the larger ones are well-formed rhombs 5 to 10 microns in diameter, but most are anhedral and in the range 1 to 3 microns.

Evenly sized pellets similar to those in modern lime mud and thought to be faecal pellets are more or less clearly visible in the four samples. In two dimensions, the pellets are nearly round and about 0.1 mm in diameter, except for one sample where some of the pellets are 0.1 mm thick and 0.5 mm long. The elongate pellets lie parallel to bedding. The pellets are associated with fossils in only one sample. An almost pure dolomite from the basal foot of the Brule formation in the SW 1/4 NE 1/4 sec. 29, T. 34 N., R. 48 W., is fossiliferous. Several hundred ostracod carapaces, and a few recrystallized snail shells are visible in cross section in the thin section. The shells are still mostly calcite but dolomite rhombs project into the shells from the sides and isolated rhombs seem to have grown within some shells. This fact and the presence of irregular patches of calcite between dolomite crystals indicate that at least part of the dolomite grew by replacement.

Not all the dolomite makes resistant beds. The basal 20 feet or so of the Brule formation on Isinglass hill consists of delicately laminated greenish white (5GY 9/1) material described in the field as claystone. A sample from the C. sec. 22, T. 34 N., R. 48 W., selected for clay mineral analysis, was X-rayed by A. J. Gude III (written communication, 1954) who reports "Mn stained dolomite (very abundant), montmorillonite (present), quartz (minor), andesine (minor)." Until further work is done, it must therefore be assumed that fine grained non-resistant rocks in the gypsum facies may be clayey dolomite instead of clay or claystone.

Secondary Silica.--Chalcedony occurs at most exposures of the gypsum facies. It occurs mainly as thin plates capping gypsum beds, filling veins, or growing on the bottom surface of gypsum ledges, where they have bumpy undersurfaces suggesting tiny rounded stalactites. Similar plates are abundant in the soil on the gypsum facies. Chalcedony also occurs as nearly perfect pseudomorphs of satinspar, for example, in sec. 4, T. 34 N., R. 47 W., and as sheaths on giant pure anhedral crystals of gypsum. Part of this silica was deposited recently, for the sheaths are present on weathered faces and absent two feet into the rock.

Under the microscope, replacement silica in gypsum beds is seen to be yet more common. In one sample of seemingly pure gypsum, clusters of chalcedony crystals a few tens of microns in diameter occur in the center of gypsum crystals, making an expanding arc or rosette pattern. One rosette of chalcedony was seen to cut across and replace parts of three gypsum crystals. A sample from one of the three beds at the base of the Brule formation in the NW cor. sec. 25, T. 34 N., R. 48 W., was examined under the microscope. The beds were described in the field as "dolomite, limestone, or caliche, silicified by brownish mottled chalcedony that makes extraordinarily heavy float showing vug-linings having roughly botryoidal surfaces; from 12-foot zone immediately above Chadron formation." The microscope revealed much relict gypsum, scarce carbonate, and much chalcedony having the peculiar expanding arc pattern seen where gypsum is replaced by chalcedony. The rock silicified was therefore gypsum, not dolomite or limestone or caliche. Further work with the microscope will probably show that many beds originally mapped as silicified limestone are actually silicified gypsum.

Secondary Gypsum.--Secondary gypsum occurs as veins and beds of satinspar ranging in thickness from a sixteenth of an inch to four inches, as giant anhedral crystals as large as a foot across, and as well-formed elongate crystals as much as an inch long, which project upward from the top surface of weathered beds or into incompletely filled cavities. The giant anhedral crystals grew by replacement, for where they occur in gypsum beds bearing uranium minerals, the uranium minerals are concentrated at the margins of the giant crystals and around undigested suspended inclusions within the giant crystals, suggesting expulsion during replacement.

Gypsum also impregnates carbonate and clay in the basal part of the gypsum facies, in a spotty fashion. Locally, sheen of cleavage faces indicates that the gypsum throughout at least a cubic foot of the original rock belongs to one crystal; the rock thus resembles sand-calcite crystals. Associated with the impure giant crystals at some localities are gypsum veins, partly replaced or coated by chalcedony, that impregnate a few feet of clay underlying the basal gypsum bed, for example in the NW 1/4 NE 1/4 sec. 1, T. 34 N., R. 47 W. Limestone or dolomite is replaced by gypsum on a large scale in the basal part of the gypsum facies. Such large-scale replacement suggests downward-moving waters laden with sulfate.

Interfingering of Gypsum and Clastic Facies.--Interfingering between the upper part of the gypsum facies and the clastic facies can be seen near and southeast of the Isinglass bench mark on Isinglass Hill and is illustrated by the following section:

Partial section of Brule formation, Southeast Side Isinglass Hill, Secs. 22, 23, 26, T. 34 N., R. 48 W., Dawes County, Nebraska

Brule formation	Feet
Gypsum facies and clastic facies interfingered	
Clay and gypsum interlaminated, light yellowish gray (5Y 8/1), largely covered; this and next 9 beds measured near Isinglass bench mark and in gully to east	12
Gypsum, light yellowish gray, medium to coarsely crystalline, thin bedded	3

Siltstone, very pale orange (10YR 8/2), calcareous, massive; has gray translucent chalcedony in vertical veins a quarter-inch wide; grades northwestward into light greenish gray banded rocks within 500 feet, then into solid greenish gray clay laminated with gypsum as described on other side Isinglass Hill 32

Gypsum, pink to red, coarsely crystalline, laminated to thin bedded, wavy bedded; bed is persistent and distinctive 4

Clay, not exposed; soil indicates clay and gypsum interlaminated as above . . . 11

Gypsum, light yellowish gray (5Y 8/1), medium to coarsely crystalline, thin bedded to laminated, wavy bedded; contains 8 beds of satinspar in lower half, which range in thickness from 1/4 to 1 inch and are largely replaced by chalcedony 6

Pellet siltstone, very pale orange (10YR 8/2), calcareous, massive; grades in 100 feet to light greenish gray (5GY 8/1) clay and interlaminated gypsum 18

Gypsum, light yellowish gray (5Y 8/1), coarsely crystalline, thin bedded, wavy bedded 4

Gypsum and clay interlaminated, light yellowish gray (5Y 8/1); crystals in gypsum laminae are sand size and soil is markedly sandy with gypsum 5

Clastic facies

Mudstone, light yellowish gray (5Y 8/1) vaguely tinted in pinks and greens to produce coarse color banding best recognized from a distance, rich in silt .40

Mudstone and minor sandstone interlaminated, coarsely banded pinkish brown (10YR 7/2) and light greenish gray (5GY 8/1), lumpy cement; sandstone forms thin, resistant, parallel bedded ledges and is clayey; rich in oreodons and turtles; this and remaining beds measured in gulley heading in NW cor. sec. 26 30

Sandstone and mudstone interbedded; sandstone is light gray, clayey, fine grained, poorly sorted, rounded to angular, thin bedded and parallel bedded, but some beds are cross-laminated; mudstone is light pinkish brown and light greenish gray and most abundant in lower part 65

Mudstone and chalcedony layers, color banded in greenish gray, brown, and gray; mudstone is rich in clay; chalcedony is brown and forms 4 layers in lower part, may be silicified gypsum or carbonate 32

Chadron formation

Lime pan, white

Total thickness Brule formation . 262

Onlap at Base of Gypsum Facies.--Onlapping relationship can be seen in the lower tens of feet of the gypsum facies on the divide west of Beaver Creek, where the inferred center of the gypsum belt lies. Resistant gypsum beds near the base of the gypsum sequence grade to clay or claystone northward and southward from the promontory near the C SW 1/4 sec. 3, T. 34 N., R. 47 W. Successively higher beds extend successively farther away from this locality. The onlap toward the north is the most evident. The rocks showing this onlap are thought to be the oldest part of the gypsum facies. They differ from the basal part of the gypsum sequence at other localities in lacking limestone and dolomite beds and in locally containing carbonaceous matter. Onlap provides one way to approximate the slope of the onlapped surface. In a distance of about 1800 feet at this locality about 40 feet of onlap toward the north occurs, a slope of about 1°.

It is evident from the gentle slope and from the interfingering with the clastic facies that we are not dealing with a 300-foot gorge cut into older rocks and then filled with gypsum, clay, and carbonate.

Original Extent of Gypsum Facies.--The original width of the gypsum belt is imperfectly known. The gypsum facies can be seen to interfinger to the southeast with the clastic facies on the southeast side of Isinglass Hill, and outcrops of the gypsum facies and clastic facies are not far apart on the divide west of Beaver Creek. Elsewhere the southern margin of the gypsum facies is lost to erosion, although its position can be interpolated. The northern margin of the gypsum facies originally lay south of the outcrops of the undifferentiated White River group in the far northern part of the area, which are about 8 miles to the north of the outcrops of the gypsum facies. The northern margin also lay south of the lower part of the clastic facies cropping out in the NW 1/4 sec. 20, T. 34 N., R. 48 W., at least during the time recorded by the lower part of the clastic facies. The narrowness of the south side of the gypsum facies and preserved similarities of the two sides suggest that the northern margin originally lay near the north side of the present outcrop of gypsum facies. The gypsum facies is thus inferred to have been no more than a few miles wide.

The original length of the gypsum facies is also imperfectly known. Gypsum is as abundant in the western end of the belt of exposures as it is in the eastern end, indicating that the original length was greater than the 12 miles remaining in the Chadron area. Indeed the gypsum facies probably extended at least 20 miles to the west, for an area in northwestern Dawes County is known as Gypsum mesa, and a request to mine gypsum on public land in the part of the mesa in secs. 33 and 34, T. 35 N., R. 52 W., is a matter of public record. Vondra (1958, p. 85) measured a section 3 miles south of there and reports white gypsum, gypsiferous claystone, siliceous limestone, and thinly interbedded grayish white siltstone and light green claystone in the upper 12 feet of the Chadron formation. A section measured about 3 miles farther south Vondra (1958, p. 90) shows that the gypsum of Gypsum mesa lies a few miles north of sandstone-red claystone in the basal part of the Chadron formation, like the gypsum of the Chadron area. The available evidence thus suggests that the gypsum facies was originally at least tens of miles long and only miles wide.

Clastic Facies

The clastic facies of the Brule formation consists of siltstone, sandstone, and mudstone, and ranges from more than 220 feet to about 195 feet. The unit presumably is yet thinner in the far northern part of the area, where the undifferentiated White River group measures about 210 feet. The outcrop belt follows the margin of the Pine Ridge escarpment and its outliers and, including the thicker part of the undifferentiated White River group, extends with interruptions to Slim Buttes. The clastic facies is generally not vegetated, and weathers to steep slopes that are intricately gullied. Slopes are about 45°, and are either stair-stepped or smooth. Throughout much of the area the clastic facies is covered by colluvium and terrace silts, which support grass.

The variety and seqûence of rock types is best illustrated by the following thick but incomplete measured section:

Partial section of Clastic facies of Brule formation
W 1/2 Sec. 33 and NE Cor. Sec. 32, T. 34 N., R. 48 W.,
Dawes County, Nebraska

	Feet
Quaternary	
Silt, loose, laminated	8
Clastic facies of Brule formation	
Siltstone, pale orange (10YR 8/4), calcareous, massive, conchoidal fracture; lime cement is concentrated to form poorly defined concretions or lumps 3 to 8 inches across; lumps are scattered and do not constitute stratification; scarce oredons	40
Siltstone, as above but without lumps	11
Sandstone, yellowish gray (5Y 8/1), calcareous, parallel-bedded, thin-bedded; sand is poorly sorted, fine to very fine grained and rich in ash and biotite; resistant ribs of sandstone look motheaten from having holes 1/4 to 1/2 inch wide and 1/4 inch deep; no sign of a source for holes is found on freshly broken surfaces	29
Pellet siltstone, pale orange (10YR 8/4), clayey calcareous, massive; numerous oredons and turtles, particularly in upper and lower thirds; skeletons apparently whole; turtles range in size from 6 to 24 inches; cement in lumps and concretions ranging in size from 2 to 12 inches and closely scattered through upper and lower thirds; pellets attain 1/16 inch and occur equally in lumps and matrix . .	39

Mudstone, light yellowish gray (10Y 8/2), calcareous, massive, rich in silt, prominent shrinkage cracks . .	15
Sandstone, clayey sandstone and mudstone interbedded, yellowish gray (5Y 8/1), calcareous with lumpy cement, rich in ash, biotite, and dark minerals; poorly sorted, thin-bedded, parallel-bedded; resistant ribs are motheaten . . .	15
Pellet mudstone, pale orange (10YR 8/4), slightly to strongly calcareous, massive; cement forms barely defined close-spaced scattered lumps, 1-foot concretions and lumpy lacework; concretions are restricted to middle 6-foot interval; pellets are clearly visible in cement concentrations, scarcely visible elsewhere, and attain 1/16 inch; turtles and oredons are numerous; most fossils and their adjacent matrix are green and nodules are green inside	32
Mudstone and sandstone interbedded, light yellow gray (10Y 8/2), calcareous, rich in ash and very fresh biotite, thin-bedded, parallel-bedded; fine-grained, mudstone is 90 percent of unit; the thickeat sandstone beds are about 3 inches thick and are cross-laminated	22
Mudstone, very silty, calcareous, ash-rich; massive except for vague color-banding of pale greenish yellow (10Y 8/2) and very pale orange (10YR 8/2)	13
Dolomite, light yellowish gray (5Y 8/1), very hard, contains biotite and ash shards	2
Silty or dolomitic clay, light greenish gray (5GY 8/1), poorly exposed	3
Dolomite, white (N 9), laminated, rich in ostracods .	4

Chadron formation

Pellet mudstone and lime pans, pale greenish near 10Y 8/2

Total thickness clastic facies 223

<u>Siltstone and Mudstone</u>.--Massive pale pink (10YR 8/2 to 10YR 8/4) calcareous siltstone makes up a large part of the clastic facies. The siltstone is remarkably pure but locally contains enough clay to exhibit very shallow close-spaced shrinkage cracks. Associated with the siltstone are similar but slightly more clayey rocks that crack a little deeper, are somewhat darker in color, and exhibit brown and green hues in addition to pink. These rocks are here termed mudstone. The actual difference in silt content is less than field appearance might indicate; a few representative samples show siltstone to contain about 80 percent silt, and mudstone to contain about 60 percent silt.

Where the formation contains only siltstone, it is massive from top to bottom, except for concentrations of cement. Where it contains both mudstone and siltstone, the resulting vaguely defined beds are measured in feet or tens of feet and are internally massive. Bedding is strikingly parallel.

Concentrations of cement form poorly defined lumps and well defined concretions of various sizes and shapes in the siltstone. The lumps resist weathering more than their matrix and thus stand out on natural exposures. All gradations in resistance, lime content, and sharpness of definition can be found between lumps and concretions. Both tend to occur in zones. The lumps or concretions of one zone differ greatly from those of other zones, but within a single zone one is remarkably like another. The siltstone between lumps or concretions contains enough calcite cement to effervesce vigorously with dilute hydrochloric acid. Mudstone effervesces less vigorously.

Extraordinary porosity characterizes the siltstone and mudstone, as indicated by samples being light in the hand. The only de-watered Recent terrigenous silts and muds known to me that are as light weight are loess and soil. Porosity has not been measured in the Chadron area, but two samples of siltstone from the Brule formation in Scotts Bluff County, Nebraska, which is similar to that in the Chadron area, are reported by Wenzel, Cady, and Waite (1946, p. 86), to have 51 percent and 54 percent porosity.

Microscopic examination of a few samples during the present study corroborates the unpublished findings of Tychsen's (1954) extensive laboratory study of the texture and mineralogy of the Brule formation in the Chadron area and elsewhere in Nebraska. Average median diameter of undifferentiated siltstone and mudstone falls near 40 microns throughout western Nebraska. Amount of silt ranges between 56 and 93 percent. Skewness is positive. Roundness averages 0.35, and sphericity averages 0.56. Quartz and feldspar are abundant, the ratio of feldspar to quartz ranging from 32/68 to 21/79, and averaging 1/2.6. In the few samples examined by me, well rounded and subrounded grains, some of medium silt size, are abundant, and many of the round and subround grains are definitely frosted. They are associated with angular and subangular cleavage fragments of fresh feldspar.

Volcanic ash and montmorillonite are common. In addition to forming thin rather pure beds, ash occurs as sedimentary particles in siltstone and mudstone. Ash seen under the microscope in mudstone in the Chadron area is partially altered to clay. Samples of mudstone similar to that containing the ash have been X-rayed and their most abundant clay mineral found to be montmorillonite. Some of the clay occurs as unabraded alteration rims on glass and as bundled aggregates that seem too delicate to have survived transport. Tychsen (1954) reports that parts of ash beds in the Brule formation are so completely altered as to be almost pure clay, that traces of volcanic glass were found in practically all samples of siltstone and mudstone, and that the predominate clay mineral in the Brule formation is montmorillonite (associated with illite and lesser kaolin), and concludes that the montmorillonite is the result of devitrification and chemical alteration of volcanic glass.

Sandstone.--Sandstone in the clastic facies of the Brule formation contrasts strikingly with sandstone in the basal part of the Chadron formation. That in the Brule formation consists of very fine to fine sand, plus silt and clay and some coarser sand; it has no gravel. Its bedding is extraordinarily thin and parallel; beds generally range in thickness from a quarter of an inch to eight inches, and are persistent; cut and fill structures are lacking. Some of the thicker beds are cross-stratified on the scale of inches, but cross-stratification on the scale of feet or tens of feet is absent, with one exception. The exception is a lenticular sand body seen in cross-section on the east side of the road in the SW 1/4 SE 1/4 Sec. 32, T. 34 N., R. 48 W. The sandstone body is less than 30 feet across and less than 15 feet thick. It occurs in siltstone well away from the main occurrences of sandstone, and interfingers with the siltstone. Fossils are extraordinarily abundant.

Individual sandstone beds show but slight differences in average grain size from top to bottom. For the sandstone sequence as a whole, average grain size generally increases upward. The lower part of the zone commonly contains more than 80 percent interbedded mudstone, the upper part less than 20 percent. This sort of vertical sequence in grain size was described by Spieker (1949, p. 64) in Cretaceous sandstone in Utah, and interpreted by him as deposited on beaches and nearshore sandy bottoms.

The sandstone was not investigated under the microscope, but the hand lens shows a poorly sorted mixture of quartz, fresh feldspar, fresh biotite or other dark mica, numerous dark grains, and volcanic ash.

Pellets.--Pellets similar to those in the pellet mudstone of the Chadron formation occur in mudstone and siltstone in the clastic facies of the Brule formation. Although coated with clay, the pellets are by no means "rolled clay pellets" (Bump, 1951, p. 41), for they are about as rich in silt as their matrix. They are most visible in mudstone but can be made out in the field at some places in siltstone. Samples in which no pellets can be seen in the field are found to be rich in poorly differentiated pellets when the samples are disaggregated in acid. Such pellets hold their form while their matrix disintegrates, as do pellets that are clearly visible in the field, but are considerably softer and more easily crumbled. Tychsen (1954, p. 130-133) digested 91 samples of the Brule formation, exclusive of sandstone, from three localities. He found pellets in 34 out of 43 samples at one locality, 21 out of 22 samples at another and 25 out of 26 samples at the third.

A phenomenon in sandstone is possibly related to pelleting. At some levels, the weathered surface of the sandstone is pock-marked with pits a quarter to a half-inch wide and a quarter-inch deep. Freshly broken surfaces show no sign of grains of that size. The pits evidently represent aggregates identical to their matrix except in cohesion.

Sandstone Dikes and Chalcedony Veins.--Sandstone dikes break the monotony of the massive siltstone along Pine Ridge in the southern part of the area. Those in sec. 1, T. 34 N., R. 46 W., extend from the base of the overlying Arikaree group down as much as 100 feet into the siltstone. They are nearly vertical and are filled with magnetite-rich sand similar to that in the basal part of the Arikaree group.

Veins of gray chalcedony a quarter of an inch to two inches wide cut vertically through tens of feet of section and extend laterally for hundreds of feet at many places in the siltstone and mudstone of the Brule formation. Many of the wider ones have a central fill of green mud or silt, showing that the fissure stood open after its walls were coated with chalcedony. Where veins cut through pink rock, the walls of the vein are bleached green for an inch or so, suggesting the action of water of negative Eh. Dogtooth calcite occurs in the central cavity of some, suggesting the water was not acid. Non-acid, reducing conditions are inferred (see the section on Eocene(?) soil above) to have characterized Oligocene or later groundwater.

Lateral Sequence in the Brule Formation

The Brule formation consists wholly of clay, gypsum, and carbonate in a narrow belt trending N. 70° W. through the center of the Chadron area. Away from this belt, the formation changes to siltstone, mudstone, and sandstone, and then to siltstone (figure 18). Three patterns are evident:

1. The formation thickens and becomes progressively more clayey and less silty toward the gypsum facies, being practically free of clay far from the gypsum facies and practically free of silt in the gypsum facies.
2. The edge of massive siltstone migrates toward the gypsum facies with the passage of time; but the main edge of the gypsum facies remains at about the same position, although thin tongues extend a few miles outward.
3. Sandstone is restricted to the near-gypsum part of the clastic facies, and fossils are extraordinarily abundant.

The patterns recorded were observed south of the center of the gypsum belt, but the results of reconnaissance to the north in the undifferentiated White River group are compatible.

Fossils and Age

Few fossils were found in the gypsum facies; many were found in the clastic facies. Ostracods and scarce snails occur in the carbonate

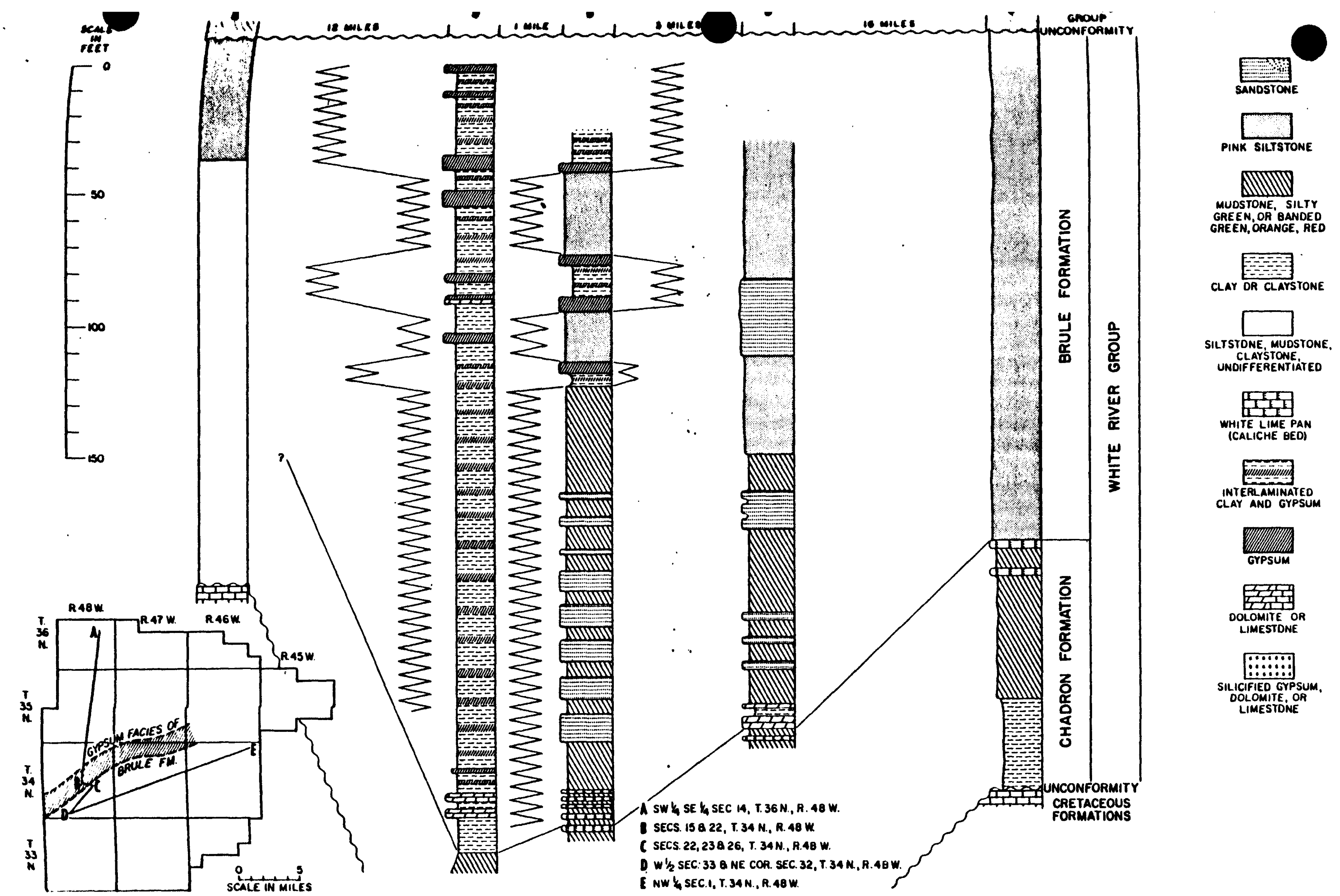


FIGURE 18.--Chart showing lateral variation of the Brule formation.

zone near the base of the formation. Plant matter occurs in clay and gypsum near the base of the formation at the one outcrop of the inferred center of the gypsum belt. Mammals and turtles occur in the sandy near-gypsum part of the clastic facies.

Ostracods.--A collection of ostracods and snails from laminated dolomite 3 to 9 feet above the base of the Brule formation in the NW 1/4 NW 1/4 Sec. 32, T. 34 N., R. 48 W., was examined by I. E. Sohn and J. B. Reeside, Jr. The snails were too poorly preserved to be identifiable (Reeside, written communication, 1955). Sohn (written communication, 1955) reported about the ostracods:

> "[The collection] contains a very large ostracod over 1-1/2 mm in greatest length. Unfortunately, internal impressions are all that are obtainable, but the shape and size resemble that of the marine Upper Paleozoic genus Paraparchites. I am particularly interested in this ostracod because Swain and Peterson figure a specimen from the Upper Jurassic Sundance formation of South Dakota as Paraparchites? sp."

The Jurassic Paraparchites? sp. comes from the Redwater shale member of the Sundance formation (Swain and Peterson, 1952, p. 1), which contains glauconite and is definitely marine. The possible presence in the gypsum facies of a genus that was restricted to marine water during late Paleozoic time and that may have reappeared in Jurassic time, again in marine water, is curious.

Pollen.--Two laterally separated samples of carbonaceous clay immediately underlying carbonaceous gypsum from 20 feet above the base of the Brule formation in the SW 1/4 SW 1/4 Sec. 3, T. 34 N., R. 47 W. were examined by R. W. Brown and E. B. Leopold. Brown (written communication,

1955) recognized "macerated vegetable debris" and a "beetle wing cover (elytron)". His comment corroborates the absence of recognizable leaves and twigs noted in the field. More luck was had with pollen. Although pollen density is slight and the grains are badly weathered, Miss Leopold (written communication, 1956) was able to list the following types:

Types		Number of grains per 22 mm^2 slide surface	
Common Names	Proper Names	USGS D1115A	USGS D1115B
	Conifer types		
	Taxodiaceae-Taxaceae Cupressaceae group (excluding Sequoia)	1	-
fir	Abies	-	2
Sequoia	Sequoia?	-	1*
	Dicot types		
Mulberry family	Moraceae cf. Morus	5	4
Elm family	Ulmaceae		
	Ulmus	6	3
	Zelkova	7	2
	Others	3	-
Birch	Betulaceae		
	Betula	1	-
	cf. Carpinus	2	2
	cf. Corylus	1	-
Oak family	Fagaceae		
	cf. Castanopsis group	-	-
	Dicots undetermined	10	9
	Monocot types		
Grass	Gramineae?	1	-

* very beat-up

Sedge	Cyperaceae	-	1**
	Spores		
"Princess pine"	Polypody fern	-	1
	Lycopodium cf. annotinum group	1	-
	Unknown pollen-sporomorphs	21	5
	Pelagic algae cf. Botrycoccus?	1	-

** rootlet

She makes these informal comments:

"It certainly is interesting to note that all of the plant genera identified here occur as pollen either in the Green River or Florissant formations, or both, but this similarity is only a very rough floristic one. In the case of the Green River and Florissant formations, the total pollen list includes only an eighth and a quarter (respectively) of the total generic list determined from leaves. Hence from similarities of pollen types in two formations it cannot be said with assurance that the floras as a whole are similar.

"Offhand this pollen association from the Brule formation seems first of all to be similar in the two samples, and second of all seems to represent a generalized temperate sort of climate. Among my 'unknowns' there were no pollen forms that could have been from groups like the Anacardiaceae, which when they appeared in the Florissant leaf sample, were interpreted by MacGinitie as probably representing a chaparral element of that flora. In fact I see no forms in the Brule pollen association which could possibly represent modern chaparral types.

"Of interest were temperate tree pollens like elm, and Zelkova, the latter being restricted to temperate Asia today, though it was common in the mid-Tertiary floras of the Great Basin. . . Groups of elm pollen (five grains sticking together, i. e.) suggest that elm was growing locally. . . The birch and oak family types can be interpreted as temperate forms. The root of sedge (cyperaceae) is a unique structure, and is unmistakable, but whether it was growing in the vicinity or washed in from an older deposit is a matter of speculation. Wood fragments of both dicots and conifer types were present in each sample."

Turtles and Mammals.--Fossils are extraordinarily abundant in the clastic facies of the Brule formation. Turtles and skeletons of small mammals thought to be mostly oreodons occur by the hundreds in the near-gypsum part of the clastic facies; oreodon or oreodon-like skeletons also occur in the solid siltstone part of the clastic facies, but are scarce. The turtles range in size from a few inches to two feet across. They are humped forms similar to modern land turtles; their shape, their wide distribution in rocks thought to be deposited on land, and their similarity to land turtles in the Big Badlands, indicate that, like diamond back terrapins and Galapagos turtles, they were land dwellers. The oreodons are unusually well preserved and many skeletons are articulated as well as modern skeletons of drought-killed cattle. A few skulls were collected for identification. About them Edward Lewis (written communication, 1955) says the following:

MAMMALS FROM BRULE FORMATION

D282-F siltstone, far southern part of clastic facies of Brule formation, about 10 feet below base Arikaree group, NE 1/4 NE 1/4 sec. 1, T. 34 N., R. 46 W., Sheridan County, Nebraska.

"Leptauchenia sp.; upper Whitney member of Brule formation (='Zone D of Brule'), latest Oligocene age. This determination rests upon available published data. Schultz and Falkenbach are working at this time on a revision of the oreodont sub-family referred to as Leptaucheniinae by them in 1940-1941 and by Simpson in 1945. It is possible that, when their results are available, the mandible with high-crowned teeth here referred to the highest Oligocene, in accordance with all previously published data, may turn out to be a form represented in the extensive Frick collections from levels lower in the Brule formation than the upper part of the Whitney member."

D207-F silstone, near-gypsum part of clastic facies of Brule formation near its gradation into distant part of clastic facies, estimated 50 to 75 feet above base of formation, SW 1/4 SE 1/4 sec. 32, T. 34 N., R. 48 W., Dawes County, Nebraska.

"Merycoidodont not otherwise determined; probably lower to middle part of Brule, probably middle Oligocene age."

D218-4F, pellet mudstone, near-gypsum part of clastic facies of Brule formation, 35 to 68 feet above base of formation, NW 1/4 SE 1/4 sec. 33, T. 34 N., R. 48 W., Dawes County, Nebraska.

"Subdesmatochoerus cf. S. socialis; upper Orella member of Brule formation (='Zone B of Brule'), late middle Oligocene age (same level as - 4mF)."

D218-4mF, same as above except 51 feet above base of formation.

"Merycoidodont, probably juvenile Subdesmatochoerus or Eporeodon; Gopherus sp."

Lewis' identification of oreodons indicates that the near-gypsum part of the clastic facies is partly of Middle Oligocene age, and that the distant part of the clastic facies is partly of Late Oligocene age. Interfingering of the gypsum facies with the near-gypsum part of the clastic facies indicates that the gypsum facies also is partly of Middle Oligocene age. The thickness of the gypsum facies being greater than the thickness of the clastic facies suggests, though does not prove, that the gypsum facies is also partly of Late Oligocene age.

Undifferentiated White River Group

The undifferentiated White River group resembles the Chadron-Brule sequence, with one puzzling exception, namely that the basal part of the White River group in three small areas resembles the Brule formation more than it does the Chadron formation.

In the area where the sandstone-red claystone belt of the Chadron formation would presumably be expected to extend, in the SW 1/4 sec. 5, T. 34 N., R. 46 W., the basal part of the White River group is green and contains even-bedded layers described in the field as "silicified limestone." The material has not been examined under the microscope, but in its even bedding it superficially resembles the "silicified limestone" in the Brule formation that turned out to be silicified gypsum.

Another group of exposures, about seven miles to the northeast, in the SW 1/4 sec. 18, T. 35 N., R. 45 W., possibly representing the further extension of the belt, exhibits 15 feet of sandstone that is white, fine-grained, calcareous, not noticeably cross-bedded, and perhaps related genetically to the sandstone in the near-gypsum part of the clastic facies of the Brule formation. Whatever its origin, it is many miles eastward of the area where white sandstone in the Chadron formation passes eastward into red clayey sandstone. Nearby, in the C sec. 24, the exposed lower 4 feet of the White River group consists of material described in the field as "clay, light yellowish gray (5Y 7/1), noncalcareous; weathers deeply to granular matter that looks like fine sand but is not gritty." Similar descriptions were recorded for interlaminated clay and gypsum in the gypsum facies of the Brule formation before the presence of gypsum recognized.

In the far northern part of the Chadron area the lower 15 feet of the White River group in the SW 1/4 sec. 29, T. 36 W., R. 46 W., contains 3 feet of "silicified limestone" and 5 feet of material described in the field as "claystone or siltstone, whitish gray, noncalcareous, very friable to extraordinary depth; fresh samples are laminated and green and break into flakes that would be shale except for their softness." This sequence resembles that at the east end of the mapped sandstone-red claystone belt in passing into silty red claystone, 28 feet of which is exposed in the SE 1/4 sec. 28, T. 36 N., R. 46 W. Nearby, in the SW cor. sec. 27, T. 36 N., R. 47 W., 8 feet of white, fine-grained, calcareous, slabby sandstone is exposed at the base of the White River group.

Further work is clearly needed in these three areas.

MIOCENE

Overlying the White River group with erosional unconformity is a 1000-foot sequence of Miocene age, which consists mostly of sandstone and covers an extensive area in western Nebraska and eastern Wyoming (Condra and Reed, 1943, p. 11). The lower half of the sequence is the Arikaree group, of which part is exposed in the Chadron area.

Arikaree Group

Definition

Darton (1899, p. 747-755) subdivided Miocene rocks of western Nebraska into two units, the Gering formation below and the Arikaree formation above. The name Gering formation was proposed for light gray, cross-bedded, laminated and massive sandstone and conglomerate as much as 200 feet thick, resting unconformably on the Brule formation. The name Arikaree formation was proposed for 500 feet of gray sandstone characterized by tubular concretions and resting on either the Gering formation or the Brule formation. Darton's Arikaree formation was subdivided by Hatcher (1902) into the Monroe Creek formation below and Harrison formation above. Later workers (Schultz, 1938, and Lugn, 1939) elevated the Arikaree to group rank and included in it the Gering formation.

Description

Less than 200 feet of the Arikaree group escaped erosion in the Chadron area. The preserved part consists of very fine-grained sandstone, siltstone, conglomeratic sandstone, and ash, which are tentatively assigned to the Gering and Monroe Creek formations. The Arikaree group forms dissected thickly wooded uplands rising above the lowlands formed by the White River group in near-vertical cliffs. Such cliffs form the north face of Pine Ridge, which bounds the Chadron area on the south and southeast, and the margins of Slim Butte in the northwestern part of the Chadron area. The Arikaree uplands that bound the Chadron area on the northeast are not cliffed.

Gering formation

The Gering formation consists of resistant sandstone and siltstone with thin ash beds, characterized by beds of conglomeratic sandstone, or by well-developed stratification, or by both, and by absence of concretions. It ranges in thickness from 160 feet in the south to a wedge edge in the north. The base is an erosional unconformity; the top is an abrupt lithologic break.

The conglomerate faction consists of pebbles, granules, and scarce cobbles. Average grain size is between 0.2 and 0.5 inches, maximum size is 6 inches. The pebbles, granules, and cobbles are well-rounded and consist of lime-cemented siltstone and fine- or very fine-grained sandstone. The siltstone resembles that in concretions in the Brule formation; the sandstone resembles that in concretions in the Arikaree group. Notable for their absence are fragments of chert from the White River group, limonite concretions from the Eocene(?) soil, resistant fossils and concretions from Cretaceous shale, and vein quartz and other crystalline rocks. The conglomerate is concentrated in the lower part of the sequence, although the basal 10 feet is free of conglomerate in some places. Most of the conglomerate occurs in lenticular beds, but some occurs in pockets or as scattered pebbles in well-sorted sandstone.

The finely stratified sandstone is divided by weathering into parallel beds ranging in thickness from 1 inch to 10 feet. In addition, most of the beds exhibit internal stratification made evident by laminae composed almost wholly of blue grains of magnetite. The magnetite laminae are only a few grains thick, but are close-spaced and persist for tens of feet. Burrows in which the lamination is destroyed make minor discontinuities. Internal stratification shows that most of the parallel beds are either cross-bedded on the scale of 1 inch to 5 feet, or are millimeter-laminated parallel to the top and bottom of beds. Some of the cross-beds appear to be the result of plunging troughs being filled. Millimeter-laminated and flaggy beds occupy the top and bottom ten feet in the C. sec. 1, T. 34 N.,

R. 46 W., where coarse cross-beds are mostly in the lower part of the sequence.

A few samples were examined under the microscope. Sorting is unusually good within any one lamina, and moderately good in samples representing many laminae. Except for conglomeratic zones, grain size ranges from coarse silt to very fine sand. Median grain shape ranges from sub-angular to sub-round, but many grains in each sample are well rounded and many are sharply angular. The bulk of the sand consists of quartz and fresh feldspar, partially decomposed volcanic ash, magnetite, green and black ferromagnesian minerals showing no signs of decomposition, and muscovite. Feldspar includes pink orthoclase, coarsely twinned plagioclase, and cross-hatched microcline. Some feldspar grains are sharply pointed cleavage fragments. Some of the well-rounded quartz is frosted.

Magnetite constitutes 60 percent of a sample of moderately laminated sandstone from Slim Buttes. Layers a quarter of an inch thick contain an estimated 80 percent magnetite. The magnetite grains are all of about the same size, averaging about 70 microns. Some are well rounded but others show the octahedral and dodecahedral shape of magnetite crystals. Each grain behaves as a tiny magnet. Loose grains in water tend to attach themselves to one another end to end, forming chains and small clumps. In the field of a magnet, the chains become tens of grains long and stand parallel to each other.

The blue color of the magnetite is a surface phenomenon. Under high magnification the grains are seen to be thinly coated with a rough porous material that appears white in reflected light and is weakly birefringent in polarized transmitted light. Grains other than magnetite are also coated. A probably related phenomenon is seen when a disaggregated sample is put in water. Many of the magnetite and other grains float. After vigorous stirring they still float. Samples of magnetite digested in hydrogen peroxide for two hours and then dried do not have the blue color and when put in water either sink directly or sink after gentle stirring. The white birefringent coat, however, remains. Burning has the same effect. The blue color and unusual ability to float are probably due to a surface coat of water-repellant organic matter similar to that described by Bradley (1957, p. 665). The organic matter seems not to be related to recent weathering, for samples a foot behind the weathered surface have it also.

Monroe Creek formation

The Monroe Creek formation consists of very fine grain sandstone, weakly resistant siltstone, and ash, and is characterized by lime concretions and poorly developed bedding. In its massiveness the Monroe Creek formation resembles the siltstone of the Brule formation. Cylindrical concretions resembling aligned horizontal pipes are common. Zones of coalesced concretions on Slim Butte resemble lime pans in the pellet mudstone of the Chadron formation.

The observed thickness remaining in the Chadron area is less than 100 feet.

Lateral Variation

The Arikaree group exhibits pronounced changes from south to north across the Chadron area. In the south, the Gering formation is 160 feet thick and consists mostly of well-stratified sandstone and siltstone, and the Monroe Creek formation lacks prominent pipe-like concretions in its basal part. In the north, the Gering formation is thin or absent and consists mostly of conglomeratic sandstone, and the Monroe Creek formation has prominent pipe-like concretions in its basal part. The southern facies is illustrated below:

Partial section of Arikaree group
C. sec. 1, T. 34 N., R. 46 W.
Sheridan County, Nebraska

	Thickness in Feet
Monroe Creek formation	
Sandstone, grayish orange (10YR7/4), very fine grained, soft; at base is lime concretion shaped roughly like a corkscrew 8 inches wide; lacks pebbles and magnetite laminae; not resistant	10+
Gering formation	
Sandstone and siltstone, yellowish gray (5Y7/2), sand is very fine grained, noncalcareous except for 1-inch ledges at base, thin bedded and parallel bedded.	10

Sandstone, yellowish gray (5Y7/2), very fine grained except for scarce conglomeratic beds, noncalcareous to calcareous; rich in blue magnetite; bedding ranges from mm-laminated to massive, and from cross-stratified to parallel-bedded; cross-stratified beds are a foot or less thick; less conglomeratic than below; contains 4 beds of ash 6 inches thick, the top of one being plastically deformed 120

Sandstone, as above but very rich in magnetite, cross-bedded on the scale of 1 to 5 feet, more numerous beds of conglomeratic sandstone 20

Sandstone, as above but thin-bedded and parallel-bedded to millimeter-laminated; base is erosional unconformity; pockets of conglomeratic sandstone occupy depressions on the unconformity. 10

Brule formation

Total thickness of Gering formation 160

The northern facies is illustrated below:

Partial section of Arikaree group
Slim Butte, SW 1/4 SE 1/4 sec. 14, T. 36 N., R. 48 W.
Shannon County, South Dakota

Monroe Creek formation	Thickness in Feet
Siltstone, yellowish gray (5Y7/2), calcareous; weakly cemented and soft except for 1-foot ledges near base; abundant lime concretions in form of horizontal pipes and irregular masses	22+
Ash, white (N9), thins to a knife edge in 400 feet; bedding contorted by load casting involving overlying siltstone.	6
Sandstone, yellowish gray (5Y7/2), calcareous; weakly cemented and soft; grain size ranges from coarse silt	

to very fine sand; contains poorly defined lime concretions; interrupted by several lenses of greenish gray (5G6/1) ashy sandstone as much as 2 feet thick, which wedge out in a few hundred feet. 25

Gering formation

Sandstone, yellowish gray (5Y7/2), slightly conglomeratic, coarse to very coarse grained, calcareous; interrupted by several ashy sandstone lenses as above, and capped by one 3 feet thick that extends 2000 feet before wedging out 28

Sandstone and conglomeratic sandstone, yellowish gray (5Y7/1) to blue (5B5/1), noncalcareous except for pebbles, mostly fine grained; patchy parallel-stratification and cross-stratification shown by laminae of blue magnetite; thins erratically to 2 feet; base is erosional unconformity irregular on small scale. 15

White River group

Total thickness Gering formation 43

The Gering formation is absent in sec. 20, T. 36 N., R. 46 W. There siltstone and sandstone bearing concretions in the form of lumps and horizontal pipes rests directly on lumpy siltstone of the Brule formation with no sign of erosion. A mile to the south, just north of the fault, a gulley exposure in the NW1/4 NE1/4 sec. 29, T. 36 N., R. 46 W., shows 3 feet of pebbly sandstone of the Gering formation underlying pipy sandstone of the Monroe Creek formation and unconformably overlying pink and green lumpy siltstone and mudstone rich in turtles and oreodons of the White River group. How much of the lateral variation in the Arikaree group is due to onlap and how much to facies change remains a problem for the later work.

Fossils and Age

Except for burrows in laminated sandstone, no fossils were found in the Arikaree group. Falkenbach and Schultz (1951, p. 50) report that the oreodont Leptauchenia major is common in the Gering formation of western Nebraska and Wyoming, and that the Arikaree group of western Nebraska is conventionally considered to be of Early Miocene age.

PLEISTOCENE AND RECENT

The youngest sediments in the Chadron area constitute a discontinuous sheet of gravel, sand, silt, clay, and various mixtures of these bounded above by the modern land surface and bounded below by a great erosional unconformity. The unconformity cuts across the sequence from the Graneros formation to the Arikaree group, and has a relief of about 1,000 feet.

Three more or less laterally and vertically segregated parts can be recognized within this complex stratigraphic unit: upland sand, gravel, and silt, referred to on the map as terrace deposits and loess; lowland silt and sand, or alluvium; and slope debris, or colluvium. Where thick, terrace deposits and loess, and alluvium are mapped, and colluvium is noted but not mapped.

Terrace Deposits and Loess

Deposits of coarse gravel and sand as much as 40 feet thick, and commonly 20 feet thick, underlie poorly defined terraces on both sides of the White River. The terrace deposits occur at different heights above the river, but all are in the interval 130 to 210 feet, as measured between the base of the terrace deposit and the low water level of the river. During deposition of the terrace gravel and sand, the floor of the White River Valley was more than 7 miles wide north of Chadron. The terrace deposits southeast of Chadron are excluded from this measurement, because their composition indicates that they were deposited by Bordeaux Creek. The floor of the valley is now about 1 mile wide.

The terrace deposits consist mostly of material from the Arikaree group. The fine fraction consists of fine and very fine grained sand, including magnetite; the coarse fraction consists mostly of well-cemented gray sandstone similar to that in lime concretions in the Arikaree group. Also in the coarse fraction are angular fragments of blue and gray chalcedony plates from the White River group, banded agate, vein quartz, and other cobbles and pebbles from the Chadron formation, cobbles of green shale from the Eocene(?) soil, and limestone concretions bearing *Inoceramus* and *Baculites* from the Pierre shale. Composition varies from place to place. For example, blue and gray chalcedony makes up 15 percent of the gravel in a 13-foot deposit in the NW 1/4 sec. 32, T. 35 N., R. 47 W., 150 feet above the river; whereas it makes up only 5 percent of the gravel in a 12-foot deposit in the SW 1/4 sec. 36, T. 35 N., R. 48 W., 205 feet above the river.

Average size of the gravel fraction is 2 inches in a 30-foot deposit in the NW 1/4 SE 1/4 sec. 20, T. 34 N., R. 48 W., where about 1 percent of the gravel is 1 to 2 feet in diameter. Large-scale cross-bedding is well displayed at this locality. Cross-beds are several feet thick and extend for about 20 feet laterally. The upper 3 feet of bedded gravelly sand at this locality grades laterally into massive very fine grained sand.

Thick massive silt as much as 40 feet thick caps most of the ridges and hills in the uplands. The maximum thickness can be seen in the SW 1/4 sec. 25, T. 35 N., R. 47 W.; thicknesses of 10 to 20 feet are common. The silt is soft but stands in nearly vertical faces. It is highly porous and calcareous, contains snail shells, is extraordinarily well sorted, and conforms to pre-existing topography. Silt on ridges at higher altitudes shows no difference from silt on ridges at lower altitudes. The silt is interpreted as wind-deposited, i.e., as loess.

In some places, other processes modified the loess. For example, in the SW 1/4 sec. 9, T. 35 N., R. 46 W., unoriented chips of shale in the lower few feet of a 15-foot loess indicate reworking by gravity creep. The middle third of a 20-foot loess in the SW 1/4 sec. 31, T. 34 N.,

R. 47 W., is laminated and clayey, probably having been reworked by water. Massive silt and layers of terrace gravel are interbedded in the SW 1/4 sec. 20, T. 34 N., R. 46 W., suggesting either that a site of wind deposition was intermittantly flooded by gravel-bearing currents, or that what appears to be a wind deposit is actually an ancient flood plain deposit.

Alluvium

White River and its tributaries are flanked by as much as 65 feet of silt and sand, shown on the map as alluvium. The alluvial silt resembles upland silt in being massive, but differs from upland silt in being very poorly sorted and in being restricted to the lower part of valleys. Alluvial silt is rich in clay, very fine sand, and plant matter. Scattered pebbles commonly occur in the lower few feet. The A zones of two buried soils occur in the upper 10 feet of a 50-foot exposure in the bank of White River in the NE 1/4 SE 1/4 sec. 32, T. 35 N., R. 47 W. The flat upper surface of the alluvial silt and parallelism of bedding indicates deposition from flood water, perhaps supplemented by deposition of dust. Lack of stratification indicates the sediment was subject to soil-making during accumulation. The alluvial silt is thus a flood plain deposit. Low terraces or flood plains occur at several levels above the White River, but they proved too complex to differentiate.

A few miles upstream from the last mentioned locality, the alluvial silt is underlain by quite different material. In the NE 1/4 NW 1/4 sec. 7, T. 34 N., R. 47 W., the bank of White River shows what seem to be the same two buried soils in about 10 feet of alluvial silt, but the alluvial silt is underlain by 52 feet of finely laminated parallel-bedded sand. Lamination is shown by variation in grain size, from coarse silt and very fine grained sand to coarse sand composed partly of blue and gray chalcedony. Some of the chalcedony is pseudomorphic after fibrous gypsum. Between the laminated sand and the Pierre shale, which is at water level, 2 feet of gravel occurs locally. The gravel consists of fragments of sandstone from the Arikaree group and chalcedony and dolomite or limestone from the White River group. The laminated sand is older than the alluvial silt, by virtue of superposition. Probably a time of erosion intervened, for channel-fill of alluvial silt or colluvium cuts out the laminated sand a few hundred yards south of the river, and the bank of the river shows what appears to be the outline of a cutbank. The upper 20 feet of the laminated sand is missing beneath the cutbank and the remainder of the sand is again overlain by alluvial silt bearing two buried soils. The excellent stratification and lack of cross-bedding suggest that the laminated sand was deposited in standing water that was quiet, presumably in a lake.

Colluvium

Unsorted mixtures of silt, sand, and scarcer clay, commonly rich in scattered gravel, occur on most slopes. The debris forms a practically continuous sheet at the foot of Pine Ridge and other steep slopes. Water wells indicate it is a few tens of feet thick several miles downslope from Pine Ridge. The coarse fraction consists of angular fragments of chalk or limestone downslope from cliffs on the Niobrara formation, siltstone downslope from the Brule formation, and sandstone downslope from the Arikaree group. Angularity, correspondence of coarse fraction to material at higher elevation, and lack of sorting indicate that the debris was transported by gravity creep.

STRUCTURE

Deformation in the Chadron area was mild. Although structural relief is about 1,900 feet, dips greater than 10° are exceptional and faults large enough to be mapped are few. Because deformation was mild, structure contour maps portray the general structure of the area to better advantage than cross-sections.

METHOD OF STRUCTURE CONTOURING

Two contour horizons were selected for structure contouring: 1) the top of the Greenhorn limestone (fig. 19), and 2) the base of the White River group (fig. 20). The structure contour interval is 100 feet. Surface elevations were obtained by aneroid barometer, and it was not possible to maintain a high degree of precision because at many places lines of elevation were projected long distances from control stations. Datum elevations were computed from surface elevations, surface attitudes, and stratigraphic thicknesses, and from records of dry holes drilled for oil or gas. Structure contours were not drawn in the southeastern and far northeastern parts of the area, where colluvium and Miocene rocks are at the surface.

CHADRON ARCH

The Chadron arch, which dominates the structure of the Chadron area, is a compound anticlinal uplift trending northwest-southeast.

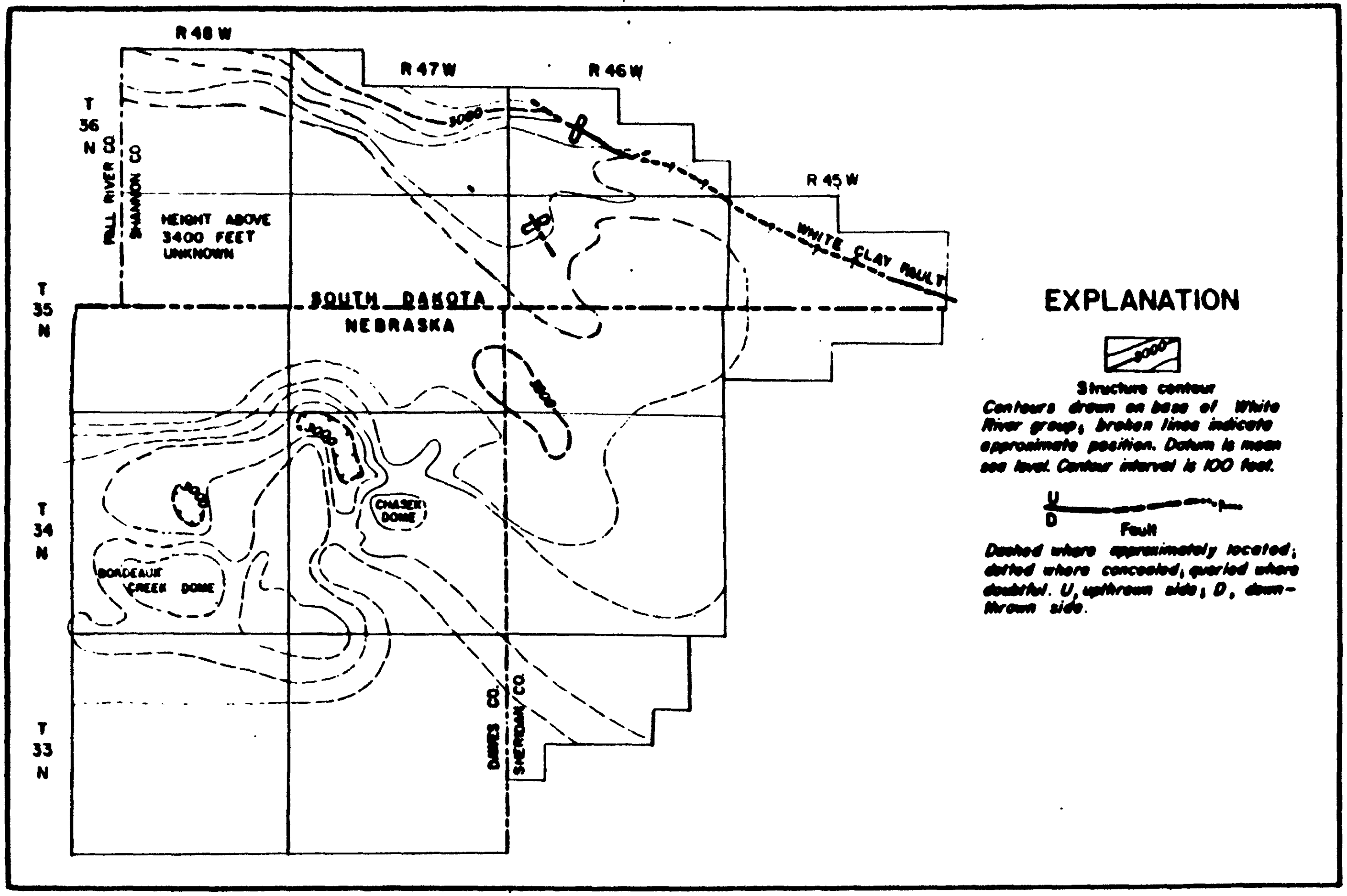
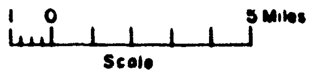


FIGURE 20.--Map showing geologic structure of Oligocene rocks.



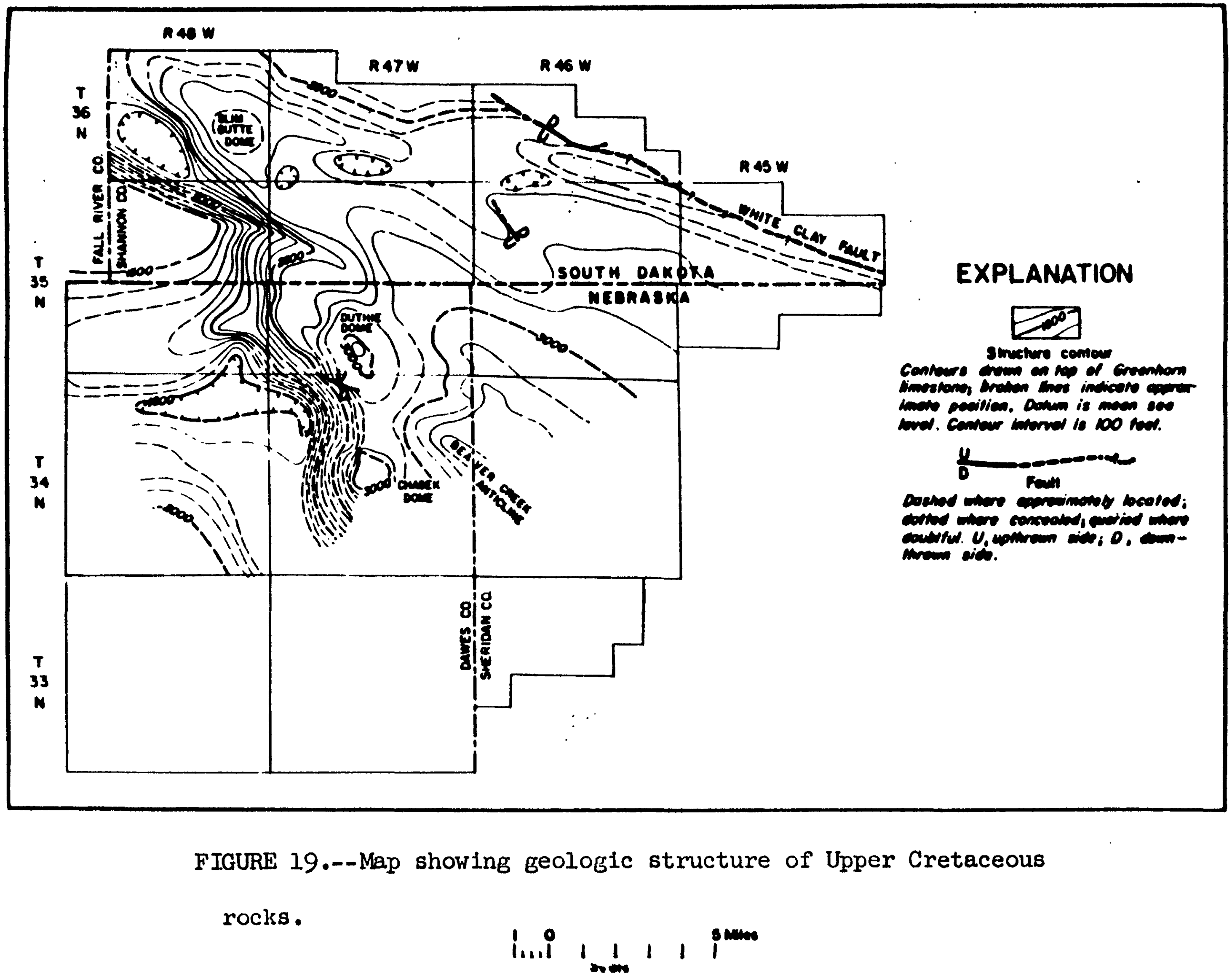


FIGURE 19.--Map showing geologic structure of Upper Cretaceous rocks.

gional studies by Merriam and Atkinson (1955) show it to be one of a series of roughly aligned elongate uplifts forming a broad arcuate anticlinal trend convex to the southwest and extending from the Black Hills uplift of South Dakota through the Chadron arch and adjacent Cambridge arch, the central Kansas uplift, and the Chautauqua arch of Kansas. Only the north end of the Chadron arch, the part in the Chadron area, has readily appreciable surface expression.

At the level of the base of the Greenhorn limestone (fig. 19), the arch has structural relief of about 1,900 feet. The arch plunges northwestward, losing about 900 feet elevation in 15 miles. It is markedly asymmetric, the steeper side being on the southwest. At the level of the base of the White River group (fig. 20), the arch is still recognizable, but its structural relief is only about 700 feet and its plunge and asymmetry are indistinct.

Minor Folds on the Chadron Arch

As shown by the structure contours on the Greenhorn limestone (fig. 19), the Chadron arch exhibits several minor highs and lows. The principal high, Beaver Creek anticline, marks the crest of the arch and shares its northwestward plunge. The other highs, Duthie dome, Slim Butte dome, and Chasek dome, have closure in the range of 200 to 300 feet. All have been drilled one or more times; seven dry holes mark the vicinity of the Duthie dome. Only one of the four, the Chasek dome, is recognizable in the structure contours drawn on the base of the White River group.

The area of the Bordeaux Creek dome (fig. 20) was contoured on the base of the White River group but not contoured on the top of the Greenhorn limestone, because recent drilling activity restricted the availability of subsurface information.

WHITE CLAY AND OTHER FAULTS

The northeast side of the Chadron arch in the mapped area is marked by the White Clay fault, which trends northwest-southeast. Along much of its extent, the fault is a poorly exposed but remarkably straight contact between the Arikaree and the White River groups. Exposures in the central part of the mapped extent of the fault, where the existence of the fault is queried, are extremely poor. Best exposures are on the bluff in T. 36 N., R. 46 W. Near locality 49, sec. 28, T. 36 N., R. 46 W., the White Clay fault dips 55° northeast and throws the basal beds of the Arikaree group in contact with the basal beds of the White River group; the fault thus is normal and has a stratigraphic displacement of about 200 feet on the base of the White River group. Whether or not the displacement is greater on the top of the Greenhorn limestone is unknown.

Normal faults of a few feet displacement are extraordinarily numerous in the outcrops of the lower part of the Sharon Springs member of the Pierre shale and the upper part of the Niobrara formation, suggesting that this part of the sequence was relatively brittle during deformation. Most of these small faults seem not to extend across unconformity into the White River group; some definitely end at the unconformity, for example the one shown in sec. 4, T. 34 N., R. 47 W. At least one of the small faults, however, did extend across the unconformity before modern erosion, for the oxidized zone of the Eocene(?) soil is in fault contact with unweathered shale at the top of hills in secs. 6 and 8, T. 35 N., R. 46 W.

TECTONIC HISTORY

Deformation happened in at least two stages, as shown by discordance between the top of the Greenhorn limestone and the base of the White River group, and by truncation of about 1,800 feet of Cretaceous strata beneath the unconformity at the base of the White River group, as discussed in the section on stratigraphy. The first stage recorded by outcropping rocks was in late Cretaceous-early Tertiary time, after deposition of Maestrichtian rocks and before formation of the Eocene(?) soil. The second stage was during middle Tertiary or later time; Oligooene rocks were folded and Miocene rocks were faulted. A paleogeologic map (fig. 21) shows that the Chadron arch had acquired most of its present form by the end of the first stage of deformation. (The area of the White Clay fault is left blank on the paleogeographic map -- available evidence would allow the fault to be either a late fault or an early fault that was rejuvenated.) Tectonic events preceding those recorded by outcropping rocks are indicated by subsurface information. Description of subsurface geology is outside

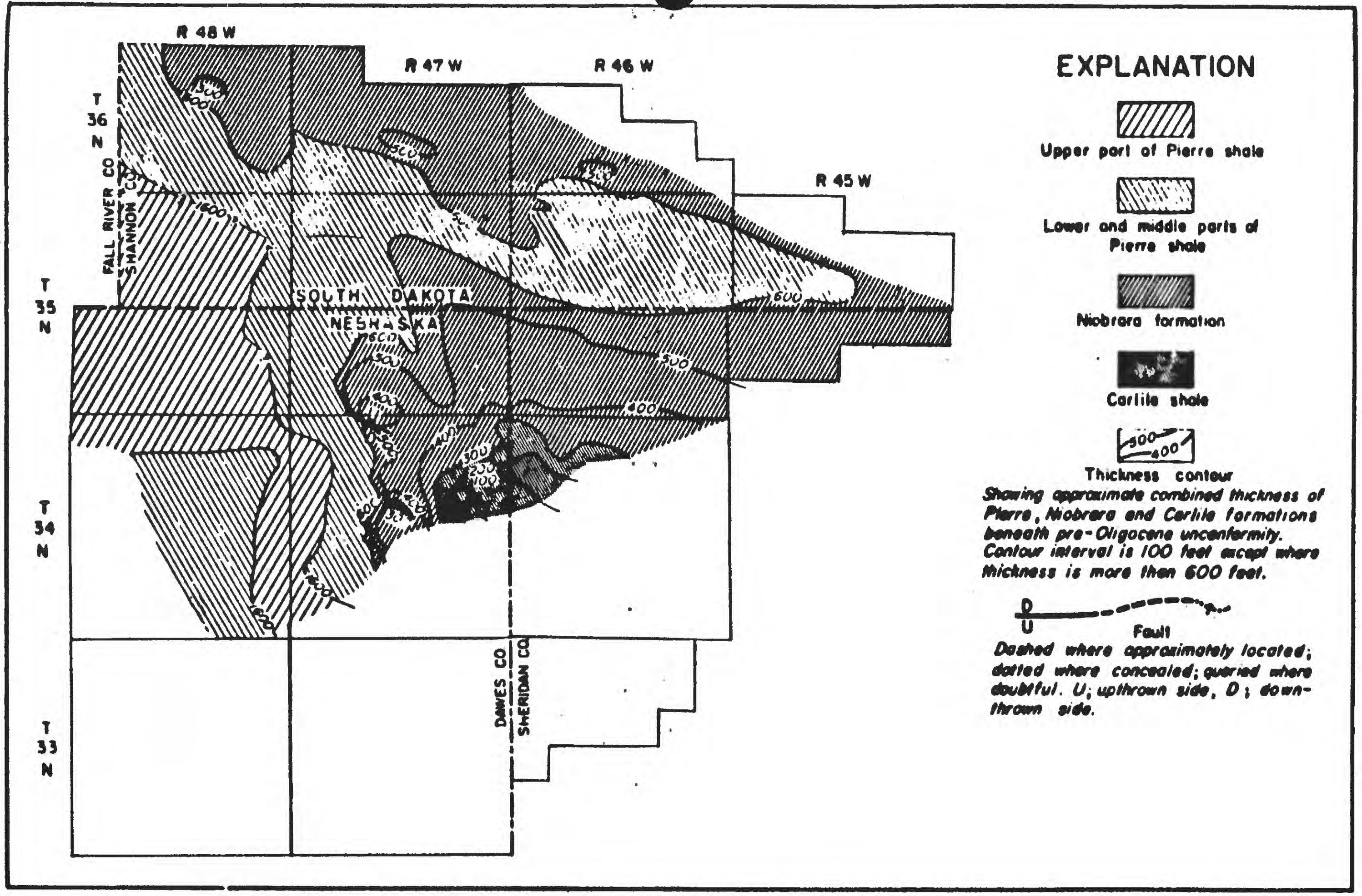
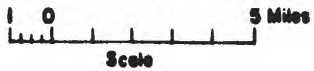


FIGURE 21.--Paleogeologic map showing inferred areal distribution of Upper Cretaceous rocks at beginning of Oligocene time.



scope of the present report, but J. G. Mitchell (written communication, 1956) notes that Pennsylvanian Des Moines rocks rest unconformably on Precambrian crystalline rocks in the Valentine Oil Company Murphy No. 1 well in sec. 5, T. 34 N., R. 46 W., near the crest of the Chadron arch; and Condra and Reed (1943, p. 60-61) report that Mississippian rocks present on both sides of the Chadron arch are absent from its crest because of Pennsylvanian erosion.

URANIUM

Average uranium content of the earth's crust is about 0.002 percent by weight, according to Fleischer (1953, p. 2); average uranium content of natural waters in the United States and Alaska that are not appreciably affected by dispersion auras of uranium deposits is about 0.000 000 01 percent, or 0.001 ppm, according to Fix (1956, p. 669). Concentrations of uranium in excess of ten times these values occur in the Chadron area in water, and in Cretaceous shale, Eocene(?) soil, Oligocene gypsum and associated rocks. Although some of the occurrences contain uranium minerals and more than 0.1 percent uranium, none is commercial.

The analyses reported below as percent uranium refer to percent by weight of the element, as determined chemically. Those reported as percent equivalent uranium refer to "the ratio of the radioactivity of the sample to the radioactivity of a uranium-ore standard which is in equilibrium with all of its decay products", and are determined in the laboratory, and are expressed in terms of "the amount, in percent, of primary parent, under the assumption of radioactive equilibrium, required to support the amount of daughter product actually present in the sample", as stated by Rosholt (1959, p. 4). Routine analyses for equivalent uranium do not report alpha, beta, and gamma radiation separately. The purpose in much of the sampling was to locate potentially mineable occurrences of uranium rather than to discern the overall uranium content of stratigraphic units. Consequently, results are biased in favor of high uranium percentages on two counts: 1.) many collections are dominated by samples collected because field surveys with portable counters indicated unusual radioactivity; 2.) many samples having 0.003 percent or less equivalent uranium were not analyzed chemically, and thus their uranium content is unknown.

URANIUM IN WATER

Uranium content of water in the Chadron area (Table 2) averages 0.086 ppm in 23 samples, ranging from 0.001 ppm for a pond in the Chadron formation to 0.780 ppm for a seep in the Sharon Springs member of the Pierre shale. Water from Cretaceous shale averages 0.164 ppm uranium in 11 samples, ranging from 0.002 to 0.780 ppm. Water from Oligocene rocks averages 0.014 ppm uranium in 6 samples, ranging from 0.001 to 0.025 ppm. Water from Pleistocene and Recent sediment averages 0.024 ppm uranium in 3 samples, ranging from 0.020 to 0.028 ppm. Water from streams averages 0.009 ppm uranium in 3 samples, ranging from 0.005 to 0.014 ppm.

The high average uranium content for water from Cretaceous shale is due mostly to the influence of samples of water from the Sharon Springs member of the Pierre shale. Water from the Sharon Springs member averages 0.425 ppm in 4 samples, and is notably acid. Sirilar results for water in the Sharon Springs member are reported by Kepferle (1959, p. 586) from the eastern and southern flanks of the Black Hills in Fall River and Custer Counties, South Dakota. He found water from

Table 2 -- Uranium Content of Water in Dawes County, Nebraska, and Shannon County, South Dakota

Analysts: R. Deming, R. McClure, P. Schuch

Source	Laboratory No.	Location	Uranium Content (ppm)	pH	Remarks
		WATER FROM CRETACEOUS ROCKS			
Carlile shale	219658	Loc. 14, sec. 26, T.35N., R.47W., Dawes Co.	0.011	7.4	Pond.
Niobrara formation	219648	Loc. 13, sec. 13, T.35N., R.46W., Shannon Co.	0.010	7.6	Pond in calcareous shale of upper part of Niobrara, with run-off from Pierre shale.
Niobrara formation	213418	Loc. 17, sec. 16, T.35N., R.47W., Shannon Co.	0.075	3.7	Seep from calcareous shale in upper part of Niobrara, with run-off additions from Sharon Springs.
Sharon Springs member of Pierre shale	231109	Loc. 51, sec. 16, T.35N., R.47W., Shannon Co.	0.780	2.6	Seep from shale above bentonite beds.
Sharon Springs member of Pierre shale	213419	Loc. 51, sec. 16, T.35N., R.47W., Shannon Co.	0.56	2.3	Seep from shale directly above Ardmore bentonite.
Sharon Springs member of Pierre shale	219653	Loc. 23, sec. 33, T.36N., R.47W., Shannon Co.	0.32	3.1	Seep from shale below bentonite zone.
Sharon Springs member of Pierre shale	223973	Loc. 52, sec. 26 T.36N., R.48W., Shannon Co.	0.040	-	Seep.
Middle part of Pierre shale	219649	Loc. 9, sec. 8, T.35N., R.45W., Shannon Co.	0.003	7.6	Pond about 50 feet above base of unit, with run-off from White River group.
Middle part of Pierre shale	219647	Loc. 12, sec. 12, T.35N., R.46W., Shannon Co.	0.002	8.2	Pond.
Upper part of Pierre shale	213422	Loc. 19, sec. 28, T.35N., R.48W., Dawes Co.	0.005	6.9	Pond.
Upper part of Pierre shale	213426	Loc. 25, sec. 35, T.35N., R.48W., Dawes Co.	0.003	6.8	Pond.
		WATER FROM OLIGOCENE ROCKS			
Chadron formation	219656	Loc. 3, sec. 8, T.34N., R.47W., Dawes Co.	0.013	8.4	Pond.
Chadron formation	213421	Loc. 6, sec. 14, T.34N., R.48W., Dawes Co.	0.001	7.3	Pond.

Table 2 -- Uranium Content of Water in Dawes County, Nebraska, and Shannon County, South Dakota (cont.)

Source	Laboratory No.	Location	Uranium Content (ppm)	pH	Remarks
		WATER FROM OLIGOCENE ROCKS (cont.)			
Brule formation	219660	Loc. 1, sec. 9, T.33N., R.48W., Dawes Co.	0.025	8.4	Well.
White River group	219652	Loc. 8, sec. 5, T.35N., R.45W. Shannon Co.	0.012	8.3	Well.
White River group	213425	Loc. 22, sec. 29, T.36N., R.46W., Shannon Co.	0.013	7.6	Spring flowing 0.3 gal/min from mudstone.
White River group	219651	Loc. 20, sec. 36, T.36N., R.46W., Shannon Co.	0.020	8.2	Well.
		WATER FROM PLEISTOCENE AND RECENT SEDIMENT			
Terrace deposits and loess	219650	Sec. 1, T.35N., R.46W. Shannon Co.	0.023	8.6	Well in loess.
Terrace deposits or loess	219655	Loc. 4, sec. 27, T.34N., R.47W., Dawes Co.	0.028	8.1	Well in loess.
Alluvium	219659	Loc. 2, sec. 2, T.33N., R.48W., Dawes Co.	0.020	8.0	Well.
		WATER FROM STREAMS			
White River	213420	Loc. 5, sec. 8, T.34N., R.48W., Dawes Co.	0.014	7.5	
White River	213427	Loc. 16, sec. 32, T.35N., R.47W., Dawes Co.	0.005	7.1	
Beaver Creek	219657	Loc. 15, sec. 35, T.35N., R.47W., Dawes Co.	0.009	7.7	

the Sharon Springs to average 0.104 ppm uranium in 6 samples, ranging from 0.007 to 0.300 ppm. Kepferle also reports water from the Niobrara formation to average 0.035 ppm uranium in 8 samples, ranging from 0.002 to 0.090 ppm, with the qualification that part of this uranium could have been derived from the overlying Sharon Springs member.

The origin of the uranium in the water in the Chadron area evidently is due to present day leaching. The subjects of shale-leach and ash-leach are discussed further on subsequent pages.

URANIUM IN SHARON SPRINGS MEMBER AND OTHER CRETACEOUS SHALE

Abundance of Uranium

The radioactivity of Cretaceous shale in the Chadron area is somewhat above background as shown by field surveys with radiation counters. The Sharon Springs member of the Pierre shale attracted attention during reconnaissance investigations (Tourtelot, 1956), and detailed investigations were therefore concentrated on the most radioactive part of the Sharon Springs member. Channel samples of this 30-foot zone were collected from 8 representative localities (fig. 22). Additional samples of the Sharon Springs member and of higher and lower Cretaceous shale were also collected. Radiometric analyses of the resulting 101 samples (Table 3) showed them to average 0.003 percent equivalent uranium. Chemical analyses were not made for 43 samples containing 0.003 percent or less equivalent uranium; the remaining 58 samples average 0.002 percent uranium. These values are comparable with those reported for 300 samples of the Sharon Springs

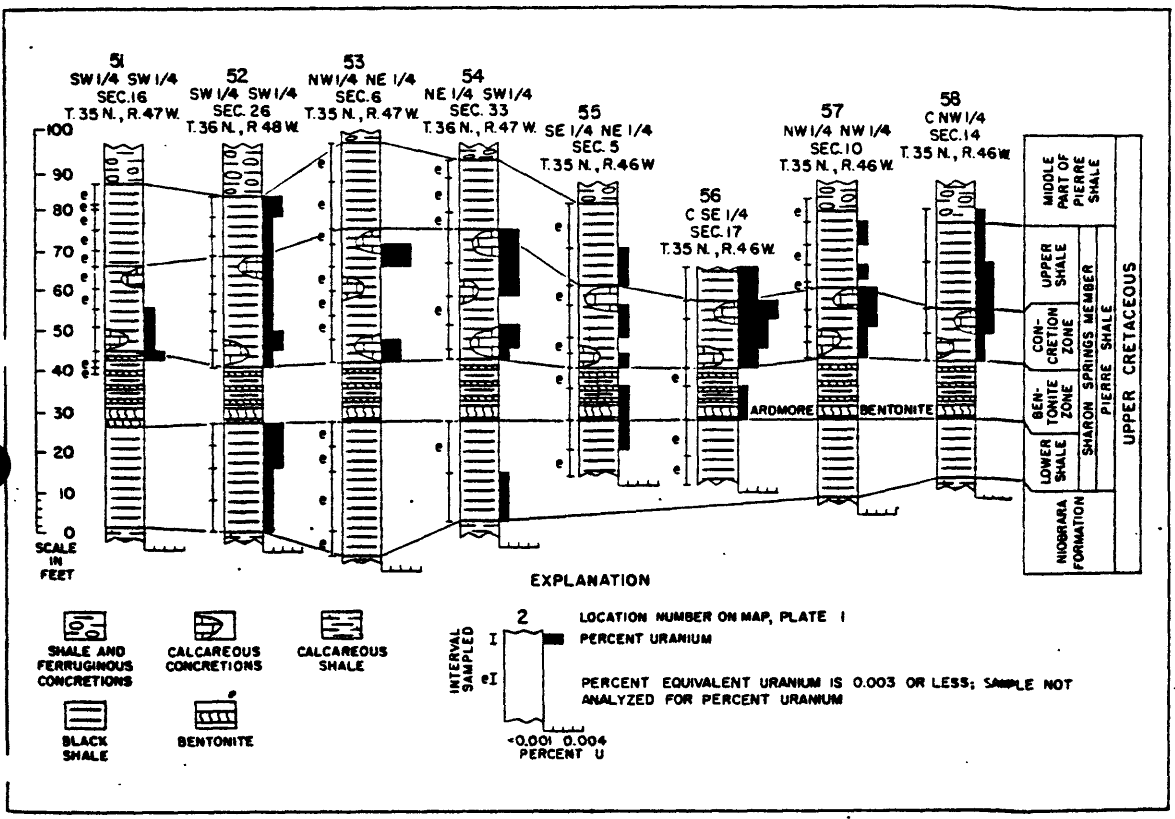


FIGURE 22.--Columnar sections of Sharon Springs member of Pierre shale showing uranium content in Shannon County, South Dakota.

[illegible] of Cretaceous shale in Dawes and Sheridan Counties, Nebraska, and Shannon County, South Da[illegible]a.

[Analysts: C. Angelo, H. Bivens, G. Daniels, R. Daywit, M. Finch, S. Furman, J. Goode, H. Lipp, B. A. McCall, J. McClure, T. Miller, R. Moore, J. Rosholt, J. Schuch, A. Sweeney, J. Wahlberg, J. Wilson]

Lithologic unit	Number and type of samples	Average (per cent) U	Average (per cent) eU	Median (per cent) U	Median (per cent) eU	Maximum (per cent) U	Maximum (per cent) eU
Pierre shale, above Sharon Springs member	3 grab	0.001	0.002	0.001	0.002	0.001	0.003
Sharon Springs member of Pierre shale, most radioactive part	35 channel (55 channel)*	0.002	0.003 (0.003)	0.002	0.003 (0.003)	0.005	0.007 (0.007)
Sharon Springs member of Pierre shale, other parts	13 channel (26 channel)	0.001	0.002 (0.002)	0.001	0.002 (0.002)	0.002	0.003 (0.003)
Niobrara formation, various parts of upper 180 feet	7 channel (18 channel)	0.003	0.005 (0.005)	0.003	0.003 (0.002)	0.007	0.008 (0.008)

*Data in parentheses include lower grade samples for which only eU percentage was determined.

members in South Dakota and northeastern Nebraska by Kepferle (1959, p. 585), who found uranium content to average about 0.0015 percent throughout the region studied, and with those reported for 123 samples of the Sharon Springs member in Kansas and 29 samples of the lower part of the Pierre shale in Colorado by Landis (1959, p. 316), who estimates uranium content to average about 0.001 percent.

Distribution of Uranium

Lateral Distribution

Uranium in Cretaceous shale is evenly distributed parallel to bedding. Uranium is not concentrated along joints. Appreciable consistent differences in lateral distribution were found in none of the stratigraphic units. Such differences were searched for in one unit, the Sharon Springs member of the Pierre shale, through its 100 square miles of outcrop. Although the unit thins eastward from 105 to 65 feet, percent uranium remains roughly constant.

Vertical Distribution

Different stratigraphic units contain different percentages of uranium, but the degree of difference is small.

As shown in the preceding table, the calcareous shale of the upper part of the Niobrara formation averages 0.003 percent uranium in 7 samples, the most radioactive third of the Sharon Springs member averages 0.002 percent uranium in 35 samples, the remainder of the Sharon

Springs member averages 0.001 percent uranium in 13 samples, and the Pierre shale above the Sharon Springs member averages 0.001 percent uranium in 3 samples. The Carlile shale and Belle Fourche shale were not analyzed, but radiometric surveys in the field indicate that they probably contain less than about 0.001 percent uranium. Limestone of the Niobrara and Greenhorn formations, which is notably deficient in radioactivity, probably contains considerably less than 0.001 percent uranium.

Vertical distribution of radioactivity in subsurface is indicated by gamma-ray logs, of which one is shown in Figure 23. Although radioactivity may be only a rough guide to uranium content, due to disequilibrium relationships discussed later, it is interesting that the upper part of the Niobrara foundation constitutes the main mass of relatively great radioactivity, which tends to confirm the results of surface sampling. That the upper part of the Niobrara formation is more uraniferous than the Sharon Springs member was not suspected in the field, and is contrary to generzl experience that black noncalcareous shale is more uraniferous than gray calcareous shale.

Whether the 20-foot zone of peak radioactivity at the top of the main radioactive sequence in the upper part of the Niobrara formation is in the Niobrara formation or in the Sharon Springs member is in doubt. Three wells supply information: the W. T. Oil Company Ormesher No. 2 (fig. 23), SW 1/4 NW 1/4 NW 1/4 sec. 8, T.34N, R.48W. (gamma ray log, samples); the Big Horn-Powder River Corporation Ormesher No. 1, NE 1/4 NE 1/4 SW 1/4 sec. 8, T.34N., R.48W. (gamma

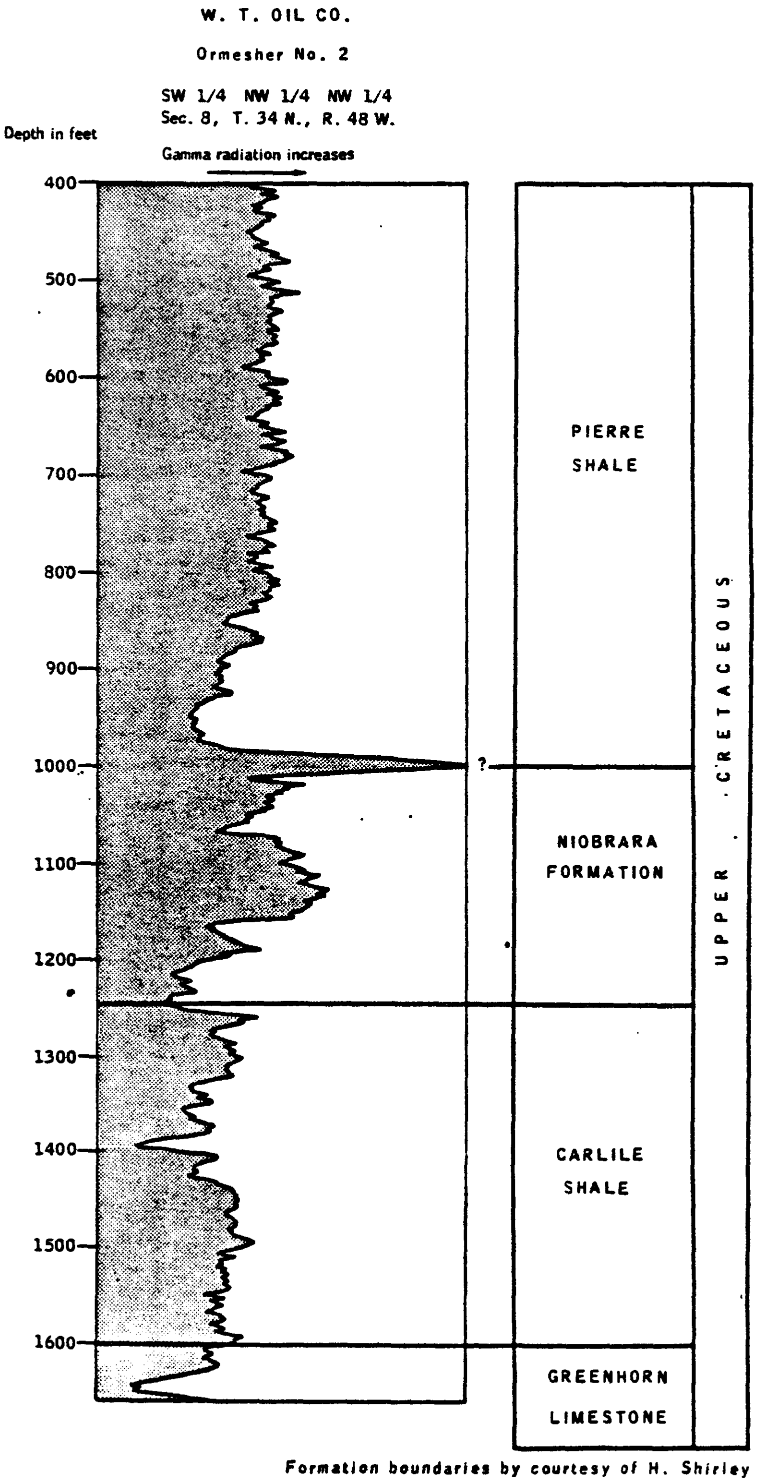


FIGURE 23.--Columnar section showing vertical distribution of radioactive beds of Late Cretaceous age.

ray log, electrical log); and its offset, the McRae Oil and Gas Company Ormesher No. 1, SW 1/4 SW 1/4 NE 1/4 sec. 8, T. 34N., R. 48W., (electrical log, samples).

The zone of peak radioactivity straddles the contact between the Sharon Springs member and Niobrara formations, according to examination of cable tool samples of the W. T. well and McRae well by Mr. Hal Shirley, consultant to the operators (oral communication, 1956); or lies 70 feet below the top of the Niobrara formation, according to examination of samples of the McRae well by Mr. Harold Hurst, stratigrapher for Shell Oil Company (written communication, 1961); or else lies 15 feet above the base of the Sharon Springs member, according to scout reports on file at Petroleum Information, Denver, Colorado. Which of these assignments is correct is unknown. Tourtelot (1956, p. 73) has shown that regionally the Sharon Springs member is conspicuously more radioactive than underlying and overlying Cretaceous rocks; and thus the Chadron area would be anamalous if peak radioactivity were in the Niobrara formation. Such anamalies, however, are known elsewhere; for example in Jackson County, South Dakota (Baker, 1953, p. 34, and gamma ray log), and possibly in Carson County, South Dakota, and Kidder and Ward Counties, North Dakota (Kepferle, 1959, Pl. 53).

Radioactive Disequilibrium

The equivalent uranium content of most samples of Cretaceous shale in the Chadron area is larger than the uranium content, the greater the uranium content, the less the degree of disequilibrium (fig. 24).

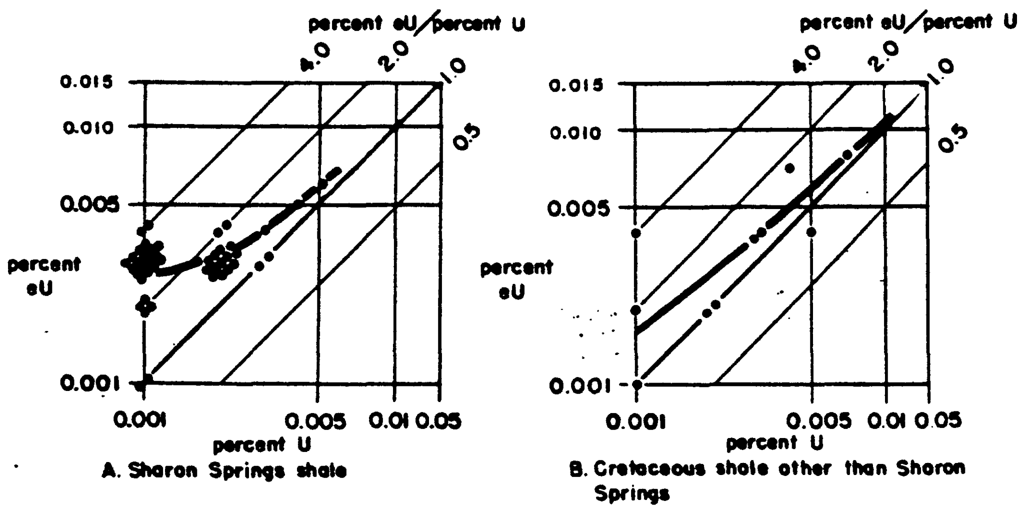


FIGURE 24.--Graphs showing percentage of uranium and equivalent uranium in Cretaceous shale.

Tourtelot (1956, p. 68) has suggested that the disequilibrium is due to modern weathering, uranium having been removed to leave a residual concentration of radioactive radium salts immobilized by sulfate from decomposing pyrite, and that the equivalent uranium content of weathered shale therefore may be representative of the uranium content of some unweathered shale. Water analyses show that uranium is now being removed from the shale. Although no residual concentrations of radium salts were recognized in the Chadron area, the water analyses support Tourtelot's hypothesis.

On the other hand, recent leaching alone does not readily account for the decrease of degree of disequilibrium with increasing uranium content. Also, no appreciable difference was detected between the disequilibrium of the few samples collected near the weathering surface and those collected from trenches a foot to 3 feet behind the weathering surface. It must be admitted that although the trench samples look fresh, they are not unweathered. Samples that probably are unweathered were collected from deep core holes by Roy C. Kepferle (written communication, 1955). His analyses of 17 Sharon Springs shale samples taken from the cores from the Irish Creek well in Ziebach Co., South Dakota and from a test hole at the Oahe dam site, Hughes Co., South Dakota are summarized in Table 4. Comparing these samples with the disequilibrium in the most radioactive part of the Sharon Springs member in the Chadron area indicates that the hypothesis of recent leaching does not explain all of the observed disequilibrium, although recent leaching is surely operative.

Table 4 -- Uranium content and radioactivity of subsurface cores of Cretaceous shale, Ziebach and Hughes Counties, South Dakota.

Lithologic Unit	Number and type of samples	Average (per cent)		Maximum (per cent)	
		U	eU	U	eU
Sharon Springs member of Pierre shale	17 selected	0.0018	0.0024	0.002	0.003

Form of Uranium

Uraniferous shale generally resists attempts to isolate and identify uranium minerals. None were identified in the Chadron area. Water analyses indicate that much of the uranium is in a form that is acid-soluble during weathering; the three water samples containing more than 0.3 parts per million uranium are more acid than pH 3.5.

Intimate association between uranium, pyrite, and organic matter would indicate that the uranium is in the low-valent form. Several observations attest to the association. Cretaceous shale contains uranium, pyrite, and organic matter, as described previously. The association seems intimate. One of the two samples containing the most uranium in the sequence consists of pyrite concretions from the Niobrara formation at locality 51, sec. 16, T.35N., R.47W.; it contains 0.007 percent uranium. The other consists of burned shale from the Sharon Springs member at locality 71, sec. 7, T.35N., R.46W., which presumably burned because of its abundant organic matter; it contains 0.005 percent uranium.

Kepferle (1959, p. 599) found a positive correlation coefficient of 0.36 between iron and uranium in a group of 82 samples of the Sharon Springs member, the iron being in the form of pyrite. In order to check quantitatively the association between uranium and organic matter in the Chadron area, special study was given a grab sample of the upper shale 7 feet below the top of the Sharon Springs member and a grab sample of calcareous shale 15 feet below the top of the Niobrara formation, both from locality 51, sec. 16, T.35N., R.47W. The Sharon Springs sample contains 0.0029 percent uranium. The Niobrara sample contains 0.0009 percent uranium. (Analyses are not included in Table 3). Both were treated according to the method described by Deul (1956), except that the middlings fraction was separated into its components. The samples were ground to colloidal size in a mixture of kerosene and water in a ball mill operated for 300 hours. In both cases, the result, probably a mixture of an impure organosol of organic matter in kerosene and an impure hydrosol of mineral matter in water, was an emulsion instead of a paste and slurry, and thus resembled Deul's carbonaceous shale in the Dakota sandstone instead of his Chattanooga shale. When separated, the emulsions yielded two very impure fractions: a dark colored organic concentrate, and a light colored mineral concentrate. Results of analyses for uranium and ash, shown in Table 5 show that uranium does tend to be associated with the organic fraction. The results quantitatively are less than satisfactory, inasmuch as both fractions of Sharon Springs shale contain less uranium than does the bulk sample. Evidently prolonged grinding caused part of the uranium to go into solution, and

Table 5 -- Uranium content of physically separated fractions of Cretaceous shale.

[Analyzed by Shell Development Company]

Sample	Ratio of organic fraction to mineral fraction, by weight	Uranium content (percent)	Ash (percent)
Sharon Springs	1.8	0.0029	80.8
Mineral fraction		0.0009	91.9
Organic fraction		0.0024	80.4
Niobrara	0.20	0.0009	82.7
Mineral fraction		0.0007	84.1
Organic fraction		0.0022	75.3

repeated washing removed the dissolved uranium.

Origin of Uranium

The uranium is distributed parallel to bedding planes; lack of concentrations on joints suggests that the uranium was emplaced early. Pyrite and organic matter, which are a clue to reducing environments, are associated with uranium in the Chadron area, as is true for uraniferous shale of other areas (Swanson, 1956, p. 453). Sulfate-reducing bacteria, which are expectable in reducing environments, produce hydrogen sulfide capable of localizing pyrite and uranium (Jensen, 1958). Organic matter of various kinds is known to be an avid collector of uranium (Breger and Deul, 1956). A likely explanation thus is that organic matter, alive or dead, directly or indirectly, concentrated uranium from sea water or from ascending compaction water during or soon after deposition of the shale.

URANIUM IN EOCENE(?) SOIL

Abundance of Uranium

The Eocene(?) soil averages 0.054 percent uranium in 43 samples, ranging from 0.0004 percent in the transformed zone to 1.12 percent in the boundary zone (Table 6). Percent uranium was not determined for 31 other samples containing 0.003 percent or less equivalent uranium. The uranium in the Eocene(?) soil is distributed extensively but sporadically through the area, occurring mostly in the upper part of the boundary zone in isolated remnants and pinnacles of gray shale. Remnants and pinnacles at 14 localities average

Table 6 -- Uranium content and radioactivity of Eocene(?) soil, Dawes and Sheridan Counties, Nebraska, and Shannon County, South Dakota.

Analysts: C. Angelo, H. Bivens, G. Daniels, R. Daywit, M. Finch, S. Furman, J. Goode, H. Lipp, B. A. McCall, J. McClure, T. Miller, R. Moore, J. Rosholt, J. Schuch, A. Sweeney, J. Wahlberg, J. Wilson.

Soil Zone	Laboratory Number	Location	Rock Type	Sample Type	Equivalent Uranium (percent)	Uranium (percent)	Remarks
			Soil developed on Carlile shale				
Transformed	138891	Loc. 26, sec. 11, T. 34N., R.47W., Dawes Co.	limonite	1-pint grab	0.006	0.007	Concretionary lense.
Boundary	138884	Loc. 27, sec. 15, T.34N., R.47W., Dawes Co.	gr. calc. sh.	1-pint grab	0.018	0.027	Upper part 5 x 1-ft. pinnacle. Average of 2 analyses
Boundary	138883	Loc. 27, sec. 15, T.34N., R.47W., Dawes Co.	gr. calc. sh.	1-pint grab	0.002	---	Lower part same pinnacle
			Soil developed on calcareous shale of the Niobrara formation				
Transformed	230107	Loc. 28, sec. 21, T.34N., R.47W., Dawes Co.	platy white clay	2.5-ft. channel	0.002	0.0005	
Transformed	230108	Loc. 28, sec. 21, T.34N., R.47W., Dawes Co.	white clay	2-ft channel	0.001	0.0004	
Transformed	230109	Loc. 28, sec. 21, T.34N., R.47W., Dawes Co.	yllw. and red limonitic clay	1-ft. channel	0.002	---	Heavily impregnated with limonite
Transformed	230110	Loc. 28, sec. 21, T.34N., R.47W., Dawes Co.	yllw. and red limonitic clay	2-ft channel	0.002	0.0010	
Transformed	230111	Loc. 28, sec. 21, T.34N., R47W., Dawes Co.	yllw. clay	3-ft. channel	0.001	0.0010	
Transformed	213475	Loc. 36, sec. 24, T.35N., R.46W., Sheridan Co.	yllw. clay	2.3-ft. channel	0.001	---	

Table 6 -- Uranium content and radioactivity of Eocene(?) soil, Dawes and Sheridan Counties, Nebraska, and Shannon County, South Dakota. (cont.)

Soil Zone	Laboratory Number	Location	Rock Type	Sample Type	Equivalent Uranium (percent)	Uranium (percent)	Remarks
Transformed	213474	Loc. 36, sec. 24, T.35N., R.46W., Sheridan Co.	red and yllw. clay	5-ft. channel	0.002	---	
Transformed	213430	Loc. 42, sec. 29, T.36N., R.46W., Shannon Co.	red and yllw. clay	6-ft. channel	0.002	---	
Transformed	213458	Loc. 43, sec. 30, T.36N., R.46W., Shannon Co.	yllw. clay	1-pint grab	0.002	---	
Transformed	213459	Loc. 43, sec. 30, T.36N., R.46W., Shannon Co.	red clay	1-pint grab	0.002	---	
Transformed	213461	Loc. 44, sec. 30, T.36N., R.46W., Shannon Co.	yllw. clay	1-pint grab	0.002	---	
Oxidized	230112	Loc. 28, sec. 21, T.34N., R.47W., Dawes Co.	yllw. calc. sh.	3-ft. channel	0.001	0.0004	
Oxidized	224032	Loc. 37, sec. 30, T.35N., R.46W., Sheridan Co.	yllw. calc. sh.	1-pint grab	0.004	0.004	
Oxidized	224031	Loc. 37, sec. 30, T.35N., R.46W., Sheridan Co.	yllw. calc. sh.	1-pint grab	0.003	0.002	
Oxidized	213443	Loc. 42, sec. 29, T.36N., R.46W., Shannon Co.	yllw. calc. sh.	1-ft. channel	0.002	---	
Oxidized	213442	Loc. 42, sec. 29, T.36N., R.46W., Shannon Co.	yllw. calc. sh.	2-ft. channel	0.003	---	
Oxidized	213441	Loc. 42, sec. 29, T.36N., R.46W., Shannon Co.	yllw. calc. sh.	5-ft. channel	0.003	---	
Oxidized	213440	Loc. 42, sec. 29, T.36N., R.46W., Shannon Co.	yllw. calc. sh.	5-ft. channel	0.002	---	

Table 6 -- Uranium content and radioactivity of Eocene (?) soil, Dawes and Sheridan Counties, Nebraska, and Shannon County, South Dakota. (cont.)

Soil Zone	Laboratory Number	Location	Rock Type	Sample Type	Equivalent Uranium (percent)	Uranium (percent)	Remarks
Oxidized	213439	Loc. 42, sec. 29, T.36N., R.46W., Shannon Co.	yllw. calc. sh.	2-ft. channel	0.002	---	
Oxidized	213438	Loc. 42, sec. 29, T.36N., R.46W., Shannon Co.	yllw. calc. sh.	1-ft. channel	0.003	---	
Oxidized	213437	Loc. 42, sec. 29, T.36N., R.46W., Shannon Co.	yllw. calc. sh.	1-ft. channel	0.003	---	
Oxidized	213436	Loc. 42, sec. 29, T.36N., R.46W., Shannon Co.	yllw. calc. sh.	1-ft. channel	0.003	---	
Oxidized	213435	Loc. 42, sec. 29, T.36N. R.46W., Shannon Co.	yllw. calc. sh.	1-ft. channel	0.002	---	
Oxidized	213434	Loc. 42, sec. 29, T.36N., R.46W., Shannon Co.	yllw. calc. sh.	1-ft. channel	0.002	---	
Oxidized	213433	Loc. 42, sec. 29, T.36N., R.46W., Shannon Co.	yllw. 2nd red calc. sh.	6-ft. channel	0.002	---	
Oxidized	213432	Loc. 42, sec. 29, T.36N., R.46W., Shannon Co.	yllw. 2nd red calc. sh.	10-ft. channel	0.001	---	
Oxidized	213431	Loc. 42, sec. 29, T.36N., R.46W., Shannon Co.	yllw. calc. sh.	10-ft. channel	0.001	---	
Oxidized	224022	Loc. 47, sec. 27, T.36N., R.47W., Shannon Co.	yllw. v. calc. sh.	1-pint grab	0.003	0.001	
Boundary	138889	Loc. 28, sec. 21, T.34N., R.47W., Dawes Co.	gr. calc. sh.	1-pint grab	0.020	0.007	Upper part 6 x 2 ft. pinnacle, average of 3 analyses

Table 6 -- Uranium content and radioactivity of Eocene(?) soil, Dawes and Sheridan Counties, Nebraska, and Shannon County, South Dakota. (cont.)

Soil Zone	Laboratory Number	Location	Rock Type	Sample Type	Equivalent Uranium (percent)	Uranium (percent)	Remarks
Boundary	138888	Loc. 28, sec. 21, T.34N. R.47W., Dawes Co.	gr. calc. sh.	1-pint grab	0.004	0.003	Upper part of nearby lower pinnacle
Boundary	213410	Loc.34, sec. 2, T.35N., R.46W., Shannon Co.	gr. calc. sh.	1.5-ft. channel	0.003	0.001	1.5 x 2-ft. remnant
Boundary	138965	Loc. 35, sec. 3, T.35N., R.46W., Shannon Co.	gr. calc. sh.	2-ft. channel	0.051	0.058	2 x 4-ft. remnant
Boundary	224022	Loc. 36, sec. 24, T.35N., R.46W., Sheridan Co.	yllw. calc. sh.	2-ft. channel	0.003	0.001	
Boundary	213484	Loc. 36, sec. 24, T.35N., R.46W., Sheridan Co.	limonite	0.1-ft. channel	0.003	---	
Boundary	213483	Loc. 36, sec. 24, T.35N., R.46W., Sheridan Co.	yllw. calc. sh.	1-ft. channel	0.003	---	
Boundary	213482	Loc. 36, sec. 24, T.35N., R.46W., Sheridan Co.	gr. calc. sh.	1-ft. channel	0.003	---	
Boundary	213481	Loc. 36, sec. 24, T.35N., R.46W., Sheridan Co.	yllw. calc. sh.	0.7-ft. channel	0.006	0.0032	
Boundary	213479	Loc. 36, sec. 24, T.35N., R.46W., Sheridan Co.	gr. calc. sh., low	0.2-ft. channel	0.018	0.005	Lower part, 0.3 x 1.5-ft. remnant
Boundary	213480	Loc. 36, sec. 24, T.35N., R.46W., Sheridan Co.	gr. calc. sh., high	0.2-ft. channel	0.12	0.042	Upper part same remnant, average of 3 analyses
Boundary	213478	Loc. 36, sec. 24, T.35N., R.46W., Sheridan Co.	yllw. calc. sh.	3-ft. channel	0.002	---	

Table 6 -- Uranium content and radioactivity of Eocene(?) soil, Dawes and Sheridan Counties, Nebraska, and Shannon County, South Dakota. (cont.)

Soil Zone	Laboratory Number	Location	Rock Type	Sample Type	Equivalent Uranium (percent)	Uranium (percent)	Remarks
Boundary	213477	Loc. 36, sec. 24, T.35N., R.46W., Sheridan Co.	yllw. calc. sh.	3-ft. channel	0.001	---	
Boundary	213476	Loc. 36, sec. 24, T.35N., R.46W., Sheridan Co.	yllw. calc. sh.	2-ft. channel	0.001	---	
Boundary	223617	Loc. 37, sec. 30, T.35N., R.46W., Sheridan Co.	gr. calc. sh., high	1-cc	0.59	0.72	Outer rind of 0.3 x 1.5-ft. remnant
Boundary	224040-B	Loc. 37, sec. 30, T.35N., R.46W., Sheridan Co.	gr. calc. sh., high	1-cc	0.035	0.028	Core of same remnant
Boundary	224040-A	Loc. 37, sec. 30, T.35N., R.46W., Sheridan Co.	gr. calc. sh., high	0.3-ft. channel	0.061	0.026	Same remnant
Boundary	224033	Loc. 37, sec. 30, T.35N., R.46W., Sheridan Co.	gr. calc. sh., high	1-pint grab	0.037	0.027	Nearby 1 x 5-ft. remnant, upper part
Boundary	224034	Loc. 37, sec. 30, T.35N., R.46W., Sheridan Co.	gr. calc. sh., high	1-pint grab	0.011	0.016	Middle part same remnant
Boundary	224035	Loc. 37, sec. 30, T.35N., R.46W., Sheridan Co.	gr. calc. sh.	1-pint grab	0.009	0.012	Lower part same remnant
Boundary	224041	Loc. 37, sec. 30, T.35N., R.46W., Sheridan Co.	gr. calc. sh.	1-pint grab	0.022	0.012	East part same remnant, average of 2 analyses
Boundary	224039	Loc. 37, sec. 30, T.35N., R.46W., Sheridan Co.	gr. calc. sh.	1-pint grab	0.055	0.024	West part same remnant, average of 2 analyses
Boundary	224047	Loc. 37, sec. 30, T.35N., R.46W., Sheridan Co.	gr. calc. sh.	1-pint grab	0.016	0.019	Nearby 2.5 x 8-ft. remnant, upper part

Table 6 -- Uranium content and radioactivity of Eocene(?) soil, Dawes and Sheridan Counties, Nebraska, and Shannon County, South Dakota. (cont.)

Soil Zone	Laboratory Number	Location	Rock Type	Sample Type	Equivalent Uranium (percent)	Uranium (percent)	Remarks
Boundary	224036	Loc. 37, sec. 30, T.35N., R.46W., Sheridan Co.	yllw. calc. sh.	1-pint grab	0.004	0.003	0.5-ft. Beneath same remnant
Boundary	224042	Loc. 37, sec. 30, T.35N., R.46W., Sheridan Co.	gr. calc. sh.	1-pint grab	0.008	0.006	Upper part main gr. sh. where overlying remnants are absent
Boundary	138906, 227654	Loc. 49, sec. 28, T.36N., R.46W., Shannon Co.	gr. calc. sh.	0.2-ft. channel	0.47	1.12	0.2 x 2-ft. Remnant, average of 3 analyses
Boundary	138908	Loc. 49, sec. 28, T.36N., R.46W., Shannon Co.	yllw. calc. sh.	0.5-ft. channel	0.039	0.063	Laterally adjacent to same remnant, average of 2 analyses
Boundary	138907	Loc. 49, sec. 28, T.36N., R.46W., Shannon Co.	gr. calc. sh.	0.3-ft. channel	0.003	0.006	Adjacent remnant, similar except weakly radioactive
Boundary	138909	Loc. 49, sec. 28, T.36N., R.46W., Shannon Co.	yllw. calc. sh.	0.5-ft. channel	0.002	0.003	Laterally adjacent to same remnant
Boundary	213445	Loc. 42, sec. 29, T.36N., R.46W., Shannon Co.	gr. calc. sh.	0.5-ft. channel	0.002	0.0020	0.5 x 3-ft. Remnant beneath a higher remnant
Boundary	213444	Loc. 42, sec. 29, T.36N., R.46W., Shannon Co.	gr. calc. sh.	1-ft. channel	0.006	0.003	1 x 2-ft. Remnant
Boundary	213411	Loc. 39, sec. 35, T.36N., R.46W., Shannon Co.	gr. calc. sh.	1-ft. channel	0.083	0.010	1 x 10 x 30-ft. Remnant
Boundary	230106	Loc. 50, sec. 35, T.36N., R.46W., Shannon Co.	gr. calc. sh.	1-pint grab	0.006	---	0.5 x 3-ft. Remnant
Boundary	230105	Loc. 50, sec. 35, T.36N., R.46W., Shannon Co.	yllw. calc. sh.	1-pint grab	0.004	---	Laterally adjacent to same remnant

Table 6 -- Uranium content and radioactivity of Eocene(?) soil, Dawes and Sheridan Counties, Nebraska, and Shannon County, South Dakota. (cont.)

Soil Zone	Laboratory Number	Location	Rock Type	Sample Type	Equivalent Uranium (percent)	Uranium (percent)	Remarks
		Soil developed on Sharon Springs member of Pierre shale					
Boundary	224057	Loc. 33, sec. 16, T.35N., R.45W., Shannon Co.	dk. gr. sh.	0.2-ft. channel	0.050	0.020	0.2 x 1-ft. Poorly defined remnant, average of 2 analyses
		Soil developed on middle part of Pierre shale					
Boundary	138911	Loc. 45, sec. 12, T.35N., R.46W., Shannon Co.	gr. sh.	1-pint grab	0.004	0.005	Zone poorly defined
Boundary	138910	Loc. 45, sec. 12, T.35N., R.46W., Shannon Co.	red sh.	1-pint grab	0.002	0.002	
Boundary	224043	Loc. 38, sec. 31, T.35N., R.47W., Dawes Co.	gr. sh. flecked with red	2-ft. channel	0.024	0.023	Poorly defined 2 x 5-ft. remnant
		Soil developed on upper part of Pierre shale					
Oxidized	138885	Loc. 7, sec. 25, T.34N., R.48W., Dawes Co.	yllw. sh.	2-ft. channel	0.002	---	
Oxidized	138894	Loc. 31, sec. 36, T.34N., R.49W., Dawes Co.	greenish white shale	1-pint grab	0.005	0.002	Bleached beneath Oligocene channel-fill
Boundary	138887	Loc. 7, sec. 25, T.34N., R.48W., Dawes Co.	gr. sh.	1-ft. channel	0.010	0.013	1 x 2-ft. Remnant
Boundary	138886	Loc. 7, sec. 25, T.34N., R.48W., Dawes Co.	yllw. sh.	2-ft. channel	0.002	---	Yllw. sh. next below same remnant
Boundary	213412	Loc. 29, sec. 36, T.35N., R.48W., Dawes Co.	gr. sh.	1-ft. channel	0.012	0.003	1 x 1.5-ft. Remnant

0.083 percent uranium in 27 samples. Most of the samples contain on the order of 0.01 percent, the median being 0.012 percent; some contain 0.1 percent, and one contains 1.0 percent. The volume of individual enriched masses is generally less than ten cubic feet. At a few places uranium occurs in iron oxide concretions in the transformed and oxidized zones or in carbonate-apatite fish remains in the boundary zone.

Distribution of Uranium

Lateral Distribution

Throughout most of the Chadron area the upper part of the boundary zone contains concentrations of uranium. Lateral variation is related mainly to parent rock.

Relationship to Parent Rock

The concentrations of uranium are richest and most numerous where the Eocene(?) soil is developed on parent rock of calcareous shale in the Niobrara formation, but they occur in every mapped stratigraphic unit made into ancient soil and in every type of bedrock except chalk. Maxima observed, mostly as channel samples through remnants, are 0.027 percent uranium in the Carlile shale, 1.12 percent in the Niobrara formation, 0.019 in the Sharon Springs member, 0.023 in the middle part of Pierre shale, and 0.013 in the upper part of the Pierre shale.

Relationship to Structural Position

Structure seems to have played no direct role in localizing uranium concentrations. The areal distribution of sites of enrichment does not coincide with any preferred structural position. Nor is there any sign of lineation such as would be expected from fault control. On the other hand, the richest remnant in the area occurs at locality 49, sec. 28, T.36N., R.46W., near the one large fault in the area; yet nowhere else along the length of the fault is there another site of great enrichment.

Relationship to Zones of Permeability

Uranium elsewhere is commonly localized along zones of permeability; for example, in the areas of uraniferous lignite described by Denson and Gill (1956). A direct relationship between concentrations of uranium in the Eocene(?) soil and zones of permeability would be genetically significant.

Porosity and permeability of Eocene(?) soil.--From his reconnaissance in the Chadron area, Tourtelot (1956, p. 82) reports that "the altered zone is more porous and permeable than unaltered shale", which implies that the Eocene(?) soil is a relatively porous and permeable zone. Tourtelot does not say what evidence led him to this opinion, unless it be that oxidation locally reaches deepest along joints.

First to consider porosity. It will be recalled that laboratory measurements on three samples showed effective porosity to be 19.1 percent in the upper part of the transformed zone, 22.7 percent in the lower part of the transformed zone, and 36.1 percent in bedrock shale of the Niobrara formation. The sample of bedrock shale is probably representative, because its porosity is in the range of 23.8 to 37.6 percent measured by Rubey (1930) on 9 samples of Cretaceous shale in the Black Hills. The two samples of the claystone of the transformed zone are sufficiently alike to indicate that they, too, are representative. Because porosity shows a vertical trend, decreasing as the degree of alteration increases, it seems that loss of porosity and soil-making are genetically related. Samples small enough to fit in the measuring device cannot adequately represent the whole of a rock body, but the error in porosity from such things as joints is slight. Additional series of analyses are needed for certainty, but the quantitative evidence now available seems to indicate that the ancient soil is less instead of more porous than the bedrock shale.

Laboratory measurements of permeability are more subject to error. It will be recalled that measurements made on the three samples show each to be almost impermeable, the bedrock shale having a permeability to air of 1.0 millidarcies and the claystone of the transformed zone having less than 0.1 millidarcies. In masses small enough to measure, the soil is thus less permeable than its bedrock, perhaps more than 10 times less. In nature, however, the presence of joints would make both the soil and its bedrock more permeable. Joints are definitely present in the bedrock shale. Joints are present also in the boundary zone of the soil; as noted by Tourtelot, oxidation locally extends deepest along joints. The prominence given joints in the boundary zone by this phenomenon tends to make one overlook the equally numerous joints in the bedrock. Joints also are present in the oxidized zone, where they are commonly impregnated by limonite. In contrast, the transformed zone lacks joints, just as it lacks shaly bedding. Such compact cohesive claystone impresses one as a better barrier than conduit. Nowhere in the Chadron area does the ancient soil provide water for wells or springs; although it does serve as a clay bottom stock tank.

The scant quantitative evidence presented above, plus visual estimates made in the field during the present investigations, fail to confirm the existence of a direct relationship between uranium and relative porosity or permeability.

Permeable Oligocene rocks.--Oligocene rocks in contact with the ancient soil are practically impermeable throughout most of the area. Exceptions are where conglomeratic sandstone of the sandstone-red claystone of the Chadron formation is in contact with the soil. If there were an association between uranium distribution and zones of permeability, the association might well be evident there.

The oxidized zone is bleached from yellow-orange to greenish-white, and is impregnated with powdery jarosite thought formed by modern decomposition of pyrite deposited during bleaching, at its contact with permeable Oligocene sandstone at locality 31, sec. 36, T.34N., R.49W. Bleaching, and deposition of pyrite record the passage of Oligocene or later groundwater. A sample of the oxidized zone at the contact was analyzed in hopes of finding uranium related to a known zone of permeability. The analysis shows only 0.002 percent uranium. Much richer concentrations of uranium occur where the soil is overlain by, impermeable green claystone. The available evidence thus indicates no relationship between uranium and zones of permeability.

Vertical Distribution

Uranium content of the Eocene(?) soil shows a profile (fig. 25). Compared to parent rock, the transformed zone and the upper part of the oxidized zone are depleted in uranium, and the boundary zone is locally enriched.

Gross Distribution

The top-preferential nature of the uranium concentrations in the boundary zone is striking. To illustrate, on any vertical line where the Eocene(?) soil exhibits enrichment of uranium, the highest part of the gray shale in the boundary zone contains the highest percentage of uranium. Where several isolated remnants occur one above the other (fig. 26), the top remnant contains a higher percentage than any lower remnant. Furthermore, the top of an isolated individual enriched remnant contains a higher percentage than the bottom. In a typical exposure there may be ten places where the top of one isolated remnant or pinnacle is clearly higher than its immediate neighbors; when we compare the "high" remnants with one another, the top preferential distribution is again shown, for notable enrichment is restricted to the highest of the high remnants at each exposure. Joints seem to have

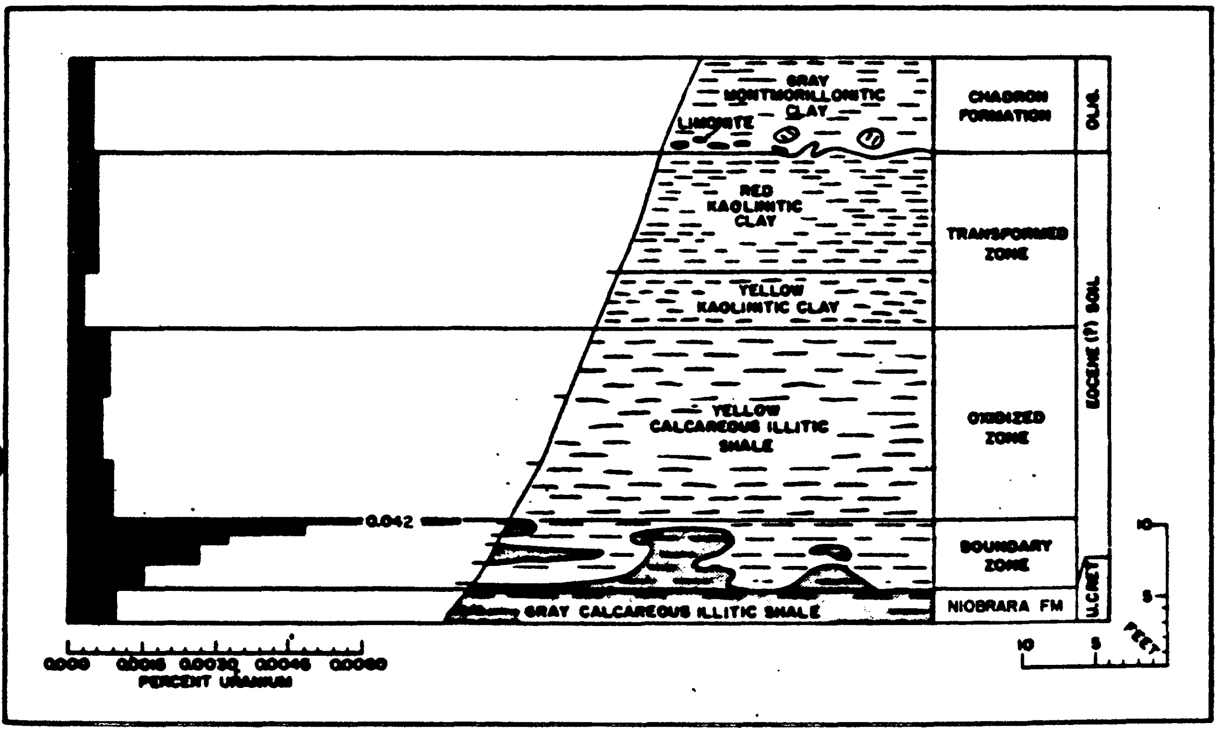


FIGURE 25.--Columnar section showing uranium content of rocks exposed at locality 36, sec. 24, T.35N., R.46W., Sheridan County, Nebraska.

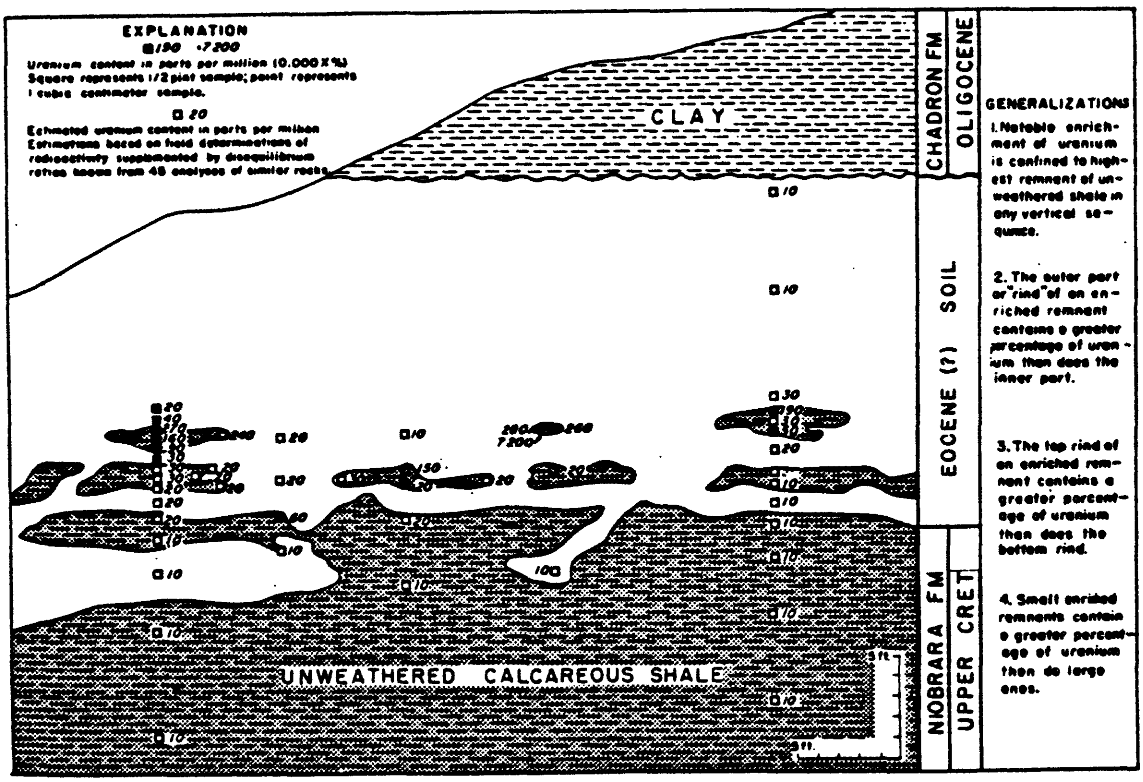


FIGURE 26.--Field sketch showing top preferential distribution typical of uranium associated with Eocene(?) soil, locality 37, sec. 30, T.35N., R.46W., Sheridan County, Nebraska.

exerted no control over the localization of uranium. If the uranium were related to passage of water through joints, the sides of remnants near joints should be richest in uranium. Such side-preferential distribution was not found.

Fine-Scale Distribution

Most of the samples on which this study is based are 2-inch to 6-foot channel samples having a volume of one pint, which were collected in order to evaluate the commercial possibilities of the uranium in the boundary zone. Near the end of the field season, autoradiographs revealed that analyses of pint samples provide a distorted view of the precise distribution of uranium. The distortion lies in greatly subduing the maxima of greatest enrichment, for such maxima occur in laterally restricted intervals too thin to supply a pint sample. Therefore, it is necessary to distinguish gross distribution shown by pint samples from fine-scale distribution shown by one-cubic centimeter samples.

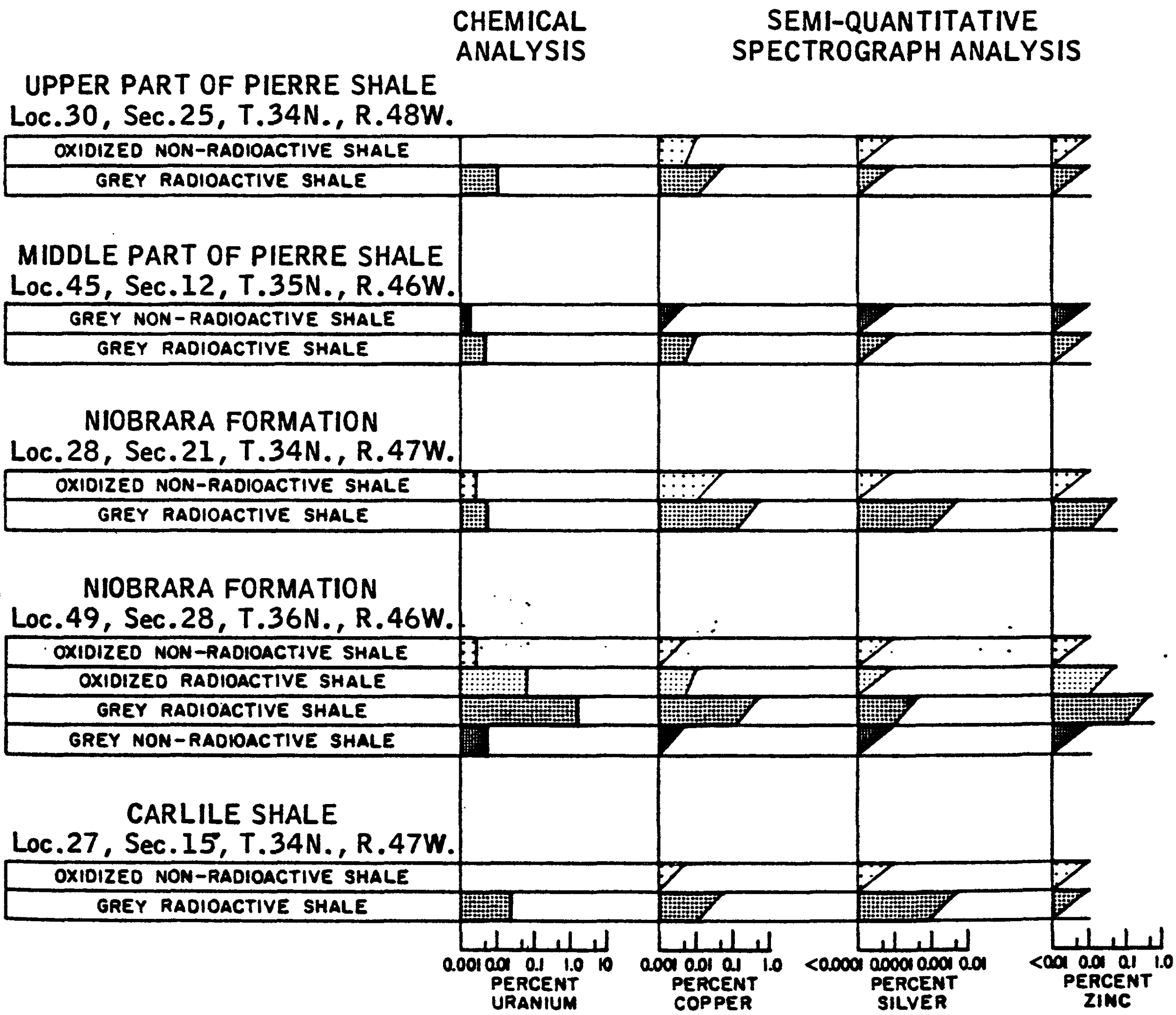
One 5-by 18-inch ellipsoidal remnant of Niobrara shale from locality 37, sec. 31, T.35N., R.46W., was collected nearly whole with the associated yellow oxidized material attached. A 1-pint channel sample of the remnant, collected earlier, contains 0.026 percent U. This specimen was sliced and exposed to film for ten days. The resulting autoradiograph shows radioactivity to be concentrated mainly in a half-inch rind in the outer inch of the gray shale and concentrated more abundantly in the upper part of the remnant than in the lower part of the remnant. J. N. Rosholt analyzed one-cubic centimeter samples from the rind and from the core. The rind contains 0.72 percent uranium, whereas the core contains 0.028 percent uranium. Pint samples of different parts of larger remnants were collected at the same locality (fig. 26), and analyzed. This less sensitive method corroborates the rind and core pattern of distribution. The outer part of each remnant sampled contains a greater percentage of uranium than the inner part, and the upper part contains a greater percentage than the lower part or the side parts. Autoradiographs of other remnants show the same distribution.

Association with Copper, Silver, and Zinc

Copper, silver, and zinc concentrations occur in the boundary zone in the same isolated remnants and pinnacles in which uranium is concentrated. Paired samples from oxidized and unoxidized parts of the boundary zone developed on the Carlile, Niobrara, and Pierre formations were analyzed spectrographically with the results shown in Figure 27.

Form of Uranium in the Boundary Zone

A heavy black magnetic concentrate was obtained from the sample that analyzed 1.12 percent uranium (locality 49). Radiometric analysis by J. N. Rosholt showed that the concentrate contains more than 10 percent equivalent uranium. As seen under the microscope, the concentrate consists of 75-micron aggregates of organic matter and spherulitic or framboidal (Bastin, 1951, p. 30) pyrite, with minor inclusions of calcite, barite(?) and clay. The framboidal pyrite is strikingly similar to



NOTE: Semi-quantitative spectrographic analyses are reported as bracketed values; for example, 0.01-0.05. The bar graphs are therefore closed with lines that slant across the width of the applicable bracket.

FIGURE 27.--Bar graphs of paired samples from the boundary zone of the Eocene(?) soil showing content of uranium, copper, silver, and zinc.

to that from which Love (1958) described hydrogen sulfide-producing anerobes, Pyritosphaera barbaria. Similarity is in size as well as structure. Those described by Love average 7.5 microns, ranging from 2 to 30 microns, some samples having less range; those in the Chadron area average about 6 microns, ranging from about 1 to about 18 microns. Similar aggregates of organic matter and framboidal pyrite with inclusions constitute concentrates from the rind of the remnant from which 1-cubic centimeter samples were analyzed by Rosholt (locality 37).

The aggregates sink in bromoform, do not fluoresce in ultraviolet light, and are sufficiently magnetic to adhere to an iron magnet. Optically similar aggregates of organic matter and framboidal pyrite occur in microscopic lenticles of organic matter in the rind of a polished section cut to transect the margin of the undisturbed remnant. Yellow oxidized shale just outside the margin differs from the rind in that the lenticles of organic matter are absent and the pyrite is largely altered to limonite.

X-Ray Patterns

Repeated attempts to identify the mineralogic form of the uranium in the concentrates by X-ray analysis failed. Powder camera patterns of the concentrated rind and of the concentrated richest sample show no sign of uranium minerals, according to W. F. Outerbridge and A. V. Gude, III. X-ray diffractometer patterns of the concentrated rind by Shell Development Company correspond to pyrite and minor clay, quartz, and calcite.

Alpha Tracks

Nuclear stripping film shows very dense alpha radiation from each of the aggregates in the concentrate after ten days exposure. The alpha tracks do not seem to be localized over particular parts of the aggregates, and ratio of pyrite to organic matter in individual aggregates does not correlate with intensity of radiation. According to L. B. Riley (oral communication, 1955) the density of alpha radiation is greater than that shown by carnotite and other 6-valent minerals, and is indicative of a black uranium mineral, such as uraninite.

Inhomogeneity

Some samples from the boundary zone were chemically analyzed two or more times, a different 10-gram split being used each time. The different splits in six cases gave surprisingly different results. For example, the richest sample from locality 26, sec. 24, T.35N., R.46W. was analyzed to 3-place precision once and to 4-place precision twice by D. L. Skinner with results ranging from 0.037 percent to 0.0445 percent uranium; and the rich sample from locality 49 assayed 1.10 and 1.20 percent uranium in different splits of 1 sample and 1.07 in a second sample. The standard assay technique of grinding and splitting, which was used for all samples from the Chadron area, is ordinarily capable of distributing elements much more uniformly. Skinner (oral communication, 1955) observed that in a sample containing unevenly distributed minute particles of very high grade, it is impossible to obtain uniform splitting. The unevenness of splits indicates that the uranium is present in the form of minute particles of very high-grade material.

Spectrographic Analysis

The concentrate containing more than 10 percent equivalent uranium (locality 49) was analyzed by the semiquantative spectrographic method, with the results shown in Table 7.

Conclusion as to Mineralogic Form

Failure to identify a uranium mineral visually or by X-ray technique indicates that either the uranium is not in mineral form, probably being sorbed by organic matter, or that it is in mineral form but the crystals are too small to be seen with the light microscope and too small and disordered to produce diagnostic X-ray reflections. The latter alternative is here subscribed to tentatively. Reasons for doing so are three:

1.) It is quite possible for the uranium to be in the crystalline form without being recognized, because the aggregates contain considerable copper and zinc plus enough magnetite or other magnetic mineral to adhere to a magnet without these minerals being recognized optically or by X-ray technique. The abundance of copper and zinc could be due to sorbtion by organic matter, but magnetism is a crystal property.

2.) The density of alpha tracks on nuclear stripping film, the difficulty in homogenizing samples, and the richness of concentrates indicate the presence of specks of matter very rich in uranium.

3.) The specks are probably uranium minerals, because organic matter containing uranium in the noncrystalline form is characteristically of low grade compared to minerals in which uranium is an essential element. Uraniferous coal containing adsorbed uranium or urano-organic compounds, but lacking uranium minerals, has not been found richer than 0.1 percent uranium, according to Vine (1956, p. 408). Uranium-rich concentrates of coal obtained by Breger, Deul, and Rubinstein (1955, p. 210) contain less than 0.1 percent uranium.

If the alternative of a discrete uranium mineral is reasonable, the question arises as to whether a uranium mineral having the required properties is known. Uraninite has the required properties. It is commonly associated with organic matter and pyrite, and contains as much as 90 percent U_3O_8 (Frondel, 1958, p. 19). It does not fluoresce in ultraviolet light, is black, and is strongly radioactive.

Other uranium minerals also satisfy some or all of these requirements, but the spectrographic analysis eliminates most of these. To illustrate, Frondel (1958, p. 353-360) lists 47 uranium minerals that are not fluorescent. Fourteen can be eliminated because phosphorous, arsenic, thorium, and bismuth were looked for but not detected in the sample, and are essential elements in the minerals in question. One, kasolite, can be eliminated because the sample contains far too little lead to satisfy the requirements imposed by uranium. Twelve can be eliminated because the sample is similarly deficient in molybdenum, vanadium, nickel, tantalum, and titanium. Fourteen can be eliminated because concentrates show no sign of yellow, orange, red, or green. The remaining five are uraninite, ideally UO_2, actually $(U^{+4}_{1-x} U^{+6}_{x}) O_{2+x}$; coffinite, $U(SiO_4)_{1-x}(OH)_{4x}$; clarkeite, (Na, K, Ca, Pb) $U_2O_7 \cdot n H_2O$; ianthinite, $2UO_2 \cdot 7H_2O$ (?); richetite, hydrated oxide of U and Pb (?); and vandenbrandeite, Cu (UO_2) $O_2 \cdot 2H_2O$. Of these, uraninite seems the best fit, because it is relatively common, because Frondel (1958, p. 35) reports, "The high radioactivity of uraninite is a characteristic and often convenient diagnostic feature", and lastly, because uraninite may consist of crystallites too small and disordered to produce an identifiable X-ray pattern, as shown by artificial uraninite made at room temperature and by some natural uraninite from Hummelfurst, Saxony (Croft, 1954), and from Lake Athabaska, Canada (Brooker and Nuffield, 1952).

Radioactive Disequilibrium

Most of the analyzed samples of Eocene(?) soil do not contain the abundance of uranium expected from their radioactivity, assuming equilibrium between uranium and its radioactive decay products (fig. 28). About as many are out of balance in favor of uranium as are out of balance in favor of equivalent uranium (radioactivity). Modern weathering probably causes the disequilibrium, but not in a simple manner.

Four samples of Eocene(?) soil developed on Niobrara calcareous shale were submitted to J. N. Rosholt, Jr., for detailed disequilibrium analysis. His results are shown graphically in Figure 29, and are tabulated in a separate publication (Rosholt, 1959, p. 25-26). Content of uranium was chemically determined and is expressed in terms of percent. Content of thorium 230, protoactinium

Table 7 -- Elements detected by semiquantitative analysis of heavy concentrate from isolated remnant of gray shale in Eocene(?) soil developed on Niobrara formation, locality 49, sec. 28, T. 36 N., R. 46 W., Shannon County, South Dakota

[Analyst: R. G. Havens]

Laboratory No. 227771[1]

Element[2]	Percent	Element	Percent
Fe	XX.	V	0.0X+
U	X.+	Mn	0.0X
Al	X.+	Mo	0.0X
Ca	X.	Ni	0.0X
Ba	X.-	Ag	0.0X-
Zn	X.-	Co	0.0X-
Cu	0.X+	Cr	0.0X-
Mg	0.X+	Y	0.0X-
Pb	0.X	Sn	0.00X+
Ti	0.X		
Sb	0.X-		
Sr	0.X-		
Zr	0.X-		

1. Usual sensitivities not attained; sample diluted 1:3.64.

2. Looked for but not detected: P, K, As, Au, B, Be, Bi, Cd, Ce, Dy, Er, Ga, Gd, Ge, Hf, Hg, In, Ir, La, Li, Nb, Nd, Os, Pd, Pt, Rh, Ru, Sc, Sm, Ta, Th, Tl, Te, and W.

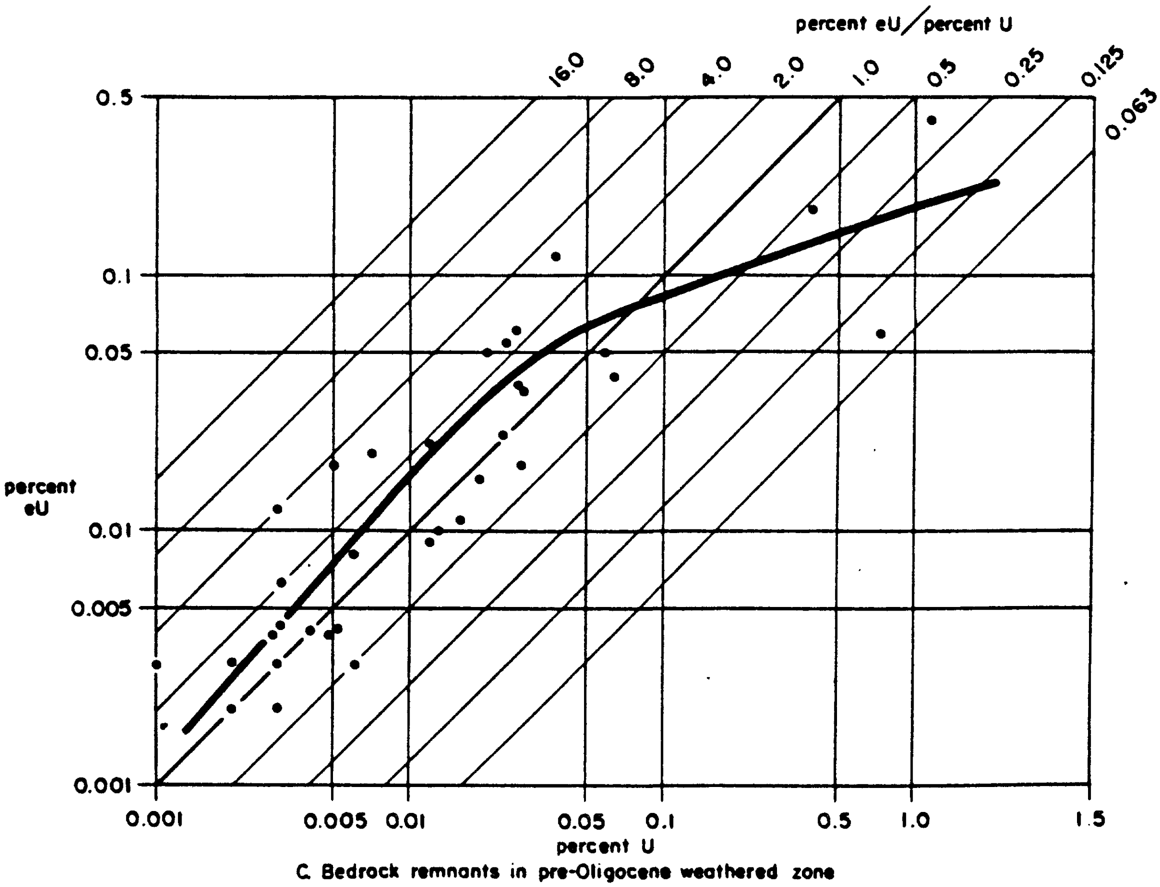


FIGURE 28.--Graph showing percentage of uranium and equivalent uranium in gray shale remnants in Eocene(?) soil.

231, radium 226, radon 222, and lead 210 was determined by alpha-particle measurement, and is expressed in terms of percent equivalent. Percent equivalent uranium was determined by routine analysis, which may give anomalously low results, as discussed by Rosholt (1959, p. 6). The upper left part of Figure 29 illustrates an imagined sample containing 0.06 percent uranium in equilibrium with its daughter products.

Analysis of a channel sample of the richest remnant in the area (locality 49) is shown in the lower left of Figure 29, labeled "channel of A". The disequilibrium pattern is characterized by daughter-product deficiency and equivalent radium 226 considerably less than equivalent thorium 230, which is the rather short-lived (80,000-year half-life) parent of radium 226. Rosholt reasons (1959, p. 10) that disequilibrium of this type is due to preferentially greater leaching of daughter products than of uranium, instead of to recent deposition of uranium. Because radium 226 is "the most common, and, in most samples of this type, the only long-lived daughter product which can be leached", the deficiency in radioactivity is probably due, at least in large part, to leaching of radium. Why radium should be leached is unknown; on a priori grounds one would expect with Tourtelot (1956, p. 81) that radium would be immobilized by the sulfate produced by decomposing pyrite, and that radioactivity would be a clue to the amount of uranium present before modern weathering.

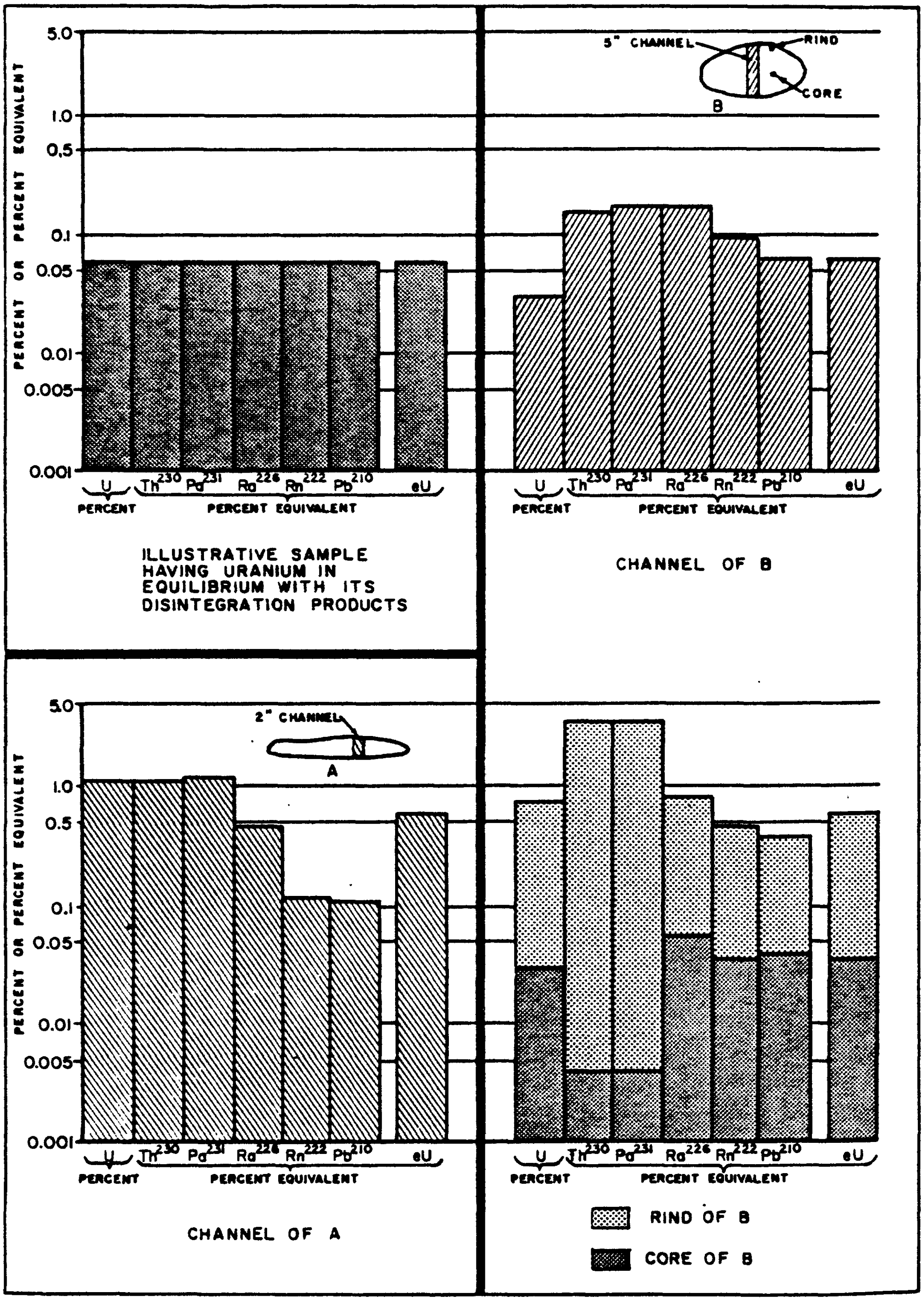


FIGURE 29.--Bar graphs showing content of uranium and its decay products in remnants of Niobrara shale in Eocene(?) soil.

Analysis of a channel sample of a second remnant (locality 37), illustrated in the upper right of Figure 29 and labeled channel of B, shows a quite different disequilibrium pattern. This pattern is characterized by excess radium 226 compared to relatively low uranium content. Rosholt (1959, p. 12) suggests that in general "disequilibrium of this type, found in samples taken from an oxidized environment, is the result of leaching of uranium". Leaching of uranium fits with the field evidence, because the samples were collected from the oxidizing environment, and because seeps from similar dark pyrite-bearing uraniferous shale contain an abundance of dissolved uranium.

Separate samples of the same remnant, one from the rind and one from the center, or core, were also analyzed. Results of analyses are illustrated in the lower right of Figure 29. Although there is about 25 times more uranium in the rind than in the core, the two patterns are rather similar except for relative abundance of thorium 230 and protoactinium 231, which differ strikingly from one pattern to the other. The percent equivalent thorium 230 and protoactinium 231 in the core is considerably less than the percent uranium; whereas the percent equivalent thorium 230 and protoactinium 231 in the rind is considerably greater than the percent uranium. About 850 times more thorium 230 and protoactinium 231 is in the rind than in the core. Rosholt (1959, p. 26) classifies the pattern shown by the rind of the remnant in the same group as that shown by the channel of the remnant. He (p. 12) suggests that in general "disequilibrium of this type, found in samples taken from an oxidized environment, is the result of leaching of uranium". If so, the rind would have contained 3.5 percent uranium before the onset of modern weathering, which value is more than three times the maximum known for the area! He (p. 26) classifies the pattern shown by the core with a group represented mainly by samples of pyritic ores or ore dumps, and comments (p. 12) that such samples "are the result of differential leaching of all components" and that sulfates formed in these materials would retain the radium even though it might migrate somewhat, whereas the sulfuric acid formed would leach and remove uranium."

A more conservative alternative explanation for the large content of thorium 230 and protoactinium 231 in the rind may be that both are migrating out of the core into the rind. Thorium ions diffusing out from the center of a remnant would be immobilized as soon as they reached a site where pyrite was producing abundant iron hydroxides, for thorium co-precipitates with iron hydroxides (Rankama and Sahama, 1950, p. 573). Protoactinium ions probably would behave the same; their chemical behavior is so similar to thorium that separating the two for analysis is extremely difficult, according to Rosholt (oral communication, 1955). Choosing between these alternatives is not yet possible. Rosholt (p. 12) notes that in the pattern shown by the rind "daughter products may possibly have been added to the host rock", which allows the second explanation; but continues to say that "it is difficult to select samples definitely showing that this occurred". J. A. S. Adams (written communication, 1958) is of the opinion that "any movement of thorium isotopes in a shale sample is highly unlikely because all our attempts to leach thorium from clay under drastic laboratory conditions have failed and because it fits theoretically as regards the chemistry of a tetravalent ion".

Uraniferous Apatite and Limonite

Concentrations of uranium in the Eocene(?) soil other than those in isolated remnants and pinnacles of gray shale in the boundary zone are minor. The autoradiographs previously mentioned show alpha radiation emanating from small dark bodies in yellow oxidized and gray unoxidized calcareous shale near the margin of remnants. Enough material for X-ray analysis was hand-picked from one of the larger dark radioactive bodies. W. F. Outerbridge reported it to be carbonate apatite. Apatite is the mineral constituting fossil bones and fish scales, larger pieces of which are common in Cretaceous shale in the Chadron area. Noticeably uraniferous apatite was found nowhere in the Eocene(?) soil except in the boundary zone.

A concretionary lens of limonite in the upper part of the preserved transformed zone of the Eocene(?) soil contains uranium at locality 26, sec. 11, T.34N., R.47W. Analyses show 0.007 percent uranium and 0.006 percent equivalent uranium. Identical values obtain in pebbles of limonite derived from this lens and incorporated in the unconformably overlying Oligocene rocks. No other concretions of limonite from the Chadron area were analyzed, but N. M. Denson collected similar concretions containing 0.01 percent uranium from beneath the unconformity at the base of the White River group in North Dakota (oral communication, 1956).

Origin of Uranium

The uranium in the ancient soil developed on Cretaceous shale is epigenetic. The zone of uranium concentration cross-cuts stratigraphic units from the Carlile shale to the upper part of the Pierre shale, and maintains a rather constant distance beneath the erosional unconformity above. Several epigenetic hypotheses come to mind. At first thought, the occurrence of uranium in the basal zone of an ancient soil suggests that the uranium was emplaced as a result of soil-making, and that interpretation is the one here considered most probable. Two other possibilities to be considered are 1.) that the uranium is hydrothermal, and 2.) that the uranium was derived from overlying tuffaceous sediment and emplaced by ground water.

Shale-leach

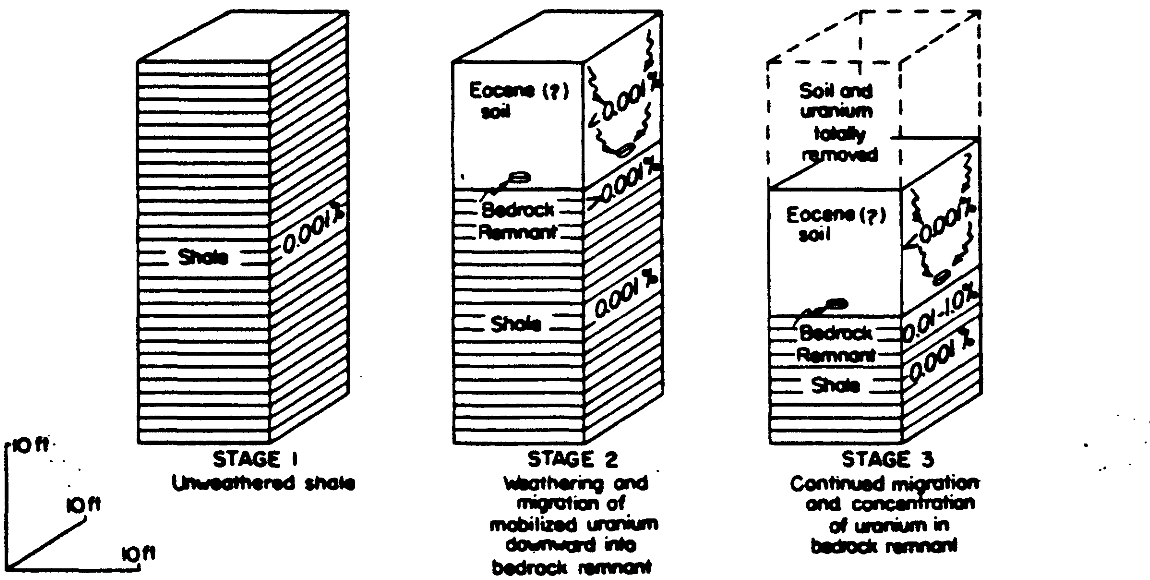
The shale-leach hypothesis proposes that lateritic weathering in Eocene(?) time oxidized and leached 4-valent primary uranium from low-grade Cretaceous shale, that percolating water carried the resulting 6-valent uranium down to the water table, and the 6-valent uranium was then reduced and precipitated in the boundary zone. The hypothesis shares many similarities with Altschuler, Clarke, and Young's (1958) account of supergene enrichment of uranium during highly acid lateritic weathering of the aluminum phosphate zone of the Bone Valley formation of Florida, and with Gruner's (1956) account of multiple migration-accretion.

Source of Uranium

In terms of total amount of uranium available, Cretaceous shale is an adequate source for the uranium in the Eocene(?) soil, as illustrated in Figure 30. Whether the shale also was able to produce a potentially mineralizing solution in Eocene(?) time remains to be shown.

Water now issuing from Cretaceous shale in and near the Chadron area averages 0.108 ppm uranium according to 11 analyses from the Chadron area plus 6 analyses from the Sharon Springs member and 8 analyses from the Niobrara formation reported by Kepferle (1959, p. 586). For comparison, water now issuing from Oligocene and Miocene rocks in South Dakota and Wyoming averages 0.035 ppm uranium, according to 92 analyses reported by Denson, Zeller, and Stephens (1956, p. 674), and 0.014 ppm for 6 samples in the Chadron area. Inasmuch as these rocks have been widely suggested as the source of the uranium in western coals (Miller and Gill, 1954), it seems that Cretaceous shale also would be capable of producing a potentially effective mineralizing solution.

Relationship between acidity and uranium content.--Figure 31 shows that although the water in each of the Cretaceous units contains considerable uranium, the most acid waters carry the most uranium. If it can be concluded that the water in the Eocene(?) soil was strongly acid, then it follows that the water could have contained a large amount of uranium.



Concentration of a hundredth the uranium originally present in 1,000 cubic feet of 0.001 percent U shale in upper 10 feet of column is quantitatively adequate to account for 0.01 percent U in 1 cubic foot-bedrock remnant. Delivery of all uranium leached from 10-foot column or of a tenth the uranium from a 100-foot column would account for 1.0 percent U.

FIGURE 30.--Diagram illustrating quantitative adequacy of Cretaceous shale to supply uranium occurring in Eocene(?) soil.

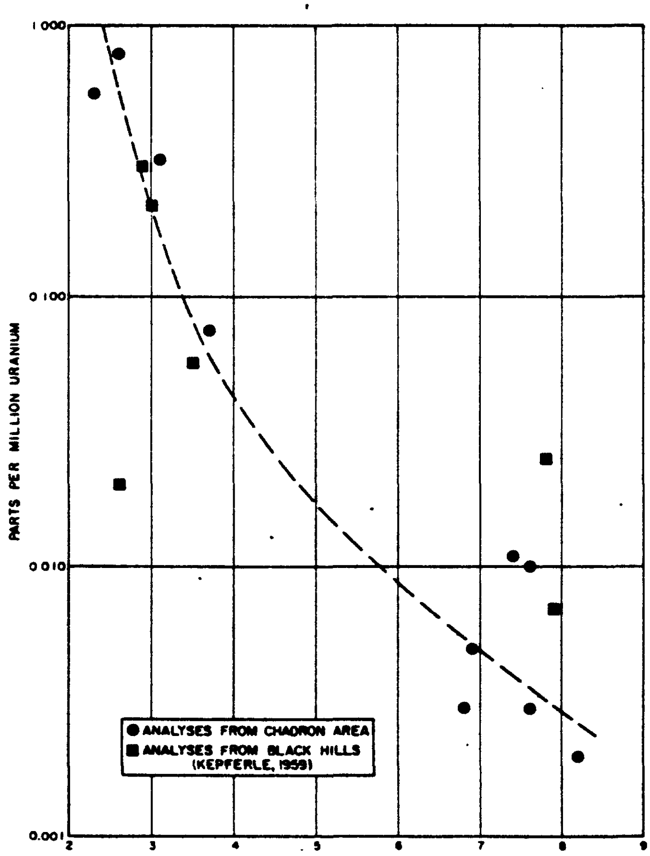


FIGURE 31.--Uranium content and acidity of water issuing from Cretaceous shale.

Theoretical reasons for increased acidity in Eocene(?) time.--There are four reasons for inferring that water in the Chadron area was more acid than it is now:

1.) Intense chemical weathering in a hot wet climate would produce plentiful sulfuric acid even in parts of the Cretaceous sequence whose pyrite content is less than that of the Sharon Springs member.

2.) Previous removal of bases would allow hydrogen ions to replace basic ions adsorbed on soil colloids, which would create a reservoir of acid, according to Thorne and Seatz (1955, p. 230). In contrast, modern soil of the Chadron area is being enriched in bases.

3.) Forests, which characterize lateritic soil, would litter the ground with a mantle of decaying organic matter. Rain washes humic acid and other organic acids and matter out of accumulating humus and carries them downward.

4.) Warm moist soil air, which characterizes lateritic soil, would encourage prolific growth of soil micro-organisms, which, in turn, would produce more acid.

Degree of acidity in Eocene(?) time.--Evidence bearing on the degree of acidity in the Eocene(?) soil comes from measurements made on analogous modern soil, and from inferences drawn from the composition of the ancient soil.

The Eocene(?) soil is a lateritic soil of the red and yellow podzolic type. Modern soils judged analogous to the ancient soil have pH values averaging about 4.5. Table 8 shows representative values, which have been averaged for individual profiles where more than one soil zone was measured at a locality.

TABLE 8
ACIDITY OF SOME LATERITIC
MODERN SOILS

Area	pH	Reference
Southeastern China	4.2-4.7	1
Alabama, Sumter County	4.5-6.4	2
North Carolina, Carteret County	3.6-5.4	3
North Carolina, Lee County	4.4-5.5	4
North Carolina, Pamlico County	4.4-5.4	5
Ecuador and Peru	4.0-610	6

References:
1. Hseung and Jackson (1952, p. 294)
2. Swenson and others (1941, p. 76)
3. Perkins and others (1938, p. 28)
4. Perkins and Goldston (1933, p. 38)
5. Miller and Taylor (1937, p. 26)
6. Miller and Coleman (1952, p. 242)

Four aspects of composition bear on acidity:

1.) Calcite being completely removed from the transformed zone developed on calcareous shale shows that the soil water was on the acid side of pH7.

2.) Kaolinization of the transformed zone is further evidence of acidity. To illustrate the general agreement on this subject, Mohr and Van Baren (1954, p. 180), from study of tropical soils, conclude that kaolinite records acid waters. Frederickson (1952, p. 6), from study of clay minerals, concludes, "Kaolinite characteristically develops in an acid environment often produced by organic acids or the oxidation of sulfide minerals." Rankama and Sahama (1950, p. 503), from various geochemical work, reports that kaolinite is formed during weathering where soil water is acid and alkali metals and alkaline-earth metals have previously been removed. Pure kaolinite theoretically would have a pH of about 4.5 (Thorne and Seatz, 1955, p.223).

3.) The presence of alunite, $K_2Al_6(OH)_{12}(SO_4)_4$, in kaolinite-alunite concretions and replacing limestone concretions also indicates acid water. King (1953) reports that at Pidinga, western South Australia, kaolinite-alunite occurs as alunitized clay "in the pallid zone of the kaolinitic clays" formed by lateritic weathering. The abundance of pyrite in associated clay and lignite, the regional abundance of sulfate in ground water in western South Australia, and field relations concerning impeded drainage and limestone allowed King to conclude that alunite was formed during lateritization where the pH of acid sulfate solutions was locally raised by presence of alkaline reagents such as limestone. In the Chadron area, acid water carrying potassium, aluminum, and sulfate apparently moved downward through the ancient soil. Where the acid water encountered a limestone concretion, it was neutralized and alunite was precipitated.

4.) Vertical distribution of iron and aluminum indicates a pH ranging around 4. Depletion of iron in the upper part of the transformed zone, resulting in white bleached claystone, indicates low pH. Depletion of iron is a common feature in modern acid soils. In fact, removal of iron from the A to the B horizon (zone), leaving the lower part of the A horizon (zone) ashy white, characterizes podzols. The acidity of a typical podzol ranges from pH 3.7 in the leached zone to pH 4.1 in the enriched zone, according to Jenny (1941, p. 158), although some kinds of podzols are locally as acid as pH 3.03 (Jenny, 1941, p. 98). Upward increase in abundance of alumina indicates that aluminum was concentrated during soil making. According to Rankama and Sahama (1950, p. 502), aluminum freed during weathering tends to remain in solution in solutions whose pH is lower than 4. Enrichment in aluminum thus indicates that the pH of the soil water was higher than 4, at least during part of the period of soil making.

Depletion of silica, which is suggested by the chemical analyses, does not refute the inference that the soil was acid. Acid waters are fully capable of removing silica. Martin and Doyne (1927, p. 534-539) found the laterite and lateritic soil of Sierra Leone, Africa, to have a pH of 4.2 to 4.3. Bennet and Allison (quoted in Joffe, 1949, p. 472) described mature laterites having less than 0.31 percent calcium oxide made from calcareous rocks having 50 percent calcium oxide. The soil water causing silica and lime to be leached there was obviously acid.

In sum, the acid weathering in Eocene(?) time probably produced acid soil water in parts of the Cretaceous sequence whose water is now alkaline, and very acid water in parts of the sequence whose water is now acid. Values in the range of pH 2.5 to 4.5 seem reasonable for the upper part of the soil.

Inferred uranium content of Eocene(?) soil water.--If the inference is valid that increased acidity implies increased uranium content, then Eocene(?) soil water contained more uranium than does water now issuing from the Cretaceous shale. Figure 31 suggests uranium content in the range of 0.030 to 0.700 ppm uranium for water ranging from pH 4.5 to 2.5

There is independent evidence indicating that Eocene(?) soil water actually did carry uranium. The transformed zone and upper part of the oxidized zone are depleted in uranium, apparently because of leaching in Eocene(?) time. Uraniferous limonite occurs as concretionary lenses in the ancient soil and as pebbles in the overlying Oligocene rocks. The limonite was evidently made prior to its incorporation in Oligocene rocks. The lenses and the pebbles having identical uranium content, and identical ratio of uranium to equivalent uranium, suggests that the limonite had received its uranium before being eroded, that is, in Eocene(?) time. T. G. Lovering (1955), in his general study of uraniferous limonite, lends strong theoretical support to the suggestion, for he concludes that the uranium in uraniferous limonite enters the limonite by adsorption while the limonite is still in the form of colloidal ferric oxide hydrate gel. Had the uranium entered the lenses and the pebbles during Oligocene or later time, one would wonder what caused the uranium to be precipitated in solid limonite.

Mobilization and Transport

As discussed on an earlier page, the uranium in the Cretaceous shale is associated with pyrite and organic matter, and is probably 4-valent. Eocene(?) weathering destroyed the organic matter and converted the pyrite to limonite. Theoretical considerations, detailed below, indicate that during these events the 4-valent uranium was oxidized and dissolved in the form of uranyl ion. Uranyl ion soon changed into uranyl sulfate, uranyl hydroxide, and uranyl carbonate complex ions, in one or more of which forms it traveled down to the boundary zone.

Mobilization of uranium.--Dependence upon acidity suggests that the uranium probably would have gone into solution in micro-environments whose pH was considerably lower than average. Consider a soil micro-environment containing 4-valent uranium and atmospheric oxygen, and dominated by a crystal of chemically decomposing pyrite. The uranium oxidized to the 6-valent form and produces hydrates or other compounds that are soluble in acid soil water (Gruner, 1956,

p. 497). The pyrite oxidizes and dissolves with the formation of ferrous sulfate and sulfuric acid; ferrous sulfate in turn oxidizes to ferric sulfate and ferric hydroxide (which rapidly hydrolyzes to form ferric oxide hydrate and then limonite); and finally the ferric sulfate breaks down to yield more ferric hydroxide and more sulfuric acid (Lovering, 1955, p. 191). The degree of acidity in such a micro-environment is certainly large enough to dissolve uranium and, assuming that a crystal of pyrite can be thought of as a miniature sulfide ore body, the degree of acidity may be very large. Phair and Levine (1953, p. 359) report that water issuing from an oxidizing sulfide ore body near Central City, Colorado is a 0.13 normal solution of sulfuric acid. (Even a sulfuric acid solution as weak as pH 4 is able to contain 6.9 parts per million uranium, given sufficient uranium in the source, as shown experimentally by Bethke, 1953, p. 173). Once the very acid soil water moves away from the immediate vicinity of the decomposing pyrite crystal, it is diluted and may be partially neutralized, so that pH rises.

The imagined situation deals with sulfuric acid from pyrite, but bacterial decomposition of specks of organic matter originally in the shale, or washed down from the overlying forest litter, would presumeably produce very acid micro-environments also. These and any other acids in the soil would join the sulfuric acid in dissolving uranium.

Ionic form of uranium in transport.--The ionic form taken by the uranium as it traveled in solution from its original site to the boundary zone was probably determined largely by pH. A summary

Miller and Kerr (1954),

of experimental results by Miller ~~(1954)~~ (1958) and Gruner (1952, 1956) will illustrate:

1.) Much low-temperature laboratory experimentation has been done with uranyl ion, UO_2^{+2} and uranyl sulfate ions, $UO_2(SO_4)_2^{-2}$ and $UO_2(SO_4)_3^{-4}$, at low pH. Miller (1958) reports that pure uranyl and uranyl sulfate ions are stable in solution below pH 3.5 at 25° C; and that they are reduced to uranous ion, UO^{+2}, in the presence of hydrogen sulfide, sulfur dioxide, or hydrogen, then precipitated as uraninite (pitchblende). Uranous ion oxidized to uranyl within 12 hours at 25°C between pH 1 and pH 7 in the presence of air. Gruner (1952) precipitated uraninite at pH 1.89 - 2.18 at temperatures as low as 50° C by reducing uranyl ion with hydrogen sulfide, ferrous iron, or organic reagents. Miller and Kerr (1954) accomplished the same thing at 25° C with hydrogen sulfide alone at pH 2.

2.) Uranyl and uranyl sulfate ions convert to uranyl hydroxide ion $UO_2(OH)^{+1}$, at pH 3.5 at 25°C (Miller, 1958). Uranyl hydroxide then is stable in solution from pH 3 to pH 4.5. The degree of instability above pH 4.5 is shown by experiments in which the amount of uranium in one liter of solution changed from 1.12 grams at pH 4.7 to 0.004 grams at pH 5.8.

Uraninite is precipitated at 50°C in experiments lasting from five minutes to three months by reducing uranyl hydroxide ion with hydrogen sulfide or hydrogen. The 6-valent uranium is reduced to 4-valent uranous ion and from this state reacts with water to form uraninite.

3.) Uranyl hydroxide ion converts to uranyl carbonate ions, $UO_2(CO_3)_2^{-2}$ and UO2

$(CO_3)_3^{-4}$, above pH 4.5 at 25° (Miller, 1958). Acidity controls the development of uranyl carbonate ion in place of uranyl hydroxide ion through its effect on carbonate ion concentration. Below pH 4.5 most of the carbonate ion will escape as carbon dioxide and no carbonate complex will form. Uranyl carbonate ion remains stable in solution to pH 11.5. It is stable in solution in the presence of sulfate, less stable in the presence of phosphate ion, and unstable in the presence of sulfide ion. It will precipitate in the presence of hydrogen sulfide, sulfur dioxide, or hydrogen as uraninite at temperatures above 50° C and at all pH values, and will precipitate in the presence of hydrogen sulfide as a uranous sulfide that converts on standing to uraninite at 25° and pH 8.

4.) All the above mentioned ions will react with a reducing agent such as hydrogen sulfide to form uraninite characterized by extremely small crystal size and diffuse X-ray reflections (Miller, 1958; Croft 1954). Gruner (1956, p. 513) refers to the uraninite as colloidal.

Transport in soil developed on calcareous shale.--Uranium in micro-environments dominated by decomposing pyrite probably went into solution in soil developed on calcareous shale in the form of uranyl or uranyl sulfate ions. Once away from their points of mobilization these ions would convert to uranyl hydroxide ion. Uranium mobilized in the oxidized zone soon would convert to uranyl hydroxide, because excess hydrogen ion would be neutralized by reaction with the calcium carbonate in the oxidized zone. Uranium mobilized in the transformed zone probably remained in the uranyl hydroxide form until it reached, or almost reached, the top of the oxidized zone. In either case the uranium in soil developed on calcareous shale in the Niobrara formation would be in the form of uranyl carbonate when it reached the boundary zone, where precipitation was to take place.

Transport in soil developed on noncalcareous shale.--Uranium mobilized in the soil developed on noncalcareous shale might have remained in the uranyl, uranyl sulfate, or uranyl hydroxide forms all the way to the boundary zone in some Cretaceous units. It will be recalled that limestone concretions belowthe oxidized zone are, dissolved and replaced by limonite, which shows that the percolating soil water remained acid to the base of the soil developed on noncalcareous shale containing limestone concretions. The degree of acidity near the surface probably excluded uranyl carbonate from most of the transformed zone, but whether the oxidized zone was more or less acid than the pH 4.5 needed for uranyl carbonate is questionable. The acidity of waters now issuing from the Sharon Springs member indicates that both uranyl carbonate and uranyl hydroxide were probably excluded from all parts of its soil, leaving the uranium in the form of uranyl and uranyl sulfate ions. The siderite in the basal zone of the middle part of the Pierre shale suggests that the acidity of its oxidized zone may have been in the range of uranyl carbonate -- lack of analyses for siderite in the oxidized zone, and abundance of ferric iron in the oxidized zone leaves this matter undecided. The acidity of the oxidized zone on noncalcareous shale bearing limestone concretions was probably somewhat less than that on the Sharon Springs member and somewhat more than that on calcareous shale, possibly between pH 4 and pH 6.5.

These conclusions lead to the inference that uranium reached the boundary zone in the form of uranyl and uranyl sulfate ions in the Sharon Springs member, uranyl hydroxide and uranyl carbonate in the Carlile shale and most of the Pierre shale, and uranyl hydroxide or uranyl carbonate in the basal 75 feet of the middle part of the Pierre shale.

Physical form of transport.--The present low permeability of claystone in the transormed zone makes one wonder whether uranium could be transported in solution through the soil. That transport was, in fact, possible is shown by calcite being removed from the transformed zone. Other indications of moving water come from the inferred migration of clay in the soil.

The muddy water that percolates downward through soil after a rain and evaporates within soil between rains can be expected to leave a record in ancient as well as modern soils. The expectation is satisfied in bauxite. Allen (1952, p. 677) describes veins and pores filled with clay due to migration of clay minerals and says, "The addition of clay minerals to a bauxite deposit increases its volume and destroys or obscures the original structure of the parent materials by filling all the available openings and crowding aside the old material". Two things indicate that the ancient soil in the Chadron area also was impregnated with clay.

1.) One is the kneaded structure of the transformed zone, which seems to record crowding. Collapse of spaces leached of small particles of calcite would account for loss of bedrock shaly bedding and joints, and collapse around dissolved limestone concretions would account for some slump structure, but the production of extensive kneaded structure probably requires crowding due to introduction of clay.

2.) The second indication of migrating clay is the presence of concretions of kaolinite-alunite in the transformed zone on calcareous shale and the presence of veins and concretions of kaolinite-alunite in the oxidized zone on noncalcareous shale bearing limestone concretions. The solutions evidently moved downward. Downward-moving solutions are required by the occurrence of kaolinite-alunite caps lying above but not below limestone concretions.

Study of modern soils shows that the ancient soil should have been more permeable in Eocene(?) time than it is now. Modern soils are penetrated by shrinkage cracks and by roots and burrowers, which leave paths of easy permeability (Baver, 1948, p. 243). Inasmuch as the Eocene(?) soil is a lateritic soil, decayed tree roots and root hairs probably contributed greatly to permeability. Compaction of the transformed zone after burial beneath the water table would then eliminate practically all the openings large enough to act as permeability paths. Damp soil compacts readily.

Transport by diffusion is indicated by banded arrangements of ferric iron colors in the transformed zone, but its role cannot be quantitatively evaluated.

Precipitation

The experimental results of Miller (~~1954,~~ 1958) Miller and Kerr (1954) and Gruner (1952, 1956), summarized earlier, shows that uranyl, uranyl sulfate, uranyl hydroxide, and uranyl carbonate are all readily precipitated as uraninite when they are reduced. The sharp boundary between yellow oxidized shale and gray unoxidized shale in the boundary zone marks the position of an ancient oxidation-reduction interface. Localization of practically all the uranium in the boundary zone at this interface indicates reduction. The problem of precipitation is thus mainly one of reduction.

Oxidation-reduction potential.--The presence of concretions and stains of limonite and hematite shows that oxidation was part of soil making. The absence of both in the bedrock shows that oxidation was limited downward. The oxygen required for most oxidation, including bacterial oxidation, comes ultimately from the atmosphere, by way of passageways in the soil. Merkle (1955, p. 205) notes:

> "Because of decomposition of bacterial products in the soil and the slow rate of movement of air through soils, the soil air contains more carbon dioxide and less oxygen than does the outside air. Analyses of the soil air show that the carbon dioxide content varies from about 0.3 percent to about 10 percent. In general, as the carbon dioxide increases, the oxygen content decreases, and vice versa. In nearly all instances the carbon dioxide content increases with depth."

Compared to the atmosphere, soil air at depth thus may contain 300 times as much carbon dioxide, and very little oxygen. The abundant signs of oxidation in weathered rocks tend to obscure the fact that reduction also plays an important role in soil-making. Merkle (1955, p. 209 and 207) generalizes about eH from 23 investigations of soil, "Soil systems are seldom more oxidizing than + .700 volt or more reducing than - 0.300 volt".

A reducing environment exists in soil near its surface and again near its base. The uppermost part of modern soils is a strongly reducing litter of decaying organic matter. From this surface layer, organic solutions, colloids, and larger particles of organic matter percolate down through the soil. As the organic matter moves downward, it directly or indirectly reduces various things in contact with it and is itself destroyed, wholly or in part, in the process. Bacteria and other fungi do much to destroy the organic matter, producing carbon dioxide both in the organic litter at the surface and within the soil, plus the very effective reductant hydrogen sulfide. The abundance of organic matter thus decreases downward in the upper part of a soil. Below some shallow depth the abundance of organic matter, compared to the abundance of oxygen, decreases enough for the soil to become generally oxidizing.

Near or at its base, where pores are filled with nearly stagnant water, soil becomes again generally reducing. This is shown by studies of waterlogged soils reported by Merkle (1955, p. 207-209), and by the presence of fresh pyrite in cores taken from below the modern water table. Merkle notes that in wet regions reducing conditions due to saturation lie in the tillable part of the soil profile in the early spring when the water table is high. Reducing conditions then retreat as spring advances and the water table falls, thus allowing the land to be worked and to support the desired crops.

Water below the zone of air penetration probably is reducing for the same reasen that black shale marine bottoms are reducing. That is, some particles of organic matter escape being destroyed in their downward travel toward the zone of saturation. When these reach oxygen-bearing nearly stagnant water at or near the water table, oxygen-dependent bacteria living there, or brought down with the organic matter, will begin to destroy them. Oxygen used up in the process is replaced very slowly. Once oxygen is gone, anerobes take over.

Among the anerobes at the water table are those that generate hydrogen sulfide in the course of their life processes. Many bacteria generate hydrogen sulfide from organic matter (ZoBell, 1946, p. 158), which was available in the water at the base of the Eocene(?) soil in the form of washed-down Eocene(?) matter as well as in the form of indigenous Cretaceous matter. Desulfovibrio generates hydrogen sulfide by reduction of sulfate, which was in the water at the base of the Eocene(?) soil due to decomposition of pyrite in the transformed zone and oxidized zone.

Reduction of uranium.--Five reagents have been used to reduce and precipitate uranium in the laboratory: hydrogen sulfide, sulfur dioxide, ferrous ion, organic reagents, and hydrogen gas. The list of possible reducing agents should also include organic sulfur in the cell walls of woody matter, and pyritic sulfur, according to Miller's (1955) studies in the White Canyon district of Utah. Except for sulfur dioxide, each of these were probably present in the boundary zone during Eocene(?) time.

1.) Hydrogen sulfide seems rather likely to have been the chief reducing agent. It was probably produced in abundance at the water table during Eocene(?) time by anerobic bacteria. Other hydrogen sulfide incorporated or generated in Cretaceous shale before Eocene(?) time would have also been available -- the present existence of such hydrogen sulfide is evident from the smell of freshly broken samples of shale. Gruner (1956, p. 514) considers hydrogen sulfide, or the sulfide ion, to be the "best direct reductant.... in nature". Jensen (1958, and written communication, 1961) has evidence from sulfur isotopes strongly suggesting that hydrogen sulfide derived from anerobic bacteria caused precipitation of the uraninite in sandstone-type uranium deposits of the Colorado Plateau and Wyoming, and in many other deposits.

Association of the uranium in the soil with framboidal pyrite of the type Love (1958) found to be precipitated by hydrogen sulfide-generating anerobes suggests that hydrogen sulfide was the chief reducing agent, as does association of the uranium with copper, silver, and zinc, which are like iron in being precipitated by hydrogen sulfide.

2.) Ferrous iron in pyrite was present in and below the boundary zone and may possibly have reduced some uranium as it began to oxidize to ferric iron. If the uranium in the soil were concentrated in yellow oxidized shale, instead of in gray relatively unoxidized shale, this possibility would be more attractive. The same objection applies to the sulfur in pyrite.

3.) Organic reagents of the kinds derived from forest litter (some of which probably contained organic sulfur) were surely present in the ancient soil, but their effectiveness cannot be judged.

4.) Hydrogen gas, which is produced where hydrogen sulfide and ferric oxide react to form pyrite (Jensen, 1958, p. 615), might very well be generated in the boundary zone during slight fluctuations in position of the water table. The possibility that hydrogen was the reducing agent for uraninite would account for intimate association with pyrite. It does not account for the equally intimate association with lenticles of organic matter of Cretaceous origin; oxidation of original ferrous iron to produce the ferric oxide needed to make new pyrite would probably be accompanied by destruction of original organic matter.

5.) Sulfur in cell walls of woody and other organic matter may have reduced uranium directly, or it may have been organically converted to hydrogen sulfide, which in turn reduced the uranium.

The probable existence of one or more effective reducing agents in the boundary zone, and the probable existence of various uranium ions in the water percolating down to the boundary zone, indicates that the shale-leach hypothesis is credible. If so, it would seem that very little of the uranium that reached the oxidation-reduction interface succeeded in escaping immediate or almost immediate precipitation; otherwise the concentrations of uranium would be continuous along that interface and would not be so strongly top-preferential. Some independent movement of ions through the solution under the influence of concentration gradients set up around sites of first precipitation apparently accompanied the downward movement; otherwise low points on the uninterrupted oxidation-reduction interface would be enriched.

Re-cycling

Downward migration of the soil profile would bring early concentrations of epigenetic uranium back into contact with atmospheric oxygen and acid water, with the result that the whole process of enrichment would be repeated.

Cause of Greater Enrichment in Niobrara Formation

Three explanations for the relatively great enrichment in calcareous shale of the Niobrara formation suggest themselves:

1.) This shale was originally richer in uranium than other shale.

2.) Uranium from the Sharon Springs member was epigenetically concentrated in the Niobrara formation.

3.) The uranyl carbonate ion produced in the Niobrara formation was capable of greater enrichment than the other ions. Miller's (1958) measurements of the concentration of uranium in the solutions from which uraninite has precipitated suggest that at 25° C uranyl carbonate might be one or two orders of magnitude more effective than the other ions.

Possible Sorbtion of Uranium by Organic Matter

Identification of the uranium in the boundary zone as a discrete low-valent uranium mineral is critical to the details of the above discussion. If the uranium was sorbed by Cretaceous organic matter instead of precipitated as a mineral, then deposition is due to the downward moving soil water having first encountered Cretaceous organic matter when it reached the gray shale of the boundary zone.' This alternative weakens the shale-leach hypothesis, because compacted organic matter in lithified shale is not known to have the ability of sorbing uranium, but with either alternative the shale-leach hypothesis is competent to account for the uranium in the boundary zone of the Eocene(?) soil.

Hydrothermal

The hydrothermal hypothesis envisions uraniferous magmatic fluids rising into the sedimentary cover and precipitating uranium at the base of the relatively impermeable soil. A point favoring the hydrothermal hypothesis is that the Chadron area is largely occupied by the Chadron arch, and crustal uplift is commonly associated with hydrothermal activity. Points strongly against this hypothesis are:

1.) No independent evidence of hydrothermal activity, such as hydrothermal alteration, is known.

2.) The lateral distribution of uranium exhibits no structural control; ascending hydrothermal waters would probably seek out structurally defined zones of permeability.

3.) The vertical distribution of uranium is top-preferential within the boundary zone; ascending water would not be likely to bypass a low remnant to deposit its uranium in a high remnant, nor to favor the upper part of an isolated remnant at the expense of the lower part.

4.) The hydrothermal hypothesis does not account for the depletion of uranium in the upper part of the ancient soil.

Ash-leach

H. A. Tourtelot (1956), who discovered the uranium in altered Niobrara shale beneath the sub-Oligocene unconformity during his reconnaissance search for uraniferous shale in the central Great Plains and was the first to ponder its origin, recognized that the origin of the uranium is involved with the origin of the altered zone. He also recognized that the alteration is pre-Oligocene, at least in large part. He (1956, p. 83) says:

> "The source of the uranium concentrated in unaltered marl within the altered zone where it is made up of the Niobrara formation may have been the marl that was altered in the formation of the zone. Unaltered marls of the Niobrara formation 5-10 feet below the base of the altered zone are not radioactive, however, where tested at the localities shown on Figure 9 and the effectiveness of the unaltered marls as a source of the uranium cannot be evaluated."

Denson, Bachman, and Zeller (see Denson and Gill, 1956) had previously proposed what has been called the ash-leach hypothesis to account for uraniferous lignite in the northern Great Plains: In brief, the ash-leach hypothesis is that uranium in Oligocene and Miocene tuffaceous rock is leached and carried to lignite beds by ground water, then extracted by the lignite. Tourtelot (1956, p. 62, p. 83) boldly suggested that the ash-leach hypothesis might also account for the uranium in the altered shale, saying:

> "The coextensive distribution of the altered Cretaceous zone and of the overlying White River group suggests that most [or some, p. 83] of the uranium in the small masses of unaltered marl in the altered zone has been derived from the White River group."

He argues (1956, p. 82) that although the altered zone is in large part pre-Oligocene in origin, "The zone has been affected also by ground water in subsequent geologic time, since the altered zone is more porous and permeable than unaltered shale." Once aware that the unaltered shale is in fact uraniferous, Tourtelot (written communications, 1955, 1956) attributed equal merit to the shale-leach and ash-leach hypotheses, saying in support of the ash-leach hypothesis:

> "The altered zone beneath the Oligocene is more permeable and more porous than the underlying unaltered Cretaceous. Therefore, the nature of the altered zone probably is the result of ground water conditions since the formation of the zone as well as the processes that led to the formation of the zone in the first place. Some or most of the uranium in the base of the altered zone could have been derived from the Oligocene rocks instead of having been concentrated during pre-Oligocene weathering."

Source of Uranium

The chief attraction of the ash-leach hypothesis is that the Oligocene and Miocene rocks in the Chadron area contain uranium and yield their uranium to passing subsurface water. Average uranium content of the water is 0.014 parts per million in the Chadron area, which is considerably less than the average for water from Cretaceous shale, but probably still adequate. That Oligocene and later waters carried uranium in the Chadron area is shown by the presence of uranium minerals in Oligocene gypsum.

Transport of Uranium

Difficulties arise concerning transport.

1.) There is no chemical evidence that ground water flowed through the boundary zone in sufficient quantity to affect the shale. Bleaching and pyritization, which characterize the effects of ground water alteration at the contact between soil and permeable Oligocene sandstone, do not extend as much as a foot into the soil. The alteration seen along the joints in the boundary zone records oxidation, not the reduction characterizing the ground water alteration known in the Chadron area.

2.) The rate of ground water motion is slow under good conditions. Hubbert (1953, p. 1959) refers to ground water flow as "creeping". When the slow flow to be expected in shale and claystone below the water table is combined with the rather small amount of uranium in Oligocene and Miocene water, one wonders if there has been enough time for the observed enrichment. Possibly these difficulties can be eliminated by calling on vadose instead of ground water.

3.) Direction of flow was downward, which necessitated the crossing of permeability barriers. To explain, ground water carrying uranium from Tertiary rocks would have to reach the basal part of the buried soil. Two alternatives are possible: the ground water could move directly downward, or it could move first downward then laterally until it reached the site of deposition. If ground water reached the site of deposition by lateral flow, one could not account readily for the strongly top-preferential distribution of the uranium, nor for the lack of side-preferential distribution, nor for localization of uranium precisely in the upper part of the boundary zone. Organic matter in the lower part of the boundary zone and in shale beneath the boundary zone, such as the log and other organic matter in the Sharon Springs shale and the plant fragments in sandstone of the Carlile shale, should be as good a receptor of uranium as that in the gray shale of the upper part of the boundary zone; but the lower organic matter is not enriched.

As discussed earlier, the available evidence gives no reason to expect that ground water would move laterally through the boundary zone in preference to bedrock shale, or particularly in preference to sandstone in the Carlile shale. For these several reasons, it seems that the ash-leach hypothesis requires that the groundwater move directly downward, depositing its uranium where receptor material is first met.

This requirement raises a serious objection. Above many uranium concentrations lies the transformed zone, which is thought to be almost impermeable, and the green claystone of the Chadron formation, which appears equally impermeable. For ground water to move through these barriers in sufficient quantity to produce the known concentrations of uranium in the boundary zone seems highly improbable. Furthermore, the ash-leach hypothesis would lead one to expect the boundary zone to be extraordinarily rich in uranium where channels of permeable Oligocene sandstone are in contact with the oxidized zone, and even where less permeable Oligocene rocks are in contact with the oxidized zone. This expectation is contrary to fact.

A possible alternative to bodily movement of uranium-bearing water is diffusion of uranium ions through stationary water under the influence of a concentration gradient. Diffusion can explain the presence of uranium a few inches inside beds of impermeable lignite. For diffusion to explain the uranium in the boundary zone according to the ash-leach hypothesis, diffusion would have to act over a distance measured in tens of feet instead of inches. One may assume that the difference in concentration of uranium between the water in the boundary zone and the water in the Tertiary rocks would be of about the same order of magnitude as the difference between the water inside and outside of the uraniferous lignite. If so, the concentration gradient into the boundary zone would be extremely small, presumeably too small to affect large-scale diffusion (fig. 32).

Precipitation of Uranium

The ability of peat, lignite, and sub-bituminous coal to extract uranium from water is well known (Moore, 1954), and that ability is one of the strong supports for the ash-leach hypothesis as applied to uraniferous coal. The organic matter in Cretaceous shale is thought for reasons already discussed

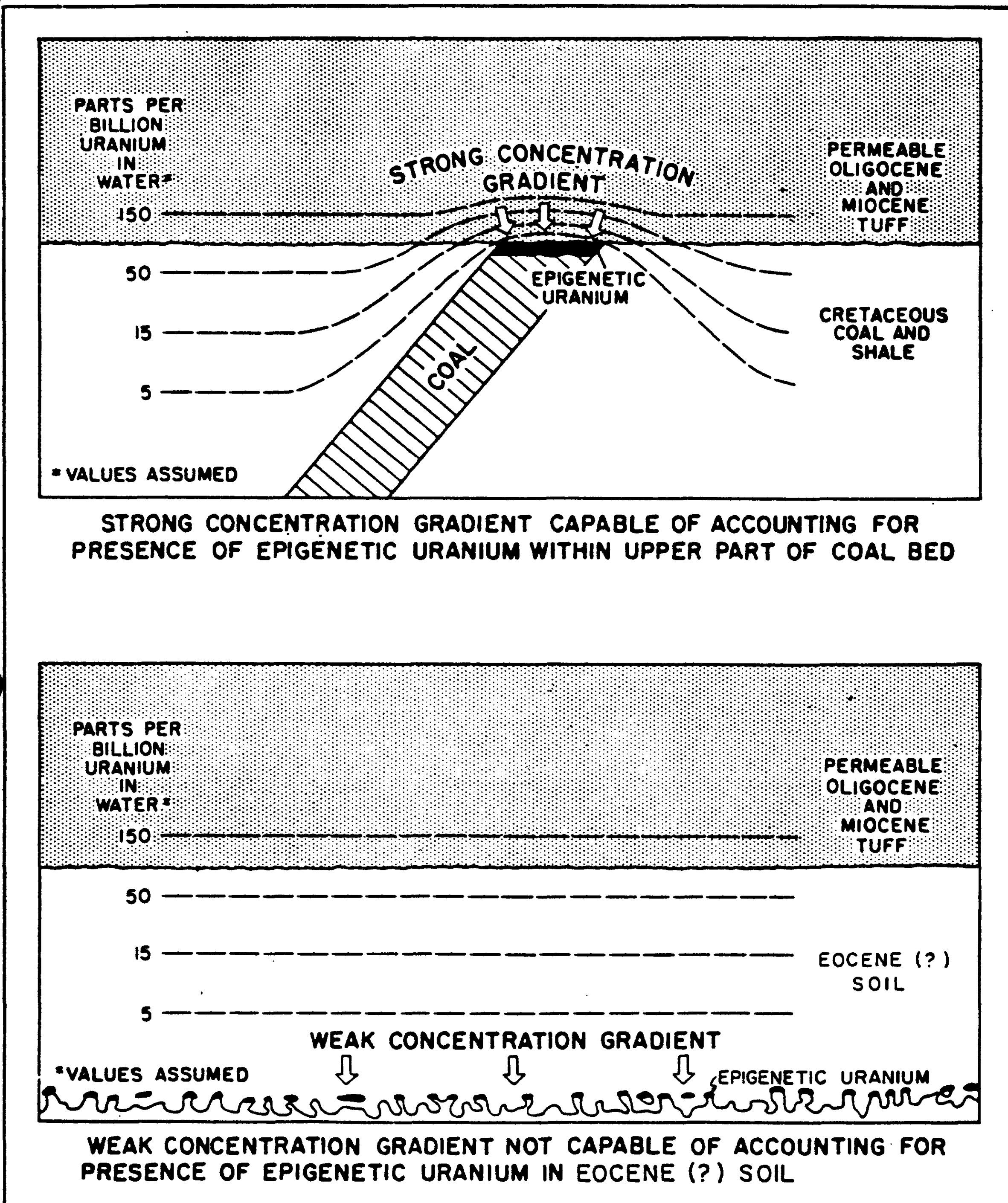


FIGURE 32.--Sketches illustrating role of concentration gradient in diffusion of uranium from Oligocene and Miocene tuff into Cretaceous rocks.

to have had that ability also, prior to the time the shale was lithified. What has not been established is that compacted organic matter enclosed in deeply-buried lithified shale is able to extract uranium from ground water.

Depletion of Uranium in Upper Part of Soil

The ash-leach hypothesis by itself does not account for the upper part of the soil being leached of uranium. Possibly leaching of uranium from the upper part of the soil and enrichment of uranium in the lower part of the soil is merely coincidental, but to assume this is to weaken the hypothesis.

Conclusion as to Origin

The above discussion shows that lateritic weathering is competent on theoretical grounds to explain the uranium in question. Lateritic weathering clearly affected the area, and therefore, opportunity must be added to competency. Although certain proof of origin is necessarily lacking, the explanation offered by the shale-leach hypothesis seems more probable than that offered by known alternatives.

URANIUM IN GYPSUM FACIES OF BRULE FORMATION

Abundance of Uranium and Description of Occurrences

The basal 25 feet of the gypsum facies of the Brule formation contains notable concentrations of uranium. They are the only ones known in the Oligocene and Miocene sequence in the Chadron area, excepting mammal bones containing 0.012 to 0.038 percent uranium at localities 66 and 67, secs. 32 and 33, T.34N., R.48W., and excepting re-deposited limonite discussed previously, Uranium content of the gypsum facies averages 0.042 percent in 27 samples, ranging from 0.004 to 0.43 percent (table 9).

The uranium occurrences are of two types: 1.) mineralized gypsum and clay of rather high grade and small extent, which averages 0.066 percent uranium in 16 samples, ranging from 0.004 to 0.43 percent, and 2.) uraniferous dolomite and limestone of low grade and large extent, which averages 0.007 percent uranium in 10 samples, ranging from 0.004 to 0.004 to 0.012 percent.

Mineralized Gypsum and Clay

Carnotite, $K_2(UO_2)_2(VO_4)_2 \cdot 1\text{-}3H_2O$, sabugalite, $HAL(UO_2)_4(PO_4)_4 \cdot 16H_2O$, and autunite, $CA(UO_2)_4(PO_4)_2 \cdot 10\text{-}12H_2O$, occur at localities 40 and 41, sec. 3, T.34N., R.47W. (fig. 33).

Description of Enriched Masses

The uranium minerals are in bedded gypsum and clay, most of which is carbonaceous. The vicinity of these two localities is unusual in two respects. It is the only place in the Chadron area where gypsum, instead of dolomite and limestone, dominates the basal part of the gypsum facies, and the only place where gypsum is carbonaceous. It is also the inferred center of the gypsum belt.

Mineralized masses are highly radioactive but small. Radioactivity of the four masses at locality 40, two of which are not shown on Figure 34, ranges from 20 to 65 times background; exposed

Table 9 -- Uranium content and radioactivity of gypsum facies of Oligocene Brule formation, Dawes and Sheridan Counties, Nebraska.

Analysts: G. Daniels, M. Finch, S. P. Furman, J. Goode, H. Lipp, R. Moore, J. E. Wilson.

Laboratory number	Location	Rock type	Sample type	Equivalent Uranium (percent)	Uranium (percent)	Remarks
		Mineralized gypsum and clay				
221497	Loc. 40, sec. 3, T.34N., R.47W., Dawes Co.	gypsum	2-ft channel	0.11	0.12	Carbonaceous carnotite and sabugalite, brown & yellow stained.
221499	Loc. 40, sec. 3, T.34N., R.47W., Dawes Co.	gypsum	1-ft channel	0.12	0.15	As above.
221500	Loc. 40, sec. 3, T.34N., R.47W., Dawes Co.	gypsum	1.5-ft channel	0.023	0.043	
221501	Loc. 40, sec. 3, T.34N., R.47W., Dawes Co.	clay	8-ft channel	0.009	0.017	
221502	Loc. 40, sec. 3, T.34N., R.47W., Dawes Co.	clay	1-ft channel	0.29	0.43	Autunite.
221504	Loc. 40, sec. 3, T.34N., R.47W., Dawes Co.	clay	1.5-ft channel	0.089	0.14	Sparse autunite.
221505	Loc. 40, sec. 3, T.34N., R.47W., Dawes Co.	pellet mudstone	2-ft channel	0.006	0.011	
223137	Loc. 40, sec. 3, T.34N., R.47W., Dawes Co.	clay	1.5-ft channel	0.041	0.011	Sparse autunite; stratigraphically above No. 221497.
223138	Loc. 40, sec. 3, T.34N., R.47W., Dawes Co.	clay	1-ft channel	0.084	0.010	Sparse autunite; probably stratigraphically below No. 221500.
223139	Loc. 41, sec. 3, T.34N., R.47W., Dawes Co.	gypsum	3-ft channel	0.005	0.004	
223140	Loc. 41, sec. 3, T.34N., R.47W., Dawes Co.	limestone & gypsum	1-ft channel	0.005	0.006	
223142	Loc. 41, sec. 3, T.34N., R.47W., Dawes Co.	gypsum	1.5-ft channel	0.006	0.009	
223141	Loc. 41, sec. 3, T.34N., R.47W., Dawes Co.	gypsum	1.5-ft channel	0.018	0.024	Carbonaceous, carnotite and sabugalite.

Table 9 -- Uranium content and radioactivity of gypsum facies of Oligocene Brule formation, Dawes and Sheridan Counties, Nebraska (cont.).

Laboratory number	Location	Rock type	Sample type	Equivalent Uranium (percent)	Uranium (percent)	Remarks
223143	Loc. 41, sec. 3, T.34N., R.47W., Dawes Co.	clay	0.3-ft channel	0.046	0.059	Carbonaceous, autunite.
223144	Loc. 41, sec. 3, T.34N., R.47W., Dawes Co.	clay	1-ft channel	0.009	0.008	
223145	Loc. 41, sec. 3, T.34N., R.47W., Dawes Co.	clay	2-ft channel	0.012	0.014	Carbonaceous, autunite, laterally equivalent to No. 223141.
		Uraniferous dolomite and limestone				
216658	Loc. 61, sec. 21, T.34N., R.48W., Dawes Co.	limestone	3-ft channel	0.007	0.008	
223149	Loc. 62, sec. 21, T.34N., R.48W., Dawes Co.	limestone	1-ft channel	0.003	---	
223148	Loc. 62, sec. 21, T.34N., R.48W., Dawes Co.	dolomite & gypsum	3-ft channel	0.005	0.004	
223152	Loc. 63, sec. 21, T.34N., R.48W., Dawes Co.	dolomite	1-ft channel	0.006	0.006	
223151	Loc. 63, sec. 21, T.34N., R.48W., Dawes Co.	dolomite	1-ft channel	0.006	0.007	
223150	Loc. 64, sec. 21, T.34N., R.48W., Dawes Co.	dolomite	1-ft channel	0.010	0.011	
216657	Loc. 65, sec. 21, T.34N., R.48W., Dawes Co.	clay and gypsum	1-pt grab	0.004	0.004	Probably stratigraphically above No. 216658.
138897	Loc. 59, sec. 22, T.34N., R.48W., Dawes Co.	limestone	8-ft channel	0.004	0.004	Composite of 3 beds.
223147	Loc. 60, sec. 22, T.34N., R.48W., Dawes Co.	limestone	3-ft channel	0.004	0.004	
216659	Loc. 46, sec. 29, T.34N., R.48W., Dawes Co.	limestone	1-ft channel	0.011	0.012	
223135	Loc. 10, sec. 31, T.35N., R.46W., Sheridan Co.	limestone	2-ft channel	0.007	0.004	
223136	Loc. 10, sec. 31, T.35N., R.46W., Sheridan Co.	clay	1-ft channel	0.004	0.004	

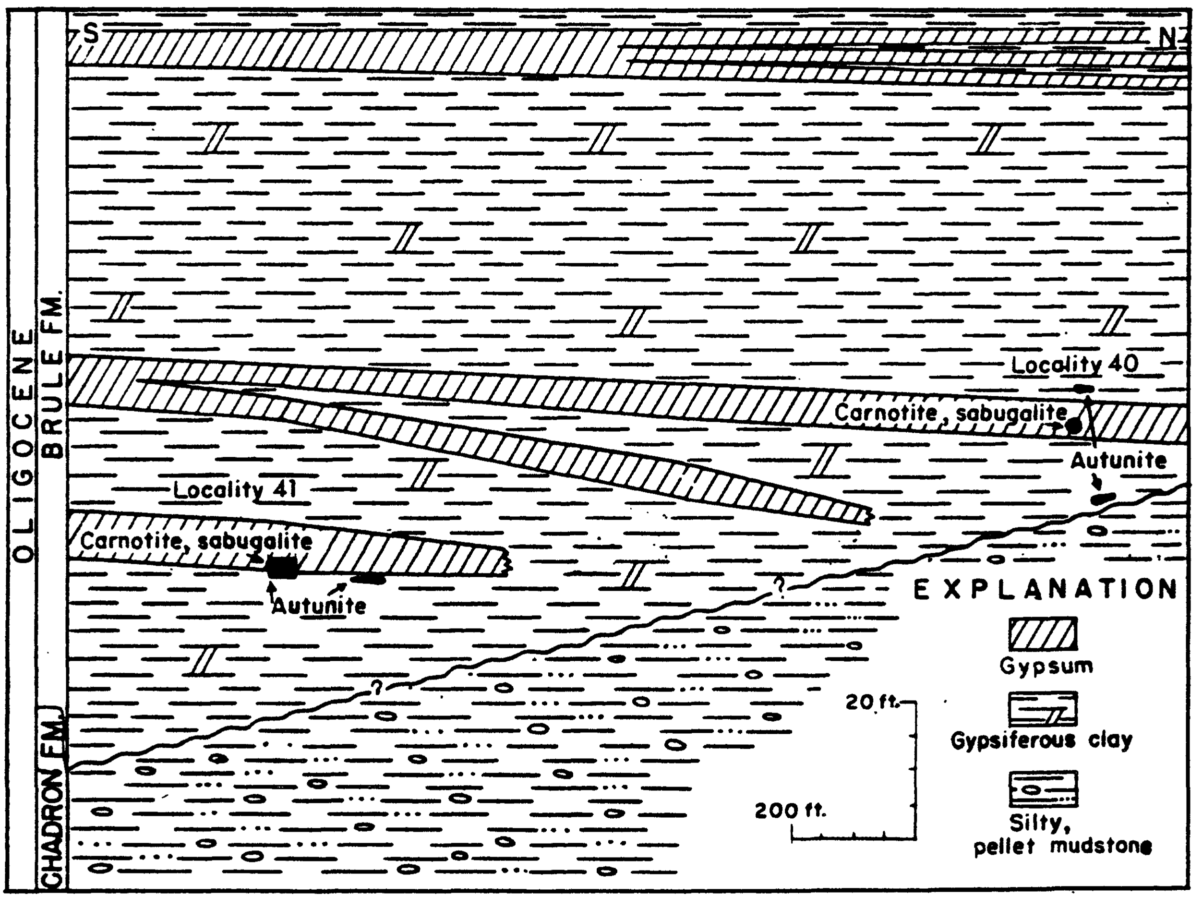


FIGURE 33.--Stratigraphic diagram showing relationship of uranium minerals to gypsum beds of Brule formation, sec. 3, T.34N., R.47W., Dawes County, Nebraska.

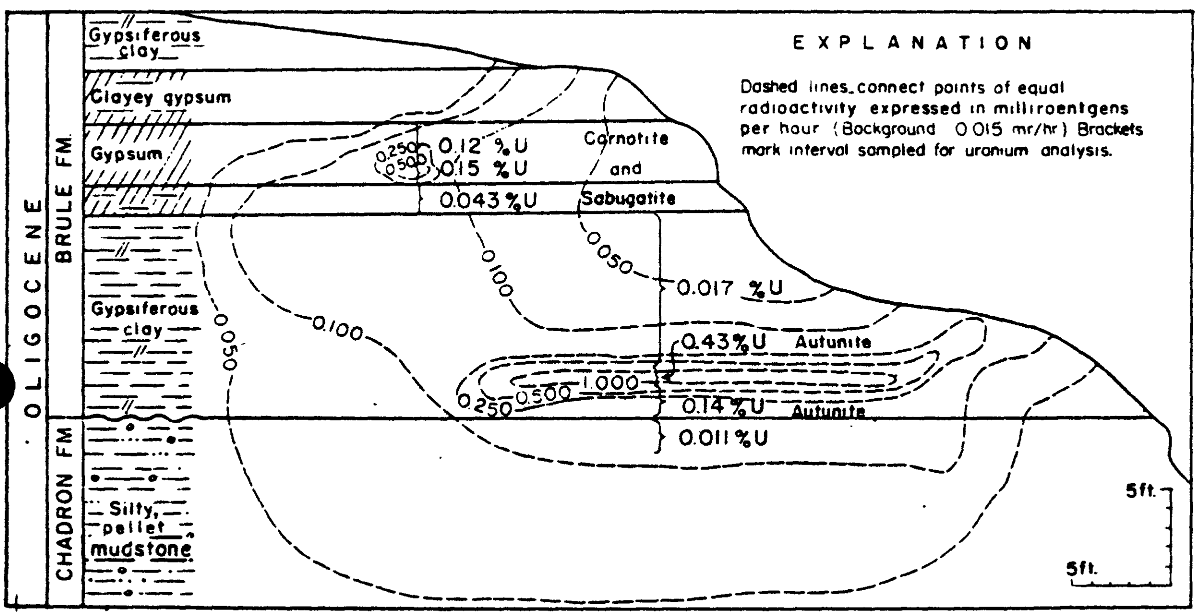


FIGURE 34.--Sketch showing distribution of uranium and radioactivity at locality 40, sec. 3, T.34N., R.47W., Dawes County, Nebraska.

size is about 2 x 40-feet for both. Less than 100 tons of rock having 0.10 percent uranium is indicated by surface measurements at the two localities.

Description of Uranium Minerals

The three uranium minerals, which were identified by J. W. Adams from chemical, optical, and X-ray data, are each characterized by color or fluorescence, and thus their occurrence can be studied in the field.

1.) Carnotite, which is yellow and nonfluorescent, is restricted to bedded carbonaceous gypsum. It occurs in vague irregular veinlets, in poorly-defined pore fillings, and in minute blebs in gypsum crystals. Some of the blebs of carnotite are regularly distributed in alignment with cleavage cracks.

2.) Sabugalite, which is almost colorless and has yellow green fluorescence, is also restricted to bedded carbonaceous gypsum, where it is a little less abundant than carnotite. Its occurrence in the gypsum is similar to that of carnotite, except that veinlets are somewhat better defined (fig. 35).

3.) Autunite, which is yellow green and brightly fluorescent, is restricted to clay directly above and directly below bedded gypsum that bears carnotite and sabugalite. In some masses, the clay is carbonaceous; in others, it is not. The autunite occurs as fracture coatings

FIGURE 35.--Photomicrograph of irregular veins of sabugalite in gypsum, plane light, X 100.

and as dispersed granular aggregates. It also occurs as globular grains adhering to the surface of veins of satinspar that are partially replaced by opal and chalcedony. The clay is more highly mineralized for an inch or so adjacent to these veins. Where grass grows on the mineralized clay, rootlets are brightly fluorescent with autunite. Apparently uranium has migrated during modern weathering, which supposition would accord with the deficient radioactivity of the autunite-bearing samples.

Uraniferous Limestone and Dolomite

The dolomite and limestone zone that constitutes the basal part of the gypsum facies in all outcrops away from the inferred center of the gypsum belt is also uraniferous. Although the uranium content is slight, averaging 0.007 percent, it seems significant. Bell (1956, p. 382) reports, "The syngenetic uranium contents of carbonate rocks and sediments are among the lowest of all the rocks of the earth's crust." His 11 samples of limestone and dolomite of Precambrian to Pleistocene age contain uranium in the range of 0.00007 to 0.00038 percent and average 0.00019 percent, which is about 35 times less than the average for the dolomite and limestone of the Chadron area. The uraniferous dolomite and limestone is commonly rich in secondary gypsum visible in the field.

Enriched masses are weakly radioactive and laterally extensive (fig. 36). Radioactivity ranges from 2 to 10 times background

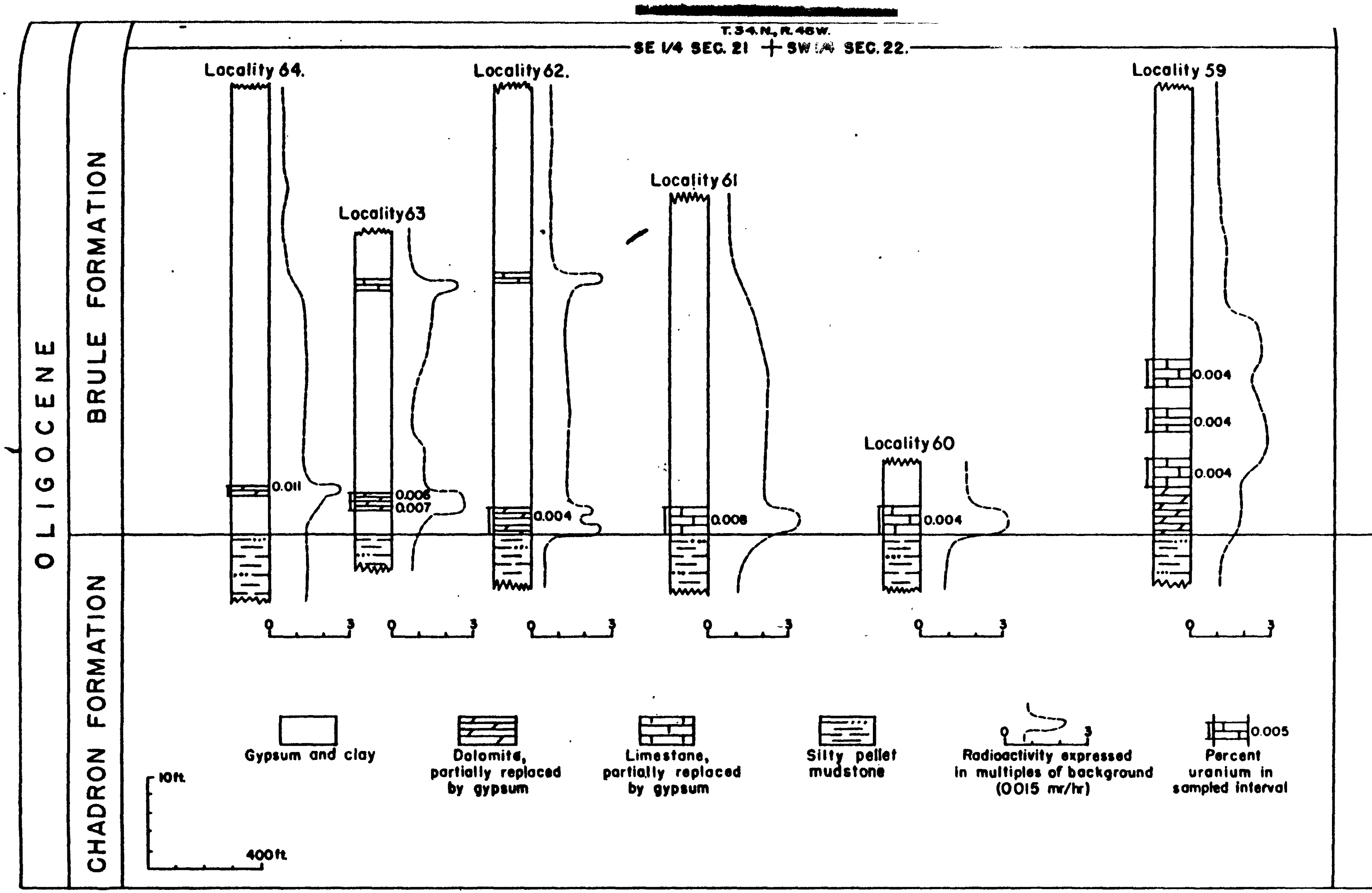


FIGURE 36.--Columnar sections showing relationship of uranium and radioactivity to carbonate rocks in basal part of gypsum facies of Brule formation.

at the 10 localities sampled; and exposed size ranges from 3 x 50-feet to 5 x 600-feet. Comparable values apply to locality 21, sec. 6, T.34N., R.46W., locality 32, sec. 29, T.34N., R.48W., locality 48, sec. 3, T.34N., R.47W., locality 68, sec. 2, T.34N., R.47W., locality 69, sec. 10, T.34N., R.47W., and locality 70, sec. 4, T.34N., R.47W., which were not sampled.

Whether the uranium occurs as submicroscopic uranium minerals or in the crystal lattice of other minerals is unknown; microscopic examination failed to reveal uranium minerals. The microscope did confirm the field evidence for extensive replacement by secondary gypsum.

Distribution of Uranium

The mineralized gypsum and clay and the uraniferous limestone and dolomite share several resemblences. For that reason, they will be treated as a genetic unit.

Relationship to Host Rock

Rich concentrations of uranium are co-extensive with intervals of gypsum and clay containing carbonaceous matter. Lean concentrations are restricted to dolomite and limestone. These favorable host rocks are absent above the basal part of the gypsum facies, except for very thin beds of dolomite. Concentrations of uranium are also absent.

Relationship to Overlying Gypsum

The known concentrations of uranium in the Brule formation in the Chadron area are restricted to the gypsum facies. The relationship could be real or could be an indirect effect of the relationship to host rock; however, one of the favorable types of host rock, the dolomite and limestone, projects out of the gypsum facies into the clastic facies. Notable radioactivity and uranium content disappear at the facies boundary. It thus seems that favorable host rock must be overlain by gypsum if uranium is to be concentrated.

Relationship to Structural Position

The localities of rich concentration of uranium occur on the south end of the Duthie dome and roughly on trend with a small fault a mile to the northwest of the uranium localities. It might be thought that rich concentration is therefore related to structural position more than to host rock. On the other hand, the Duthie dome and the fault are pre-Oligocene features -- the dome is not present on the map showing Oligocene structure, and the fault is covered at one end by unfaulted Chadron formation. Uranium content of the limestone and dolomite zone is unrelated to structural position. Relationship between uranium and structural position thus seems weak or absent.

Relationship to Fractures

Veinlets of carnotite and sabugalite suggest that uranium is related to fractures. Macroscopic veins or mineralized fractures bearing these minerals, however, are not evident in the field. Autunite does coat fractures, but this may be the result of modern weathering. Macroscopic fractures in the limestone and dolomite zone apparently did not localize uranium.

Origin of Uranium

The problem of origin of the uranium in the gypsum facies is largely unsolved. A few tentative inferences are possible.

Time of Emplacement

The uranium probably is epigenetic rather than syngenetic. Syngenetic uranium is typically scarce in evaporites and carbonates, according to the meager analytical data of Bell (1956, p. 382-384). The inconclusive evidence from fractures suggests that the uranium was emplaced after the rocks had hardened enough to fracture, but before fracturing had gone very far.

Direction of Transport

The uranium probably was delivered by descending water. Had the uranium entered the site of precipitation from below, or from the sides, the relationship to overlying gypsum would be unaccounted for; ascending or laterally delivered water would be as likely to leave its uranium in favorable host rock in the clastic facies as it would to leave its uranium in favorable host rock in the gypsum facies.

Agents of Precipitation

Carbonaceous matter is a well known precipitant, acting either directly or indirectly. Calcite may also be a precipitant. In their paragenetic studies of uranium deposits of the Colorado Plateau, Laverty and Gross (1956, p. 201) found that "organic remains and calcite were the two main precipitants for the black uranium ore minerals." Dolomite might possibly be a precipitant also, but this need not be postulated, because the dolomite could have been calcite when the uranium was precipitated.

If the inference of descending water is valid, then Bethke's (1953, p. 182) experimental work seems applicable to the uraniferous dolomite and limestone. He shows that available sulfate ion concentration is a controlling factor in holding uranium in a uranyl solution. He says that the uranyl ion uses the sulfate ion as a vehicle, so to speak, with which to move in ground water solution, and that any substance that can rob the uranyl ion of its sulfate ion vehicle will precipitate it as a uranium mineral.

Water moving downward through gypsum would surely be rich in sulfate ion. As long as the concentration of sulfate ion remained high, the solution could carry uranium, but where the solution began to replace dolomite and limestone at the base of the gypsum sequence, the concentration of sulfate ion would have been diminished, and uranium would consequently have been precipitated. The abundance of secondary gypsum in the limestone and dolomite zone is evidence that sulfate actually was lost at the place where uranium was precipitated.

Source of Uranium

Several possible sources of uranium can be listed. Reliably evaluating them calls for more evidence than is now available

Hydrothermal

Conceivably, uranium-bearing hydrothermal water could rise, mingle with ground water, descend through the gypsum facies, then precipitate its uranium. Alternatively, the hydrothermal water could produce high-grade deposits which would serve as source for the uranium in the gypsum facies and then be eroded away. Although both speculations are within the realm of possibility, they lack supporting evidence.

Volcanic Ash Leached After Deposition of Gypsum

The ash-leach hypothesis, which was discussed in the section on uranium in Eocene(?) soil, is fully competent to account for the available evidence about the uranium in the gypsum facies. Two variations of the hypothesis can be differentiated. The conventional one is that uranium was leached from the ash by sub-surface water after the gypsum had been deposited. Water analyses show that leaching is still going on.

Volcanic Ash Leached During Deposition of Gypsum

The second variation of the ash-leach hypothesis is that uranium was leached from the ash by surface water during Oligocene time, the uranium later migrating down to the base of the gypsum facies. The possibility is worth listing because Oligocene surface water probably was alkaline enough to be an extraordinarily effective leaching agent. This inference is based on the following line of reasoning:

1.) The solubility of silica in the form of volcanic ash, or glass, increases sharply above pH 9, as shown by Krauskopf (1959, p. 10).

2.) Modern lakes rich in sodium carbonate are highly alkaline, pH as high as 12 being reported by Hutchinson (1957, p. 690).

3.) Lakes in volcanic terrain in dry country are rich in sodium carbonate, as shown by Clarke's (1924, p. 156-162) study of Searles, Great Salt, and other western lakes.

4.) The body of surface water in which the Oligocene gypsum was deposited lay in volcanic terrain rich in sodium, as shown by Wanless (1922, p. 197), and in dry country, as shown by gypsum being precipitated.

5.) The ancient body of surface water therefore probably was more alkaline than pH 9; if so, it was an extraordinarily effective solvent of volcanic ash.

Leaching done by surface water probably would have been supplemented by leaching done by soil water that seeped into the body of surface water. Alkali soils, which characterize low-lying land near alkali lakes are notoriously alkaline, pH being as high as 11 according to Millar and Turk (1951, p. 429).

How uranium in surfacewater would have reached the basal part of the gypsum sequence is unknown. Density differences or diffusion could cause downward migration. A perhaps more attractive possibility is that once or more near the end of Oligocene time the ground water table sank, with the result that surface water became descending subsurface water. Lowering of the water table near the end of Oligocene time is independently indicated by the erosional unconformity at the base of the Miocene sequence.

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