GEOLOGY

OF THE KNIFE RIVER AREA

NORTH DAKOTA

By

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U. S. GEOLOGICAL SURVEY

OPEN FILE REPORT

1953

This report is preliminary and has not been edited or reviewed for conformity with U. S. Geological Survey standards and nomenclature

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ILLUSTRATIONS

Plates 6 thru 28 are photos and are not reproduced in this copy (Pages 296-318)

The Knife River area, consisting of six 15-minute quadrangles, includes the lower half of the Knife River valley in west-central North Dakota. The area, in the center of the Williston Basin, is underlain by the Tongue River member of the Fort Union formation (Paleocene) and the Golden Valley formation (Eocene). The Tongue River includes beds equivalent to the Sentinel Butte shale; the Golden Valley formation, which receives its first detailed description in this report, consists of two members, a lower member of grey to white sandy kaolin clay and an upper member of cross-bedded micaceous sandstone.

Pre-Tongue River rocks that crop out in southwestern North Dakota include the Ludlow member of the Fort Union formation, the Cannonball marine formation (Paleocene) and the Hell Creek, Fox Hills, and Pierre formations, all Upper Cretaceous. Post-Golden Valley rocks include the White River formation (Oligocene) and gravels on an old planation surface that may be Miocene or Pliocene.

Surficial deposits include glacial and fluvial deposits of Pleistocene age and alluvium, dune sand, residual silica, and landslide blocks of Recent age. Three ages of glacial deposits can be differentiated, largely on the basis of three fills, separated by unconformities, in the Knife River valley. All three are of Wisconsin age and probably represent the Iowan, Tazewell, and Mankato substages. Deposits of the Cary substage have not been identified either in the Knife River area or elsewhere in southern North Dakota. Iowan glacial deposits form the outermost drift border in North Dakota. Southwest of this border are a few scattered granite boulders that are residual from the erosion of either the White River formation or a pre-Wisconsin till. The Tazewell drift border cannot be followed in southern North Dakota. The Mankato drift border can be traced in a general way from the South Dakota State line northwest across the Missouri River and through the middle of the Knife River area.

The major land forms of southwestern North Dakota are: (1) high buttes that stand above (2) a gravel-capped planation surface and (3) a gently-rolling upland; below the upland surface are (4) remnants of a broad valley stage of erosion into which (5) modern valleys have been cut. The broad valley profiles of many streams continue east across the Missouri River trench and are part of a former drainage system that flowed into Hudson Bay. Crossing the divides are (6) large trenches, formed when the former northeast-flowing streams were damme by the glacier and diverted to the southeast. The largest diversion valley is occupied by the Missouri River; another diversion system, now largely abandoned extends from the Killdeer Mountains southwest to the mouth of Porcupine Creek in Sioux County. By analogy with South Dakota, most of the large diversion valleys are thought to have been cut in Illinoian time.

Numerous diversion valleys of Illinoian to late Wisconsin age cut across the divides. Other Pleistocene land forms include ground and end moraines, kames, and terraces. Land forms of Recent age include dunes, alluvial terraces floodplains, and several types of landslide blocks. One type of landslide, called rockslide slump, has not previously been described.

Drainage is well adjusted to the structure, most of the streams flowing down the axes of small synclines.

The bedrock formations have been gently folded into small domes and synclines that interrupt a gentle northward regional dip into the Williston Basin. Three episodes of deformation affected southwestern North Dakota in Tertiary time: (1) intra-Paleocene, involving warping and minor faulting; (2) post-Eocene, involving uplift and tilting; (3) Oligocene, involving uplift and gentl folding.

Mineral resources include ceramic clay, sand and gravel and lignite coal. The Knife River area is the largest lignite-producing district in the United States.

INTRODUCTION

Location and extent of the area

The Knife River area is in west-central North Dakota, about 60 miles northwest of Bismarck, and consists of six 15-minute quadrangles, covering about 1,270 square miles. The Knife River rising west of the town of Manning in western North Dakota, flows eastward to the town of Stanton, where it empties into the Missouri River. Its short course of about 90 miles is all in the soft Tertiary rock of the Great Plains, and, in consequence, the stream is usually a muddy one, heavily loaded with fine sand and silt. The area covered by this report takes in the lower 44 miles of the Knife River and a short segment of the Missouri River.

Mercer County, the leading lignite-producing county of the United States, is nearly all within the Knife River area, which includes also parts of Dunn, McLean, Oliver and Stark counties. The location of the area and its relation to other coal-bearing areas mapped by the U. S. Geological Survey are shown in fig. 1. The six quadrangles that comprise the Knife River area are grouped in two tiers and form a capital "L" lying on its side (fig. 2). The four quadrangles of the northern tier are Stanton, Hazen, Beulah, and Golden Valley, and extend from 101° 15' to 102° 15' west longitude and from 47° 15' to 47° 30' north latitude. The two quadrangles of the southern tier are Medicine Butte and Broncho, and extend from 101° 45' to 102° 15' west longitude and from 47° 00' to 47° 15' north latitude.*

*Some current index maps show only the names "Broncho" and "Golden Valley." The other names on these maps are: AA (Medicine Butte), Kasmer (Beulah), Krem (Hazen), and Deapolis (Stanton). The names used in this report were formally adopted in 1948 and 1949 as the result of field work by both the Topographic and Geologic Divisions of the U. S. Geological Survey.

In order to fill in a small unmapped area between the Fort Berthold Indian Reservation, the Minot area, and the six quadrangles just named, the Knife River area was extended north to include the southeast corner of the Blackwater and the southern edge of the Emmett quadrangles (see fig. 2).

Purpose and scope of the report

The Knife River area was mapped as part of the Department of the Interior's program for development of the Missouri River Basin. The main objectives of the project were to study the Tertiary and Pleistocene stratigraphy of the area and to determine the types and amounts of valuable mineral resources present.

The Bureau of Reclamation's proposed Broncho Dam and Knife River Irrigation Project lie within the mapped area, and basic geologic data were desired to aid both in the construction program in the future development of the region. Also, accurate geologic maps of the coal-bearing formations were needed to aid in land classification and in estimating total reserves of the area because the opening of Truax-Traer's "Dakota Star Mine" north of Hazen in 1944 and the modernization of equipment in the mines at Beulah and Zap skyrocketed Mercer County into the lead among the lignite-producing counties of the country.

The detailed mapping was supported by reconnaissance over much of the southwest part of North Dakota, and the results of this reconnaissance will be summarized in this report.

Previous investigations

The geology of the Knife River area had not previously been mapped in detail, although the coal beds in certain parts of the area have been examined by a number of workers. Wilder (1905, pp. 34-35) and Smith (1908, pp. 19-24) described briefly some of the lignite outcrops along and near the Missouri River in the Stanton quadrangle; Bauer and Herald (1921) mapped the lignite beds in the part of the Fort Berthold Indian Reservation that is included in the northern parts of the Beulah and Golden Valley quadrangles; and Leonard, Babcock, and Dove (1925, pp. 121-122 and 125-131) mapped the outcrop of the Beulah-Zap coal bed in the vicinity of Beulah, and describe outcrops of other beds near Hazen and Stanton.

General stratigraphic studies in western North Dakota have been made by Leonard (1908, 1909, 1909 and 1922), Thom and Dobbin (1924), Kline (1942), Seager (1942), Hernen (1943), and Brown (1948). The Pleistocene geology is discussed briefly by Todd (1922), Leonard (1916 and 1916), and Alden (1932).

Clapp, Babcock, and Leonard (1906) studied some of the clays in the Knife River area in a paper dealing with structural and ceramic clays of North Dakota.

Wood's (1904) reconnaissance of part of west-central North Dakota includes most of the Knife River area, and this paper is outstanding for the number of good observations that must have been made in a very short time. Wood was one of the best observers and geologic thinkers who have worked in North Dakota. He was careful to differentiate fact from inference, and, although one may disagree with some of his interpretations, his observations and descriptions of outcrops are excellent, and his reasoning is sound.

Field work and acknowledgments

Field investigations were conducted in the summers of 1946 through 1949 in consequence of an allotment of funds from the U. S. Department of Interior's Missouri River Basin appropriation. I was in charge of these investigations and was assisted in 1946 by R. E. Basile and R. B. Colton, in 1947 by R. B. Colton and F. Stugard, Jr., and in 1948 by R. M. Lindvall, H. S. Mayberry and J. R. Scurlock.

Except for the Stanton quadrangle, which has been mapped topographically, planimetric base maps for the Knife River area were compiled from General Land Office township plats and aerial photographs. The plats were used as horizontal control, and the drainage and culture were taken from the photographs. I compiled the base for the Broncho quadrangle; the Topographic Division of the Geological Survey compiled the base maps for the rest of the area. Except for the Stanton quadrangle, latitude and longitude lines are approximate and subject to correction.

The field mapping was done directly on aerial photographs at a scale of about 1:20,000, and the information was transferred to the base maps with the aid of a vertical sketchmaster. Primary vertical control was obtained from Coast and Geodetic Survey bench marks, from the Stanton topographic quadrangle, and by spirit leveling. Bench marks established by these methods were used as a basis for surveying with plane table and with a Paulin altimeter. The altimeter traverses were more rapid, and were considered sufficiently accurate for most of the work.

I wish to thank the various members of the Knife River party for their fine assistance and cooperation during the field studies. Thanks are due also to many of the local residents of North Dakota, who aided the work in many ways, from supplying critical information on wells and mines to supplying tractors to aid our mired trucks. The cooperation of the following persons and organizations in supplying maps, well logs, and other pertinent information is greatly appreciated: J. M. Hughes, Land Commissioner of the Northern Pacific Railway Company, U. S. Engineers, Garrison District; U. S. Bureau of Reclamation, Bismarck Office; and Dr. Wilson M. Laird, State Geologist of North Dakota. I wish to acknowledge especially the aid and cooperation of Professor R. F. Flint of Yale University and R. W. Brown of the Geological Survey.

Flint, who was in charge of regional Pleistocene studies in South Dakota, visited the area several times and discussed the field relations of the glacial deposits. Brown, in addition to identifying the fossil plants, visited the Knife River party for several days each summer from 1947 through 1949 and worked with us on the general stratigraphic relations of the Tertiary deposits.

GEOGRAPHY

General setting

Fig. 3, a sketch map of the physiographic subdivision of North Dakota, shows that the Knife River area lies entirely within the glaciated portion of the Missouri Plateau which in turn is a section of the Great Plains Province (Fenneman, 1923, pages 276 to 277). The Missouri Plateau occupies the western half of North Dakota and is divided into glaciated and unglaciated portions. The eastern half of the State is occupied by the Western Lake section of the Central Lowlands province. The boundary between these two provinces is the Missouri Escarpment, which lies 30 to 90 miles east of the Missouri River, and trends north-northwest from South Dakota to the Canadian border. The name "Coteau du Missouri" has been applied to this escarpment and to the high ridge of morainic hills just west of it but Andrews and Lemke (Andrews, 1939, p. 50; Lemke, manuscript in preparation) quote a decision by the U. S. Board of Geographic Names to the effect that the name "Coteau du Missouri" should be applied to the part of the Missouri Plateau that lies between the escarpment and the Missouri River. This leaves the escarpment itself without a name, and I prefer the usage of Simpson (1929, pp. 10-11) who gives the following description:

> "On the western border of the Drift Prairie rises an escarpment which is even more abrupt than that which bounds the prairie on the east. This feature is the eastern edge of the Missouri Plateau and is known as the Missouri escarpment. This escarpment trends northwest and passes near and to the west of Crosby, Kenmare, Minot, Carrington, and Jamestown. It is in general 500 to 600 feet above the lower plain to the east. The plateau, which stretches westward from this escarpment to and beyond the western border of the state, occupies fully half of the state and is a characteristic portion of the Great Plains."

East of the Missouri Escarpment, the Western Lakes section of the Central Lowlands province is divided into the Drift Prairie and the Red River Valley. The Red River Valley in the extreme eastern part of the state is the floor of glacial Lake Agassiz and has virtually no relief except for a few beach ridges of sand and gravel. The western boundary of this old lake floor is the low and indistinct Pembina Escarpment, from which the Drift Prairie rises gradually westward. The Drift Prairie consists of a bedrock surface buried by 50 to several hundred feet of late Wisconsin glacial drift, mostly ground moraine. The ground surface has very low relief, and the few hills that rise above the general surface probably have bedrock cores. Drainage is poorly integrated, and numerous small lakes and ponds occupy shallow depressions in the surface of the drift. A few larger lakes, such as Devils Lake and Stump Lake, probably occupy former stream channels, now partly buried by the thick drift.

Mantling the surface of the Missouri Escarpment and capping the edge of the Missouri Plateau is a large morainic belt, 5 to 20 miles wide, that has been called the "Altamont moraine." Bedrock outcrops are very few and the illusion is created that the whole height of the escarpment is due to the accumulation of a huge end moraine. Several workers, however, have noted that bedrock crops out in some of the highest hills in the moraine and along the slopes of the escarpment (Howard, Gott, and Lindvall, 1946, pp. 1204-1205, and Townsend and Jenke, 1951, pp. 845-948) and it now seems certain that the position of the escarpment is controlled by the buried bedrock topography. The bedrock escarpment, in turn, probably controlled the location of the moraine by retarding the rate of advance of the glacier and keeping the edge of the ice at or near the same position for many years.

The evidence of bedrock control of both the Missouri Escarpment and its morainic cap has been discussed recently by Townsend and Jenke and is not treated in this report. Townsend proposes the name "Max moraine" to replace the old term "Altamont," because the moraine in North Dakota is not demonstrably continuous with the Altamont moraine at its type locality in eastern South Dakota; in fact, it is not even certain whether the two moraines are of the same age. I agree with Townsend, and in this report I shall use the term Max moraine.

The edge of the Missouri Plateau must have been dissected into a narrow tract of badlands before it was covered by the Pleistocene ice sheets, for although bedrock crops out in some of the higher hills, Townsend reports that some drill holes have penetrated up to 300 to 400 feet of drift before encountering bedrock.

Southwest of the Max moraine the level uplands at the Coteau du Missouri are blanketed by drift 10 to 30 feet thick, but bedrock is exposed in nearly all of the small valleys.

South and west of the Missouri River, the Missouri Plateau is a gently rolling upland ranging in altitude from 1,800 to 2,800 feet above sea level. Numerous buttes and mesas stand above the general level of this upland, among which are Sentinel Butte, Bullion Butte, and H. T. Butte, the last named being the highest point in North Dakota, with an altitude of 3,468 feet. Into the rolling upland of the Missouri Plateau have been carved the mature valleys of the Cannonball, Heart, Knife, and Little Missouri rivers, all of which are tributaries to the Missouri River. Narrow tracts of badlands border each of these streams along some parts of its course, but none of the badland areas is comparable in size or in depth of dissection to the badlands of the Little Missouri River. These badlands have a local relief of 200 to 600 feet and flank the river in a belt 2 to 10 miles wide throughout most of its course in North Dakota (pl. 6A).

The Missouri River itself occupies a great trench-like valley 200 to 600 feet deep and 1 to 3 miles wide. In contrast to the valleys of its tributaries, the Missouri trench is incised sharply into the surface of the Plateau with little or no regard for the regional slope to the northeast. The valleys of the Knife, Heart, and Cannonball rivers can be seen from many miles away because the land slopes gently down toward these valley floors, but in many places one can be within 4 or 5 miles of the Missouri River and see no sign whatsoever of the valley. In some places the surface of the Plateau actually slopes away from the trench of the Missouri. This topographic discrepancy between the Missouri River valley and the valleys of its tributary streams is due to the unusual origin of the Missouri River trench, and will be discussed in connection with the glacial history.

Although the northeastern part of the Missouri Plateau in North Dakota has quite obviously been modified by glaciers, the boundary between the glaciated and unglaciated areas is topographically indistinct. Southwest of the Missouri River the drift cover thins and the glaciers had little or no effect on the topography. The actual drift border is marked only by the limit of erratic stones brought down from Canada by the ice sheets.

Topography

The Knife River area is within the glaciated portion of the Missouri Plateau but it has surface features typical of both the glaciated and unglaciated portions.

The uplands in the northern and eastern parts of the area are covered by glacial drift 5 to 20 feet thick with typical ground moraine topography. The Krem moraine, a small recessional moraine with a local relief of about 20 feet, caps the divide between the Knife- and Missouri River drainages in the northern parts of the Golden Valley, Beulah, and Hazen quadrangles. Bedrock in this part of the area is exposed chiefly in the stream valleys and in the narrow badland tracts that border the Missouri River. There are no prominent buttes or mesas and the nearly flat till-covered uplands merge imperceptibly with the gently sloping sides of most of the smaller valleys.

Southwest of Beulah the glacial drift thins, becomes patchy, and finally disappears except for the few erratic boulders of granite and limestone that remain on the surface of the ground. The topography seems to have been modified very little by the ice sheets.

The interstream divides consist of gently rolling grass-covered uplands that grade without sharp break into the maturely dissected slopes of the valleys. A more youthful topography is characteristic of the valleys themselves and the areas immediately bordering them. Bordering the Knife River and some of its major tributaries are small tracts of badlands.

The most prominent landmark in the Knife River area is Medicine Butte, a conical hill that stands about 200 feet above the surrounding uplands. Medicine Butte is in the west-central part of the quadrangle that bears its name and is clearly visible for many miles from the north, east, and west. To the south the upland gradually rises to a high point about 3 miles from the butte. The crest of this topographic high area actually is a few feet higher than the top of Medicine Butte and effectively blocks a view of the butte from the south.

The highest point in the Knife River area is in the Golden Valley quadrangle in sec. 22, T. 146 N., R. 90 W. This point, which is occupied by the United States Coast and Geodetic Survey's Triangulation Station "Miller," is about 2,420 feet above sea level (determined by Paulin altimeter). The lowest point in the area is in the southeastern corner of the Stanton quadrangle where the flood plain of the Missouri River is about 1,670 feet above sea level. The maximum relief, therefore, is about 750 feet, although local relief in most parts of the area is not more than 300 or 400 feet.

The most striking topographic feature of the Knife River area is the series of through valleys or trenches that cross the area from northwest to southeast with little regard for the major drainage pattern. Although these valleys are large, some of them as large as the valley of the Knife River itself, they contain only small streams, or, in some segments, no streams at all. Like the Missouri trench they are believed to have been cut by waters flowing at or near the margin of an ice sheet. The largest of these valleys are in the southern part of the area in the Broncho and Medicine Butte quadrangles and today are occupied by the South Fork of the Knife River and Elm Creek. These two valleys continue southeast out of the Knife River area, cross into the Heart River drainage basin, and come together just east of the town of Glen Ullén about 15 miles south of the Medicine Butte quadrangle (see fig. 13). They are a small segment of a long Pleistocene drainage course that extends from the Yellowstone River across to the Little Missouri River and from there to the Knife, Heart, and Cannonball River drainages, finally joining the Missouri River near Fort Yates in southern North Dakota. Other large trenches in the Knife River area are: The Goodman Creek trench, which connects the Little Missouri River drainage with Spring Creek in the Golden Valley quadrangle; the Golden Valley trench, which crosses the high area between Spring Creek and the Knife River in the Golden Valley, Beulah, and Medicine Butte quadrangles; and the Beulah trench, which connects the Missouri River with Spring Creek and the Knife River in the Beulah and Hazen quadrangles. The Beulah trench splits into two parts about 5 miles north of the town of Beulah. One branch trends southwest and joins Spring Creek about 3 miles east of the town of Zap; the other branch trends east to join Antelope Creek and then southeast to join the Knife River near Hazen. All of these through valleys or trenches have wide, nearly flat floors and are partly filled with unknown thicknesses of alluvial and colluvial material.

Drainage and water supply

The Knife River area is entirely within the drainage basin of the Missouri River. Runoff flows directly into the Missouri River in the northern and eastern parts of the area and into the Missouri River by way of the Knife River and its tributaries in the rest of the area, with the exception of a small tract in the northwestern part of the Golden Valley quadrangle. This tract is drained by Hans Creek, which rises near the Dunn County - Mercer County line, and flows northwest through the Goodman Creek trench to the Little Missouri River.

The Missouri River forms a small part of the northern boundary of the area and flows south through the Stanton quadrangle. The floodplain of the Missouri in this quadrangle is 2 to 3 miles wide and has a gradient of about 1.6 feet per mile. During the early pioneer days the Missouri River was an important route of travel between east and west and was an important source of water for domestic and livestock use. The Lewis and Clark Expedition followed the Missouri River valley and the site of Fort Mandan, their first winter's camp, is in the southeastern part of the Stanton quadrangle. With the development of railroads and highways the Missouri River Valley was virtually abandoned as a route of travel, but it is still an important source of water supply for towns, ranches, and farms that are located along its course. In the Knife River area the town of Riverdale, which overlooks the Garrison Dam site, obtains its water from the Missouri River.

The Knife River enters the area in the western part of the Broncho quadrangle and flows east and northeast to its confluence with the Missouri River near the town of Stanton. The flood plain of the Knife River is 1 to 2 miles wide and has a relief of about 10 to 15 feet. Above its junction with Spring Creek, about 1 mile west of Beulah, the gradient of the Knife River flood plain is about 7 feet per mile; from Beulah downstream to the mouth the gradient is about 4 feet per mile. All of the major tributaries of the Knife except Spring Creek enter from the south. From west to east these major tributaries are: the South Fork of the Knife River, Willow Creek, Elm Creek, Beaver Creek, Brush Creek, Otter Creek, and Kinneman Creek. The South Fork of the Knife River and Elm Creek are underfit streams that occupy two of the trenches that cross the area. The rest of the tributaries appear to be normal in that they fit their valleys.

Spring Creek enters the area in the southwestern part of the Golden Valley quadrangle and flows east across that quadrangle and the Beulah quadrangle to join the Knife River one mile west of

Beulah. Its floodplain is about one mile wide and has a gradient of 12 feet per mile. Spring Creek's only large tributary in the area is Goodman Creek, which rises in the western part of Mercer County and flows southeast to join Spring Creek near the town of Golden Valley.

Both Spring Creek and the Knife River rise in the Great Plains and are therefore subject to great seasonal variations of the North Dakota climate. They are fed by enough springs to insure a perennial flow, but the summer flow is so small that neither stream is used as a water supply for any of the small towns in the area.

With the exception of Riverdale all the towns and ranches in the Knife River area derive their water supply from wells. A few of the ranches situated along the bottomlands have shallow wells in the alluvial fills of the valleys, but for the most part both municipal and domestic wells tap aquifers in the Fort Union formation (Paleocene). The well at Truax-Traer's Dakota Star Mine north of Hazen goes through the Fort Union, Cannonball (Paleocene), and Hell Creek (Cretaceous) formations and gets part of its water from the Fox Hills sandstone (Cretaceous). The aquifers in the Fort Union formation are lignite beds and some of the sandstone beds. As a general rule the lignite aquifers are better and give a stronger flow of water. Water from the sandstone aquifers has a better taste than that from the lignite beds but it is also harder and is therefore not preferred. Water supply for livestock is derived in part from wells and in part from springs that issue from lignite outcrops.

In the central part of the Broncho quadrangle are three artesian wells; two are in the bottom of the Knife River valley and one is in the valley of Elm Creek. A fourth well, located in sec. 24, T. 143N., R. 90W., is about 300 feet deep and its collar is about 150 feet above the Knife River. This well is not flowing but the head of water comes within a few feet of the surface. The head of water in this small artesian basin, therefore, is about 150 feet above the flood plain of the Knife River. Were it not for this fourth well, the three flowing wells might be catalogued in Fuller's narrow valley type of artesian system (1908, p. 39). But the presence of a head of water almost 150 feet above the Knife River floodplain at a distance of 2 miles from the river suggests that this is truly a small artesian basin. From the structure contour map shown in pl. 5 it can be inferred that the valley of the Knife River is about 150 feet lower structurally than the southern boundary of the area. The strata continue to rise to the south so that it is quite possible to get enough artesian head between the Knife River Valley and a point about 20 miles south of the area to account for these wells.

Climate

North Dakota, in the center of the great interior plains of North America, has a continental climate. Winters are long and severe; summers, rather short and hot. The mean annual temperature for the state from the years 1892 to 1949 is 39.6 degrees F., but this gives little indication of the extreme range of temperature. Winter temperatures are frequently below -20°; summer temperatures are frequently above 100°. The highest temperature ever recorded by a U. S. Weather Bureau station is 124° F. at Medora in Billings County on Septmeber 3, 1921. The lowest official temperature on record is -60° at Parshall in Mountrail County on February 15, 1936, but an unofficial low of -74° F. was recorded by the Lewis and Clark Expedition at Fort Mandan in the Stanton quadrangle on December 16, 1804. The average annual precipitation for the State is between 17 and 18 inches, more than half of which falls during the summer months. The highest precipitation is in the southeastern part of the State in the Red River Valley, where the average is more than 22 inches per year. This average decreases to the west to a low of less than 14 inches at the Montana-North Dakota State line. The average annual precipitation in the Knife River area is about 16 inches per year.

Since 1940 average precipitation in North Dakota has been above or less than one inch below normal and the crops by and large have been good. The most severe year in North Dakota was 1936. The average precipitation for this year was only 8.83 inches and practically no crops were harvested. February of that year was the coldest month on record, and July the hottest month; the temperatures ranged from -60° F. at Parshall on February 15 to + 121° F. at Steele in Kidder County on July 6.

The growing season (the period between the latest and the earliest killing frosts) ranges from 110 to 120 days. Although this is a comparatively short season, the growth of crops is favored by the length of the days in the summer months. On June 21, the longest day of the year, the sun shines for about 16 hours.

Crop growth is also favored by two other factors, the large number of clear days during the growing season, and the fact that more than half the annual rainfall comes during the summer months. Most of the summer precipitation occurs as local thunder showers so that although the average precipitation for the State may be high, certain local areas can have crop failures during a year when the average precipitation is above normal.

The success or failure of wheat and other grain crops depends not only on the location of the local thunder showers, but also on their timing. If showers fall when grain is sprouting and when it is filling out, a successful crop may be harvested even though the precipitation is below average. If showers do not fall at these critical periods the crop may fail even though the annual average is above normal.

Vegetation

The Knife River area has a prairie type vegetation. Native grasses cover most of the uncultivated uplands and slopes, and trees are confined to the valley bottoms and to protected gullies where the water supply is more plentiful.

Boxelder, cottonwood, green ash, and white elm are the most abundant types of trees, and of these only the green ash is commonly found away from springs or the bottoms of stream valleys. Small groves of green ash are found on the north and northeast sides of some hills where evaporation is slower than it is on slopes more directly exposed to the hot summer sun. Cottonwood is abundant along the bottoms of the major streams. Apparently it is limited to areas where the water table is within a few feet of the surface.

Rocky Mountain juniper, falsely called cedar, is quite common in the badlands of the Little Missouri River, but in the Knife River area the only native conifer is a low-creeping juniper. (Ponderosa pine does not occur naturally but has been grown successfully in some windbreaks.) The creeping juniper prefers steep, partially bare slopes and is abundant on the sandy clay outcrops of the basal member of the Golden Valley formation (Eocene).

Bur Oak was found in some of the gullies adjacent to the Missouri River but appears to be absent over most of the area. Quaking aspen occurs in small groves usually at the heads of gullies near the Knife and Missouri Rivers. Several small varieties of willow border most of the streams that have water during the summer months, but the only species that grows to the size of a small tree is the peach leaf willow. In the latter part of the 19th century many of the early settlers planted trees as windbreaks and shade around their homesteads; but the types of trees were ill chosen to stand the rigors of the climate. And the settlers did not realize the need for cultivating their groves. As a result nearly all of these early plants soon died out. Today, however, improved methods of cultivating and a wiser selection of the types of tree has shown that windbreaks and shade belts can be successfully grown around the farms and ranch houses. Russian olive has been imported and is a major constituent of most windbreaks.

Native fruits include wild plum, western chokecherry, buffalo berry or bull berry, and service berry. Buffalo berry is most abundant in the stream valleys but is common also on some parts of the upland.

The following list of trees and shrubs is not complete but shows the common types identified in the Knife River area:

Conifers:

(1) Ground Juniper (*Juniperus sp.*?)

Deciduous trees and shrubs:

(1) Black Sage (*Artemsia tridentata*)

(2) Boxelder (*Acer negundo*)

(3) Serviceberry (*Amelanchier florida*)

(4) Dogwood (*Cornus sp.*)

(5) Black Hawthorn (*Cretaegus douglassii*)

(6) Green Ash (*Fraxinus pennsylvanica lanceolata*)

(7) Quaking Aspen (*Populus tremloides*)

(8) Plains Cottonwood (*Populus sargentii*)

(9) Wild Plum (*Prunus americana*)

(10) Western Chokecherry (*Prunus virginiana* var. *demissa*)

(11) Wild Rose (*Rosa humilis*)

(12) Peachleaf Willow (*Salix amygdaloides*)

(13) Silver Buffaloberry (*Shepherdia argentea*)

(14) Nannyberry (*Viburnum lentago*)

(15) White Elm (*Ulmus americana*)

(16) Bur Oak (*Quercus macrocarpa*)

Cultivated trees:

(1) Maple (*Acer sp.*)

(2) Russian Olive (*Elaeagnus angustifolia*)

(3) Western Yellow Pine (*Pinus ponderosa*)

Native grasses cover most of the region that is not under cultivation and are one of the chief natural resources. The most abundant types are the blue stems, western wheat grass, slender wheat grass, quack grass, cord grass, wild rye, the blue joints, grammas, buffalo grass, and prairie June grass. The blue joints, sand grass, and cord grasses are the principal hay crops on the moist bottom lands. Over-pasturing during the dry summer months has killed out some of the climax grasses in many of the pastures with the result of permanent injury to these tracts. Every possible effort should be made to preserve the native grasses; they are naturally adapted to the conditions and it is improbable that introduced forms can take their places satisfactorily.

The vegetal cover has a pronounced effect on the rate of runoff and evaporation in this area. In wooded areas, the thick forest litter and humus soil retain moisture that falls as rain or snow, and the shade of the woods slows evaporation. In contrast, the prairie grasses that cover most of the Knife River area form a thick matted sod that is fairly impervious, preventing much of the rainfall from soaking in, and increasing the runoff from heavy showers. This sod also holds the moisture from light rainfalls near the surface where evaporation is relatively rapid. The ground water table, therefore, is relatively deep; in fact most of the water tables are actually perched, in that they are confined to aquifers above and below which the beds are dry. The breaking up of the tough impermeable sod by cultivation has further lowered the water table in many places. Although the rainfall is absorbed more readily in the cultivated soil, evaporation is also more rapid and the new vegetation makes a heavy demand upon the ground water. The result is lowered water tables, increased drying up of springs and streams, and a need for deeper wells.

Culture and accessibility

George Meriwether Lewis and William Clark were not the first white men to see the Missouri River in North Dakota, but the diary of the expedition under their command is the first detailed account we have of the region. They reached what is now North Dakota in the fall of the year 1804, and built Fort Mandan, their first winter camp, on the floodplain of the Missouri River a few miles downstream from the mouth of the Knife River (sec. 14, T. 144,N., R. 84 W.). This stretch of the Missouri valley was at that time inhabited by four smaller tribes of Indians, the Mandans, the Ahnahaways (also called Wattasoons and Shoes), the Minnetarees of the Willows, and the Minnetarees proper a tribe of the Fall Nation. These tribes built lodges of wood, mud, and skins, and the sites of most of their villages are still easy to find, especially with the aid of air photographs. The locations of all but one of the villages occupied in 1804 were found and have been shown on the Stanton quadrangle. The large village north of the Knife River in sec. 21, T. 145 N., R. 84 W., was occupied by the Minnatarees, a tribe of about 450 braves. The village in the northern part of sec. 33 was inhabited by Minnetarees of the Willows, and the village on the hill near the center of the same section was that of the Ahnahaways, a tribe of about 300 people. The village in sec. 16, T. 144 N., R. 84 W., was one of two Mandan villages;

the other Mandan village was on the north side of the Missouri near the expedition's camp, and the site of this village was not seen. The village near old Fort Clark in sec. 14 was probably also a Mandan village that had been abandoned prior to 1804. The two Mandan villages had a total population of about 500, all that was left of the tribe that a few decades earlier had totaled nearly 2,000 and had occupied nine villages farther down the Missouri near the modern cities of Bismarck and Mandan. Disease and war had reduced the Mandans in number, and they had moved north to be near the other tribes for mutual protection against the Sioux. It was during the stay at Fort Mandan that the expedition obtained the services, as an interpreter of Jacques Charbonneau, a French trapper, who lived with the Ahnahaways with his two Indian wives. One of the wives was Sacajawea (Sha-ka-ja-way-ha), who was later to earn a place in American history as a member of the expedition.

The Knife River area west of the Missouri was peopled, in 1804, by the numerous and warlike Sioux nation. The Sioux were nomadic, and the sites of their villages are difficult to find, as they consist today of tepee rings, that is stones arranged in circles to act as anchors for the bottoms of the tepees. Most of these rings have been obscured by the works of the white men, but a few can still be seen on those level parts of the upland that have not been farmed. In the Broncho quadrangle, in secs 1 and 15, T. 142 N., R. 90 W., are small grassed-over pits dug into residual concentrations of dark brown to black flint. These pits are the work of the Sioux, who used the flint for weapons and other implements. Evidently the Indians did not fashion their tools around the pits, because, although broken pieces of flint are numerous, no half-formed or broken artifacts can be found in or around the diggings. Apparently the flint was dug, hand cobbed, and the best pieces taken elsewhere for manufacturing.

The present population of the Knife River area is about 11,000. According to the 1950 census figure, Mercer County alone has 8,686 people, over half of whom live on ranches or farms. Beulah is the largest town, with a population of 1,501; Hazen, with a population of 1,230, is the only other town of more than 1,000 people.

Prior to 1900 most of the towns in the Knife River area were along the Missouri and Knife rivers, with a few scattered in the upland regions. The small settlements on the Missouri River were important shipping centers for grain, and the village of Krem in the uplands near the center of the Hazen quadrangle was a small milling center. In the early part of the 20th century the Northern Pacific Railway Company put a branch line across the Knife River area west to the town of Killdeer. Villages not adjacent to the railroad were gradually abandoned and the population shifted to the valleys of the Knife River and Spring Creek, the course followed by the railroad.

A few miles south of the Knife River area another east-west string of towns follows U. S. Highway 10 and the main line of the Northern Pacific Railway Company.

Most of the Knife River area is easily accessible by automobile. The majority of the section lines have been left open as right-of-ways, and many of these have been graded and partly graveled. Two State highways cross the area. Highway 49, an all-weather gravel road, runs north near the eastern edge of the Medicine Butte quadrangle and connects Beulah with U. S. 10 about 15 miles south of the area. Highway 25 runs east-west across the central part of the area, following nearly the same route as the Killdeer Branch of the Northern Pacific Railway Company except in the Stanton quadrangle where it turns south toward Hanover. This highway is paved in the Stanton quadrangle and is an all-weather gravel road in the rest of the area.

Several of the county-serviced roads in the northern tier of quadrangles have been heavily graveled and are passable in most weather. In the Broncho and Medicine Butte quadrangles, Highway 49 is the only all-weather road. Some of the other roads have been partly graveled but some sections of them are impassable after heavy rains. All surface transportation is subject to the vagaries of the severe winters in North Dakota, and both the roads and the railroad may be blocked for many days after a severe blizzard. In the exceptionally severe winter of early 1949, the towns of the Knife River valley were isolated several times for periods as long as 2 1/2 weeks, during which the only method of communication and supply was by air.

Stock ranching and dry farming are the chief occupations in this fertile but submarginal land. The 16-inch average annual rainfall makes dry farming a gamble in the Knife River area. In years of average or above average rainfall the crops are for the most part excellent, for the soils formed on the Fort Union formation and on the glacial deposits are good. During dry years virtually no crops are harvested, and during the extreme drought of the 1930's even the pasture land succumbed to the rigors of the weather. The little livestock that was kept during these years had to be fed by hay that was imported or that had been stored. New and improved techniques of dry farming have improved the yield of crops enough that most of the farmers can make a successful living if only about 1/2 of the years have above average rainfall. It therefore seems likely that barring a drastic change in climate, this area will remain a combined ranching and farming region.

STRATIGRAPHY

The strata underlying the Knife River area and adjacent parts of North Dakota are described in five general categories: (1) the subsurface rocks not exposed in the State but known from drilling are briefly mentioned; (2) the late Cretaceous and early Paleocene rocks known from nearby areas; (3) the Paleocene and Eocene rocks exposed within the area; (4) younger Tertiary formations not present in the Knife River area; (5) surficial deposits.

Advance Summary

The Knife River area is just southeast of the center of the Williston Basin, a shallow structural basin occupying most of western North Dakota. The greater part of the Williston Basin is directly underlain by the Tongue River member of the Fort Union formation (late Paleocene).

Early Paleocene and late Cretaceous rocks crop out around the margins of the basin in the southern and southwestern parts of the State; Eocene and Oligocene beds cap some of the higher buttes and underlie small synclinal areas in the central part of the basin. Deep wells drilled to explore the possibilities for oil and gas in the Williston Basin show that strata ranging in age from Cambrian to late Cretaceous underlie but do not crop out in the basin.

Only two bedrock units, the Tongue River member of the Fort Union formation (Paleocene) and the Golden Valley formation (Eocene) crop out within the Knife River area. This classification of the Tertiary beds differ from that commonly accepted for the area. During the mapping it was found that beds formerly called Sentinel Butte shale (Eocene) by Seager and other (1942) and [illegible] (1943) contain a Paleocene flora and interfinger with the Tongue River member of the Fort Union formation. They have therefore been included in the Tongue River, and the Paleocene-Eocene boundary has been shifted upward several hundred feet in the section. The strata above this revised Tongue River member contain a wasatch (early Eocene) flora and for these I have proposed the name Golden Valley formation (Benson and Laird, 1947, and Benson, 1949).

Mantling the bedrock in the Knife River area are thin glacial deposits of Wisconsin age. At least three substages are represented, the oldest being the Iowan and the youngest probably the Mankato substage. Deposits of the Cary substage may be missing. The border of the late Wisconsin (Mankato) drift is rather indistinct but trends northwestward across the area through the Golden Valley, Broncho, and Medicine Butte quadrangles. Southwest of this line the drift is very thin and patchy and in most places consists of boulders scattered on the bedrock surface. Northeast of this border the till is from 5 to 20 feet thick on the upland surfaces, and bedrock is exposed chiefly in the sides of large valleys and in the bottoms of small ones.

Pleistocene deposits other than till include glaciofluvial deposits, valley fills related to the glacial deposits, and isolated gravel deposits of indeterminate origin. The stratigraphic succession of the valley fills and glacial deposits is the main evidence that three glacial substages are represented in the Knife River area.

Recent deposits include windblown sand, landslide blocks, residual deposits of silicified boulders, and two ages of alluvium. local thick deposits of colluvium, especially in some of the larger valleys, have been mapped with the alluvium.

Subsurface rocks

Rocks not exposed in North Dakota

The Williston Basin contains a thick series of strata, ranging in age from Cambrian (Deadwood formation) to late Cretaceous (Niobrara formation), that do not crop out anywhere in the State. These rocks are not dealt with in this report, but have been described from drill logs by Ehlers (1943, pp. 1618-1620) and by Laird (1944). A preliminary log of the Kelley-Plymouth Leutz #1 well, drilled in the Medicine Butte quadrangle in 1950, is given in the appendix.

The present search for oil in the Williston Basin will certainly yield a great deal more information on these buried strata within the next few years.

Late Cretaceous and early Paleocene rocks

The oldest rocks exposed in the Williston Basin of North Dakota are the Pierre shale and Fox Hills sandstone of the Montana group (late Cretaceous). The Pierre shale is a gray to black marine shale composed largely of montmorillonitic clay with local thin beds of bentonite. It is about 930 feet thick in the eastern part of North Dakota and thickens to about 2400 feet in the western part of the State. Under the Knife River area it is about 1200 to 1300 feet thick. In South Dakota the Pierre shale has been divided into eight members by Crandell (1950, pp. 2337-2346), but these members have not as yet been distinguished in North Dakota.

Overlying the Pierre shale with a transitional contact is the Fox Hills sandstone, a marine formation consisting of gray and green shaly sandstone and sandy shale that characteristically weathers to a rusty brown. Many of the sandstone beds are glauconitic. The Fox Hills sandstone ranges in thickness from about 60 to 85 feet along the east flank of the Cedar Creek anticline in Bowman County, to nearly 300 feet thick along the Missouri River in Sioux, Morton and Emmons counties. Along the Cedar Creek anticline the upper part of the Fox Hills consists of a light gray sandstone known as the Colgate sandstone member. The Colgate member contains thin lignites and some fossil plants, but it also contains the fossil Halymenites major, which is supposedly indicative of brackish water. In Sioux and Emmons counties a light gray sandstone, the probable equivalent of the Colgate member, is locally present at the top of the Fox Hills formation, and appears to interfinger with a sequence of banded shale and sandstone containing marine fossils.

The Fox Hills sandstone is disconformably overlain by the Hell Creek formation, the uppermost Cretaceous formation in North Dakota. The Fox Hills and Hell Creek formations appear conformable structurally but the upper surface of the Fox Hills was eroded and channelled prior to the deposition of the Hell Creek. I have seen this disconformity at Glendive, Montana, near Marmarth in Bowman County, North Dakota, and also along the Cannonball River in Sioux County, North Dakota. Smith (Smith, Wendell, personal communication) reports it east of the Missouri River in Emmons County and Jensen (Jensen, F.S., personal communication) has found it near Jordan, Montana.

The Hell Creek was formerly a member of the Lance formation, and was raised to formation rank after it was discovered that the

Cretaceous-Tertiary boundary lies in the middle of the old Lance formation in North Dakota and Montana (Dorf, Erling, 1940 and Brown, R.L., 1938). The Hell Creek formation of North Dakota is now thought to be the equivalent of the type Lance formation in Carbon County, Wyoming. Except for the local Breien member in Morton and Sioux counties, North Dakota, the Hell Creek formation consists of non-marine calcareous gray sandstones and brown to black carbonaceous and bentonitic clays. Thin lignite beds are fairly common in the lower third of the formation but the upper part contains no persistent beds of carbonaceous clay or lignite. Dinosaur bones are common and are easily found wherever the Hell Creek crops out, and these, together with a typical late Cretaceous flora (Brown, R.L., personal communication) are the evidence for the age of the Hell Creek.

In south-central North Dakota a thin fossiliferous marine sandstone interfingers with the lower part of the Hell Creek formation. This sandstone, the Breien member, contains a brackish-water fauna that includes Halymenites and Ostrea glabra, and records a local readvance of the sea into southern North Dakota. According to Laird and Mitchell (1942, pp 14-15) the Breien member lies about 20 feet above the base of the Hell Creek formation and grades both above and below into typical non-marine Hell Creek beds.

The Cretaceous-Tertiary boundary in North Dakota is marked by no unconformity and by no sharp lithologic break. The basal Fort Union formation overlies the Hell Creek with a contact that is conformable at every place where I have seen it. In some places the colors of the two formations contrast sharply, but elsewhere even this color contrast is absent. Typically the Fort Union is a lighter and yellower gray than the more sombre Hell Creek but at some localities this color contrast is reversed and the Hell Creek is actually lighter than the basal Fort Union. According to Brown (Brown, R.L., personal communication) the most reliable lithologic criteria for mapping this contact are the persistent lignite beds that typify the Ludlow member of the Fort Union formation. The dying out of the dinosaurs and the appearance of Tertiary elements in the flora both seem to take place just beneath these first persistent lignites.

The Fort Union formation (Paleocene), directly underlies most of the Williston Basin and the upper part of this formation accounts for most of the bedrock outcrops in the Knife River area. The Fort Union formation in North Dakota has been divided into three members, the Ludlow lignitic member, the Tongue River member, and the Sentinel Butte shale member. The Ludlow lignitic member is the lowest member of the formation and does not crop out in the Knife River area. It is the approximate equivalent of the Tullock and Lebo members of the Fort Union formation in central Montana (See fig. 4). The Ludlow member consists of yellow-gray sandstones, light to dark gray shaly clays, and thin beds of lignite; it resembles the overlying Tongue River member except for a generally darker color and thinner and less persistent lignite beds. In many places in southwestern North Dakota it is impossible to draw a sharp boundary between the Ludlow and the Tongue River members. The Ludlow member interfingers eastward with the Cannonball marine formation. The Tullock and Ludlow members of the Fort Union, together with the Cannonball formation, were formerly designated as members of the Lance formation but the recent work of Brown (1938), Dorf (1940), and Fox and Ross (1942), has shown that all of these are Paleocene and the Tullock and Ludlow are now considered members of the Fort Union formation.

The Cannonball marine formation was deposited in a shallow sea that occupied central North Dakota during early Paleocene time. It intertongues with and overlies the Ludlow member of the Fort Union formation in south-central North Dakota. Two tongues of the Cannonball formation have been identified in the Ludlow exposures along the little Missouri River near Marmarth (Hares, 1928, p.24, and Brown, 1948a, p.1271). At its type locality along the Cannonball River in south-central North Dakota, the formation consists of 250 to 300 feet of light to dark brownish gray shaly sandstone and dark gray marine shales that contain an abundant fauna of pelecypods, gastropods, foraminifera, and sharks' teeth. The formation thins to the west, is concealed beneath glacial drift to the northeast, and until recently was thought to be restricted to southern and central North Dakota. Recent work by Lemke and Brown, however, has shown that the Cannonball persists into northern North Dakota and covers a large area in the eastern part of the Minot region (Brown, R.L., and Lemke, R.W., 1948, and Lemke, R. W., 1950). Stanton (1920,pp 10-15) originally thought that the megascopic fauna of the Cannonball formation was a relict of the Fox Hills fauna and indicated a late Cretaceous age. But Fox and Ross (1942) show that the age of the megascopic fauna can be Paleocene as well as late Cretaceous. They state also that the foraminifera are more closely related to the fauna of Paleocene Midway formation of the Gulf Coast region than they are to any known Cretaceous fauna. The Cannonball formation crops out along the Missouri River as far north as the town of Washburn, about 10 miles east of the Knife River area.

The raising of the Cannonball to the rank of a formation, while leaving the Tullock and Ludlow as members of the Fort Union formation, results in the anomalous situation in which the Fort Union formation both overlies and underlies the Cannonball formation at its type locality. To me it would seem more logical to retain the Cannonball as a marine member of the Fort Union formation, just as it was a marine member of the Lance formation, but in this report I shall follow the official usage of the Geological Survey, which designates the Cannonball as a separate formation.

Rocks exposed in the Knife River area

The sedimentary rocks exposed in the Knife River area comprise the Tongue River member of the Fort Union formation (Paleocene) and the Golden Valley formation (early Eocene), here designated as a formation for the first time. This represents a revision in the stratigraphic section formerly accepted for this region, and, in order to clarify the terminology, the history of the naming and correlation of the formations will be discussed before the formations are described in detail.

Historical background

Previous correlations of the various formations and members of the late Cretaceous and early Tertiary strata in western North Dakota are given in fig. 4. The details of some of these correlations will now be discussed.

FORT UNION FORMATION

General history

The Fort Union formation was first described by Meek and Hayden (1862, p. 433), who called it the Fort Union or Great Lignitic group of beds. The type locality, near the mouth of the Yellowstone River in western North Dakota, consists of beds some of which are now correlated with the Sentinel Butte shale (Brown, 1948a, p.1270), but Meek and Hayden included in this group all the beds overlying the Fox Hills sandstone and underlying the Wind River deposits in Wyoming. Several years later Hayden (1869, pp. 89-92) extended the Lignitic group to include beds along the Rocky Mountain front as far south as Denver, and possibly as far as the Raton coal field in southern Colorado. In 1876 Hayden replaced the term Lignitic group with the name Laramie group (1876, pp. 20-27 and 40-46), and in 1878 (p.IV) he stated that the old Lignitic group evidently included beds of at least three different ages, namely, Wasatch on Fort Union on Laramie.

By 1900 the correlation of the Laramie group had become so confused that Hatcher (1903) redefined Upper Cretaceous beds in eastern Wyoming as the Lance Creek beds, later called the Lance Formation. Hatcher defined the Lance as the sombre-colored beds, containing ceratopsian dinosaur bones, overlying the Fox Hills sandstone and underlying the Fort Union formation. He considered the Lance to be the equivalent of type Laramie and to be Upper Cretaceous. According to Brown (personal communication) and Dorf (1940) Hatcher's type Lance in Wyoming is still a valid formation and is of late Cretaceous age. When later workers extended the name Lance to the north and northeast of its type locality, they included beds that are now known to be Paleocene. In Montana the Lance included the Hell Creek and Tullock members. Traced eastward the Tullock intertongued with and was replaced by the Ludlow lignitic member, which in turn gave way to the east to the Cannonball marine member. Overlying the Lance was the Fort Union formation, which in central Montana consisted of the Lebo and Tongue River members and in western North Dakota of the Tongue River and Sentinel Butte shale members. As stated above, by 1940 the great controversy about the Lance formation had been settled to the satisfaction of nearly all the geologists who had worked in the area and now it is generally agreed that the Cretaceous-Tertiary boundary is at the top of the Hell Creek beds in Montana and the Dakotas and at the top of the original type Lance in eastern Wyoming. The Tullock and Ludlow have now been made members of the Fort Union formation, and the Cannonball has been raised to the rank of a formation.

The Fort Union formation as now defined includes all the continental beds of Paleocene age in western North Dakota and Montana. In central Montana it consists of the Tullock, Lebo, and Tongue River members. Traced eastward (fig. 4) the Tullock and Lebo merge and grade into the Ludlow lignitic member and in western North Dakota the Fort Union formation consists of the dark Ludlow member, light-colored Tongue River member, and, at the top, the controversial Sentinel Butte shale member.

Sentinel Butte shale

Previous correlations

The Sentinel Butte shale was first described by Leonard and Smith (1909, p.16) as a member of the Fort Union formation in western North

Thom and Dobbin (1924) called it Fort Union (?) but suggested that it correlates with the so-called intermediate coal group of northern Wyoming, and with the Kingsbury conglomerate that overlaps the granite core of the Bighorn Mountains. This overlap they regarded as the base of the Wasatch and suggested, therefore, that the Sentinel Butte is of Wasatch age also. Although this correlation was only tentative and did not have supporting paleontologic evidence, the Wasatch age of the Sentinel Butte shale has largely been accepted by later workers, including Seager and others (1942) and Hennen (1943).

Seager and others classified the early Tertiary formations of western North Dakota as follows (1942, pp. 1414-1415):

Eocene series
  Wasatch formation
    Unnamed member
    Sentinel Butte shale member
Paleocene series
  Fort Union formation
    Tongue River member
    Cannonball member - Ludlow member

They stated also (p.1417) that the Sentinel Butte shale extends east from its type locality near Sentinel Butte and is the surface rock in most of Dunn County and part of Mercer County - in other words, it underlies a large part of the Knife River area. They did not, however, describe the lithologies of the Tongue River and Sentinel Butte members in these counties, nor do they discuss the nature of the contact between them.

Hennen (1943) attempted a reconnaissance correlation of all the Tertiary formations in the western part of North Dakota and reaffirmed that the Sentinel Butte shale, which he too regards as Wasatch, extends east to the Knife River area. He relied, however, neither on paleontology nor on lithologic differences between formations, but on the assumed great lateral persistence of sand and lignite beds, and assumption not confirmed by the detailed mapping in the Knife River area. Hennen relied particularly on the assumed continuity of a silicified bed supposed to contain volcanic ash and silicified plant remains. This is his "marker sandstone 21", which he places near the top of the Tongue River member. Brown and I together have examined this "marker sandstone" in the vicinity of Sentinel Butte and Medora, and we believe it is a silicified carbonaceous shale, probably formed along the margin of a coal swamp. We found no evidence of volcanic ash in the unit. Hennen's belief that there is only one such bed in this part of the stratigraphic column is contradicted both by the earlier work of Hares (1928,pp.34-36) and by the detailed mapping in the Knife River area, where six similar silicified beds were found at six different stratigraphic horizons. Most of the objections to using silicified shales as marker horizons over wide areas were discussed by Brown (1948a, pp.1268-1269); but Hennen (1948) so strongly defended his correlations that I was led to recheck some of the field relations in the badlands near Medora. Individual beds, as well as the boundary between the Tongue River and Sentinel Butte members, are easy to trace in this badland area, and it is obvious that Hennen has "jumped section" in crossing the Little Missouri River. East of the river in southern Billings County, the silicified bed that he calls "marker sandstone 21" near the entrance of Roosevelt Park and near Sully Springs railroad station is actually in the Sentinel Butte shale. West of the river in Golden Valley County the silicified bed that he also calls "marker sandstone 21", is 100 feet lower stratigraphically and is in the Tongue River member. The Sully Springs silica bed actually does extend west into Golden Valley County by [illegible] isolated knobs of Sentinel Butte shale northeast of Flattop Butte. Elsewhere west of the river, the Sentinel Butte shale and, of course, the Sully Springs silica bed, have been removed by erosion. Inasmuch as Hennen's correlations in central North Dakota are based on his identification across areas of poor exposure, of "marker sandstone 21", I think it unlikely that his Tongue River-Sentinel Butte contact in and around the Knife River area is at the same stratigraphic horizon as the Tongue River-Sentinel Butte contact near Medora and Sentinel Butte.

Results of current investigations

The mapping and study of the formations in the Knife River area indicated that the beds above the Cannonball formation and below Seager's "unnamed member" comprise but one lithologic and paleontologic unit. Their flora, according to Brown (personal communication), is a typical Tongue River assemblage. Therefore, either the Sentinel Butte shale is absent from the area or it is Paleocene in age and inseparable from the Tongue River member.

This inability to distinguish the Sentinel Butte shale in the Knife River area led Brown to reexamine the whole problem, and he concluded that the Sentinel Butte shale is, as originally defined, an upper member of the Paleocene Fort Union formation (1948a, p.1272).

At various times during the summers of 1947 through 1949 Brown and I together examined the Paleocene and Eocene formations in western North Dakota in an attempt to determine what happens to the Tongue River-Sentinel Butte contact east of Sentinel Butte and the Little Missouri River. We reached the following tentative conclusions:

(1) The contact between the Tongue River and Sentinel Butte shale members of the Fort Union formation is essentially a color boundary, with little lithologic difference between the two members.

(2) This contact cannot be traced directly east because it dips in that direction into the Williston Basin and is concealed by younger formations. It can, however, be traced along the Little Missouri River north and south from the type locality of the Sentinel Butte shale near Medora. To the south, the Sentinel Butte shale can be identified as far as the Marmarth coal field (Hares, 1928), beyond which area erosion has removed all the late Paleocene beds. To the north, the color contact can be followed, at or near the same stratigraphic horizon, as far as southern McKenzie County, where the dip into the Williston Basin carries it below the floor of the Little Missouri Valley.

(3) Beds representing the approximate stratigraphic horizon of the Tongue River-Sentinel Butte contact reappear at the surface on the east side of the Williston Basin in eastern McKenzie, northeastern Dunn and western Mercer counties. In this area, however, there is no color change. The section as a whole is dark, resembling the type Sentinel Butte shale; but it also contains numerous light beds that resemble the Tongue River.

(4) The eastward darkening of the section is probably due to eastward thinning of the Fort Union formation, especially the Tongue River member. Near Medora the combined thickness of the Tongue River and Sentinel Butte members is between 1,000 and 1,500 feet and sand comprises about half of the section. In Mercer County, the thickness of the Tongue River-Sentinel Butte beds is probably less than 800 feet, and the section is 60 to 65% gray shale. Also, as the total volume of sediments decreases, the relative abundance of carbonaceous material increases,

causing a darkening of the color. It is not surprising that the color contrast between the Sentinel Butte shale member and the Tongue River member does not persist as far east as the Knife River area.

(5) The Sentinel Butte shale, therefore, is mappable as a separate member of the Fort Union formation only near its type locality in western North Dakota. To the east it appears to intertongue, both laterally and vertically, with the Tongue River member. We therefore suggest that the name "Sentinel Butte" be used only in western North Dakota; and that beds of equivalent age in the central part of the state be included in the Tongue River member of the Fort Union formation.

GOLDEN VALLEY FORMATION

Previous descriptions

In numerous isolated localities in western North Dakota the Tongue River and/or Sentinel Butte shale member of the Fort Union formation is overlain by beds of light-colored clay and sand that have received little attention since 1906 when they were first described by Leonard, Clapp and Babcock in the Fourth Biennial report of the North Dakota Geological Survey. The authors of this report described numerous outcrops of white sandy fire clays overlying the Laramie formation (which then included the Fort Union formation) on the interstream divides of west-central North Dakota. Leonard said of these clays (p.88):

"These white clays, which cover an area of approximately 4,000 square miles, lie at an elevation of from 2,450 to 2,600 feet above sea level and are confined to the tops of the higher ridges and divides. They have a maximum thickness of about 150 feet.

"The fire clays are remarkably uniform over the entire area, not only in appearance but in chemical composition as shown by analyses of samples from many different localities. Their white color makes them conspicuous wherever they are exposed."

About 25 outcrop areas of these clays were examined in detail and chemical analyses and detailed ceramic tests were made on numerous samples. Concerning the stratigraphic position of these clays the authors said only that they are of Tertiary age and overlie the Laramie formation. In the Chalky Buttes area in Slope County, some beds of White River sandstone were included in these "light colored Tertiary clays."

In 1911 Leonard again described these clays briefly and considered them as upper Fort Union (1911, p.535). He stated that they are well exposed near Dickinson and Gladstone and several miles north of Hebron. In the same report (p.534) Leonard described the Fort Union formation along the Little Missouri River in Billings County as consisting of two members, subsequently called the Tongue River and Sentinel Butte shale members by later workers. Leonard did not state what he believes to be the relationship between the dark Sentinel Butte shale and the light-colored upper unit near Dickinson.

The only other paper that describes these light beds is the discussion by Seager and others (1942, p.1416), who considered them Wasatch (Eocene). They state:

> "The Wasatch formation of Eocene age is represented in North Dakota by two members. The younger is an unnamed light-colored unit, well exposed north of Hebron, North Dakota. The lower member is the Sentinel Butte shale, a dark bentonitic unit whose type locality is south of the town of Sentinel Butte, North Dakota."

Seager's only evidence of a Wasatch age for the "unnamed member" is the fact that it overlies the Sentinel Butte shale; and, as stated above, the Sentinel Butte shale is no longer regarded as Wasatch in age.

Results of present work

In June 1947 the Knife River field party discovered specimens of the floating fern *Salvinia preauriculata* Berry near the base of Seager's "unnamed member" in the hills north of Hebron. *Salvinia preauriculata* is considered by Brown to be diagnostic of the lower Eocene and it therefore appears that the "unnamed member" is actually Eocene and the only Eocene formation so far recognized in North Dakota.

After the discovery of *Salvinia* the "unnamed member" was studied in detail in the Knife River area and mapped in reconnaissance in the rest of southwestern North Dakota. It was proposed in 1947 (Benson and Laird, 1947, pp.1166-1167) to call these Eocene strata the Golden Valley formation and this name has been tentatively adopted pending the detailed description and definition given in this report.

Because of his great interest in the stratigraphy of the State, I originally invited Dr. Wilson M. Laird, State Geologist of North Dakota to join me in the study and Dr. Laird spent a week with me during 1947, contributing many valuable ideas in the early stages of this work. Unfortunately the pressure of other duties made it necessary for Dr. Laird to withdraw from this study. In subsequent years R. W. Brown of the Geological Survey spent several days each summer with me and his great knowledge and experience in Tertiary stratigraphy were of inestimable value in the reconnaissance study of the Eocene strata.

Tertiary system

PALEOCENE SERIES

Fort Union formation - Tongue River member

Distribution and composition

For reasons already discussed, all the Paleocene beds between the top of the Cannonball and the bottom of the Golden Valley formations have been included in the Tongue River member of the Fort Union formation. Beds stratigraphically equivalent to the Sentinel Butte shale probably comprise the upper part of this Paleocene section, but they cannot be distinguished either lithologically or paleontologically from the rest of the sequence and have therefore been mapped as Tongue River member (pl. 7A).

The Tongue River member directly underlies most of the Knife River area and is well exposed in the dissected areas bordering the Knife River, Spring Creek, and the Missouri River. In this area the member consists of beds of non-marine sand and sandstone, silt, shaly clay, and lignite. Thin beds of lenticular limestone concretions are common especially in the sand beds or at the contact between a bed of sand and a bed of shaly clay.

Contacts between beds, especially between sand and clay, are usually completely gradational both laterally and vertically, although a few exposures show sharp erosional contacts at the base of a sand bed. Therefore, correlation of the beds over areas of poor exposure is difficult and uncertain at best.

Sand and sandstone

Beds of sand and soft sandstone comprise about 30 to 35 per cent of the Tongue River member in the Knife River area. They range in thickness from a few inches up to 50 or 60 feet, and are evenly distributed throughout the section, except that the upper 100 feet of the member, which tends to have more and thicker sand beds than the lower part of the section. Despite the great thickness of some of these beds, they have little lateral persistence. Certain beds of sandstone 20 or 30 feet thick pinch rapidly and die out in a few hundred feet, so that in many places it is difficult to match accurately sand beds in sections measured less than half a mile apart.

The color of the sand beds ranges from buff and light yellow gray to medium gray with the various colors distributed uniformly in the section. The lighter-colored beds resemble the sands of the Tongue River member in eastern Montana, except that they seem to contain less white mica. The darker sand beds resemble the sands of the Sentinel Butte shale near its type locality.

Most of the sand beds are fine-to medium-grained; a few are coarse-grained, and two beds near the base of the member in the southeast part of the Stanton quadrangle are conglomeratic, the "pebbles" consisting of clayballs. The sorting is variable. Some beds are well-sorted and consist chiefly of sand-size particles; others are very poorly sorted and contain large percentages of silt and clay. There are all gradations between clayey sand and sandy clay.

Bedding is more easily seen in the beds that have been indurated to sandstone. Although most of the bedding is even and horizontal, ripple bedding is common in many of the fine-grained beds. A few of the coarse beds show cut-and-fill stratification, with the foresets having a general easterly dip.

Megascopically the sand grains appear to be mostly quartz, with some grains of angular calcite, a few pieces of fresh to weathered feldspar and a suite of heavy minerals that do not constitute more than 1 or 2% of the grains. No microscopic study was made of these heavy minerals but in the Heart Butte quadrangle, about 35 miles southeast of the Knife River area, Tisdale indicates that these heavy minerals were probably derived from metamorphic and igneous rocks (1941, pp.30-31). Tisdale further states that while some of the grains show little rounding and are probably in their first cycle of sedimentation, others are well-rounded and probably record a second or third generation of sedimentation (pl. 7B).

Some of the sand beds are weakly cemented by calcium carbonate or iron oxide to form a crumbly sandstone. The iron oxide cement is probably secondary, the result of the weathering of a sandstone whose original cement was a ferruginous calcite. In a few beds the volume of the calcite cement is greater than that of the sand grains. Many of the sand beds have little or no calcite cement but do have a considerable admixture of clay and harden to a compact soft sandstone on surface exposure. Still other beds are composed chiefly of fine-grained quartz and are not indurated at all. Many of the sandstone beds are made up of a series of large calcareous concretions. Some of these concretions are nearly pure limestone and, in places, contain fossils of plants or fresh-water gastropods.

Most of the uncemented sand beds weather light yellow to yellow-gray. The indurated beds weather light gray to dark brown, depending largely on the iron content of the cementing material. Some of the sandstone is spotted with small balls of limonite, which stain the surface a yellowish brown. A few of these balls contain cores of unweathered iron sulphide, probably marcasite. Seams of limonite are common both in the sandstones and in the shales.

The source area of the Fort Union formation was probably to the west, in the Rocky Mountain area in northern Wyoming and Montana.

Tisdale (1941, pp.30-31) found that some of the garnet fragments in the sandstones have magnetite inclusions similar to garnets in the metamorphic rocks exposed in the Black Hills and suggests that the Black Hills may have been a source for some of the Fort Union sediments. He does not believe, however, nor do I, that the Black Hills supplied all the sediments of the Fort Union formation in North Dakota. First of all the volume of the Fort Union appears to be too great to have come from so small a source area. Second, in the Knife area the sandstones with cut-and-fill type crossbedding show foresetting to the east, indicating that the major streams probably came from the west rather than the south

--Shale and clay--

Beds of shale, shaly clay, and clay make up about 60 or 65 per cent of the Tongue River member in the Knife River area and range in thickness from a few inches to several tens of feet. They range in color from light to dark gray and brown, depending largely on the carbonaceous content.

Most of the shales and shaly clays are silty to sandy, but some beds of pure plastic clay occur, especially just above or below a bed of lignite. The bedding is horizontal, and some of the silty shales show fine laminations.

The hard dry surfaces of the clay show varying amounts of cracking, and this together with the gray color has led many workers to call these beds "bentonite" and "bentonitic clay." The terms, bentonite, bentoniti clay, and volcanic ash have been applied very loosely to many of the Tor tiary sediments in the Great Plains. Any clay that cracks on outcrop is said to be bentonitic; any white sandstone is said to contain volcanic ash. Most of the beds reported to contain this volcanic material have not been investigated in the laboratory, which would seem to be essential before the terms can be safely used. In the Knife River area I found no true bentonite and only a few beds that are probably bentonitic clay. The results of petrographic tests of the drill cores from the Broncho dam site which were furnished by H. W. Kirchen of the Bureau of Reclamation indicate that most of the clay beds are composed of a mixture of montmorillonite type, illite type, and kaolinite type clays, and that the illite type and kaolinite type clays in general predominate over the montmorillonite type. One or two beds of dark gray clay do appear to swell up to 100 percent and these may actually be bentonitic. The other beds, however, appear to swell very little and the cracking on the surface is almost certainly due entirely to the drying out of the beds.

Many of the silty and sandy clay beds appear to have some calcium carbonate cement and nearly all of the clays, with or without this cement, bake to a hard surface in the summer sunlight. This induration, however, is a surface phenomenon and is temporary; when wet the clays regain their original plasticity.

--Lignite beds--

Beds of lignite range in thickness from a few inches up to many feet and are the most persistent beds in the Tongue River member. Even the lignites, however, are unreliable as marker beds across areas of poor exposure, for their lateral persistence is extremely variable. For example, the Twin Buttes lignite bed in the western part of the Medicine Butte quadrangle is a thin impure lignite that only locally exceeds

2 feet in thickness, yet it persists over about 100 square miles in this quadrangle and is easily identifiable by a thin clay parting above the middle of the bed. In contrast to this other beds of lignite 5 or 6 feet thick pinch out into clay or sand within a few hundred feet. This rapid pinching of the coal bed does not appear to be due to later channeling but rather is a facies change. The thick Beulah-Zap lignite bed crops out in over two-thirds of the Knife River area and is the best horizon marker in the Tongue River member of the Fort Union formation.

The appearance and physical properties of the lignite are described under the section on Economic Geology.

--Clinker--

Many of the thicker beds of lignite have burned along their outcrops and the fires have fused and baked the overlying sediments to form a red clinker, or "pseudo-scoria." Where the overlying beds were sandy or where the fires were not excessively hot, the alteration involved baking with little effect on the original sedimentary textures. Where the beds were clay and where the fires had a good draft, some of the strata have been fused and resemble the slag from a blast furnace or the real scoria of a lava flow. In fact, the first English description of the clinker beds of North Dakota appears to be in the diary of the Lewis and Clark expedition, where these rocks were called pumice stone, implying that they were of volcanic origin.

After they have been baked and clinkered, the shales and sandstones are much more resistant than most of the other beds in the Fort Union formation. Many benches and small isolated buttes owe their existence to their protective cappings of clinker.

The fires that burned the lignite and baked the overlying sediments have been ascribed to spontaneous combustion, lightning, and prairie fires, but the latter two causes seem totally inadequate to explain the great amount of burning that has taken place from time to time. That lignite can catch fire by spontaneous combustion was demonstrated in the summer of 1949 when a pile of lignite, stored experimentally near the Garrison Dam in the Stanton quadrangle, started to smolder without benefit of lightning or any other external fire.

The burning of the lignite beds proceeds inward from the outcrop for varying distances depending on the thickness and character of the overburden and also upon the thickness and quality of the lignite itself. Thin beds burn, but in general the combustion of these beds is slow and generates little heat. The clinker thus produced is usually thinner and lighter in color than the clinker produced by the burning of a thick bed When a thick bed of good quality burns the volume of the bed decreases to about 20% of the original volume. This causes the overlying strata to slump and crack, creating new paths to supply oxygen to the fire below. If the bed crops out on a steep slope and the overburden is thick these cracks may not extend to the surface of the ground above, and burning will stop a few feet back from the outcrop. If the slope on which the lignite crops out is gentle and the overburden is thin the collapse and cracking can continue to supply air to the fires for as much as a quarter to a half a mile back from the outcrop, and the bed will burn out thoroughly for this distance. Once the bed is set on fire it can smolder and burn for many years. The manner in which these lignite beds burn is well shown by the so called burning coal mine nort west of Amidon in Slope County, southwestern North Dakota. Here, in Sec. 14, T. 135N., R. 102W., the Harmon lignite bed is actively burning today and apparently has been burning continuously since before 1911 when Hares mapped the Marmarth lignite field. Hares reports that this bed was burning with intense heat and that large snowballs rolled into the opening of one of the vents were converted almost immediately to steam (Hares, 1928, p.51).

The burning of the lignite beds and the formation of the clinker has evidently gone on ever since the Fort Union formation was exposed to weathering and erosion. Pieces of clinker are found in the oldest glacial deposits in the Knife River area, and as these deposits are thought to be of Iowan age it indicates that the beds were extensively burned prior to Wisconsin time. On the other hand, in the northern part of the Beulah quadrangle in many parts of T. 146N., R.88W., till of late Wisconsin (Mankato) age has been clinkered by the burning of the Beulah-Zap bed. Some hand specimens of this clinker show in themselves two generations of burning, for the baked till includes pieces of older clinker. Hares (1928, p.52) shows that the White River formation in southwest North Dakota and eastern Montana contains a few fragments of ancient clinker, and I have found two small pieces of what appear to be clinker in the White River sandstone on West Rainy Butte in Slope County. Thus, the burning of the lignite beds seems to have started in the Tertiary period as soon as the streams carved deep enough to expose the Fort Union formation, and has continued through to the present.

--Silicified wood--

Silicified stumps and logs occur at many stratigraphic horizons in the Knife River area. Usually these stumps are found at the top of a bed of coal or carbonaceous shale but locally they are in sandstone beds

Most of the fossil wood retains enough carbonaceous material to color it dark gray to black. This dark color, however, can be seen only on a fresh break, for on exposure it bleaches rapidly to light yellow or white. In general the original cell structure of the wood has been well preserved, and is easily seen with a hand lens. Although the Fort Union formation contains abundant fossil leaves of deciduous trees, all of the wood found in the Knife River area was of a coniferous type. This is probably due to the fact that the deciduous trees grew on slightly higher and dryer ground. From this position their leaves could be washed into the basins of accumulation, but the wood of dead or dying trees would quickly rot away. The coniferous trees, on the other hand, were probably swamp dwellers, similar to the bald cypress of today, and when these tree died or were blown over during a storm, many of them were submerged or were buried quickly below the water table where decay was inhibited. According to Brown (personal communication) many of these trees were probably of the genus Metasequoia, but some of them may have been close relatives of the modern bald cypress. At one locality in the Broncho quadrangle R. B. Colton discovered a fossil stump that had knobs or knees similar to those found on the bald cypress.

It is not possible to say definitely when the wood was silicified but it was probably not long after the deposition of the sediments. The acid waters underlying the coal swamps of Fort Union time probably had a higher content of dissolved silica than the ground waters of any succeeding geologic epoch. Also, it seems unlikely that the original cellulose of the trees could have withstood the pressure of many hundreds of feet of overlying sediments without destroying much of the cell structure. Carbonized logs and stumps that comprise parts of the coal beds have been crushed and flattened, but most of the silicified wood in the Fort Union formation shows excellent preservation of the cell structures.

--Silicified shale and sandstone--

Besides replacing the wood, silica has invaded, cemented, and partly or completely replaced other local beds in the Tongue River member. In general, three types of silicified beds can be differentiated, but they are probably part of a gradational series and there is no sharp dividing line between them. The most striking type of silicified bed is probably the silicified sandstone or fine-grained quartzite. These beds consist of very fine-grained quartz in a matrix of microcrystalline silica. The whole rock is gray and homogeneous in appearance; it is very hard and breaks into sharp angular fragments when hit with a hammer. Local beds of this silicified sandstone occur in many parts of North Dakota and at various stratigraphic horizons in all the formations of continental origin. Blocks of this silicified sandstone or quartzite are extremely resistant to both chemical and mechanical weathering and persist on the surface long after the weaker strata above and below them have been eroded away. In Sioux County, southern North Dakota, I have seen large blocks of this sandstone more than five miles from the outcrop of their parent bed, which here is in the Hell Creek formation. These blocks do not appear to have been transported laterally but rather seem to have been let down vertically more than 200 feet from their original position

The second type of silicified bed is silicified shale. The silicified shale is similar to the sandstone except that it tends to be yellower, splits along definite bedding planes, and shows few or no quartz grains under the hand lens or under the microscope. Prior to silicification these beds were apparently gray shale. Commonly, the silicified shale contains many plant impressions, nearly all of which appear to have been rushes or other swamp dwelling plants. Numerous cylindrical holes pass completely through blocks of the silicified shale and appear to record the position of former roots or stems that were not silicified and that have been destroyed by weathering.

Boulders of silicified sandstone and shale are not as common in the Knife River area as they are in some other parts of western North Dakota. A group of hills in the southeastern part of the Medicine Butte quadrangle and extending south beyond the boundary of this quadrangle is capped by residual boulders of silicified sandstone and shale, but this is the only large concentration known in the area. These residual blocks are probably let down from a silicified bed in the Golden Valley formation.

The third type of silicified rock is actually a variety of silicified shale, but the original bed, instead of being a gray shale, was a black carbonaceous bed probably a lignitic shale around the margin of a coal swamp. This is the most common type of silicified rock in the Knife River area and occurs in at least 6 different stratigraphic horizons within the area. These silicified carbonaceous shales range in thickness from about $\frac{1}{2}$ inch to 8 inches and are very thin bedded and platy. Like the fossil wood these beds bleach white on weathered outcrops but the fresh material is dark gray to black and appears to contain a great deal of residual carbonaceous materal. Locally, silicified stumps and logs rise out of these old soil zones. Apparently the silicified black shales grade laterally into silicified gray shale, silicified sandstone, or into a dark, dense chert. Residual concentrations of this chert were formerly dug by the Sioux Indians in Secs. 1 and 15, T. 142N, R. 90W.

Hennen's "marker sandstone 21" (1943, pp.1569-1570), which he believed to be a bed of volcanic ash that persisted over most of western North Dakota, appears to consist of a number of local silicified carbonaceous shales. These silicified zones are very helpful in detailed local correlations of the strata but there is no reason to suppose that any one of them persists over many miles, or that, once it has pinched out in a given direction, a silicified zone a few miles farther on is a continuation of the first bed.

The silicified sandstones and shales have been described by Tisdale (1941, pp.13-14) and in slightly more detail by Hares (1928, pp.34-36). During his mapping of the Heart Butte quadrangle Tisdale did not find any of these silicified rocks overlain by other bedrock strata, and postulated that they might be due to upward moving ground water which is depositing silica at the present day surface. This seems to me a rather unlikely explanation. First, there is little other evidence to show that the present ground waters are carrying much silica in solution or that they are depositing it at any particular horizon. Second, although these silicified beds apparently do not crop out in the Heart

Butte quadrangle they may be seen in place, overlain by other Tertiary strata, in many parts of western North Dakota, and they have been penetrated by some water wells. Hares cites numerous occurrences of these silicified beds in North and South Dakota, and in many of these places the silicified beds are exposed in place on a hillside. Where they have been encountered in wells the silicified beds do not appear to be quite as hard as they are on the surface, and it is quite possible that Tisdale is correct to the extent that the beds are case-hardened by surface weathering. The siliceous cement, however, appears to have been introduced into the bed long before its exposure from the present surface.

It is impossible to say when these beds were silicified. It certainly happened before the beds were carved into their present topography and before the roots and stems of the swamp plants had decayed and rotted away. My own opinion is that the silicification probably took place during the early Tertiary shortly after the deposition of the sediments.

--Measured sections--

The following partial sections of the Tongue River member of the Fort Union formation are typical of its lithology and appearance in the Knife River area:

Section of the Tongue River member of the Fort Union formation measured in the east half of sec. 14, T. 144N., R. 84W. The base of the section is the bottom of the bluff of the Missouri River Valley near the Lewis-Clark monument. Top of section is capped by residual of clinker of the Stanton coal bed. On adjacent hills this clinker crops out about 15 feet higher stratigraphically than the top of this section.

	Feet
1. Clay, silty, light gray, soft.	9.0
2. Lignite, black, impure	0.2
3. Clay, dark gray, silty	1.1
4. Unexposed	2.0
5. Shale, gray, sandy, interbedded with sand, light gray with clay binder.	8.0 approx.
6. Silt, gray, weathers light yellow	2.5
7. Lignite and carbonaceous clay	0.5
8. Clay, dark gray, plastic	3.3
9. Clay, yellow-brown, soft, silty	2.8
10. Clay, brown, carbonaceous	0.1
11. Shale, light gray, silty	6.0
12. Shale, gray-brown, carbonaceous	0.5
13. Clay, shaly, yellow-gray, with iron oxide seams	9.2
14. Lignite	1.6
15. Clay, light gray	2.8
16. Clay, shaly, light gray to brown, carbonaceous with many plant remains	2.1
17. Shale, light gray with yellow silt bands	3.1
18. Lignite, impure	0.1
19. Shale, gray	3.0
20. Unexposed	3.0 approx.
21. Limestone and sandstone concretionary horizon	1-2½
22. Sand, clayey, weathers hard with drab yellow-gray color	11.5

23. Shale, brown carbonaceous	0.2
24. Clay, gray, plastic, non-silty	1.1
25. Shale, black	0.1
26. Sand, and sandy clay, drab gray with iron oxide seams	5.1
27. Shale, drab yellow-gray with iron oxide seams	4.4
28. Clay, brown carbonaceous	0.1
29. Shale, light gray	2.3
30. Limestone concretion	1.0
31. Clay, shaly, drab yellow-gray-	6.0
32. Lignite	0.4
33. Clay, medium gray, carbonaceous	0.6
34. Sand, hard, clayey, with concretionary zones, stained yellow by iron oxide	12.2
35. Limestone concretions	0.7
36. Shale, drab yellow-gray, fossiliferous near the base	12.8
37. Lignite, impure	0.1
38. Shale, gray, silty, slightly sandy	7.7
39. Poorly exposed unit, mostly yellow silt and sandy shale	10. approx.
40. Sandstone, fine grained, ripple bedded and cross bedded, light gray. Harder ledge-forming beds at the top.	45.0
41. Shale, carbonaceous, sandy, with numerous fresh water invertebrate fossils including Campeloma and Viviparus	0.8
42 Unexposed	20. approx.

Bottom of section at floodplain of Missouri River, altitude about 1680 f.

Total thickness 203.1

Section of Fort Union formation measured in the northeast quarter sec. 1, T. 143N., R 88W.

		Feet	
	1. Till	3. approx.	
Beulah-Zap bed ---	2. Lignite	6.4	Beulah-Zap bed
	3. Shale, gray, well bedded with silt and sand laminae	2.8	
	4. Sand, fine-grained, micaceous with carbonaceous laminae	3.1	
	5. Lignite	3.0	
	6. Unexposed	2.3	
	7. Shale, brown, carbonaceous with abundant fossil wood	2±	
	8. Clay, shaly, gray, soft	4±	
	9. Sand, fine-grained, soft, gray, with silt laminae	5.0	
	10. Clay, shaly, gray, with laminae of silt, Local zone of concretions about 3 feet above base	11.5	
	11. Clay, dark gray plastic	1±	
	12. Lignite	1.1	
	13. Shale, brown carbonaceous	0.8	
	14. Clay, dark greenish-gray, very plastic, swells on exposure, may be bentonitic	5.2	
	15. Shale, light brown to gray, carbonaceous, many fossil leaves including <u>Osmunda</u>	1.0	
	16. Lignite and lignitic clay	1.1	
	17. Clay, dark gray, very soft	1.7	
	18. Shale, gray to light brown, carbonaceous abundant leaf fragments	6.2	
	19. Lignite	1.7	
	20. Clay, carbonaceous	0.5	

21.	Shale, silty, interbedded with sand, fine-grained, Laminated; all stained light yellow by limonite	7.8
22.	Lignite - the Spaer bed	2.6
23.	Shale, light brown, carbonaceous	0.6
24.	Unexposed	2.3
25.	Clay, shaly, hard, greenish-gray with limonite concretions	15.7
26.	Claystone, light gray	1.5
27.	Clay, gray, silty	0.9
28.	Sand, gray-brown, clayey	2 +

Base of exposure

Section of the Tongue River member of the Fort Union formation measured in the northwest quarter of Sec. 5, T. 142N., R. 89W., and the southwestern corner of Sec. 30, T. 143N., R. 89W.

Top concealed

		Feet
1.	Sandstone, light gray, fine-grained	1.0
2.	Clay, shaly, gray	3.5
3.	Sand, gray, clayey	1.0
4.	Clay, gray, silty and sandy	5.8
5.	Shale, brown, carbonaceous	0.5
6.	Shale, dark gray, silty	3.5
7.	Sand, and sandstone, clayey, light yellow-gray	12.0
8.	Clay, shaly, gray to brown	3.3
9.	Lignite and carbonaceous clay, -Schoolhouse bed	6.6
10.	Shale, brown carbonaceous	0.5
11.	Unexposed	3.5
13.	Sand, gray, fine-grained	0.8

13.	Clay, dark gray, plastic	2.5
14.	Clay, dark gray, carbonaceous	0.5
15.	Silt, soft gray with sand laminae	4.5
16.	Sand, and sandstone, fine-grained, thin bedded, clayey, with calcareous concretions	9.8
17.	Sand, dark brown carbonaceous	0.1
18.	Clay, gray, sandy	3.2
19.	Clay, dark gray, silty	3.8
20.	Shale, brown carbonaceous with lignitic streaks	2.0
21.	Clay, sandy, silty, gray	5.2
22.	Sand and sandstone	1.5
23.	Claystone, gray, silty to sandy, very hard	5.5
24.	Clay, black, lignitic	0.3
25.	Clayey sand to sandy clay, gray	4.0
26.	Shale, brown, carbonaceous, with many fossil leaves	1.5
27.	Clay, gray	1.0
28.	Sand, clayey, gray	2.5
29.	Clay, silty to sandy	3.2
30.	Shale, brown carbonaceous	0.8
31.	Sand, gray, clayey, interbedded with silty clay	3.5
32.	Unexposed	11.5
33.	Clinker of Beulah-Zap coal bed	8 approx.
34.	Unexposed	2.0
35.	Shale, gray to brown	5.5
36.	Shale, dark brown, carbonaceous	0.2
37.	Lignite, impure	3.0

38. Clay, gray brown carbonaceous	0.5

Section of the upper part of the Tongue River member of the Fort Union formation measured in the northern part of Sec. 1, T. 142N., R. 91W.

Top-Golden Valley Formation

	Feet
1. Unexposed; contact between Golden Valley and Fort Union formations in this interval	6 +
2. Sand, light gray, soft, with local calcareous concretions	3.0
3. Sand, very fine-grained, clayey, light gray to buff	12.0
4. Lignite, with interbedded brown carbonaceous shale	2.9
5. Sand, dark gray	1.0
6. Clay, silty, dark gray	6.0
7. Clay, black lignitic	0.5
8. Clay, shaly, dark brown to gray, carbonaceous	8.2
9. Clay, dark gray	3.0
10. Unexposed	6.0
11. Sandstone, medium to light yellow gray, calcarous, with limestone concretion lenses	1.5
12. Clay, gray plastic with limonite concretions at the base	1.0
13. Clay, medium gray, soft	4.2
14. Clay, light gray, stained white on the surface	4.0
15. Clay, medium to dark gray, silty, very plastic	5.5
16. Unexposed	2.0
17. Clay, gray, shaly	0.6

18. Shale, brown carbonaceous	0.2
19. Lignite, - Twin Buttes bed	2.0
20 Clay, brown carbonaceous	1.0

Thickness

No one exposure or area shows the complete section of the Tongue River member. If the beds have been correlated correctly between many partial sections measured in different parts of the area, a total of about 550 to 575 feet of the member is exposed. Inasmuch as the Cannonball marine formation crops out on the Missouri River just to the east of the Stanton quadrangle it would appear at first glance that this figure represents nearly the total thickness of the Tongue River member in this part of North Dakota, certainly the top of the Cannonball cannot be very far below the base of the section measured in the Stanton quadrangle. However, the core of a hole drilled at the Garrison Dam site indicates that the ~~lower~~ part of the Tongue River member below the Garrison Creek coal bed is 175 to 200 feet thicker than it is in the southeastern part of the Stanton quadrangle. The thickening of the Tongue River strata in this direction may be due either to marine offlap or to the sinking of a local basin during deposition. At any rate, this extra 175 feet plus the 575 feet indicated by exposures in the Knife River area give a total thickness of about 750 feet for the Tongue River in the northern part of the Stanton quadrangle. Data from deep wells drilled in other parts of the Knife River area are unreliable but appear to indicate that the Tongue River member is at least 750 or 800 feet thick over most of the area.

Relation to adjacent formations

In central North Dakota the Tongue River member of the Fort Union formation overlaps and is essentially conformable with the Cannonball formation, as can be seen in exposures a few miles southeast of the Stanton quadrangle. The upper contact with the Golden Valley formation appears to be conformable in all but a few exposures, where the basal sand of the Golden Valley fills in small channels in the top of the Tongue River.

Fossils

Leaf impressions are common or even abundant in many of the shale of the Fort Union formation and are found sparingly in some of the sandstone beds and in some of the limestone concretions. A single floral assemblage is persistent throughout the formation in the Knife area, and is, according to Brown, a typical Tongue River flora. Brown has identified the following types from specimens collected during this survey:

Coniferous trees:
- *Glyptostrobus* sp.
- *Thuja* sp.
- *Metasequoia* sp.

Deciduous trees:
- *Cercidiphyllum arcticum* (Heer) Brown
- *Aralia notata* Lesquereux
- *Viburnum antiquum* (Newberry) Hollick
- *Sapindus grandifolius* Ward
- *Ulmus* sp.
- *Quercus penhaloe* (?)
- *Platanus* sp.

Ferns:
- *Osmunda* sp.
- *Onoclea* sp.
- *Dryopteris* sp.

Water plants:
- *Paranymphea*
- *Equisetum*
- *Alisma*

Freshwater gastropods and pelecypods are found locally throughout the section. In a very few local beds these shells are so abundant that form small ledges of coquina. The following types, typical of th Fort Union formation, have been tentatively identified from collectior made in the Knife River area:

Goniobasis nebrascensis Meek and Hayden
Campeloma sp.
Unio sp
Corbula sp.
Viviparus trochiformis Meek and Hayden
Viviparus sp.

Although many of the badland exposures were searched carefully, remains of fossil mammals were found in the Knife River area. The on bones noted were a few vertebrae of the reptile *Champsosaurus* and som pieces of turtle shell.

Interpretation

The transitional contact between the Tongue River member of the Fort Union formation and the underlying Cannonball marine formation suggests that the Cannonball sea became shallow and was gradually replaced by a low-lying coastal-plain swamp. The Fort Union formation is often spoken of loosely as being of fluvial origin, but this implie deposition by aggrading streams on wide flood plains an environment that would not be likely to produce a formation like the Fort Union. The long, horizontal bands of laminated shale and the even thin-bedde sandstones of the Fort Union record deposition in quiet waters or waters that were flowing only gently. The extensive lignite beds shc that great swamps persisted for long periods of time. The fossil woc appears to represent trees that had much the same habitat as the balc cypress of the Gulf Coast today and the only common vertebrate fossil found in the Fort Union of North Dakota are Champsosaurus, a crocodile-like reptile, and one or two species of turtle. These various facts indicate that the Fort Union formation was laid down as a coastal-plain deposit marginal to the Cannonball sea. Much of the country probably resembled the mouth of the Amazon River in Brazil. The great development of the lignite beds and the sub-tropical floral assemblage indicate that the climate was moist and very warm.

EOCENE SERIES

Golden Valley formation

The Golden Valley formation here receives its first detailed description. Because all previous references to the beds that comprise this new formation have been brief, the following descriptions and measured sections will not be confined to the Knife River area, but will embrace the outcrop area of the Golden Valley formation in southwestern North Dakota.

Name and Definition

The Golden Valley formation is defined as the strata of Eocene age in western North Dakota that overlie the Tongue River and Sentinel Butte shale members of the Paleocene Fort Union formation and that are unconformably overlain by the Oligocene White River formation. The nar was chosen because of the excellent exposures of the formation in the vicinity of the town of Golden Valley in Mercer County. No one sectio shows the entire formation, but exposures in secs. 32 and 33, T. 144N. R. 90W. and in secs. 2 and 5, T. 143N., R. 90W. south and southwest of Golden Valley show the character of both the upper and lower members of the formation. The choice of this area as a type locality can be criticized on the grounds that the basal contact is not well exposed, and, as the formation caps the hills, the upper limit is not defined. However, the thickest and most extensive remnants of the formation are preserved in this area. In other areas where White River beds overlie the Golden Valley formation, pre-White River erosion has removed most or all of the thick upper member of the Golden Valley formation. In the areas where the basal contact is better exposed, the remnants of the formation are thin and patchy.

The Golden Valley formation as here defined includes most of Leonard's "light colored Tertiary clays" (1906, p.88) and most of Seage "unnamed member" of the Wasatch (1942, pp. 1414-1422).

Distribution

All the known outcrops of the Golden Valley formation are in North Dakota and it seems probable that the formation is confined to this State. To the south, east, and west, older strata rise around the margins of the Williston Basin and any equivalent of the Golden Valley formation has been stripped by erosion.

Remnants of the Golden Valley formation are preserved on the interstream divides and in small synclinal basins over a large part of southwestern North Dakota. The distribution of these remnants can be seen on the geologic map pl. 2. Most of the areas were mapped during the study of the Golden Valley formation in the summers of 1947 through 1950. The outcrops in Oliver County were mapped by W. D. Johnson, Jr. of the Fuels Branch of the Geological Survey, and some of the outcrops in the Fort Berthold Indian Reservation in Northern Dunn County were compiled from recent mapping by Ellis Gordon and Robert Dingman of the Water Resources Division of the Geological Survey.

The largest outcrop areas of the Golden Valley formation are in the eastern part of Dunn and western part of Mercer counties, in northwest Morton County, and in central and northeast Stark County. Many small isolated outcrops are scattered over these counties and also in McKenzie, Billings, Hettinger, Slope and Oliver counties. The southwestern limit of known outcrops of the formation is in the Little Badlands area in Stark and Hettinger counties. The easternmost outcrop is in southern Oliver County.

In the Knife River area the Golden Valley formation underlies large parts of the Broncho and Golden Valley quadrangles and a few small tracts in the Medicine Butte and Beulah quadrangles. It has been removed by erosion from the Hazen and Stanton quadrangles.

Composition

The Golden Valley formation is easily divisible into two members, the lower of which is so distinctive in lithology, lateral persistence, and prominence of outcrop that it can be used as a marker bed over the entire outcrop area of the formation.

--Lower member--

The lower member of the Golden Valley formation consists chiefly of kaolinitic clays and shales 15 to 35 feet thick. The shales are light to dark gray and weather very light gray to very light purplish gray. They are typically silty and locally contain fine sand, but in some exposures they are very plastic and nearly free of coarse material.

Locally they contain numerous fossil plants. The clays are very light gray to white, tough, and are slightly sandy to very sandy. Certain parts of the clay beds are mottled and stained a bright yellow-orange by iron oxide, a brighter staining than is present in any other beds either in the Golden Valley formation or in the upper part of the Fort Union formation. The staining seems to come from small pellets of iron oxide that are in turn relicts of siderite pellets. Thin layers of iron oxide and crystals of gypsum are common in both the shales and clays (pl.14).

In gross aspect most outcrops of this member consist of three major units: (1) a basal unit of light purplish-gray shale; (2) a middle unit of tough white sandy clay, the middle or top part of which is stained yellow; and (3) an upper unit of light gray to purplish shale similar to the basal unit. This sequence is, of course, not invariable but it is typical of at least 2/3 of the outcrops of the member (pl.9).

Locally a thin, discontinuous unit of brown, micaceous, carbonaceous shale and fine-grained sand underlies the "marker-bed" kaolins and appears to belong with the Golden Valley formation rather than with the underlying Fort Union formation. This unit is well developed in a section taken about three miles northwest of Hebron in sec. 23, T 140N., R 91W., where the Golden Valley formation caps a few isolated buttes. Northeast of this locality the "marker-bed" lies directly on the Harnisch lignite, and, in the pit of the Hebron Brick Company, a sandy phase of the "marker-bed" channels into this lignite. This channel contact is taken to be the Paleocene-Eocene boundary. In the locality just cited, however, about 14 feet of silty, micaceous sand and shale lie between the Harnisch lignite and the kaolin clays, and I have tentatively placed this unit in the Golden Valley formation.

The description of the "unnamed member" by Seager and others (194?

p.1416) is evidently intended to apply to the marker bed shales and sa

clays. They state:

"Large, bright yellow, calcareous sandstone concretions not exceed- ing six feet in diameter, imbedded in an ashy white matrix are characteristic of this formation. The concretionary zone is overlain by a bed that appears to contain a volcanic ash, and it in turn is overlain by more than 15 feet of yellow bentonitic clay. In some localities hard plish gray bench forming sandstone lies several feet above the bentonite layer."

The "yellow bentonitic clay" and "purplish sandstone" are probably the yellow stained clay and a sandy facies of the overlying carbonaceous shales of the lower member. I have examined carefully many outcrops the Golden Valley formation and have found no beds that are bentonitic that contain glass shards.

Several types of laboratory tests indicate that the light colored clays and shales of the lower member consist chiefly of kaolin clay mixed with varying amounts of silica, either in the form of opal or a discrete quartz grains. (1) The many chemical analyses and ceramic t made by Leonard, Clapp and Babcock (1906 pp. 132-191) show that these clays and shales are typical kaolin type with an admixture of silica. (2) Thermal dehydration tests made by Miss E. C. Fisher of the Geological Survey indicate that most of the clay is kaolinite with some small percentages of halloysite or endellite. The thermal dehydration curves show also that there is a large amount of material that is in and cannot be identified by this. (3) Thin sections of the white s clays show that most of the clay has a low birefringence typical of kaolinite. Thin stringers of a clay mineral with slightly higher birefringence may be an iron montmorillinite. These stringers occur along small fractures and were probably formed during some post-Eocene period of weathering.

Lignites up to two or three feet thick are present locally but have no lateral persistance except for one thin carbonaceous zone at the top of the member. This carbonaceous or lignitic zone is only a few inches thick in most localities but is present in nearly all of the outcrops that were examined. In places it thickens to as much as 6 feet but in general it is very lenticular and is not thought to contain valuable reserves of coal. In the Knife River area this bed has been mapped as the Alamo Bluff Bed wherever it is more than two feet thick.

--Local variations of "marker bed" kaolin clays--

Although in general the lower member of the Golden Valley formation is much the same over its whole outcrop area, it does show three types of facies change, all local, but all recurring in enough places to make them noteworthy. These facies changes are:

(1) Locally the entire sequence of kaolinitic clays and shales grades rapidly into a white kaolinitic sand. A few samples of this sand were examined under binocular and petrographic microscopes and consist chiefly of the following minerals: Angular to subangular quartz, 60 to 65%; angular calcite, about 30%; fresh to slightly weathered feldspar, 2 to 3%; heavy minerals, 2 to 3%. The heavy minerals were not studied in detail but appear to be similar to those found in the Fort Union sands. Garnet, tourmaline and kyanite were particularly common in the samples examined under the petrographic microscope.

(2) Another variation or facies change in the lower member is the local pinching out of the white sandy clays so that in some outcrops

the entire member consists of very light gray to light purplish-gray shales. In most places this variation is extremely local and outcrops within a quarter of a mile of the abarrent section show the typical three-fold division.

(3) In Stark County, south of Dickinson and also between Gladstone and Taylor, the "marker bed" shows a third type of lateral variation. In these areas the yellow staining of the white clays is scarcely noticeable on outcrop; the whole member is white to very light gray and appears to contain substantial amounts of free silica, especially near the top. Locally this free silica has indurated both shale and sandstone to form hard silicified beds like those described in the Fort Union formation. Siliceous blocks from the Golden Valley formation litter the slopes of Davis Butte, a few miles North of Dickinson.

--"Marker bed" in Fort Union formation--

I know of only one bed in North Dakota that can be mistaken for the lower member of the Golden Valley formation. This bed which is just above the base of the Tongue River member and 50 to 75 feet below the Harmon lignite, crops out in southwestern North Dakota in Bowman and Slope counties and is almost identical in appearance to the lower member of the Golden Valley formation. It is well exposed in the Medicine Pole Hills southwest of Bowman and can be traced north from this locality to a point about 13 miles east of Amidon. Over much of this distance the bed has a silicified zone at the top and the yellow staining is less pronounced than in the "marker-bed" of the Golden Valley formation. One of the best exposures of this bed is in the valley of

Deep Creek in the southeast corner of sec. 30, T. 135N., R. 102W. in Slope County. Although it was not described by Hares it would seem to be an excellent local marker horizon for stratigraphic work in the Marmarth area. A light gray kaolin bed in about the same stratigraphic position crops out at the base of Anarchist Butte in Harding County northwest South Dakota.

--Upper member--

The upper member of the Golden Valley formation is as a rule poorly exposed. It consists largely of coarse to fine-grained, yellow to gray micaceous sand and silt with minor amounts of gray shale and silty clay.

The maximum thickness observed is about 150 feet and is in the type area south of the town of Golden Valley. The total thickness of the formation in this area is about 180 feet and this is the thickest section observed anywhere in the state. In most other outcrop areas erosion has spared less than 100 feet of the Golden Valley formation.

Shales, silts, and clays comprise about 25 to 30% of the member and are most abundant in the lower part. Some of these beds, especially the silts, have a greenish cast not found in the Fort Union beds, others of them, especially the dark gray and brown carbonaceous shales, are identical in appearance to the Fort Union shales.

Beds of fine-to-coarse-grained micaceous sand and calcareous sandstone comprise 70 to 75% of the member as a whole and are thickest and most persistent in the upper part. Individual beds are as little as 6 inches and as much as 50 feet thick. In general the sands and sandstones of the Golden Valley formation resemble those of the Fort Union formation except for the following features: (1) the coarse-grained beds of the Golden Valley formation are more highly cross-bedded, exhibiting both cut-and-fill-type and deltaic-type cross-bedding. (2) The coarse-grained beds are locally conglomeratic, the pebbles consisting mostly of clayballs and reworked fossil wood, with a few well-rounded fragments of quartz and chert. As noted above, the only "pebbles" in the Fort Union formation are a few clay balls. (3) The Golden Valley sands tend to be better sorted and have beds with large percentages of clay. (4) In the Knife River area, at least, there is much more mica in the sands of the Golden Valley formation than in the Fort Union sands. In the extreme western part of North Dakota the sands of the Tongue River member of the Fort Union formation becomes more micaceous, and there is less distinction between them and the Golden Valley formation.

Coarse cross-bedded brown sandstone with mica flakes up to 1/8 inch in diameter locally compreses most of the upper member of the Golden Valley formation. Medicine Butte in the Knife River area is capped by about 80 feet of this sandstone (see pl.10B). Other prominent buttes capped by this sandstone are the Blue Buttes in McKenzie County which were formerly thought to be capped by the White River formation (Leonard, 1922, p.227 and Nevin, 1946, p.4). Black Butte, in Hettinger County, is composed partly of this sandstone, but is probably capped by White River beds.

Lignite beds are locally present, but do not have the thickness or lateral persistance of the Fort Union coals. The Shaffner bed in the Broncho quadrangle is in a local shaly facies of the upper member of the Golden Valley formation.

--Oxidation and bleaching of upper member --

Around the margin of the Little Badlands syncline in western Stark County the upper member changes its appearance. The outcrops around the south and east sides of this basin resemble outcrops of the upper member elsewhere in the State, consisting mostly of yellow to gray micaceous sands and silts interbedded with thin carbonaceous shales. Around the northern and western edges of the syncline, however, the upper member has been bleached and oxidized and appears in many outcrops as white to light green and pinkish gray micaceous sands, some of which are stained bright yellow by iron oxide. These colors are similar to the colors of the marker bed in the lower member, but the lithology is typical of the upper member. The gradation between oxidized and unoxidized phases of the upper member can be seen in the northwest quarter of sec. 14, T. 138N., R. 98W. Here, the "marker bed" crops out on the east bank of a small north-flowing stream, and dips southward into the syncline at an angle of about 5 degrees. Overlying the "marker bed" are brown carbonaceous shales and yellow-gray fine-grained sand and sandstone beds. Followed to the south the "marker-bed" dips below stream level and the color of the upper beds gradually changes to light greenish gray and while with yellow mottlings.

The oxidized phase of the upper member of the Golden Valley formation is well exposed also in sec. 15, T. 138N., R. 98W., and at White Butte in the northwest corner of sec. 32, T. 139N., R. 97W. At both localities the Golden Valley formation is overlain by white conglomeratic sandstone of White River formation, and at White Butte this basal White River sandstone channels 15 to 20 feet into the Golden Valley formation (see pl. 13). Diagnostic Eocene fossils were found just below this unconformity at White Butte.

This oxidation of the Golden Valley formation evidently records period of deep weathering that preceded deposition of the White River formation.

--Oxidation of other formations--

Southwest of the Little Badlands in Slope County, the White River formation in H. T. Butte and the Chalky Buttes is underlain by 30 to 50 feet of white, yellow, and pink sands interbedded with variegated green, pink and yellow shales. Although these beds greatly resemble the oxidized upper member of the Golden Valley formation in Stark County, they are not underlain by the distinctive Kaolin clay of the marker-bed member and all the fossils I found in them are typical Fort Union species. It is my opinion that these beds are probably Fort Union strata, oxidized in pre-White River time, just as were the strata of the Golden Valley formation in the Little Badlands area. This opinion is further supported by tracing the White River formation south toward the Black Hills. Evidently the Black Hills area was domed in the post-Golden Valley pre-White River interval, and the land was deeply eroded and stripped. The amount of this erosion increased toward the center of the uplift, and the White River formation lies on progressively older beds as one goes south toward the Black Hills. Regardless of their age, the beds im-immediately underlying the White River in northwestern South Dakota have in many places been bleached and oxidized to various shades of green, pink, yellow and light gray.

--Measured Sections--

The following detailed sections show the typical lithology and general appearance of the Golden Valley formation in southwestern North Dakota. Because this is a new formation that has not heretofore been described in detail, I have included several sections measured outside the Knife River area. Section of the Golden Valley formation measured NE$\frac{1}{4}$, sec. 2, T. 143N., R. 90W., Broncho quadrangle, Mercer County. This section is in the type area of the formation.

Upper member	Feet
1. Sandstone, gray to brown, fine- to coarse-grained micaceous, conglomeratic	64 approx.
2. Sand, gray to buff, weathering yellow-brown, fine- to coarse-grained with conglomeratic zones containing clayballs and fossil wood; highly cross-bedded; similar to unit 1 but not cemented	20.0
3. Clay, dark gray, toward top becomes silty and contains thin beds of fine sand; large gypsum crystals at the top of this unit	9.9
4. Lignite, impure, interbedded with dark brown lignitic shale	1.3
5. Clay, brownish-gray to dark gray interbedded with sand, very fine-grained, micaceous, contains gypsum crystals	11.6
6. Sand, fine-grained, micaceous, carbonaceous	1.6
7. Clay, dark to medium gray with iron oxide seams	4.0
8. Unexposed	13.5
9. Sand, very fine-grained, micaceous, poorly exposed, partly cemented to calcareous sandstone	5.1
Lower member	
10. Shale, light to dark gray with brownish gray carbonaceous layers and a few thin stringers of lignitic clay, yellow zones stained by iron oxide	6.3

11. Clay, massive, tough, light gray to white, mottled and stained yellow-orange on weathered surface, small limonite pellets, slight sandy in lower two feet — 5.3

12. Shale, light to medium gray, slightly puplish, carbonaceous, numerous plant remains, some yellow streaks of iron oxide — 8.7

Base not exposed

Section of the Golden Valley formation measured NE¼, sec. 8, T. 144N., R. 90W., Golden Valley quadrangle, Mercer County.

Upper member	Feet
1. Sand, fine-grained micaceous, extensively ripple-bedded and cemented into concretionary sandstone, minor amounts of interbedded gray-green shale	17.0
2. Shale, greenish-gray with some minor sandstone	7.0
Lower member	
3. Lignitic clay	0.2
4. Clay, light gray, slightly carbonaceous, shaly, with minor amounts of iron staining	15.4
5. Clay, tough, white, sandy, mottled bright yellow by iron oxide, numerous iron oxide concretions	3.3
6. Shale, medium gray, fairly well bedded, numerous plant fossils including *Metasequoia*, *Platanus*, and *Sapindus*	6.0

Base of formation concealed

Section measured in sec. 1, T. 142N., R. 91W., Broncho Quadrangle, Dunn County. The lower part of the section was measured along the center of the north line. The upper part was measured in the southwest quarter of the northwest quarter of the section

Golden Valley formation

Upper member

1. Sandy, fine-grained, micaceous, gray to buff, capped by calcareous sandstone	25.0

2.	Shale, alternating brown and gray, carbonaceous	2.1
3.	Lignite, impure	2.0
4.	Clay, brown, carbonaceous	1.9
5.	Shale, light gray	8.0
6.	Lignite, the Shaffner bed	2.4
7.	Clay, brown, carbonaceous	1.0
8.	Unexposed	5.0
9.	Sand, fine-grained, soft, micaceous	12.0
10.	Sandstone, fine-grained, ripple-bedded, calcareous	1.0
11.	Sand, fine-grained, micaceous	14.0
Lower member		
12.	Clay, black, lignitic. Alamo Bluff lignite zone	0.7
13.	Clay, light gray to white, blocky, silty	4.8
14.	Shale, light brown, carbonaceous with fossil plants weathers light purplish	5.0
15.	Clay, black, lignitic	0.5
16.	Sand, clayey, kaolinitic, interbedded with sand, dark brown, carbonaceous, weathers light pinkish gray	5.5
17.	Clay, brown, carbonaceous	1.0
18.	Unexposed, contact between Golden Valley and Fort Union formations somewhere in this interval	6. approx.
Fort Union formation, Tongue River-Sentinel Butte member		
19.	Sand, light gray, crossbedded with local sandstone concretions	3.0
20.	Sand, very fine-grained, clayey, interbedded with soft gray silt	12.0
21.	Shale, dark brown, carbonaceous with thin beds of lignite	2.9
22.	Sand, fine-grained, dark gray	1.0
23.	Clay, dark gray, silty	6.0
Base of exposure		

Section of the Golden Valley formation measured SE$\frac{1}{4}$, SE$\frac{1}{4}$ sec. 10, T. 142N., R. 88W., Medicine Butte Quadrangle, Mercer County.

1.	Till	4.5

Golden Valley formation

Upper member

2.	Sandstone, very fine-grained, silty, micaceous, ripple-bedded	2.3
3.	Shale, medium gray, silty, weathers yellow-buff	12.1

Lower member

4.	Lignite, soft to hard - Alamo Bluff bed	2.4
5.	Shale, light to medium gray, slightly silty, upper part weathers light purplish-gray, large gypsum crystals	9.3
6.	Clay, shaly, brownish-gray, weathers light gray, heavy deposits of iron oxide along joints and bedding planes	3.8
7.	Clay, white, slightly sandy, extensive yellow-orange mottling, iron oxide in concretions and along joints	5.7
8.	Shale, medium gray to dark brown, carbonaceous, silty, weathers purplish-gray	3.0

Section measured SE$\frac{1}{4}$, SE$\frac{1}{4}$ Sec. 23, T.140N., R. 91W., northeastern Stark County.

Golden Valley formation

Upper member

1.	Sandstone, fine-grained, micaceous	3.9
2.	Silt, clayey, laminated, micaceous, yellowish-gray to brown	7.0
3.	Clay and shale, gray to reddish brown, carbonaceous, interbedded with impure lignite	2.8

4.	Sand, fine-grained, very micaceous, with weathered iron oxide concretions	5.3
5.	Clay, silty grading upward into silt, light to medium gray	3.8

Lower member

6.	Shale, dark brown, carbonaceous	0.9
7.	Clay, medium gray, weathers dark purplish-gray	6.8
8.	Clay, light gray to white, poorly bedded, with reddish-yellow mottling by iron oxide	9.1
9.	Shale, hard, gray, carbonaceous, micaceous	0.9
10.	Shale, dark brown to black with lignitic laminae	0.7
11.	Shale, gray, silty with plant fossils	2.7

Golden Valley formation

Local basal unit

12.	Sand, very fine-grained, micaceous, crossbedded with minor amounts of interbedded silty, carbonaceous clay, grades laterally into carbonaceous shale	14.0

Fort Union formation, Tongue River member

13.	Lignite, with stringers of brown carbonaceous shale - The Harnisch bed	5.8
14.	Shale, dark gray to brown, carbonaceous	2.8
15.	Lignite	0.7
16.	Shale, gray, carbonaceous with plant fossils	3.0
17.	Lignite	1.0
18.	Shale, carbonaceous	1.0
19.	Shale, dark gray to brown, carbonaceous, sandy at the top	10.0

Section measure SE$\frac{1}{4}$, SE$\frac{1}{4}$ sec. 3, T. 140N., R. 90W., Golden Valley formation

Upper member	Feet
1. Sand, light gray to buff, fine-grained, micaceous	11.0
2. Sandstone, crossbedded, light gray, calcareous	3. approx.
3. Sand, light gray to buff, fine-grained, silty crossbedded, numerous concretions	7. approx.
Lower member	
4. Clay, light gray, plastic	1.6
5. Clay, very dark, carbonaceous with lignite fragments, contains abundant leaves including <u>Salvinia</u>, <u>Metaseouoia</u> and <u>Nymphea</u>	2.5
6. Shale, slightly silty, light brownish-gray	9.9
7. Shale, medium gray to brown, laminated	6.2
8. Clay, light gray, non-silty, poorly bedded	3.0
9. Shale, dark brown	2.5
10. Clay, light gray to brown	1.5
11. Clay, silty to sandy, light gray with abundant leaves including <u>Cercidiphyllum</u>	3.4
12. Unexposed; contact between Golden Valley and Fort Union formation, either in or at the base of this unit	5. approx.
Fort Union formation, Tongue River-Sentinel Butte member	
13. Lignite - the Harnisch bed ?	4 +

The top of this lignite was located by an auger hole base of the section. This section of the lower member represents one of the local variations or facies changes of this bed. The middle unit of sandy kaolin with pronounced yellow staining is absent at this exposure and has been replaced by a light brownish-gray to gray carbonaceous clays. The yellow stained bed is present, however, in the exposures one-half mile to the west.

Section measured at White Butte, four miles southeast of South Heart, NE¼ sec. 32, T. 139N., R. 97W., Stark County

White River formation	Feet
1. Clay, swelling, probably bentonitic, gray-brown weathering very light gray, extremely plastic	10.0
2. Siltstone and claystone, very sandy with siliceous cement, thinly bedded, capped by coarse conglomeratic sandstone	11.0
3. Siltstone, hard, clayey, pinkish-white	11.7
4. Sand, weakly cemented by calcium carbonate, white, coarse to very coarse-grained with granules of quartz and pebbles of chert, quartzite and andesite porphyry, upper part grades laterally into sandy clay and micaceous clayey sand	21.3
Channel unconformity	
Golden Valley formation, upper member	
5. Clay, greenish-gray, silty, micaceous, laminae of very fine-grained micaceous sand, stained yellow by iron oxide	0 to 8. feet
6. Clay, light gray to white, numerous iron oxide concretions and yellow iron staining, 2 inch bed of carbonaceous clay near the top	6.5
7. Shale, silty, micaceous, dark gray, grading laterally into yellow-green and brown	7.0
Base of exposure	

Section of the Golden Valley formation on Lone Butte, 7 miles northeast of Grassy Butte, SE¼ sec. 33, T. 147N., R. 98W., McKenzie County.

Golden Valley formation

Upper member

1. Sand, light gray, silty, micaceous	12.0
2. Shale, gray-brown, silty	3.4
3. Shale, gray, carbonaceous	1.1

4. Shale, gray-brown, silty	2.1
5. Sand, fine-grained, gray, micaceous with local large concretions	11.7
6. Shale, light gray, silty, sandy	5.3
7. Shale, dark brown, carbonaceous	0.4
8. Clay, shaly, light gray	5.6
9. Lignite and carbonaceous shale	1.0
10. Sand, fine-grained, yellow to gray, micaceous	5.9
11. Shale, brown, carbonaceous	0.4
12. Shale, light gray, silty, micaceous	8.8
13. Shale, carbonaceous	1.1
14. Clay, shaly, light gray to brown, silty	12.0
15. Shale, brown, carbonaceous	1.0
16. Clay, light yellow-gray	12.2
Lower member	
17. Shale, light gray to gray-grown, carbonaceous	2.5
18. Shale, dark purplish-gray, yellow stained at the base	2.8
19. Clay, light gray to white, very sandy, some yellow staining	20.5
20. Sand and sandstone, white, kaolinitic, highly crossbedded	2.1
21. Clay, dark gray-brown, very hard	1.8
22. Shale, light gray	4.9
23. Sandstone, silicified with plant impressions	0.6
24. Sand and sandstone, clayey, fine-grained, crossbedded	3.6
25. Shale, dark gray to brown, carbonaceous	8.5

Fort Union formation, Sentinel Butte shale member

26.	Lignite, locally clinkered	3.1
27.	Shale, dark gray	2.1
28.	Sand and sandstone, silty, thin bedded	10.8

Several hundred feet of Fort Union strata are exposed below the base of this unit.

Fossils

The only animal fossils collected from the Golden Valley formation consist of one Garpike scale and a few crushed gastropods from the lower member, and a fragment of a small mammalian leg bone from the upper member. Plant remains, however, are common especially in the purplish-gray shales of the lower member. The following types have been identified:

Lower member:

Salvinia preauriculata, Berry

Sapindus grandifolius, Ward

Cercidiphyllum arcticum, (Heer) Brown

Betula sp.

Celastrus sp.

Corylus sp.

Hicoria sp.

Juglans sp.

Salpichlaena sp.

Equisetum sp.

Metasequoia sp.

Sequoia (?)

Ginkgo sp.

Nymphea sp.

Upper member:

Salvinia preauriculata, Berry

Quercus castaneopsis Lesquereux

Cercidiphyllum arcticum, (Heer) Brown

This flora, according to Brown, is an Eocene assemblage. Plants in general evolve less rapidly than animals. As a result most plant species are fairly long ranging and difficult to use in age determination unless a fairly complete floral assemblage is collected. In the northern Great Plains and Rocky Mountain front region, however, the base of the Eocene (Wasatch) is marked by the sudden appearance of the floating fern, Salvinia preauriculata Berry, (see plate 11). The leaves of the Salvinia are small and oval to heart shaped, and are easily recognized by their pecular pattern of anastomosing veinlets and by a pecular puckering that gives many specimens the appearance of being punctate. In describing the Kingsbury conglomerate, Brown says this about Salvinia (1948b, pp. 1169-1170):

> "...at localities north, south, and east of Kingsbury Ridge, where the conglomerate fingers out among fossiliferous carbonaceous shales or sandy clays, the latter contain an Eocene species of floating fern, Salvinia preauriculata Berry..... I have collected thousands of fossil plant specimens from hundreds of localities in the Paleocene terrane of the Rocky Mountains and Plains, but I have never found a Paleocene Salvinia. In 1941, however, I found a Cretaceous species (plate 1, figure 11) in the "Laramie" formation (Lance) east of Craig, Colorado. The absence of Salvinia from the Paleocene record of the Rocky Mountain region is, therefore, somewhat anomalous. Its simultaneous re-appearance at about the same stratigraphic levels nearly everywhere in Wyoming, Montana, and North Dakota is unexplained, but, in consequence, Salvinia preauriculata serves, at least locally and tentatively, as an Eocene "index species"."

Brown also advises (personal communication) that in most localities in Montana and Wyoming he has been able to find Eocene vertebrates in beds that contain the Salvinia or that interfinger with the Salvinia-bearing beds.

In southwestern North Dakota Salvinia has been positively identified from 6 outcrops and tentatively identified in a seventh. Two of the outcrops are in the upper member of the Golden Valley formation; the other five, in the lower member. Because much of the work on the Golden Valley formation was of reconnaissance type, many outcrops were not examined for fossil content and Salvinia will probably be found at many other localities.

The location of the outcrops that yielded Savinia are shown on the on the map on plate 2. The localities where Salvinia has been identified a lower member are:(1) in northwest Morton County, SE$\frac{1}{4}$, sec. 3, and (2) NE$\frac{1}{4}$ sec. 11, T. 140N., R. 90W.; (3) in Oliver County, NW$\frac{1}{4}$, sec.27, T. 141N., R. 86W.; and (4) in southwest Mercer County, NE$\frac{1}{4}$ sec. 29, T. 143N., R. 90W. A possible fifth locality is in southern McKenzie County about 4 miles southeast of the Grassy Butte post office, sec. 29, T. 145N. , R. 98W. A few fragmentary plants were collected from the marker-bed in this area and some of the fragments seem to be Salvinia.

All 5 occurrences of Salvinia in the lower member of the Golden Valley formation are in the upper 1/3 of this member. The absence of Salvinia in the white sandy clay and the lower purplish shale of this member may be due to imperfect collecting, or it may be due to a time lag in the migration of the species. The sudden appearance of Salvinia in beds of Wasatch age in the Rocky Mountain region is evidently due to migration, inasmuch as no Paleocene species are known from this region. If this migration was west to east, Salvinia may not have reached North Dakota until shortly after the beginning of the Eocene, that is until part of the Golden Valley formation had already been deposited.

The occurrences of <u>Salvinia</u> in the upper member of the Golden Valley formation are in Stark County, SE$\frac{1}{4}$, sec. 4, T. 137N., R. 96W., and NW$\frac{1}{4}$ sec. 32, T. 139N., R. 97W. At the latter locality <u>Salvinia</u> is found in a thin bed of black carbonaceous shale that contains also specimens of <u>Quercus castaneopsis</u>, Lesquereux. <u>Quercus castaneopsis</u> is, according to Brown, common in the Green River formation of middle Eocene age. Inasmuch as <u>Salvinia</u> is also found in the middle Eocene, it is possible that the upper member of the Golden Valley formation may be middle Eocene, the time equivalent of the Green River formation.

Relation to adjacent formations

The Golden Valley formation is essentially conformable on the Tongue River and Sentinel Butte members of the Fort Union formation. Where the lower member consists of white kaolinitic sand there was some erosion and channeling of the Fort Union beds. Where the lower member consists chiefly of clay and shale the contact appears to be conformable, even gradational (pl. 12A).

The upper contact of the Golden Valley formation is not exposed in the Knife River area. It is visible on Antelope Butte in eastern Stark County and along the northern margin of the Little Bad Lands syncline in western Stark County. In both localities the White River beds are disconformable on the Golden Valley formation. At White Butte in sec, 32, T. 139N., R. 97W., conglomerates of the White River formation channel into the oxidized upper member of the Golden

Valley formation with a visible disconformity of about 20 feet (pl.13). Wherever the White River formation is present in North Dakota the Golden Valley formation is either greatly thinned or is missing altogether. This thinning of the formation is apparently due to pre-Oligocene erosion.

Interpretation

It is difficult to say exactly under what conditions the Golden Valley formation was deposited. The upper sandy member seems to have been deposited by streams flowing over a low flat plain, possibly a coastal plain. The few lenticular beds of shale and lignite indicate that at times parts of this plain were swampy, but the general scarcity of lignite and greater grain size of the sediments, as compared with the Fort Union formation, indicate that the streams were flowing more rapidly than in Fort Union time and that the margin of the sea was probably farther east. The environment of the lower member is harder to envision. The suite of minerals in the sandy facies of this member and the lack of weathering of these minerals indicates that the kaolin was not weathered in situ but was transported from some source area. Crossbedding in both members dips generally to the east, indicating that this source area was to the west. The kaolin seem to have been transported as kaolin and deposited as one continuous or nearly continuous blanket over southwestern North Dakota. This suggests deposition in a broad, extremely shallow freshwater lake. The water must have been shallow so that the streams could build their natural levees and carry sand for some distance out into the lake. Even so, it is still difficult to understand how such a large blanket of relatively pure kaolin could be brought in by streams without having that kaolin mixed with montmorillonite clays or with large amounts of other materials.

YOUNGER FORMATIONS NOT PRESENT IN THE KNIFE RIVER AREA

Tertiary System

OLIGOCENE SERIES

White River formation

General Description

The White River formation almost certainly extended over the Knife River area at one time, but they have long since been removed by erosion. However, the lithology and distribution of the White River formation in southwestern North Dakota is important in deciphering the late Tertiary and Quaternary history of the State in general and the Knife River area in particular.

In South Dakota beds originally called the White River formation are now called the Chadron and Brule formations of the White River group. These beds underlie large areas in western South Dakota and are well exposed in the Badlands National Monument east of the Black Hills. In North Dakota the Oligocene beds have not yet been divided into separate formations and are known collectively as the White River formation rather than the White River group. The White River formation has largely been eroded from most of the southwestern part of North Dakota and is preserved only where it caps high buttes or underlies some of the smaller synclines in the Williston Basin.

Present-day knowledge of the distribution and lithologic characteristics of the White River formation in North Dakota combines the work of many geologists. Detailed descriptions of the lithology and paleontology of the formation are given by Douglas (1904), Quirke (1918), and Leonard (1922). Other localities at which the White River formation crops out were described briefly by Lloyd (1914), Hares (1928), Seager (1942), and Powers (1945). During the reconnaissance study of the Golden Valley formation I visited all the previously recorded outcrops of the White River formation in southwestern North Dakota and in addition identified the formation on the tops of four other buttes.

Little Badlands and Chalky Buttes areas

The largest remnant of the White River formation in North Dakota is preserved in the Little Badlands syncline southwest of Dickenson in Stark County. Here the formation underlies about 65 square miles and is about 200 feet thick. It can readily be divided into three members or units. The lowest of these units is probably the equivalent of the Chadron formation in South Dakota; the upper two, the equivalent of the Brule formation. The same three units are recognizable in the Chalky Buttes syncline in Slope County, where they have a total thickness of about 320 to 350 feet.

The lower unit consists of light gray to white fine to coarse-grained sandstone interbedded with light colored calcareous and siliceous clays. The sandstone beds contain numerous pockets of stringers of well rounded pebble to cobble gravel. This unit is 40 to 60 feet thick in the Little Badlands and 80 to 145 feet thick in the Chalky Buttes. In both areas it is overlain by a dark gray swelling clay that resembles bentonite. Thermal dehydration tests on one sample of this clay collected from the Little Badlands area indicate that it is a hydromica close to the composition of illite. In both areas the sandstone is weakly cemented by calcite and breaks down readily on the surface of weathered outcrops.

The pebbles contained in the conglomeratic beds consist chiefly of well-rounded cherts and brown, purple, and pink quartzites. These quartzites closely resemble the pre-Cambrian belt series of west central Montana and were probably derived from these rocks. In addition to the quartzites and cherts, which comprise 80 to 95% of the pebbles, the gravels contain numerous well-rounded fragments of brown to red andesite-porphyry similar to the lava flows in and around Yellowstone Park. Several pebbles of limestone were picked up in the Little Badlands area and one of these contained a well-preserved Spirifer, suggesting that this pebble was derived from the Madison limestone in the Rocky Mountain region. On the western edge of the Little Badlands syncline I found two well-rounded boulders of pink granite weathering out of the conglomeratic beds. These two boulders, very likely, were derived from the Black Hills. Wood (1904, pp. 116-117) noted several granite boulders in and around the town of Dickinson in Stark County. He ascribes these boulders to glacial origin, but the proximity of Dickinson to the Little Badlands syncline suggests that they may be residual from the White River formation.

No diagnostic fossils have been collected from the lower unit in either the Chalky Buttes or the Little Badlands, although a few fragments of large teeth are probably titanothere.

The middle unit of the White River formation consists predominantly of clay that locally has enough lime content to be classified as a marl or impure limestone. This unit also contains beds indurated by silica to form rough ledgy outcrops. In the Little Badlands these beds are predominantly pink and are about 50 feet thick. In the Chalky Buttes the same beds are predominantly green with minor tinges of pink and are about 60 feet thick. This middle unit of the White River formation contains an abundant vertebrate fauna, which Douglas identifies as Middle Oligocene, and which he correlates with the "Oreodon beds" of South Dakota.

The upper unit of the White River formation consists of greenish gray shales and clays interbedded with and overlain by green sandstone that contains pebbles and angular fragments of marl and silicified clay, probably derived from the middle White River beds. The upper beds are about 70 feet thick in the Little Badlands and about 125 feet thick in the Chalky Buttes. Locally they contain bone fragments that Douglas identified as rhinoceros.

Douglas (1904, p.288) suggests that the White River formation was derived from the Black Hills area, but the lithologies of the conglomerate indicate that the bulk of the material probably came from the Rocky Mountains to the west. The eastward dipping foresets of many of the sandstone beds also suggests that the streams depositing the White River beds came from the west. As indicated elsewhere the Black Hills area was differentially uplifted before deposition of the White River sediments and some of the formation was undoubtedly derived from this source area. The amount, however, was probably small compared to the volume of materials of western provenance.

Other previously described localities

Quirke (1918) measured about 400 feet of White River sediments in the Killdeer Mountains in western Dunn County. He divided this sequence of beds into seven units which he describes as green crumbly calcareous clays interbedded with marly limestones and green conglomeratic sandstones. Powers (1945) suggests that Quirke's seven units represent the lower and middle White River beds of the Chalky Buttes area.

Capping many of the high buttes in southwestern North Dakota is a thick, coarse-grained sandstone that is locally conglomeratic. This sandstone is very hard and appears to have a siliceous cement. Except for its cementation this sandstone lithologically resembles the softer sandstones and conglomerates in the Little Badlands and the Chalky Buttes. Hares describes this sandstone (1928, p.40) and correctly correlates it with the White River formation in the Chalky Buttes. He mentions it as capping H. T., Bullion, Flattop, Sentinel, Camel's Hump, and East and West Rainy Buttes.

Lloyd, (1914, p. 11) states that three buttes in southwestern Grant County (now known as Coffin Buttes) are capped by the White River formation.

Leonard (1922) states that the White River formation also caps Blue Buttes in McKenzie County and occurs as a loose gravel cap on some low hills about 9 miles southwest of Bowman. Nevin (1946, p.4) also mentions the sandstone cap of Blue Buttes in McKenzie County and calls it White River.

Seager (1942, pp.1415-1416) and Powers (1945, p.1192) note that

White River beds cap Young Man's Butte and Antelope Buttes in eastern Stark County, and some low buttes in southern Stark and northern Hettinger counties near the town of Lefor. I have visited all the above localities and agree with the identification of the White River formation in all except Blue Buttes. These are capped by the coarse micaceous sandstone of the upper member of the Golden Valley formation.

Since the preparation of this report, Miller Hansen of the North Dakota Geological Survey has been investigating the lithology and distribution of the White River formation in North Dakota and advises that it caps Black Butte in Hettinger County.

New localities

As a by-product of the study of the Golden Valley formation, four new White River localities were added to the geologic map of North Dakota. These are:

(1) The Medicine Pole Hills in the northern part of T. 130N., R. 104W., Bowman County.

Hares (1928, p.41) describes the Medicine Pole Hills as being underlain by the Fort Union formation and capped by residual deposits derived from the White River formation. R. W. Brown and N. M. Denson and I visited this locality in the summer of 1950, and found that the gravel cap of the hills is 15 to 25 feet thick and contains abundant bones that show no evidence of being rounded or eroded by streams. We concluded, therefore, that these gravels have not been reworked and are probably the equivalent of the lower White River beds in the Chalky Buttes and Little Badlands. The collection of vertebrate fossils from the Medicine Pole Hills is the best assemblage from the lower White River beds in North Dakota. The following types were identified by

C. L. Gazín; Leptomeryx sp., Hyaenodon, Dinictis, Hyracodon, and Poebrotherium. In addition there are numerous large fragments of Titanothere teeth. According to Gazín, this fauna indicates a lower Oligicene age, and these beds are the probable equivalent of the Chadron formation in South Dakota.

(2) Whetstone Buttes in northwest Adams County, which are capped by 80 to 100 feet of hard conglomeratic sandstone similar to that of the Sentinel, Flattop and H. T. Buttes.

(3) Wolf Butte, also in Adams County, and also capped by about 65 to 80 feet of sandstone that contains a few pebbles of chert and quartzite.

(4) Shepard Butte in eastern Hettinger County, which is capped by an undetermined thickness of sandstone and marly limestone resembling the White River beds near Lefor.

Stratigraphic relations

The White River beds unconformably overlie all older formations. In west-central North Dakota they channel into and overlie the Golden Valley formation. From here on south they overlie progressively older formations until in and around the Black Hills in South Dakota they rest unconformably on the Cretaceous pure shale. This indicates that the Black Hills dome was uplifted in pre-Oligocene time, and the stratigraphic evidence from North Dakota suggests that this uplift was post-Golden Valley (Wasatch), pre-Chadron (Lower Oligocene). The White River formation in North Dakota is not overlain by any younger deposits.

MIOCENE (?) OR PLIOCENE (?) SERIES

Gravels on an old erosion surface

In northeastern Montana are remnants of a high-level planation surface capped by a conglomerate known as the Flaxville gravels. Vertebrate fossils collected from these gravels by Collier and Thom indicate that this formation is late Miocene or early Pliocene (1918, pp. 180-182). Later collections made by various other geologists indicate that the Flaxville gravels may be as young as middle or late Pliocene (Colton, R. B., U.S. Geological Survey, personal communication). Russell (1950, p.58) visited several Flaxville localities in Montana, and in one of these he found two gravels separated by a soil zone. He therefore suggests that the Flaxville gravel may include deposits of two ages, one middle to late Miocene and the other early to middle Pliocene.

Until the present work, no deposits in North Dakota have been correlated even tentatively with the Flaxville gravels. The gently rolling uplands of the western part of the State were thought to have been developed in late Tertiary time, but no definite age could be assigned to them.

In southwestern Grant County, T. 131 and 132N., R. 90W., are three high buttes, known as Coffin Buttes, that are capped by the White River formation. Lloyd (1914, p.11) describes the White River in these buttes as consisting of:

> ".. about 50 feet of calcareous arkosic sandstone overlying a marly limestone, both of which are referred to the formation on faunal and lithologic evidence."

The sandstones, which are 50 to 65 feet thick contain scattered pebbles and lenses of conglomerate. The lower parts of the buttes are composed of the Fort Union formation. The upland above which these buttes stand consists, in the northern part of T. [illegible]N., R. [illegible]W., of a dissected planation surface capped by several feet of loosely consolidated gravel. The pebbles in the gravel are similar to those in the White River conglomerates. It seems probable that this gravel was deposited during a late Tertiary erosion cycle, the pebbles being derived from the erosion of the White River formation in this area. Although no fossils were found, the topographic and stratigraphic position of these gravels suggests that they were deposited at about the same time as the Flaxville gravels in Montana.

Similar deposits of gravel derived from the White River formation apparently cap some of the higher hills north of Hettinger in T. [illegible] R. 95 and 96W., but I did not have time to examine or map these deposits.

A picture of the dissected planation surface near Coffin Buttes is shown on pl. 14B.

Surficial deposits

Quaternary system

Much of the Knife River area is mantled by surficial deposits, Pleistocene to Recent in age. The Pleistocene deposits include till, glacio-fluvial deposits, and fluvial deposits. Recent deposits include alluvium, eolian sand and silt, residual silica, and landslide debris.

Over the country as a whole, the dividing line between the Pleistocene and Recent epoch is difficult to establish, either physically or philosophically; in fact, Flint (1946 pp.205-208) has questioned whether the Pleistocene epoch is ended and whether there is need or justification for the term "Recent". Although I am sympathetic to the idea that we are probably still in the Pleistocene epoch (if that epoch be defined as one in which the distribution and volume of glacier ice is greater than in the "normal" geologic past) I think also that in glaciated areas "Recent" is a convenient term for deposits that post-date the last glacial advance. In this report, therefore, I have followed the current usage of the Geological Survey and have included in the Recent Series all deposits younger than those of the Wisconsin Glacial Stage. This usage will be intelligible whether "Recent" is eventually retained as an epoch, demoted to the rank of an interglacial stage, or demoted still farther to the rank of an interglacial substage of the Wisconsin stage.

PLEISTOCENE SERIES

The subdivision of the Pleistocene epoch used in this report is as follows:

Pleistocene epoch	Wisconsin glacial stage	Mankato substage Cary substage Tazewell substage Iowan substage
	Sangamon interglacial stage	
	Illinoian glacial stage	
	Yarmouth interglacial stage	
	Kansan glacial stage	
	Aftonian interglacial stage	
	Nebraskan glacial stage	

Wisconsin stage

All the Pleistocene deposits in the Knife River area have been assigned to the Wisconsin glacial stage. There is indirect evidence of a pre-Wisconsin glacial advance, but no deposits related to this earlier advance have been found. The Wisconsin deposits represent at least three substages. The first two are probably Iowan and Tazewell (early Wisconsin); the third is probably Mankato (late Wisconsin). The Cary substage is apparently not represented in the Knife River area.

Till (Qwt)

Three major till sheets all of Wisconsin age, are present in the Knife River area. All have essentially the same appearance and composition, and their differentiation is possible only in the valleys, where they are interbedded with three fluvial and glacio-fluvial fills. On the uplands, where there are no interbedded stratified deposits, the tills are inseparable.

A fourth till sheet younger than the other three, is exposed in two localities in the eastern part of the area. This till is thin and discontinuous and probably represents a local readvance of the Mankato ice sheet rather than a separate substage.

--Distribution and topographic expression--

The late Wisconsin drift border (probably the Mankato border) trends northwest through the Medicine Butte, Broncho, and Golden Valley quadrangles (see pl. 4). In general, northeast of this border the late Wisconsin till is extensively preserved covering over half of the area, and its surface is characterized by numerous undrained depressions and unintegrated drainage. Southwest of the border, on the other hand, the early Wisconsin till is thin and patchy, covering less than 10 per cent of the area, and its surface has few undrained depressions. The actual boundary between these two types of topography, however, is indistinct and difficult to map except in a very general way.

It is characteristic of many of the large erratic boulders of granite to be at the center of small closed depressions, that appear to be not a part of the original glacial topography, but the result of the combined work of deflation and livestock. Cattle have a great fondness for collecting around these boulders and rubbing their heads and sides on them. Their hooves destroy the sod cover, and in the wet season, sink down into the mud, leaving a rough broken surface. As the soil dries out it is easily picked up by the wind and it does not take more than a few score years to form a considerable depression around a popular boulder. Around some of the boulders is a ring that at first glance appears to be polished by wind action. This ring is probably due to the rubbing of horns by the cattle. This method of producing polished boulders in closed depressions around them is discussed in more detail by Bretz (1946 pp.260-262), who ascribed some of them to the work of bison.

--Composition--

The till consists of a poorly sorted mixture of sand, silt and clay in which are imbedded larger fragments of several kinds of rock All the till in the area is highly calcareous.

The matrix of the till seems to have been derived to a great extent from local rocks. The percentages of sand, silt and clay vary widely, sometimes within the limits of a single outcrop. For example a road cut on the western edge of sec.12, T. 142N., R. 89W., shows till with a clay-silt matrix grading, in about 15 yards into till that has a matrix of sand with only minor amounts of silt and clay. Variations within a given till sheet, therefore, are probably as great as differences between tills, and in that case mechanical analyses would be of no use in differentiating till sheets.

The fragments in the till range in size from granules to boulder They are angular to round, with the majority being sub-angular and subround. These stones are of both local and foreign origin, with the foreign stones slightly in the majority. The local stones are chiefly sandstone, gray clay chert, fossil wood, and fragments of lignite ar limonite. The foreign stones consist largely of Paleozoic limestone and dolomite from the Lake Winnipeg area, and Pierre shale, granite, basalt, quartzite, chert, and vein quartz from other parts of Manitoba. In addition, the till contains also a few pebbles of quartzite and brown chert from the Rocky Mountain region. These were probably brought by streams into North Dakota or southern Canada and have been reworked into the till.

Pebble counts of the stones of foreign origin were made at numerous localities in the Knife River area in an attempt to find some differences between the till sheets. The results of some of these counts are shown graphically in fig. 6 , and they indicate that all the tills of the area have about the same types of erratic stones in about the same proportions. Limestone and dolomite are the most abundant type, contituting 65% to 70% of all the erratic pebbles. Granite is next, constituting about 15% and all other types together make up the remaining 15% to 20%. To anyone who has examined the erratic boulders that dot the surface of the land the high percentage of limestone and dolomite is surprising at first; 90% to 95% of these boulders are granite and granite gneiss, and only 2% or 3% are limestone. Presumably the limestone was more easily broken into small fragments than was the granite so that limestone and dolomite predominate in the pebble size, while granite, which was plucked as large blocks, predominates in the cobble- and boulder sizes.

The largest erratic boulder is in the Stanton quadrangle in the NE$\frac{1}{4}$, SE$\frac{1}{4}$, sec. 2, T. 146N., R. 84W. (see pl. 22B). This boulder which is composed of gneissic granite cut by two pegmatite veins, is about 22.5 feet long, 17.5 feet wide, and projects 3 to 7 feet above the ground. This large boulder is in the center of a closed depression and its great size is not apparent until the observer is very close to it.

--Color and depth of oxidation--

Unweathered till is light to medium blue-gray, but this color is seen in only a few outcrops. Apparently, because of oxidation by vadose or ground water, most of the till outcrops are light tan to yellow-brown in color. The depth of this oxidation is highly variable and bears little or no relation to the age of the till. In some places blue color is preserved in early Wisconsin till within two or three feet of the surface. In other places 20 to 30 feet of Mankato till appear to be thoroughly oxidized. Apparently, local differences in the position of the water table and local differences in the permeability of the till have much more influence on the depth of oxidation than does the age.

Therefore, depth of oxidation, while possibly useful in differentiating Wisconsin from pre-Wisconsin tills is of no value in attempting to differentiate the substages of the Wisconsin, in the Knife River a

--Solution and redeposition of calcium carbonate--

In climates more humid than North Dakota calcium carbonate is commonly leached from the upper part of a deposit and is precipitated in the lower part of the soil profile. In more arid climates, the carbonate moves upward and is precipitated on the surface as caliche. In western North Dakota, both processes appear to be operating. Upward migration of the calcium carbonate has produced a coating of caliche on the bottoms of most of the pebbles on the surface of the till. Downward migration has resulted in a faint lime-enriched zone about one foot thick just below the humified or "A horizon" of the modern soil. Evidently the balance between upward and downward migration of calcium carbonate is nearly perfect, because no exposures that were tested had been completely leached of lime; each was calcareous right to the grass roots.

Howard (1947, p.1204) investigated the possibility of using the amount of caliche on the under sides of these pebbles as a criterion of age difference of tills in North Dakota but found that variations due to local factors were apparently greater than the variations due to age differences of the tills.

In the Knife River area the depth of secondary lime accumulation in the soil is somewhat variable, but in general the lime zone of the soil on late Wisconsin till is as thick and as well developed as that on early Wisconsin till.

-"Stratified till"--

Although in most outcrops the till is an unsorted heterogeneous mixture, in a few localities it is crudely sorted and partially stratified. Lenses of silt and fine- to coarse-grained sand alternate with lentils of unsorted till. The fact that the lenses of stratified material alternate with lenses of unsorted till and the fact that in some places outcrops of the stratified till can be traced laterally into exposures of completely unsorted till indicates that the environment of deposition of the stratified material was probably subglacial. The sorting and stratification of the sand and silt on the other hand, indicates the action of water. A third significant factor is that all the outcrops of the stratified till thus far seen have been in valley bottoms. It appears that subglacial melt waters flowing at the base of the ice were concentrated in the pre-existing valleys. Where the volume and velocity were great enough, these waters were able to stratify and sort the glacial drift as it was being deposited by the ice.

Good examples of this stratified till can be seen in the NE¼, of sec. 20, T. 143N., R. 91W. in the Broncho quadrangle, and in the SW¼ of sec. 35, T. 145N., R. 85W. in the Stanton quadrangle. The exposure in the Broncho quadrangle is about 150 yards west of a church and is in a man made gully in the south side of a section-line road. It shows about 8 feet of interfingering and interbedded till, fine sand, silt and gravel overlain by loess. The exposure in the Stanton quadrangle is in a cut bank on the north side of the Knife River and shows 10 to 12 feet of poorly sorted and stratified glacial drift overlying Fort Union sandstone.

One of the largest exposures of "stratified till" in western North Dakota is about 9 miles west of the Knife River area in the eastern half of sec. 3, T. 142N., R. 93W. in eastern Dunn County. Here the Knife River has cut into the south bank of the valley and has exposed 50 to 60 feet of interbedded lentils of till, silt, fine- to coarse sand, and gravel.

--Pebble-orientation studies--

Holmes (1941) showed that in undisturbed till the pebbles tend to lie with their long axes parallel to the direction of ice movement. Accordingly, a statistical study of pebble-orientations in a till can be used, like striations, to indicate the direction of movement of the glacier.

In the Knife River area, pebble-orientation studies were made at eleven localities to see whether the direction of ice movement was significantly different for the several till sheets. The method used is essentially a modified version of the one described by Holmes (1941, pp. 1307-1308) and was suggested to me by H. E. Simpson Jr., of the Geological Survey.

The results of the studies, shown by rose diagram (fig. 8) are somowhat disappointing. Several of the diagrams show no strong preferred orientation; and in those that do have a strong orientation, the direction varies from southwest to southeast with no apparent correlation between the direction of movement and the age of the till. Variations within a given till sheet are apparently greater than any average difference between the sheets. In general the orientation diagrams seem to indicate that all the ice sheets came from the north and northeast, and deviations from this trend are probably the result of local topographic control of ice movement. Localities 10 and 11 are in the Krem moraine, and, as would be expected, show orientations about at right angles to the trend of the moraine.

Therefore, although the studies fit the hypothesis that the long axes of pebbles parallel the direction of ice movement, they are of no help in differentiating till sheets in the Knife River area.

--Differentiation of tills--

As can be seen from the above descriptions, the several tills of the Knife River area are similar in appearance and composition, and cannot be separated by any physical or chemical tests thus far tried. The late Wisconsin drift has been less eroded than the earlier drifts, and this difference can be used in mapping the approximate limits of the late Wisconsin (Mankato) till. This topographic boundary, however, is vague in many parts of the area, and topography alone is not considered adequate evidence for inferring the existence of more than one till sheet.

There is, however, ample stratigraphic proof that more than one age of till is present in the Knife River area. In the valleys of the Knife River and some of its tributaries are three fluvial and glacio-fluvial fills separated by major unconformities. Several exposures show two tills, underlying and associated with the second and third fills. Also, although the base of the first fill is not exposed, this fill is composed chiefly of glacial outwash and indicates the existence of still another glaciation. This older glacial unit is probably Iowan and was the most extensive of all the Wisconsin drifts in North Dakota. The two younger tills are probably Tazewell and Mankato. The exposures that show the critical relations between the tills and fills are described in the section on the valley fills, Qsd.

A fourth till is exposed at two localities in the eastern part of the Knife River area. The first locality, a gravel pit in SE¼, NE¼ sec. 5, T. 145N., R. 85W., shows 1 to 1.5 feet of till conformably overlying the late Wisconsin outwash gravel, Qwo. The second locality is also a gravel pit, this one in $NE\frac{1}{4}$, $NE\frac{1}{4}$, sec. 2, T. 145N., R. 84W. Here about two feet of light buff till overlie ice-contact gravel that is a part of the valley fill, Qsd_3. In both exposures the till is thin and in neither is there any evidence of a period of erosion or soil formation between the till and the underlying gravel. Therefore, this till is interpreted as recording a local readvance of the late Wisconsin (Mankato) ice sheet rather than as a separate substage.

In addition to the exposures of till interbedded with the water-laid deposits, two exposures show two tills in direct contact. The first of these is in the $NE\frac{1}{4}$, $NE\frac{1}{4}$ sec. 28, T. 146N., R. 88W., in the northern part of the Beulah quadrangle. Here, at the edge of the upland just east of the Beulah trench, a roadcut exposes a dark clay-rich till overlying a lighter sandier till (see pl.15A). At the top of the lower till is a band of pebbles, evidently concentrated by the erosion of this till before its burial by the younger deposit.

The second exposure is in the $SE\frac{1}{4}$, $SE\frac{1}{4}$ sec. 12, T. 144N., R. 86W., and is in the valley of Kinneman Creek, just south of State Highway 25 (pl.15B). A cut bank on the east side of the creek exposes about 15 feet of relatively unoxidized blue-gray till that seems to have a break in the middle. At this break there is a concentration of boulders and a dying out of many of the joints present in the lower half of the outcrop. The evidence is not clear-cut, but two tills are probably represented.

Although both of these exposures demonstrate the existance of more than one till sheet in the Knife River area there is no means of correlating them with each other or of mapping these till sheets separately.

Two beds of till separated by a thin bed of soft marl contains fresh-water gastropods are exposed in a road cut on the south side of a small valley in $NE\frac{1}{4}$, $SE\frac{1}{4}$ sec. 30, T. 146N., R. 89W., (see pl. 16A). However, exposures on the north side of the same valley fail to show either the marl bed or any evidence of two tills. The marl was probably deposited in a small pond, formed during the retreat of the late Wisconsin ice margin, and was buried by till deposited during a local readvance of the same ice.

Krem moraine (Ctr)

A small lobate recessional moraine composed chiefly of till crosses the northern part of the Knife River area in the Golden Valley, Beulah, and Hazen quadrangles. The eastern end of this moraine is a few miles north of the abandoned village of Krem, and in this report the moraine will be informally called the Krem moraine. The moraine is differentiated from the rest of the till solely on the basis of topography, and therefore, on the geologic map (pl. 1) the boundary of moraine has been shown by hachures rather than by a conventional geologic contact (pl. 16B).

The Krem moraine is local and cannot be traced much beyond the limits of the Knife River area. Its eastern end is in the northeast part of the Hazen quadrangle. Northeast of this area the moraine becomes indistinct and merges imperceptibly with the till-covered upland. The moraine dies out also in the northern part of the Golden Valley quadrangle, but, after a gap of about 3 or 4 miles, a faint extension of the moraine lies partly in the northwest quarter of the Golden Valley quadrangle and partly outside the area in the Fort

Berthold Indian Reservation. Northwest of this outlier the moraine, if ever present, has been so modified by erosion that it cannot be identified.

Throughout most of its length, the Krem moraine follows the crest of the upland between the Knife and Missouri rivers. In the central part of the Beulah quadrangle it crosses and drops into the deep Beulah trench; and in the eastern part of the same quadrangle, it crosses a broad topographic sag at the headwaters of Antelope Creek. Where it crosses these topographic lows the moraine consists partly of till and partly of ice-contact stratified drift. Elsewhere it consists almost entirely of till.

There is no reason to separate the Krem moraine in age from the late-Wisconsin till south of it. Outwash from the moraine merges without apparent break with outwash and fluvial deposits associated with the late-Wisconsin till in the Knife River valley. Also, both the east-west trend of the moraine, which lies at about 45° to the general trend of the drift borders in North Dakota, and the dying out of the moraine in the Hazen and Golden Valley quadrangles suggest that the moraine is merely a local detail in the general picture of late-Wisconsin glaciation. The Krem moraine therefore does not seem to represent the drift border of any Wisconsin substage, rather it records only the readvance of a small local lobe of the ice sheet.

Valley fills (Qsd)

In the valleys of the Knife and Missouri rivers and in some of their major tributaries are remnants of fluvial and glacio-fluvial deposits of silt, sand and gravel. The largest remnants of these fills are preserved as terraces in the Knife River valley downstream from Beulah. Upstream from Beulah patches of the fills are fewer and smaller. Three different fills have been identified, and, where possible, these have been mapped separately as Qsd_1, Qsd_2 and Qsd_3. Where it was not possible to differentiate the fills they have been mapped under the general head Qsd. Qsd_1 and Qsd_2 are of early Wisconsin age and probably represent the Iowan and Tazewell substages. Qsd_3 is late Wisconsin and probably represents the Mankato substage.

--First fill, Qsd_1--

Qsd_1 is the oldest of the three fills and has been identified only in the Knife River valley near Beulah. It consists of outwash sand and gravel with cut-and-fill type bedding that is foreset down the valley of the Knife River. The gravel beds contain stones of both local and foreign origin, with the foreign stones predominating by about 3 to 1. Many of the coarse gravels are partly cemented and stained orange by deposits of iron oxide. The sand beds, which are very much like the sands of Qsd_2 and Qsd_3, are fine-to coarse-grained and have little silt content. Characteristically they are gray and oxidize to buff on surface exposure.

The following sections show the lithology and stratigraphic relations of Qsd_1:

(1) Beulah gravel pit. This exposure is on the south side of the Knife River in NE$\frac{1}{4}$, NW$\frac{1}{4}$ sec. 36, T. 144N., R. 88W. The section given below was taken at the eastern end of the workings approximately one-tenth of a mile east of the rodeo grounds (pls. 17 and 18).

Top of exposure - approximately 32 feet above Knife River floodplain.

		Feet
1.	Spoil pile from gravel pit	2.0
2.	Colluvium with modern soil profile on top	1.9
3.	Laminated silt and fine sand, some lime enrichment especially in the silt beds in the upper 2 feet. Qsd_2	5.2
4.	Humified eolian sand	1.0
5.	Eolian sand with faint lime-enriched zone	0.2
6.	Eolian sand, light brownish gray	2.8
7.	Coarse, crossbedded sand and gravel, outwash type, limestone and granites more abundant than iron oxide and sandstone pebble, gravel beds are iron stained Qsd_1	7.0

Bottom of exposure

Traced westward through an abandoned part of the gravel pit to a cut at the north edge of the rodeo grounds, the boundaries between units become less sharp. Qsd_2 grades from laminated fine sand and silt into laminated fine to medium grain sand similar to the sand beds of Qsd_1. The eolian sand thins and the humus zone becomes faint and finally disappears. Although the humus zone is very striking in the outcrop the soil profile developed on the eolian sand is not a strong one as is shown by the very thin lime zone beneath the humified layer.

The contact between Qsd_1 and the overlying eolian sand appears to be conformable, suggesting that the original top of the old outwash is preserved in this exposure. If this is true, Qsd_1 never rose higher than about 20 feet above what is now the modern floodplain of the Knife River.

(2) Section Line exposure. This exposure, approximately ½ mile east of the Beulah gravel pit, is in a gully along the east edge of sec. 36, T. 144N., R. 88W.

Top - about 65 feet above Knife River floodplain

		Feet
1.	Poorly exposed unit; mostly fine-grained sand and silt with some beds of medium-grained gray sand	20 - 23
2.	Laminated fine sand and silt with a few thin beds of medium-grained sand	15
3.	Sand, medium-to coarse-grained, with few gravel lenses and some beds of fine sand, silt	13

Conformity

4.	Till, medium blue-gray, sandy	6

Unconformity - Qsd_1

5.	Fine-grained sand and silt, thin-bedded, with some beds of laminated silt and clay	7
6.	Coarse-grained sand outwash sand and gravel	3

Base of exposure, a few feet above the floodplain of the Knife River

The till (unit 4) has the same stratigraphic position as the eolian sand in the Beulah gravel pit. Exposures are poor between the Section Line exposure and the Beulah gravel pit so that it is impossible to tell the exact relationship between the till and the soil zone. I interpret the till as being slightly younger than the soil zone, which was either not developed in the Section Line exposure or was removed prior to the deposition of the till. East of the Section Line exposure Qsd_1 is directly overlain by Qsd_2 with an unconformable contact that ranges from about 15 feet above the Knife River floodplain to below river level.

(3) Keogh Ranch exposure. The Keogh Ranch exposure is in a gully on the face of the terrace on the south side of the Knife River, in SW¼, sec. 8, T. 143N., R. 88W. This exposure shows essentially the same stratigraphic section as the Section Line exposure.

Top of exposure	Feet
1. Eolian sand	2 -3
Qsd_2 (possibly Qsd_3)	
2. Sand, medium-grained with a few pebbles	12 - 13
Conformity	
3. Till, medium to dark blue-gray, clayey	6 - 8
Unconformity	
Qsd_1	
4. Laminated clay and silt, dark gray, bedding beneath the till slightly crumpled	0 - 2
5. Coarse-grained sand and pebble gravel, stained yellow by iron oxide	2
6. Medium-to coarse-grained sand with stringers of granual to pebble gravel; crossbedded	2
7. Very coarse gravel with boulders up to two feet in diameter	3
8. Interbedded fine-to coarse-grained sand and pebble gravel	4

Base of exposure, about 10 feet above the Knife River floodplain.

On the west side of the mouth of this gully Fort Union strata unconformably underlie Qsd_1 but the contact dips to the east and the base of Qsd_1 is not exposed in the gully itself. There is no direct connection between the Keogh Ranch exposure and the Section

Line exposure and the correlation of the units is based entirely on their physical resemblance and similar stratigraphic succession. In both exposures the till is unoxidized, suggesting that the overlying sand (Qsd_2) was deposited soon after the till.

The stratigraphic relations of Qsd_1 can be summarized as follows:

(1) The base of Qsd_1 is not exposed except at the west end of the Keogh Ranch exposure, where it rests unconformably on Fort Union strata. However, inasmuch as Qsd_1 is an outwash deposit and is separated from overlying deposits by an unconformity or by a soil zone, it presumably overlies till at least in the stratigraphic time scale if not in actual physical contact.

(2) The top of Qsd_1 is exposed at several localities. In one exposure, the Beulah gravel pit, it is overlain conformably by eolian sand on which is developed a weak soil profile. In all other exposures, the overlying deposits, either till or a younger fill (Qsd_2) lie on the eroded surface of Qsd_1. Because of this erosion and because of the weak soil profile, I believe the interval following deposition of Qsd_1 was long enough to be considered as an interglacial substage of the Wisconsin.

--Second fill, Qsd_2--

Qsd_2 is the second or intermediate fill in the Knife River valley and volumetrically the largest of the fills. It is predominantly fine-grained and consists largely of locally derived materials with only small percentages of glacial debris (fig. 7).

Beds of fine-grained sand and silt make up over half of this fill and vary in appearance from place to place. In some outcrops, they are light gray, only fairly well sorted, and greatly resemble much of the modern alluvium of the floodplain deposits. In other outcrops they are tan to yellow, well sorted and laminated, and look much like the finer grained beds of the Fort Union formation. In many exposures the upper 2 to 4 feet of the silts have been so churned up by frost action and soil creep that the laminations have been obscured, leaving a nearly structureless tan silt that looks like loess. In this structureless material, however, are small polygonal fragments that still preserve the original laminations, showing that the material is not of eolian origin but is a part of Qsd_2.

Interbedded and interfingering with the fine-grained sand and silt are beds of medium-to coarse-grained sand and lenses of pebble gravel. The pebbles of the gravel beds consist of 60 to 80 per cent iron oxide, chert, and sandstone derived from the local bedrock, which readily distinguishes these gravels from the outwash gravels of Qsd_1 and Qsd_3. The gray sands, on the other hand, are identical megascopically with the sands of the other fills.

---Distribution--- Qsd_2 is well developed and its relations to other Pleistocene deposits are best shown in the southeast part of the Beulah quadrangle. In this area the top of the fill is at least 70 feet above and the base is below the floodplains of the Knife River and Spring Creek. The following exposures show both the lithology and stratigraphic relations of Qsd_2:

(1) Three exposures, the Keogh Ranch exposure, the Section Line exposure, and the Beulah gravel pit show the contact between Qsd_2 and

the underlying till and older fill, Qsd_1. These exposures have already been described.

(2) At the west end of the main street of Beulah, Qsd_2 is exposed in a road cut on the west side of a north-south gravel road. In this exposure, Qsd_2 consists of yellow-brown laminated fine-grained sand and silt that greatly resembles certain beds of the Fort Union formation except that it contains a few pebbles of granite and limestone. About 25 yards north of this exposure and about 20 yards east of the gravel road, an excavation made in 1950 showed the fine-grained sand and silt unconformably overlain by till, which was in turn overlain by the outwash fill, Qsd_3. The contact between Qsd_2 and the till dips east into a small valley in the western half of sec. 25, T. 144N., R. 88W. Apparently Qsd_2 had been eroded from this valley prior to the deposition of the younger till and Qsd_3 (fig. 9B).

(3) An exposure in the face of the terrace on the north side of Spring Creek in NW$\frac{1}{4}$, SE$\frac{1}{4}$ sec. 20, T. 144N., R. 88W. The lower part of the exposure consists of Fort Union sandstone and shale unconformably overlain by 8 to 22 feet of laminated fine-to medium-grained sand with gravel lenses and thin clay seams. About 80 percent of the pebbles in the gravel lenses are from the Fort Union formation and this fill is believed to be Qsd_2. On the eroded surface of Qsd_2 is 5 to 17 feet of partly oxided till and against the sloping surface of the till is deposited the outwash sand and gravel of Qsd_3.

(4) On the line between secs. 19 and 20, T. 144N., R. 88W. an abandoned dugway in the face of the terrace south of Spring Creek exposes the following section:

Top of exposure, 30 feet above floodplain of Spring Creek.

	Feet
1. Spoil material	1 - 3
2. Eolian sand, dark brown, humified	2
3. Sand and gravel, poorly sorted	1
Unconformity	
4. Till, sandy, tan to buff, oxidized	6
Unconformity	
5. Sand and silt, laminated, tan to brown, Qsd_2	8

Unit 4 is late Wisconsin till (here completely oxidized), and unit 3 is a gravel skim deposited by Spring Creek as it planed across the top of the till. About 100 yards south of the exposure, the top of the terrace is slightly higher and an auger hole penetrated about 8 feet of medium-grained gray sand and gravel, which is probably a remnant of the outwash fill, Qsd_3.

(5) In the Zap branch of the Beulah trench large remnants of Qsd_2, which here consists almost entirely of fine sand and silt, are preserved in the northern part of T. 144N., R. 88W. The tops of these remnants are up to 50 or 55 feet above the present floor of the valley. Till caps some of these remnants and small patches of till overlying Qsd_2 can be found all the way down to the present valley floor, showing that Qsd_2 had been extensively eroded before this till was deposited. Overlying the till and the fine sand of Qsd_2 is an outwash terrace (Qwo) whose top is 15 to 25 feet above the present valley floor. This outwash is the equivalent of Qsd_3 in Spring Creek and the Knife River valley.

The distribution and lithology of Qsd_2 outside the area near

Beulah can be summarized as follows:

(1) West of Beulah, Qsd_2 becomes coarser grained and consists largely of fine-to medium-grained gray sand, which is difficult to separate from the sands of the other fills.

In the valley of Spring Creek, remnants of Qsd_2, overlain by till and Qsd_3, have been identified as far west as Dodge in the Golden Valley quadrangle. The best exposures of Qsd_2 and the overlying till are in railroad cuts in sec. 18, T. 144N., R. 90W.

In the valley of the Knife River, remnants of the Pleistocene fills are smaller and more widely scattered as one goes upstream from Beulah. Most of these remnants consist of medium-grained gray sand and have been mapped as Qsd, undifferentiated. Some of these sand deposits in the Medicine Butte quadrangle are almost certainly Qsd_2 for scattered over their surfaces are boulders and cobbles of granite. These stones may have been deposited on top of the sand directly by ice or may have been rafted on the icebergs in the lake that almost certainly existed in the Knife River valley upstream from the margin of the late Wisconsin ice sheet.

A fill lithologically like and probably equivalent to Qsd_2 apparently underlies at least the east-west segment of the Golden Valley trench. This fill is exposed only in the northern part of sec. 25, T. 144N., R. 90W., where a north-flowing stream has cut below the alluvium and colluvium that form the present floor of the trench.

(2) East of Beulah the Pleistocene fills form a nearly continuous terrace on the south side of the Knife River valley. In

certain isolated outcrops the fine-grained sands and silts of Qsd_2 unconformably underlie and can be distinguished from the coarser outwash gravels of Qsd_3. Most of the terrace, however, consists of fine-to coarse-grained sand with minor amounts of gravel and has been mapped Qsd, undifferentiated. Much of the surface material of the terrace has been reworked into sand dunes, especially in the Hazen and Stanton quadrangles, and it is impossible to tell the character of the underlying fill in these areas.

On the north side of the Knife River valley, east of Beulah, the fills are less continuous in outcrop but are more easily distinguished. Just west of Hazen in the lower part of the valley of Antelope Creek, several exposures show the fine-grained sands of Qsd_2 unconformably overlain by the outwash gravels of Qsd_3. One exposure, a road cut on the south side of State Highway 25, near a junction with a gravel road, in the NE$\frac{1}{4}$, NW$\frac{1}{4}$, sec. 11, T. 144N., R. 87W., shows the following section:

Top of exposure

	Feet
1. Coarse sand and gravel, Qsd_3	1 - 3
Unconformity	
2. Fine-grained sand and silt, laminated, tan to buff Qsd_2	5$\frac{1}{2}$
3. Till, clayey, tan to brown, oxidized. *	3 +

Base of exposure.

* In 1950 this exposure had slumped in so badly that the till was no longer visible without digging or augering at the base of the road ditch.

(3) In the Missouri Valley downstream from the mouth of the Knife River a fine-grained sand and silt deposit that is probably remnant of Qsd_2 is found in secs. 17, 18, 20 and 21, T. 144N., R. 84W.

The tops of these remnants are 70 to 80 feet above the present Missouri floodplain but these tops are erosional and give no indication of the original altitude of the top of the fill. The base of the fill is below the floodplain of the Missouri River.

(4) Upstream from the mouth of the Knife River Qsd_2 was not identified within the walls of the Missouri trench. In several of the small tributaries of the Missouri River, however, are patches of a fine-grained fill similar in lithology and stratigraphic position to Qsd_2 in the Knife River valley. These patches of probable Qsd_2 crop out in the following localities:

(a) In the Stanton quadrangle in SE$\frac{1}{4}$ sec. 36, T. 146N., R. 85W., a small excavation near the head of a north-flowing coulee exposes about 6 feet of light yellow to gray-brown fine-grained sand and silt, similar to the fine-grained facies of Qsd_2 in the Knife River Valley. An additional 6 feet of this material was penetrated by an auger hole. Further augering indicated that the deposit probably extends southwest into the northern part of sec. 1, T. 145N., R. 85W., and underlies the divide between the north-flowing coulee and Elm Creek, a small tributary of the Knife River. This divide is low and broad, and appears to have been enlarged by waters diverted from the Missouri trench south into the Knife River. A few small kames and patches of till are found near the floor of the divide and granite boulders dot the surface of the fine-grained fill, indicating that both the enlarging of the divide and the deposition of the fill antedated the last glaciation. Thus the fine-grained fill occupies the same stratigraphic position as Qsd_2 in the Knife River valley. The top of the fill is at an altitude of about 1890 feet, or about 200 feet above the modern floodplain of the Missouri River. Inasmuch as the base of Qsd_2 is known to extend below the modern floodplains of the streams in other parts of the Knife area, it appears that Qsd_2 was at least 200 feet thick in this part of the Missouri trench.

(b) In the northwestern part of the Stanton quadrangle in NE$\frac{1}{4}$, SW$\frac{1}{4}$, sec. 1, T. 146N., R. 85W., a cut on the south side of a gravel road leading to the abandoned site of Mannhaven exposes 10 to 15 feet of till overlying 15 to 20 feet of medium-to fine-grained brown and gray sand with some beds of laminated tan silt. This fill is correlated with Qsd_2 on the basis of similar lithology and similar stratigraphic position. The top of the fine sand is at an altitude of about 1,900 feet or about 200 feet above the present floodplain of the Missouri River.

(c) In the northern part of the Hazen quadrangle in T. 146N., R. 86W., are several deposits of fine-grained sand and silt that are probably Qsd_2.

In two localities the fine fill is overlain by late Wisconsin till. The first of these localities, a road cut on the west side of a deep coulee in NE$\frac{1}{4}$, NE$\frac{1}{4}$, sec. 17., shows the following section:

Top of exposure

	Feet
1. Outwash sand and gravel	$2\frac{1}{2}$
2. Till, sandy, yellow-brown to light gray	5
3. Outwash gravel	$1\frac{1}{2}$
4. Sand, fine-grained, tan to yellow, calcareous, probably Qsd_2 .	11

Base of exposure

The $1\frac{1}{2}$ feet of gravel between the till and the fine-grained fill is interpreted as outwash laid down in advance of the late Wisconsin ice sheet.

The second locality is in $NE\frac{1}{4}$, sec. 18, and consists of several exposures in a deep coulee that leads north to the Missouri River. These exposures show two tills that are in direct contact at the sides of the coulee but that are separated by 10 to 20 feet of fine-grained sand near the center of the coulee (see fig. 9A). Both the upper and lower contacts of the fine-grained fill are erosional. The lower contact is marked by a boulder pavement developed on the top of the underlying till. The upper contact is nearly flat but locally shows that a few of the beds of the fill were eroded prior to deposition of the upper till. In one exposure, just west of a white adobe house, the upper 18 inches of the fill are enriched in calcium carbonate; this may indicate a period of soil formation prior to deposition of the upper till, or it may indicate merely precipitation of carbonate from ground water. Where the two tills are in direct contact, the boundary between them is not marked by any concentration of stones and is difficult to pick. The upper part of the older till is well oxidized to a yellow-brown, whereas the lower part of the younger till is only partly oxidized and still preserves "islands" of blue-gray color. The contact between these color differences, however, is gradational and not easy to identify except by careful inspection.

---Stratigraphic relations--- The stratigraphic relations of Qsd_2 as indicated by the sections just described and by the sections described in connection with Qsd_1 are as follows: (1) Qsd_2 lies unconformably on Qsd_1 and the Fort Union formation. In the Keogh Ranch and Section Line exposures, Qsd_2 is separated from Qsd_1 by till with no apparent erosional break between this till and Qsd_2. In the exposures in sec.,18, T. 146N., R. 86W., however, Qsd_2 is separated from an underlying till by a boulder pavement, indicating at least a short interval of erosion. The main unconformity, however, seems to be between Qsd_1 and the overlying till rather than between this till and Qsd_2, and this unconformity is thought to represent an interglacial substage of the Wisconsin stage. (2) The upper contact of Qsd_2 is erosional in nearly every exposure. Till and Qsd_3 unconformably overlie Qsd_2 at altitudes ranging from below the floodplain of the Knife River to about 70 feet above the river near Beulah and 200 feet above the Missouri River in the Stanton quadrangle. This indicates that Qsd_2 was extensively dissected prior to the last ice advance and the déposition of the till and outwash. The extent of this dissection suggests that the interval recorded was considerably longer than the interval between Qsd_1 and Qsd_2.

---Interpretation--- The origin of Qsd_2 is not altogether clear. Although it contains some reworked glacial material, the bulk of this fill was derived from the local bedrock of the area. Despite this fact, Qsd_2 seems to be closely associated, at least in time, with the till that underlies it and separates it from the older outwash fill,

Qsd_1. It seems likely, therefore, that Qsd_2 is an inwash deposit formed during the wastage of the ice sheet that deposited the underlying till. A lobe of this ice sheet probably extended across the Missouri River trench at some point downstream from the mouth of the Knife River, causing both streams to be ponded and to aggrade their valleys.

The fine-grained sand and silt beds of Qsd_2 indicate deposition in water that was standing or flowing very slowly. The lenses of coarse-grained sand and gravel, on the other hand, indicate deposition by running water. This alternation of fluvial and fluvio-lacustrine conditions was probably caused by fluctuations in the height of the ice dam in the Missouri trench.

--Third fill, Qsd_3--

Qsd_3 is the youngest and most extensively preserved Pleistocene fill in the Knife River valley. Like Qsd_1 it consists principally of glacial outwash and most of the stones are of foreign origin. It differs from Qsd_1 in being less well size sorted and in lacking cut-and-fill type cross-bedding. A few exposures of Qsd_3 show some cross-bedding but in most places the beds are essentially parallel. Where Qsd_3 consists of interbedded sand and gravel it is easily distinguished from the underlying Qsd_2. A large part of Qsd_3, however, consists of medium-to coarse-grained gray sand with only a few stringers of pebble gravel and this facies is almost impossible to tell from the sand facies of Qsd_2. Some of the gravel beds contain cobbles and small boulders of granite, suggesting that this fill was deposited fairly close to the edge of the ice.

The thickest deposits of Qsd_3 are in the Stanton quadrangle near the mouth of the Knife River. Here the base of the fill is below the modern floodplain of the river and the top is 100 to 110 feet above the floodplain. The profile of the upper surface of Qsd_3 is gentler than that of the modern floodplain, so that west of Stanton it converges on the floodplain and Qsd_3 gradually thins. At Beulah the top of Qsd_3 is about 60 feet above the floodplain of the Knife River; and at Dodge it is about 25 feet above the floodplain of Spring Creek.

---Distribution and Interpretation--- In the valley of the Knife River, Qsd_3 has been identified from the mouth of the river at Stanton as far west as the mouth of Brush Creek in the Medicine Butte quadrangle. West of this point the Pleistocene fills consist chiefly of medium-grained sand and cannot be differentiated. As indicated in the discussion of Qsd_2, some of these sand deposits are probably the intermidate fill, Qsd_2. Others are probably Qsd_3, because the western part of the Knife River is beyond the late Wisconsin drift border, and in this area Qsd_3 probably loses its glacial character and is an inwash fill similar to Qsd_2.

In the lower 4 miles of the valley of Brush Creek Qsd_3 consists of parallel-bedded coarse-grained sand and gravel 25 to 50 feet thick. These deposits differ from Qsd_3 in other parts of the area in that they are better sorted and contain only small amounts of silt and clay. Just why the fill in this valley is better sorted than the rest of Qsd_3 is not clear, but the fact that it is makes the gravel deposits in Brush Creek one of the better sources of concrete aggregate in the Knife River area.

In the valley of Spring Creek Qsd_3 has been identified as far west as Dodge and probably extends still farther upstream. About 2 miles northeast of Golden Valley, in the southern part of sec. 12, T. 144N., R. 90W., is a deposit of very coarse sand and gravel that has been mapped as Qsd_3. The top of this deposit is 55 to 60 feet above the floodplain of Spring Creek, or about 20 feet higher than the general top of Qsd_3 in this vicinity. The bedding is foreset almost due south into the valley of Spring Creek (see pl. 20A). The deposit probably represents either a small kame built directly against ice or a delta built out into water ponded in the valley of Spring Creek. Auger holes around the margin of this deposit indicate that it lies in part on bedrock and in part on the fine-grained sand of Qsd_2.

Between Hazen and the mouth of the Knife River at Stanton the character of Qsd_3 is different on opposite sides of the valley. As indicated in the discussion of Qsd_2, the terrace on the south side of the valley consists largely of medium-grained gray sand that has been mapped as Qsd, undifferentiated. Although some of this sand may be part of the intermediate fill, Qsd_2, a large part of it belongs in Qsd_3. In contrast, the deposits of Qsd_3 on the north side of the valley consist largely of coarse-grained sand and gravel, and these deposits overlie and pinch out against remnants of the cut terrace, Qt. This terrace, presumably cut while the Knife River was flowing at the top of Qsd_3, is not developed on the south side of the valley.

The differences between the north and south sides of the valley may be explained by postulating that in this part of the valley Qsd_3 represents a kame terrace rather than a wall to wall outwash fill. The general fineness of grain size and the parallel bedding of Qsd_3 on the south side of the valley do not fit the usual concept of an ice-contact deposit. However, the valley of the Knife River downstream from Hazen is broad and open. If there were a residual tongue of ice in the northern part of the valley, the southern part could easily have been filled with a deposit of comparatively fine-grained outwash that would show no ice-contact features except at its northern margin where they could easily have been removed by later erosion.

In most exposures in the Missouri River valley, Qsd_3 consists of parallel-bedded glacial sand and gravel that is similar both in appearance and in composition to its counterpart in the Knife River valley. The largest single deposit of Qsd_3 in the Knife River area is in the Missouri valley and underlies a large terrace-like flat in the northeastern part of T. 145N., R. 84W. Although in most of the Knife River valley (except possibly for the segment between Hazen and Stanton) Qsd_3 represents a wall-to-wall outwash fill, in the Missouri River trench this fill is a kame terrace. The evidence is as follows:

(1) In several localities the medium-to coarse-grained sands of Qsd_3 are interbedded with layers of poorly sorted very coarse-grained gravel containing slabs of lignite and boulders of granite

up to 2 feet in diameter, suggesting deposition close to the glacier. These coarse beds are well exposed in the gravel pits in sec. 21, T. 146N., R. 84W., (see pl.20B).

(2) In $SW\frac{1}{4}$, sec. 16, T. 145N., R. 84W., are small gravel deposits that appear to preserve the constructional topography of small kames and crevasse fillings.

(3) In the northeast corner of sec. 2., T. 145N., R. 84W., is a gravel pit exposing 25 to 30 feet of medium-to coarse-grained sand and gravel with the collapsed bedding typical of ice-contact deposits (see pl. 21). A few exposures plus some auger holes east of the pit indicate that this ice-contact gravel interfingers with and in part underlies the parallel-bedded gravel that is more characteristic of Qsd_3. At the south end of the pit the ice-contact gravels are overlain by a bed of till 1 to 2 feet thick, indicating a local readvance of the ice across this area after Qsd_3 had been deposited. The ice front, therefore, was probably never very far from the Missouri trench while Qsd_3 was being deposited.

(4) In the center of the Missouri trench is a gravel formation, slightly younger than Qsd_3, that has been mapped as Missouri River gravel, Qmg. The base of this gravel is slightly below the modern floodplain of the Missouri River and rests on unweathered till and local deposits of lacustrine sand and clay. As indicated in a subsequent section of this report, Qmg was deposited after the ice had vacated the Missouri River trench, but before it had retreated beyond the Max moraine. Very likely Qmg antedates also the readvance of the

ice that locally deposited the till on top of Qsd_3. If, therefore, Qsd_3 was deposited as a wall-to-wall outwash fill, it was completely eroded from the center of the Missouri trench during the comparatively short interval between its deposition and the final retreat of the ice. Such rapid erosion, while not impossible, is difficult to imagine at a time when streams would normally be overloaded and would be tending to aggrade their valleys. Also, there is no evidence of this rapid erosion in the Knife River valley. If, however, Qsd_3 is a kame terrace this difficulty is eliminated. The center of the Missouri trench could have been cleared quickly and completely by the melting of the stagnant ice, leaving the space that was soon filled by the Missouri River gravels.

---Stratigraphic relations--- Qsd_3 is closely associated with, and in places directly overlies a till sheet. Where this till is absent, Qsd_3 is unconformable on Qsd_2 and older deposits. The interval between Qsd_2 and Qsd_3 was long enough to allow the erosion of more than half of Qsd_2 from the valleys of the Knife and Missouri rivers. Qsd_3 grades laterally into deposits mapped as late Wisconsin outwash, Qwo. Qwo and Qsd_3 are similar in appearance and composition and they have been mapped as separate units chiefly on the basis of geographic distribution and association with other Pleistocene deposits.

Qsd_3 is the time-stratigraphic equivalent of the ice-contact deposits, Qic. Qsd_3 is slightly older than the Missouri River gravels, Qmg, and the youngest ice-contact deposits, Qic', and is unconformably overlain by the latter deposits. All these units, however, are closely associated in time and belong to a single substage of the Wisconsin.

The eroded upper surface of Qsd_3 is locally overlain by dune sand, Qds, and post-glacial alluvium, Qal. In most localities, however, Qsd_3 is not overlain by any younger deposits.

Late Wisconsin gravels essentially contemporaneous with Qsd_3

Other than the outwash fill, Qsd_3, gravel deposits of late Wisconsin age are confined to the northeastern part of the Knife River area, within the late Wisconsin (Mankato) drift border. These deposits have been mapped under the headings of outwash (Qwo), ice-contact deposits (Qic and Qic') and Missouri River gravel (Qmr).

--Outwash (Qwo)--

In the northern part of the Knife River area, especially in the Beulah and Hazen quadrangles, are numerous deposits of late Wisconsin outwash (Qwo). This outwash consists of moderately well-sorted , parallel-bedded sand and gravel in which most of the pebbles are of Canadian provenance.(fig. 7).

Laterally the outwash grades into the valley fill, Qsd_3; and, except for the fact that the outwash is generally coarser-grained and includes some beds of cobble gravel, the two deposits are similar both in composition and in general appearance. They have been differentiated on the map for the following reasons: The deposits mapped as Qwo consist entirely of glacial material; they are all clearly related to the late Wisconsin till and many can be traced directly into the Krem moraine. In contrast, Qsd_3 cannot be distinguished in many exposures from the older fills of the Knife River valley. Moreover, although Qsd_3 consists chiefly of outwash, it contains also some inwash material derived from Knife River valley west of the late Wisconsin drift border. Therefore, all the fills in the Knife River valley have been mapped under the general heading Qsd, and have been differentiated only where their stratigraphic relations are clear. The northern edge of the Knife River valley has been chosen as the arbitrary dividing line, north of which the late Wisconsin glacio-fluvial deposits are mapped Qwo, south of which, as Qsd_3.

Between the Knife River and the Krem moraine, outwash is found both in the valleys and on the flatter parts of the uplands adjacent to the moraine. Several of the larger valleys have outwash trains that can be traced from the moraine south to the Knife River. Other valleys contain only small isolated deposits of the outwash. In many valleys, the smaller ones in particular, are remnants of a cut terrace, Qt. The profile of this terrace coincides with the tops of Qwo and Qsd_3, and the terrace was evidently cut while the streams were flowing at the top of the late Wisconsin outwash gravels. Nearly all the remnants of the cut bench are capped by deposits of outwash-type gravel ranging in thickness from one inch to several feet. For convenience, the map symbol, Qt, has been restricted to those benches whose gravel cap is less than 3 feet thick; all thicker deposits have been mapped as Qwo or Qsd_3.

North of the Krem moraine most of the deposits mapped as Qwo cap remnants of the out terrace, Qt, which flanks many of the small streams and is graded to a fill (probably Qsd_3) in the Missouri trench. Strictly speaking, these gravels are not true outwash, for they could not have been deposited until after the ice-front had retreated north of the Missouri River. They must be the result of the reworking of till by surface streams during the recession of the ice sheet. Nevertheless, these gravels are identical in composition, appearance, and mode of occurrence with the true outwash gravels south of the Krem moraine, and they have been included in the category Qwo.

--Ice-contact deposits (Qic and Qic')--

In the northern and eastern parts of the Knife River area are numerous isolated deposits of stratified drift that show the poor sorting and the steeply dipping or jumbled bedding characteristic of ice-contact deposits (see pl.22A). Most of these deposits consist of medium-to coarse-grained sand and gravel, but a few of them are fine-grained and consist mostly of silt and fine-grained sand.

Some of these ice-contact deposits are isolated mounds or kames, Others appear to have been built between ice and the sides of small valleys and could be considered rudimentary kame terraces. Still others have very little topographic expression and would probably have been overlooked except that they are exposed in road cuts or in the cut banks of streams. One deposit, in sec. 20, T. 145N., R. 88W., is expressed topographically as a low sinuous ridge and this deposit is probably a small esker.

---Qic--- The deposits mapped as Qic are essentially contemporaneous with the outwash (Qwo) and the valley fill Qsd_3. Many of these deposits are associated with the Krem moraine. The largest of these is a flat-topped kameor kame terrace at the north edge of the Beulah trench in secs. 1, 2, 11 and 12, T. 145N., R. 88W. This feature was clearly formed after the ice-front had partly retreated from the moraine but while stagnant ice filled part of the trench. Meltwater from the ice flowed southwest through two small valleys in sec. 1 and deposited sand and gravel around a block of ice in the northeast part of sec. 11. Later the ice melted, leaving a large closed depression or kettle-hole. Pl. 23 shows the typical lithology of the kame.

---Qic'--- The deposits mapped as Qic' appear to be slightly younger than those mapped as Qic. They are confined to the Stanton quadrangle and are related to a late readvance of the ice across the Missouri River trench in that area. They crop out at the following localities:

(1) In the southeast part of the Stanton quadrangle in secs. 22, 26, and 27, T. 144N., R. 84W., are two northwest-trending ridges composed of very poorly sorted boulder gravel. The ridges are about ¼ mile long, 100 to 200 yards wide, and 25 to 30 feet high. The elongate shape and bouldery nature of the deposits suggest that they may be small end moraines, but they could also be interpreted as kames. These moraines or kames are set on and rise above the "40 foot terrace" that flanks the Missouri River floodplain. As will be shown later, the terrace is capped by post-glacial alluvium (Qma) but is underlain in part by the Missouri River gravels (Qmg) and late Wisconsin till. Exposures around the ridges are poor, but seem to

indicate that the boulder gravels lie on the upper surface of the Missouri River gravels (Qmg) and are overlapped by the alluvium (Qma).

(2) In sec. 11, T. 145N., R. 84W., are several small kames composed of stratified coarse-grained sand and pebble gravel. These kames rise above and apparently lie on the upper surface of Qsd_3.

It is possible that some of the other small kames in the Stanton quadrangle, such as those in sec. 1, T. 145N., R. 84W., may be the same age as the boulder ridges and kames just described and should therefore have been mapped as Qic'. However, in the absence of direct stratigraphic evidence either for or against this correlation they have been arbitrarily designated as Qic.

The boulder ridges and kames mapped as Qic' apparently overlie and are therefore younger than both the valley fill, Qsd_3, and the Missouri River gravels, Qmg. It has already been noted (p. 111) that a thin till sheet occupies the same stratigraphic position as these ridges and kames. Therefore the till and the gravels of Qic' are probably of the same age and are related to a late readvance of the ice-front in the eastern part of the Knife River area. This readvance, whose approximate limit is shown on pl. 4, was apparently later than the readvance to the Krem moraine, for, as already noted, the deposits of the Krem moraine seem to be contemporaneous with at least the upper parts of Qwo and Qsd_3.

--Missouri River gravels (Qmg)--

In the Missouri River valley is a broad terrace, whose top is

35 to 40 feet above the present floodplain of the river. In the valleys of the Knife River and its tributaries the equivalent terrace is composed entirely of alluvium, but in the 40-foot terrace of the Missouri valley, alluvium is merely the uppermost deposit and lies on the eroded surface of bedrock, till, and a sequence of gravels unlike any other gravels in the Knife River area. For convenience these gravels are referred to in this report as "Missouri River gravels", but it is not intended that they be designated as a formation or given a formal name.

The Missouri River gravels are restricted to the 40-foot terrace in the Missouri trench, no similar or equivalent gravels having been found in any other valley in the area. The character and stratigraphic relations of the gravels are well shown in gravel pits and exposures in the face of the terrace near old Fort Clark in T. 144N., R. 84W., in the face of the terrace on the east side of the Missouri in secs. 15 and 22, T. 145N., R. 84W., and in the excavations made in connection with the building of Garrison dam.

The Missouri River gravels range in thickness from a few inches to about 40 feet. They consist of well-sorted, parallel-bedded sand and moderately well-rounded pebble gravel.

In composition the Missouri River gravels differ from all Pleistocene deposits of the area. Pebble counts that exclude stones derived from the local bedrock show that only 50 to 60 per cent of the pebbles are of Canadian provenance; the rest are of western derivation. The western stones consist of red, purple and brown quartzites (probably derived ultimately from the pre-Cambrian Belt formation), gray, brown and yellow cherts, and a few fragments of moss agate that probably came from the Yellowstone River drainage basin. Most of the western stones are sub-round to round and may be in their second or third cycle of sedimentation. The Canadian stones are mostly limestone and granite, and are sub-round to sub-angular, about the same degree of roundness as is found in the outwash or kames.

The lower contact of the Missouri River gravels is erosional. In most outcrops, the gravels lie on the slightly channeled surface of the late Wisconsin till; in a few outcrops, the till is missing and the gravels rest directly on the Fort Union formation. The amount of erosion of the till is not great, however, and the unconformity between till and gravel probably does not represent a great length of time. There is, unfortunately, no outcrop that exposes the contact between the Missouri gravels and the fill, Qsd3, but presumably, the gravels overlie the fill.

The upper contact of the Missouri River gravels is also erosional except in secs. 22, 26, and 27, T. 144N., R. 84W., where the gravels are overlain by the boulder ridges, Qic'. Exposures are poor, but in general the two deposits appear to be conformable. Elsewhere, the only deposit overlying the Missouri River gravels is the post-glacial alluvium Qma. Prior to the deposition of the alluvium, the surface of the gravels was extensively eroded. In some places, especially near the mouths of tributary streams, erosion completely removed both the gravels and the underlying till, and in these localities the 40-foot terrace consists entirely of the later alluvial fill, Qma.

In the summer of 1949 the excavations in the 40-foot terrace on the west side of the Missouri River at Garrison Dam afforded an unusually good set of exposures, showing both the character and stratigraphic relations of the Missouri River gravels. In the so-called intake channel, just north of the edge of the Stanton quadrangle, the unconformities between the gravel and the overlying alluvium and between the gravel and the underlying till were well displayed (see pl. 24). In two places in the intake channel the Missouri River gravels are separated from the underlying till by thin discontinuous deposits of dark gray lacustrine clay and medium-grained yellow sand, deposits not exposed elsewhere in the area. It has already been stated that probably the Missouri trench was filled with stagnant ice during the recession of the late Wisconsin glacier. As the stagnant ice melted, it split into blocks between which were small ponds connected by winding streams. The lacustrine clays and yellow sands were probably deposited in these ponds and streams.

The critical features of the Missouri River gravels can be summarized as follows:

The large numbers of pebbles of western provenance indicate that while these gravels were being deposited the Missouri River was flowing freely, unimpeded by ice or glacial debris. However, the large numbers of glacially derived stones indicate that the ice front had not retreated very far to the northeast and was still supplying outwash to the Missouri River. Therefore, the Missouri River gravels were deposited during the recession of the late Wisconsin ice, just of the same township are outwash.

--Gravel on older cut terraces (Qtg)--

In the western and northwestern parts of the Broncho Quadrangle are remnants of a cut or strath terrace capped by deposits of fluvial sand and gravel.

In T. 142N., R. 91W., the bench remnants with their cappings of gravel range from 60 to 100 feet above the present floodplain of the Knife River. Probably not all are remnants of the same strath but nevertheless all appear to be of the same general age.

In the northwest corner of the Broncho Quadrangle another group of gravel deposits mapped as Qtg cap remnants of a cut terrace flanking a small tributary of Spring Creek. The gradient of the terrace is much gentler than that of the present-day stream, so that the two profiles, which are nearly coincident near the headwaters of the of the stream in sec. 5, T. 143N., R. 91W., diverge rapidly downstream and in secs. 34 and 35, T. 144N., R. 91W., the deposits of Qts are 40 to 45 feet above the present valley floor.

In contrast with the older glacial gravels, which contain 70 to 90 percent pebbles of Canadian derivation, the gravels of Qtg are 50 to 60 per cent of local origin (see fig. 6).

Thus, the gravels of Qtg are similar lithologically to the gravel beds in the intermediate fill (Qsd_2) in the Knife River valley suggesting that the two deposits may be related. It is possible that streams flowing on the top of the fill Qsd_2 planed across the bedrock and subsequently deposited additional gravel on top of this bench. Under this hypothesis the cut terrace could have been formed after the valleys had been cut to their present depth. It is also possible that the bench remnants are relics of an old erosion surface that antedates the dissection of the valleys and that the fill Qsd_2 rose and capped these remnants with sand and gravel. The field evidence is consistent with either hypothesis.

--Older sand and gravel undifferentiated (Qsg)--

In contrast with the glacial deposits of Qwg and the fluvial deposits of Otg the deposits mapped as Qsg are indeterminate in origin as well as in correlation. They are so few in number and so small in size that no statistical count was made of their pebbles, but a few rough estimates were made and indicate that some of them contain 60 to 70 per cent stones of glacial origin while others contain 60 to 70 per cent stones of local derivation. Thus the map heading Qsg is probably a scrap-basket group that includes gravels of both glacial and fluvial origin. The glacial deposits may be remnants of kames or outwash; the fluvial deposits may be remnants of gravels graded to Qsd_2 in the Knife River valley. The deposits in sec. 32, T. 142N., R. 89W., and in sec. 5, T. 141N., R. 89W., are very likely of glacial origin as they contain a large proportion of granite and limestone pebbles and cobbles, some of which appear to preserve glacial soles and a few of which seem to have faint remnants of striations.

Cut terraces (Qt and Qlt)

Flanking the valleys of Knife River and many of the smaller streams are remnants of stream-cut benches at various altitudes above the modern floodplains. The highest of the these benches or strath terraces apparently fall on a single profile and have been mapped as the terrace, Qt. The lower benches do not fit any one profile, but have all been grouped in the general heading, Qlt. Although as a general rule erosional features do not belong in the discussion of stratigraphy, these terraces are so intimately associated with the Pleistocene deposits of the area that they will be discussed at this time.

The higher cut terrace, Qt, is well developed in the northern and eastern parts of the Knife River area. It is absent or at least cannot be identified in the southwestern part of the area beyond the late Wisconsin drift border. The terrace is cut on both bedrock and late Wisconsin till. The downstream slope of the terrace profile is less than the gradient of the modern floodplains. Therefore, traced upstream the profiles of the terrace and the floodplain converge; traced downstream they diverge. Thus Qt is 25 to 30 feet above Spring Creek near Golden Valley, 50 to 60 feet above the Knife River at Beulah, and 100 to 110 feet above the Knife and Missouri rivers at Stanton.

As stated in the descriptions of the outwash, Qwo, and the fill, Qsd_3, the long profile of Qt coincides with the tops of the higher remnants of these glacio-fluvial deposits. Also, nearly all the bench remnants are capped with at least a skim of these deposits. It is therefore difficult in many localities to tell where Qsd_3 or Qwo stops and Qt begins. For convenience in mapping, Qt has been limited to those bench remnants capped with less than 3 feet of gravel, and all thicker gravel caps have been mapped as Qwo or Qsd_3.

The coincidence in the profiles of Qt and the tops of Qwo and Qsd_3 suggests a genetic connection between the terrace and these glacial deposits. Apparently, after having deposited Qwo and Qsd_3, the streams flowed on the tops of these fills long enough to cut laterally into the valley walls and develop a strath across both till and bedrock.

Between the higher cut terrace Qt and the modern floodplain of the Knife River are remnants of other strath terraces that have been mapped as "lower cut terraces" (Qlt). In most of the Knife River area these lower surfaces do not fall along any definite profile and they probably represent non-paired, strath terraces, cut while the Knife River was dissecting the late Wisconsin fill, Qsd_3. Because of the upstream convergence of the terrace profiles and the present stream profiles, it was not always possible to distinguish the higher cut terrace, Qt, from the lower cut terraces, Qlt, in the Golden Valley quadrangle. Therefore strath terraces in this quadrangle were mapped as Qt, although some of them are probably correlative to the lower cut terraces.

Summary and correlation of Pleistocene deposits

The Knife River area is partly covered by three ages of glacial deposits, whose relations can be summarized as follows:

(1) The tills are lithologically similar and cannot be differentiated except where they are interbedded with stratified deposits.

(2) In the valleys of the Knife and Missouri rivers are 3 fills (Qsd). The base of each fill is below the modern floodplain of the streams, indicating that the valleys have been cut at least to the

depths of their present floors before any of these fills were deposited. The first fill (Qsd_1) is crossbedded outwash sand and gravel. There are no exposures showing it in contact with an underlying till, but its character and stratigraphic relations indicate that it must record a glacial advance. The second fill (Qsd_2) is comparatively fine-grained, consisting mostly of silt and fine-to medium-grained sand derived from the local bedrock. It is interpreted as a fluvio-lacustrine inwash fill, laid down when a lobe of ice blocked the Missouri River downstream from the mouth of the Knife River. This fill overlies and is closely associated with a till sheet. The third fill (Qsd_3) consists mostly of glacial outwash. In most of the Knife River valley this fill was "wall-to-wall", but in the Missouri River trench it was a kame terrace. This fill immediately overlies the third or youngest major till sheet, and both till and fill are confined to the northern and eastern parts of the Knife River area.

(3) The three fills are separated by pronounced unconformities. The interval between the first and second fills was characterized by a fairly small amount of erosion and weak soil-development. The interval between the second and third fills was characterized by more extensive erosion , which dissected the thick fill, Qsd_2 and removed the bulk of the two older till sheets.

(4) A fourth fill (Qmg) is restricted to the Missouri River trench, and consists partly of outwash and partly of stones derived from the west. It appears to have been deposited against the sides of the kame terrace of Qsd_3 shortly after the stagnant ice had [illegible] from the trench, and it does not record another glacial episode.

(5) A fourth till with associated ice-contact deposits is present in the extreme eastern part of the area. These deposits overlie both the third fill (Qsd_3) and the Missouri River gravels (Qmg), but there is no unconformity at their base and they probably represent merely a readvance of the ice that deposited the third till and the third fill (Qsd_3).

(6) Other fluvial and glacio-fluvial deposits in the Knife River area are the lateral and time equivalents of the three major fills Qsd_1, Qsd_2 and Qsd_3. The deposits of ice-contact stratified drift (Qic) and outwash (Qwc) in the northern part of the area are easily shown to be the time equivalent of the fill, Qsd_3. The isolated remnants of fluvial and glacio-fluvial deposits in the in the southwestern part of the Knife River area (Qtg, Qwg, and Qsg) cannot be correlated definitely but are probably the equivalent of the intermediate fill Qsd_2.

All three generations of Pleistocene deposits in the Knife River area are believed to be of Wisconsin age. Qsd_1 and Qsd_2 and their associated deposits are early Wisconsin, Iowan and Tazewell respectively. Qsd_3 is late Wisconsin and is probably Mankato. These correlations are based partly on a comparison of the stratigraphic sequence of the Knife River deposits with the sequence of dated deposits in South Dakota, Iowa and Nebraska, and partly on the tracing of Wisconsin drift borders from the North Dakota-South Dakota State line north to the Knife River. The field evidence and the reasoning can be summarized as follows:

(1) Crandell (1951, pp. 148-149) and Warren (1949, p.1926) have independently concluded that in South Dakota the Missouri River trench was established during the Illinoian glacial stage. They also agree, as does Flint (1951, manuscript in preparation) that the oldest drift in the trench is Iowan and that the base of this drift is close to the present floor of the valley. Thus, Qsd_1 occupies a topographic position similar to that of the Iowan drift in South Dakota.

(2) The outermost drift border in North Dakota has been traced from just west of the Knife River area south to the South Dakota State line, where it joins the Iowan drift border as mapped by Flint (1951, op.cit.). Although this drift has been dissected and largely removed, its remnants are conformable with the present topography (i.e. they post-date the dissection that followed the cutting of the Missouri River trench) and are found in the bottoms of some of the valleys. Thus drift of Iowan age is present in North Dakota, and has the same topographic and stratigraphic position as Qsd_1 in the Knife River area.

(3) Until a few years ago it was generally assumed that the Iowan-Tazewell interval was the longest of the Wisconsin interglacial substages. Recent work in South Dakota, Nebraska, and Kansas, however, has shown that this interval was relatively short and was characterized by minor erosion and weak soil formation (Leonard, 1950, p.1481; Schultz et al., 1951, p.7; Frye, 1951, p.406; and Flint, 1951, manuscript in preparation). This fits the description of the interval between Qsd_1 and Qsd_2 in the Knife River area. The

same recent work has shown that the Tazewell-Cary interval was relatively long and was characterized by more extensive erosion and strong soil-development (the Brady soil-forming interval in Kansas). This fits the description of the interval between Qsd_2 and Qsd_3 in the Knife River area. Therefore, Qsd_2 and its associated till sheet are probably of Tazewell age.

(4) Flint (1951, op.cit.) has found that in north-central South Dakota the border of the Cary drift is crossed and overlapped by the border of the younger Mankato drift. In southern North Dakota, this Mankato drift border is difficult to follow, but can be traced in a general way from the South Dakota State line northwest to the Knife River area, where it coincides with the limit of the third till and the valley fill, Qsd_3. I have found no evidence of any major drift border northeast of this one, either in the Knife River or anywhere else in south-central North Dakota. Certainly there is no evidence, either stratigraphic or topographic to support the old idea that the Mankato drift border is marked by the "Altamont" (now the Max) moraine. It seems probable, therefore, that in southern North Dakota the Cary drift border has been overlapped and obscured by the Mankato drift and that all the glacial deposits associated with Qsd_3 in the Knife River area should be assigned to the Mankato substage.

RECENT SERIES

As used in this report, the term "Recent" includes all post-Mankato deposits. These deposits include alluvium, eolian sand, landslide blocks, and deposits of residual silica. Thick deposits of colluvium cover some of the slopes, especially the sides of some of the larger valleys, but these have not been differentiated on the map. The landslide blocks are discussed under "Geomorphology" and are not described in this section.

Alluvium (Qma and Qal)

Post-glacial stream deposits cover the floors of all the valleys in the Knife River area. These deposits consist mostly of tan to gray fine-grained sand and silt with a few beds of coarse-grained sand and a very few lenses of pebble to cobble gravel. The alluvium in the valley of the Missouri River is all fine-grained, the coarse sand and gravel being restricted to the valleys of the Knife River, Spring Creek and a few of their tributaries. Some beds of the alluvium are well sorted and consist of thinly-bedded silt or fine sand; others are very poorly sorted and consist of a mixture of particles ranging in size from clay to fine- or medium-grained sand.

Two ages of alluvium can be differentiated locally in the Knife River area. The younger of these is represented by the modern flood-plains of the streams; the older, by a terrace flanking the flood-plains. In all the valleys except that of the Missouri River this terrace is composed entirely of alluvium. In the Missouri River valley, however, the older alluvium is merely the "caprock" of the terrace and is unconformably underlain by several Pleistocene deposits, notably the Missouri River gravels (Qmg). Therefore, because it is both lithologically distinctive and topographically prominent, the terrace in the Missouri River valley has been mapped as separate geologic units. Where the top of the terrace is underlain by the Missouri River gravels covered by less than 3 feet of alluvium, the terrace has been mapped as Qmg; where the alluvial cover is more than 3 feet thick, it has been mapped as the "alluvial terrace", Qma.(fig. 10).

Elsewhere in the area the terrace has neither the topographic prominence nor the distinctive composition that it has in the Missouri River trench, and in many parts of the valleys it is impossible or impractical to map the boundary between the two ages of alluvium. The reasons are as follows: (1) The profile of the top of the terrace has a gentler gradient than the modern floodplain, so that traced upstream the terrace and floodplain gradually converge. Thus the terrace, which is 35 to 40 feet above the Missouri River floodplain, is 15 to 20 feet above the Knife River floodplain in the Broncho and Medicine Butte quadrangles, is 5 to 10 feet above the floodplains of streams like Willow Creek and Elm Creek in the middle parts of their courses, and is coincident with the modern floodplains in the headwater areas. (2) In several of the through valleys or trenches that contain no large streams, the alluvial floor, which is obviously being augmented by current slopewash, is not dissected and is apparently graded to the alluvial terrace rather than the modern floodplain of the Knife River. (3) Even in valleys like those of Willow Creek and Elm Creek where the terrace of older alluvium is readily distinguished, the scale of the mapping makes it impractical to separate the small fragments of the terrace from the modern floodplain.

Therefore, outside the Missouri River trench both ages of alluvium have been mapped as Qal. In the valleys of the Knife River and Spring Creek, where the remnants of the older alluvium are topographically distinct and large enough to show on the map, they have been separated from the modern floodplain by a hachured line. In the smaller valleys even this differentiation was not attempted.

Eolian sand and silt (Qds)

The Great Plains is a country of high winds and little rain and the effectiveness of wind action is apparent to anyone who has spent much time in the area. It is not surprising therefore that most of the Knife River area has a thin veneer of wind-blown material. This is especially true of those parts of the area that are southeast of the major stream valleys, where there is an abundant source of loose, fine-grained material easily picked up by the winds. On the geologic maps (pl. 1) the eolian material has been shown only where it is more than 5 feet thick or where it has dune topography.

Nearly all of the deposits mapped as Qds consist of fine- to medium-grained sand and their surfaces have typical dune topography. A few consist of very fine-grained sand and silt (loess) and have smooth upper surfaces that show no signs of dune topography. These loess deposits are minor in comparison with the deposits of dune sand and are largely restricted to the bluffs overlooking the Missouri River.

In most deposits the dune sand is fine- to coarse-grained with minor amounts of very coarse sand, granules, and a few pebbles. Pebbles up to one inch in diameter are quite common in many of the thinner eolian deposits. Some of these pebble-bearing dunes are downslope from exposures of till or gravel, and the pebbles evidently rolled or crept downhill while the dunes were being formed. Other pebbles, however, are found on top of some of the dunes on the terrace near Stanton where there is no hill from which these pebbles could have come. The only logical conclusion is that the wind must have rolled them onto the surface of the dune. In color, the dune sand ranges from light yellow to dark brown depending on the amount of included carbonaceous material. In general the thin deposits have more humified matter and are darker than the thick deposits. The largest areas of dune sand are in the Stanton and Hazen quadrangles and are southeast of large remnants of the Pleistocene fills Qsd. The largest individual dunes are in the southeast part of the Hazen quadrangle in secs. 23, 24, 25, and 26, T. 144N., R. 86W. These high dunes form the southern end of a large deposit of eolian sand that caps the terrace of Qsd and extends south across the till and bedrock of the valley wall of the Knife River. The high dunes have a local relief of 40 to 50 feet and are more than 100 feet higher than the terrace to the north. Undoubtedly they have a bedrock core, but no exposures of this core could be found in the blowout areas. These high dunes are grassed over, and stabilized except in the eastern parts of secs. 24 and 25, where about 3/4 of a square mile is underlain by actively shifting sand that is migrating southeast and encroaching on the valley of Kinneman Creek (called Sand Creek by many of the local residents).

Two lines of evidence suggest that most of the dunes were deposited by northwest winds. First, as already mentioned, most of the large patches of dune sand lie southeast of areas underlain by the Pleistocene sand fills, Qsd. Second, aerial photographs show that the dune topography has a definite northwest-southeast grain or alignment. Today, although strong winds blow from nearly every quarter, weather records indicate that the strongest storm winds are still from the northwest, and the dunes would still be actively forming were not most of the loose sand grassed over.

Most of the dunes probably were formed during the "climatic optimum", about 4,000 to 6,000 years ago, when the climate of central United States was warmer and probably drier than it is today. However, although this date is plausible, it is difficult to prove. That the dunes are post-Pleistocene is indicated by the fact that they overlie all the glacial deposits in the area. That the dunes are not a product of the modern climate is shown by the fact that most of the dunes are grassed-over and stabilized. Also, on the surfaces of some of the dunes in secs. 12 and 13, T. 145N., R. 84W., I found bits of pottery and other Indian artifacts, indicating that the dunes had been stabilized prior to that particular occupation. Therefore, the stratigraphy indicates only that the dunes are post-Pleistocene and pre-modern climate, but the warm, dry climate of the "climatic optimum" would have been a favorable time for eolian action and it is reasonable to suppose that most of the dunes were made at that time.

Residual silica deposits (Qrs)

In the southern part of the Medicine Butte quadrangle several of the higher hills are capped by a rubble composed of broken blocks of silicified sandstone and shale. Similar rubble caps hills just south of the quadrangle. These silica blocks were probably derived from a bed in the lower part of the Golden Valley formation and have been let down to their present position by weathering and erosion. These deposits have been differentiated on the map because they are a potential source of riprap for facing the upstream sides of dams.

GEOMORPHOLOGY AND GLACIAL GEOLOGY OF SOUTHWESTERN NORTH DAKOTA

Prior to 1946 the late Tertiary and Quaternary history of southwestern North Dakota had received little attention and was very poorly known. What little was known was based on the good though sketchy reconnaissance work of Leonard (1912, 1916a, 1916b) and Todd (1914, 1923). Therefore, in order to provide a background for the study of Knife River area I spent a part of each summer making a reconnaissance study of the glacial drift and the land forms between the Knife River area and the North Dakota-South Dakota State line. The results of this reconnaissance are summarized in this section of the report.

In this report, southwestern North Dakota is defined as that part of the State that lies west of the Missouri River and south of the latitude of the mouth of the Little Missouri River. North of this latitude the geomorphology and glacial geology are being studied by A. D. Howard, of the Geological Survey.

Land forms

The higher parts of the interstream divides in southwestern North Dakota consist of a broad gently-rolling upland above which stand a few buttes capped by the Oligocene White River formation. Surrounding at least one group of these buttes are remnants of a planation surface capped with several feet of coarse gravel. This gravel-capped surface appears to be slightly higher than, and therefore probably older than, the broad upland. Near the edges of the broad upland the surface slopes gently down toward the valleys of all the major streams except that of the Missouri River. These gentle slopes outline broad valleys whose floors have been entrenched to form the more narrow comparatively steep sided valleys that today contain the major streams. On either side of these streams is a dissected belt composed partly of badlands and partly of more gentle grassed over slopes. These dissected areas have been carved from the gently sloping surfaces of the old broad valley profiles. The belt of badlands bordering the Little Missouri River is much larger and much more spectacular than that adjacent to any other stream. This badland area has a special history and will be described later.

Although most of these land forms are the result of erosion during the late Pleistocene and Recent epochs, some of them are relicts of the Tertiary Period. The high buttes capped by the White River formation must have had their beginnings during the period of erosion that followed the deposition of those sediments. Thus the butte tops themselves represent a surface of deposition inherited from the Oligocene epoch and the dissection of the butte slopes started either in late Oligocene or in early Pliocene, as soon as the streams had cut below the base of the White River sediments.

The gravel-capped planation surface that borders Coffin Buttes in southwestern Grant County has already been described on p. 100. Both in lithology and in mode of occurrence, the gravels resemble the Flaxville gravels of eastern Montana and they are probably of nearly the same age. Inasmuch as the Flaxville gravels contain vertebrate fossils, dated as late Miocene to middle Pliocene, the gravels near Coffin Buttes have tentatively been classified as Miocene (?) or Pliocene (?).

The broad uplands are apparently slightly younger than the planation surface gravels. If these gravels are actually the equivalent of the Flaxville gravels, then the broad upland was formed either in late Pliocene or early Pleistocene time.

In addition to the land forms just described there are a number of through valleys or trenches that cut across the divides between the major streams. All these trenches are in the glaciated area; most of them contain small streams or no streams at all with the exception of the trench that extends from Garrison Dam south to the State line. This trench contains the master stream of the area, the Missouri River. The origin and history of the Missouri River trench is one of the key factors in the Quaternary history of western North Dakota and must be understood before some of the other features can be appreciated.

Origin of the Missouri River trench

General setting

The major streams in North Dakota are shown on the sketch map in fig. 3. It can be seen at a glance that the drainage pattern southwest of the Missouri River bears no resemblence to the pattern northeast of that river. Southwest of the Missouri River the streams flow north and east and would appear to be part of a master drainage flowing northeast into Canada except that they have been beheaded by the Missouri River. Northeast of the Missouri the streams wander and the general pattern is hap-hazard. All of these streams in eastern North Dakota have been deranged by the deposits of the ice sheets. Some parts of their courses seem to be remnants of pre-glacial channels while other parts are clearly new and have been established since the glacial drift was laid down.

Just east of the Missouri River, the Coteau du Missouri is crossed by several large valleys or trenches that today contain no major streams. These valleys are nearly collinear with the valleys of the western tributaries of the Missouri River and probably represent the former courses of these rivers. The floors of the abandoned valleys hang 125 to 175 feet above the present Missouri River and therefore seem to be extensions of the broad valley profiles of the western streams.

From the Garrison Dam south to the State line the Missouri River trench bears little resemblence either to its tributaries from the west or to the streams east of the Coteau. The broad valley profile that characterizes the valleys of its western tributaries is lacking in the Missouri River trench, which is incised sharply into the upland surface of the Great Plains. In some places the upland surface slopes toward the trench for several miles on either side; but in many other places the upland actually slopes away from the trench. Evidently the Missouri River was not established in southern North Dakota until after the broad valley profiles of the other streams had been cut.

The anomalous relation between the Missouri River trench and the rest of the topography in southern North Dakota is identical to the features in South Dakota described by Flint (1949) suggesting that in both states the Missouri River has had a similar history.

Hypothesis of glacial diversion

That the present drainage pattern in North and South Dakota resulted from the diversion of streams from their former courses by the action of a glacier was first suggested by G. K. Warren. Later this idea was adopted and explored by J. E. Todd, state geologist of South Dakota. Todd's ideas on the glacial geology of both North and South Dakota has been published in several journals and his conclusions about the Missouri River were summarized in a short paper in 1917. Briefly Todd concluded that at some time in the past the streams in western North and South Dakota had continued east across the site of the present Missouri River trench. The streams in North Dakota and northern South Dakota were part of a master system that drained into Hudson's Bay; the streams in central and southern South Dakota turned south through the broad valley of the James River and entered what is now the Missouri River in southern South Dakota. The advance of the glacier blocked the downstream segments of these old valleys, and the streams were forced to turn southeast along the margin of the ice. By the time the ice had retreated this new course was so deeply entrenched that the old valleys were not reoccupied. This new southeast-trending valley was further deepened and is the present Missouri River trench.

Since the work of Todd no one except Leonard (1916a) has seriously questioned the idea that the Missouri River trench is of glacial origin. Recently Flint (1949) studied the origin of the Missouri River in more detail and has traced out the former drainage courses of the rivers in South Dakota. Concerning the method of the diversion Flint stated (p. 69):

"The James lobe of one of the Pleistocene ice sheets entered eastern South Dakota from the Northeast, as inferred from the provenance of erratic boulders. Its average thickness is believed to have been at least several hundred feet, whereas the general relief of the country invaded is inferred to have been little more than 200 feet. Hence the ice completely buried even high points on the Missouri Plateau. Flowing southwestward, this ice lobe blocked all elements of the ancient east-west drainage as far west as the sight of the present Missouri River. Because of the ice blockade, the steepest remaining component of the former eastward slope of the land became a slope toward the southeast. The streams became ponded; the main valleys filled with water that gradually backed up into the tributaries. In time each pond rose high enough to spill over the lowest part of the interfluve that separated it from the major valleys southeast of it. Most of these low points occurred between the heads of two opposed tributaries. Each temporary spillway thus formed became intrenched by the overflow. In effect the water flowed up one former tributary and down another opposed tributary. As the glacial blockade was shrinking it failed to clear the ancient valleys until after the temporary diversion routes across the interfluves had become so deeply intrenched that the diverted waters were unable to return to their former paths. The floors of the ancient valleys, partly filled with drift, were left standing somewhat above the new profile of the diverted water-the initial profile of the present Missouri River."

Thus, according to Flint's idea the Missouri River trench is a patchwork, formed from segments of small valleys that already existed. In places where there was no pre-existing lower outlet short segments of the trench were probably carved into the uplands by an ice marginal stream, but by and large the diverted waters followed the already cut valleys of the small tributary streams.

In southern North Dakota as far upstream as Garrison Dam the Missouri River trench is similar in every way to the trench in South Dakota, and probably originated in the manner outlined by Flint. Between Garrison Dam and the mouth of the Little Missouri River, however, the Missouri flows eastward through a valley whose sides slope gently toward the river and appear to outline the broad valley profile characteristic of the pre-diversion valleys in North and South Dakota. In this part of its course, therefore, the Missouri River is apparently in one of the old valleys that was part of the former Hudson Bay drainage system.

Date of the diversion

Flint (1949, p.71) pointed out that early Wisconsin (Iowan) drift was deposited in the Missouri River trench after it had been cut to about its present depth. This indicated only that the diversion of the drainage and the deepening of the trench must have taken place in some pre-Wisconsin time.

More recently, Warren (1949) and Crandell (1951, pp.148-149) have independently discovered evidence suggesting that the drainage was diverted to its present pattern during the Illinoian glacial stage. Their evidence can be briefly summarized as follows:

(1) Early Wisconsin (Iowan and Tazewell) drift occurs down in the Missouri trench well below the profile of the pre-diversion drainage. This agrees with Flint's conclusion that the trench must be pre-Wisconsin.

(2) On the uplands ~~west~~ east [Warren 1952] of the Missouri trench are deposits of coarse sand and gravel containing vertebrate fossils of probable late Kansan age. These gravels are topographically above and are therefore older than the broad valley profiles of the Cheyenne and Bad rivers; and, as has already been stated the broad valley profiles of all the streams antedate the cutting of the Missouri River trench.

(3) The establishment of the Missouri River trench, therefore, is post-Kansan and pre-Wisconsin; and, by a process of elimination, we are left with Illinoian as the only glacial stage when this could have taken place. Following the same process of elimination the cutting of the broad valley profiles was post-Kansan, pre-Illinoian and therefore must have taken place during the Yarmouth interglacial stage; and the deepening of the Missouri trench to about its present depth must have taken place during the Sangamon interglacial stage.

In southern North Dakota the evidence is not conclusive but seems to indicate that the Missouri River trench was formed at about the same time as in South Dakota. This evidence is as follows:

(1) Drift of Iowan age occurs down near the bottoms of the present valleys, well below the pre-diversion stream profiles. Thus the trench must have originated prior to the Wisconsin stage.

(2) Just as in South Dakota, the cutting of the broad valley profiles of the eastward-flowing streams antedates the formation of the Missouri River trench. Therefore the trench in both North and South Dakota seems to have been cut at the same stage in the geomorphic evolution of the landscape. It seems reasonable to assume that the broad valley profiles in both states were cut at the same time and, consequently that the Missouri River trench was also cut simultaneously on both sides of the North Dakota-South Dakota State line.

Therefore, if the Illinoian age of the trench is valid in South Dakota, probably it applies to North Dakota as well.

Pre-diversion drainage of North Dakota

Although it has been known for a number of years that the present eastward-flowing tributaries of the Missouri River in North Dakota once crossed the site of the Missouri trench and continued east and northeast into Canada, no detailed tracing of the abandoned courses east of the Missouri River has ever been attempted. Todd had suggested the approximate positions of some of the pre-diversion valleys but most of Todd's work was in South Dakota and he did little or no actual tracing of the abandoned valleys north of the State line. My own reconnaissance east of the Missouri River in southern North Dakota was too brief to permit tracing of the abandoned channels in the detail comparable to Flint's work in South Dakota. Nevertheless, I was able to locate the approximate positions of many of the larger abandoned valleys and from them reconstruct some of the pre-diversion drainage pattern of North Dakota. This reconstructed drainage is shown in fig. 12. The individual parts of this abandoned drainage will now be briefly described; the numbers in the following discussion correspond to those on the map.

1. Former drainage in southern Emmons County. - In southern Emmons County is an abandoned valley that extends from the town of Linton south to the North Dakota-South Dakota State line. This valley is the northward extention of Flint's Mound City trench (1949, p.61) and seems to be a part of a master drainage that included the present Grand, Moreau, and Cheyenne rivers. Beaver Creek, which now flows west past Linton to the Missouri River, seems to have been a tributary to this northern part of the Mound City trench.

2. Long Lake trench (the former course of the Cannonball River).- The present-day Cannonball River enters the Missouri River about 30

miles north of the North Dakota-South Dakota State line at the junctions of Morton, Sioux and Emmons counties. Four miles north of the mouth of the Cannonball River is a large abandoned valley or trench that leads northeast from the Missouri trench through northwest Emmons County across southeast Burleigh County and into Kidder County, where it is buried and obscured by the moraines of late Wisconsin drift, at the Burleigh-Kidder County line this trench is occupied by Long Lake and will be referred to in this report as the Long Lake trench. Todd suggested long ago that the Long Lake trench represents the former course of the Cannonball River (1914, p.266). Leonard (1916, p.296) objected to this idea on the ground that the mouth of the trench is 4 miles north of the present mouth of the Cannonball River. The method that Flint outlines for the formation of the Missouri River trench, however, negates this objection. The 4-mile segment of the Missouri River trench between the mouths of the Cannonball River and the Long Lake trench, is a segment of the pre-diversion Cannonball River, with the present-day drainage flowing opposite to the direction of the former drainage.

East of Long Lake the trench has been partially to completely buried by thick glacial drift and is difficult to follow. Apparently it continues northeast finally leaving the Coteau du Missouri at a low point in the Missouri escarpment at the railroad siding of Goldwin in Stutsman County. Lake Etta and Lake Isabel in Kidder County and Chase Lake in Stutsman County seem to be on the old drainage course.

3. Abandoned course of the Heart River - From its headwaters in southeastern Billings County the Heart River flows east and southeast

across Stark and Grant counties and enters Morton County in the southwest part of T. 136N., R. 84W. Here the river turns abruptly north by northeast for about 15 miles to T. 138N., R. 38W., where it again resumes a more easterly route. The valley of the Heart above and below this 15-mile segment is typical of the pre-diversion valleys in North Dakota. The uplands slope gently toward the river for several miles and the river itself is cut into the old broad valley whose floor was 125 to 150 feet above the modern floodplain. In the 15-mile segment just mentioned, however, the Heart flows in a youthful valley whose floor is 400 to 500 feet below the edge of the uplands. The broad valley profile is absent and the upland does not slope toward the river; rather it ends abruptly in a tract of badlands, 1 to 2 miles wide, that separates them from the valley floor.

Leading southeast from the sharp bend and collinear with the upstream portion of the Heart River is a wide trench that crosses from the drainage of the Heart to the drainage of the Cannonball River, joining the latter stream near Breien. The upland slopes toward this trench, and the topography of the trench walls is much more subdued than the badlands bordering the "15-mile segment". The floor of the trench is below the altitude of the broad valley profile, and the trench itself is obviously a part of the Pleistocene drainage system that extends all the way from the Little Missouri River in Dunn County to the Cannonball River in Sioux County (pl. 3). However, I suggest that the trench also represents the former (pre-Illinoian ?) course of the Heart River and that the

Heart and Cannonball rivers once were confluent near Breien. If this hypothesis is correct, the mature part of the Heart River valley below the youthful 15-mile segment was originally cut by Sweetbriar Creek and one of its tributaries. Then, for reasons that are not clear, this tributary worked its way headward and captured the Heart River. Perhaps ice dammed the lower part of Sweetbriar Creek, causing ponding and an eventual overflow to the south and southwest along the present course of the Heart River. The overflowing waters may have cut the spillway notch deep enough to permit the tributary of Sweetbriar Creek to complete the job and capture the Heart River. Whatever the cause, this capture clearly occurred after the streams had cut below their old broad valley profiles, and probably after the establishment of the Missouri River and entrenchment of that river to about its present altitude.

4. Brittin Trench. A few miles southeast of Bismarck is a broad flat terrace about 100 feet above the Missouri River. This terrace can be traced east into a large trench about 2 miles wide, that trends east across southern Burleigh County and joins Long Lake trench at the town of Moffit. The railroad siding known as Brittin is about in the center of this trench, which will therefore be called the Brittin trench.

According to my reconstruction of the old drainage, the Brittin trench is the eastward continuation of an old valley that carried the combined waters of Sweetbriar, Square Butte, Burnt, and possibly Apple creeks. One discrepant feature of the reconstruction is that the Brittin trench is nearly twice as wide as the western part of

Long Lake trench; yet Long Lake trench was presumably carrying the combined Heart and Cannonball rivers. Either the reconstruction is incorrect or there was some extraneous factor that cuased the Brittin trench to be abnormally wide.

5. Apple Creek valley. North of the Brittin trench and subparallel with it is Apple Creek, a southwest-flowing tributary to the Missouri River. The mouth of Apple Creek is nearly opposite the mouth of the Heart River at Mandan; and Todd (1914, p. 266) postulated that Apple Creek valley represents the pre-diversion course of the Heart River. Todd was undoubtedly influenced by Leonard's report that deep wells in this valley passed through about 200 feet of glacial silt and sand before reaching bedrock (1912, p. 44). However, this 200-foot thickness of outwash puts the bedrock floor at much too low an altitude to have been a part of the pre-diversion drainage system. The deep cutting and subsequent filling must have taken place after the establishment and deepening of the Missouri River trench. It is, of course, possible that some higher profile of Apple Creek valley was the extension of a river that combined Sweetbriar, Square Butte, and Burnt creeks (Todd's pre-diversion "Heart River"), but this hypothesis leaves no major stream for the Brittin trench. It seems more probable that Apple Creek was just another tributary to the Brittin trench drainage. Whether it flowed west in its present valley as far as Bismarck or whether it turned southeast at McKenzie and joined the Brittin trench near Moffit is not clear from the present topography.

6. Former courses of the Knife and "Missouri" rivers. Todd

(1914, p.266) recognized that the east-west segment of the Missouri River trench upstream from Garrison Dam was a part of the pre-diversion drainage system. He inferred also that the Knife River once turned at Stanton, and flowed north along the site of the present Missouri River trench to join the old "Missouri" at the site of Garrison Dam (Old Fort Stevenson). The combined drainage of the two streams then continued northeast through the valley of Snake Creek, across the Coteau du Missouri, and joined the Souris River somewhere east of Minot. Andrews (1939, p.62) outlined the course across the Coteau in more detail. He suggested that the ancestral "Missouri" River flowed through the Snake Creek outlet, joined what he calls the Turtle Creek spillway of glacial Lake Souris, and continued northeast through the spillway to join the Souris River near Velva.

My reconnaissance study, aided by the many newly-published topographic maps of the area, indicates the following modifications of the courses proposed by Todd and Andrews:

(a) The Missouri River trench between Garrison Dam and the mouth of the Knife River shows no evidence of having been a part of the ancient drainage.

(b) East of the Missouri River and in line with Knife River valley is a broad, very shallow trench that can be traced as far east as Falkirk, beyond which it is obscured by glacial drift. The ancient Knife River followed either this trench or else the site of the Missouri River trench as far as the mouth of Painted Woods Creek, and thence north to join the shallow trench east of Falkirk. From this point on the old course is buried by thick drift, but seems to have continued east, then northeast past Pickardville and McClusky and to have crossed the Missouri escarpment near Lincoln Valley.

(c) The ancestral "Missouri" River probably flowed northeast through Snake Creek to a point about 15 miles east of the town of Garrison, where it turned southeast, flowed through Turtle Lake, past Mercer, and joined the ancestral Knife River near Pickardville. Although buried by thick glacial drift, this route from the head of Snake Creek to Pickardville is fairly easy to follow both in the field and on topographic maps.

Northeast of Lincoln Valley the course of the combined Knife and "Missouri" rivers can not be followed with any assurance. The stream may have continued northeast to join the ancient valley now occupied by Devil's Lake and Stump Lake (probably an old course of the Sheyenne River) or it may have turned northwest to join the Souris River in McHenry County.

7. Former course of the Little Missouri River. As can be seen on the map (fig. 12) the old course of the Little Missouri River is mostly in northwestern North Dakota, in the area being studied by Howard, and will be outlined here only for the sake of completeness. The history and dating of the diversion of the Little Missouri River, however, is important to the general history of southwestern North Dakota and will be discussed more fully.

The Little Missouri River enters North Dakota in the southwest corner of the State and flows north to southern McKenzie County, where it turns sharply east and finally empties into the Missouri River near Elbowoods. Leading northeast from the sharp bend, and in line with the upstream part of the Little Missouri valley, is a large trench that joins the Missouri River near Nesson. This trench is occupied in part by Cherry Creek and in part by Tobacco Garden Creek and will be called in this report the Tobacco Garden trench. Upstream from its junction with the Tobacco Garden trench the valley of the Little Missouri is flanked by a wide strath terrace, about 150 feet above the river near the State line and 250 feet above the river in McKenzie County. Downstream from the junction this terrace is absent. The altitude and gradient of the terrace coincide fairly well with the floor of the Tobacco Garden trench, and it seems fairly clear that this trench represents the former course of the Little Missouri River. It seems probable also that in pre-Illinoian (?) time the Little Missouri continued north across the site of the Missouri River trench and joined the ancient Yellowstone somewhere near the Canadian border.

The Tobacco Garden trench has been recognized as the former valley of the Little Missouri River by many workers. It was first noted by Wilder (1903, p. 16) and was more fully exlored by Leonard (1916, pp.300-304). Leonard also recognized that the segment of the Little Missouri River below the junction with the trench coincides in part with the outermost glacial drift border, and postulated, therefore, that the diversion from the Tobacco Garden Creek route was caused by the damming action of the ice.

Two lines of evidence suggest that the diversion of the Little Missouri River from the Tobacco Garden trench did not occur until early Wisconsin time. First, Howard (personal communication) states that the bedrock floor of the northern part of the Tobacco Garden trench is graded to a baselevel at or slightly below the altitude of the present Missouri River. It is possible that Tobacco Garden Creek alone could have accomplished this grading, but it is more likely that the Little Missouri River maintained its course through the Tobacco Garden trench until the Missouri River had deepened its valley to about its present altitude. As has already been stated, the major deepening of the Missouri River trench probably took place during the Sangamon interglacial stage, and the diversion of the Little Missouri River was therefore post-Sangamon. Second, the drift border that coincides with the new course of the Little Missouri River is early Wisconsin, probably Iowan; and it seems very likely that diversion from the Tobacco Garden trench was accomplished by the ice sheet that deposited this drift.

The Iowan date for the diversion also provides an explanation of the fact that the badlands bordering the Little Missouri River are more extensive and more spectaular than those bordering other rivers in North Dakota. By Iowan time all other streams had excavated their valleys to about their present depths, but the floor of the Little Missouri River at that time is represented by the high strath terrace and the floor of the Tobacco Garden trench. The present mouth of the Little Missouri River near Elbowoods is more than 200 feet lower than the old mouth near Nesson, so that after the diversion the Little Missouri had a steeper gradient. Thus the river was rejuvenated and cut deeply into its old valley floor, leaving this floor as a strath terrace. The rapid deepening of the master stream valley steepened the gradient of all the small tributaries, enabling them to dissect the walls of the Little

Missouri River valley into badlands. This dissection has continued from early Wisconsin to the present time. Badlands undoubtedly bordered other rivers in southwestern North Dakota shortly after they deepened their valleys in response to the deepening of the Missouri River trench; but that dissection took place longer ago and since then most of the badland ridges and spurs have been rounded by weathering and mass-wasting.

Other Pleistocene diversion valleys

Major regional diversion valleys

In South Dakota the only large valley that appears to be the result of glacial diversion is that of the Missouri River itself. In North Dakota, however, west of the Missouri River trench are many trenches that cross divides between the present streams. The largest of these trenches form an anastamozing valley system that extends from the Killdeer Mountains in Dunn County southeast across Dunn, Stark, Morton, Grant, and Sioux counties, finally joining the Missouri River a few miles above Fort Yates. For convenience I have given individual names to various segments of this valley system (pl.3), but all these segments are part of one large feature and should be regarded as a unit.

Similar trenches connect the valley of the Little Missouri River in western North Dakota with the valley of the Yellowstone River in eastern Montana. These through valleys or trenches were first recognized and mapped in reconnaissance by Leonard (1916). Later, Alden (1932) mapped similar features in eastern Montana and showed that they connected with the valleys Leonard had discovered in western North Dakota.

Although Leonard doubted that the Missouri River trench originated as the result of glacial diversion, he clearly recognized the system of through valleys as the product of waters diverted from their former courses by the margin of an ice sheet (1916,pp.295-300). Concerning these valleys he stated (p.299):

"Pleistocene valley of Missouri and Yellowstone Rivers

"But while the Missouri River probably occupied its present valley for a considerable time prior to the Glacial period, the ice-sheet, when it invaded the region, blocked the valleys of both the Missouri and Yellowstone rivers and also the pre-glacial valley of the Little Missouri, forcing these streams to seek new channels. Lakes were formed in the valleys of the Yellowstone and Little Missouri rivers, the water rising until it overflowed the divide between the latter and the Knife River south of the Killdeer Mountains. The combined waters of the three rivers flowed east across Dunn County and southeast across Morton to the mouth of the Cannon Ball River. The valley thus formed crosses the divide between the Knife and Heart rivers and also that between the Heart and the Cannon Ball. The length of this Pleistocene valley of the Yellowstone and Missouri rivers from the head of the Knife to the mouth of the Cannon Ball is 155 miles."

The course of this former Pleistocene drainage as mapped by Leonard and Alden is shown in fig. 13. My reconnaissance map of the same trenches is shown in pl. 3. A comparison of the two maps shows that I disagree with Leonard's mapping of this former drainage at only three places. These are:

(1) Porcupine Creek trench. Leonard thought that in southern Morton County the old Pleistocene drainage turned east at the town of Timmer, and entered the Cannonball River near Breien,

and from there continued east to the Missouri. My reconnaissance showed that another branch of this trench trends south to Shields, then turns east, crosses the divide between the Cannonball River and Porcupine Creek, and continues east through the latter valley to join the Missouri River about four miles north of Fort Yates. After the ice had cleared southern North Dakota as far as the present mouth of the Cannonball River, probably all the drainage from the northwest joined the Cannonball at Breien, as suggested by Leonard.

(2) Killdeer trench. As can be seen from the map (fig. 13) and from his description of the diversion drainage, Leonard believed that the waters of the Yellowstone, Missouri and Little Missouri rivers were diverted to a course south of the Killdeer Mountains and entered the headwaters of the Knife River valley about six miles southeast of Grassy Butte in McKenzie County. Alden accepted Leonard's idea and postulated that the waters left the valley of the Little Missouri River in southern McKenzie County by way of Bicycle Creek. I have examined the uplands in southern McKenzie and northern Billings counties and have found no evidence of any major drainage channels in this area. Howard (personal communication) has also visited this area and has independently come to the same conclusion. On the other hand, I did find a valley in western Dunn County that probably represents the former diversion path of the Yellowstone and Little Missouri rivers. This valley, which I have called the Killdeer trench, starts

just east of the Killdeer Mountains at the low divide between Jim's Creek and the drainage of Spring Creek. The valley trends southeast past the town of Killdeer, joins and crosses the valley of Spring Creek at Lake Ilo about two miles west of Dunn Center, and continues south, entering the valley of the Knife River about a mile east of Emerson.

The diverted waters of the Yellowstone and Little Missouri rivers, therefore, probably never flowed south of the Killdeer Mountains. Early in the Wisconsin stage the waters probably flowed down the valley of the Little Missouri to the mouth of Jim's Creek east of the Killdeer Mountains, and from there spilled over into the diversion valleys to the southeast. This system of diversion valleys, however, is believed to have been cut during some pre-Wisconsin glacial stage; and, as has already been pointed out, the east-west segment of the Little Missouri River north of the Killdeer Mountains did not exist at that time. During the earlier glacial advance the Little Missouri River probably continued northeast through the Tobacco Garden trench to a point about five miles northeast of Watford City. From here it was diverted southeast through the valley of Cherry Creek and continued in this direction until it was able to spill over into the drainage of Spring Creek somewhere east of the Killdeer Mountains.

(3) Emerson trench. Leonard's map shows that after entering and crossing the valley of the Knife River the Pleistocene drainage followed three separate courses toward the southeast. To Leonard's

three branches should be added a fourth - a large shallow trench that leads south from the valley of the Knife River at Emerson, crosses the headwaters of Deep Creek and finally turns east to join the Deep Creek trench along the Dunn-Stark County line. These four branch valleys leading south from the Knife River were not used simultaneously. The altitude of their floors is progressively lower from west to east, and they were probably used one at a time, starting with the trench south of Emerson and ending with the Elm Creek trench.

DATE OF THE DIVERSION

It seems well established that the abandoned valley system just described was formed during the Pleistocene epoch when the streams of southwestern North Dakota and eastern Montana were diverted from their normal courses by a glacier. The mechanism of the diversion was exactly the same as the one which caused the formation of the Missouri River trench. As a matter of fact, the only difference between the Missouri River trench and this valley system is that the Missouri trench was successful in holding the diverted waters after the retreat of the ice sheet.

The date of this diversion cannot be definitely established. Leonard and Alden both considered that the waters of the Little Missouri and Yellowstone rivers were originally diverted by the pre-Wisconsin ice sheet that deposited the outermost drift in southwestern North Dakota. According to Leonard this drift was

Kansan; according to Alden, Illinoian (?) or Iowan.*

*At the time of Alden's work the Iowan was regarded as a separate pre-Wisconsin glacial stage.

My reconnaissance mapping of the glacial features indicates that the outermost drift is of early Wisconsin (Iowan) age. The diversion system, however, I believe to be pre-Wisconsin, probably Illinoian. The evidence, scanty and inconclusive, is as follows:

(1) Since the cutting of this valley system, mass-wasting has rounded the sharp spurs, and small tributaries have cut fairly wide straths graded to the floors of the various member trenches. In contrast, the sides of the Beulah trench in the Knife River area are youthful and are drained by steep-sided gullies; yet there is stratigraphic evidence that the Beulah trench must be as old as early Wisconsin.

(2) Small patches of early Wisconsin (Iowan or Tazewell) drift lie on the maturely dissected sides of these valleys. This also suggests that the diversion valleys are of pre-Wisconsin age.

(3) Both Crandell and Warren (op. cit.) show that the topography of western South Dakota has been inverted since Kansan time. Gravels of late Kansan or early Yarmouth age now cap divides between the major streams. It seems likely that western North Dakota has had a similar history, and that valleys of Kansan age would have been well dissected and largely destroyed by this post-Kansan erosion. But the diversion valleys under discussion are very much a part of the present topography.

I therefore suggest that this diversion system is post-Kansan, pre-Wisconsin, or in other words, Illinoian. Probably the system was established while the Illinoian ice was near its maximum. Later, as the ice retreated, a second system was established and maintained, and eventually became the Missouri River trench.

Although the Killdeer-to-Fort Yates diversion system was abandoned after the establishment of the Missouri River trench, it was undoubtedly re-used and its bedrock floor was probably lowered during at least the two early Wisconsin advances of the ice. How much of the deepening occured during the original diversion and how much during subsequent occupations is impossible to tell.

Minor diversion valleys

Between the Iowan drift border and the Missouri River trench are numerous isolated diversion valleys or trenches that trend northwest-southeast across the divides. These range in size from trenches one to two miles wide and 15 to 20 miles long to small notched divides, 50 to 100 yards wide and less than a quarter of a mile long. All these diversion valleys, large and small, originated in the same way as the Missouri River trench, except that the smaller ones were cut by smaller amounts of water and were used for shorter periods of time.

Most of these smaller diversion valleys are too small to be shown on the reconnaissance map. Those that cross the Knife River area are described in detail in a subsequent section of the report.

Wisconsin drift sheets of southwestern North Dakota

Previous Correlations

The presence of glacial drift south and west of the Missouri River trench in North Dakota has been known for many years, but most previous workers have classified it as pre-Wisconsin or earliest Wisconsin (Iowan). Leonard (1916b) thought that the so-called "Altamont" moraine on the Coteau du Missouri marks the limit of Wisconsin glaciation and that all the drift southwest of this moraine is pre-Wisconsin, probably Kansan. Alden (1932, pp.75-78) accepted the "Altamont" moraine as marking the Wisconsin drift border, but considered the older drift to the southwest to be of either Illinoian or Iowan age. Though he gave two possible ages for the older drift, Alden clearly preferred to think of it as Iowan, which he regarded as a pre-Wisconsin glacial stage. In compliling the Glacial Map of North America, Flint and others (1945) chose to emphasize the Iowan rather than the pre-Wisconsin facet of Alden's correlation, and on the glacial map all drift southwest of the "Altamont" moraine is shown as Iowan (early Wisconsin).

Townsend and Jenke (1941) pointed out that the correlation of the "Altamont" moraine of northern North Dakota with the type Altamont moraine in eastern South Dakota is just guesswork and is based neither on the stratigraphy of the deposits nor on the detailed mapping of the moraines through the intervening areas. Therefore, they proposed that the moraine in northern North Dakota be renamed the Max moraine. They also showed that the Max moraine owes its position and development to the bedrock high of the Missouri escarpment; and they suggested that this moraine may not mark the terminus of any glacial advance.

Recently Flint has studied the glacial deposits of South Dakota and has concluded that deposits of all four substages of the Wisconsin are present in that State (1951, report in preparation). Flint generously made available his map of the drift borders and this was a great help in my attempt to correlate the drift sheets in southwestern North Dakota.

Results of present work

The present study of the glacial geology of southern North Dakota indicates that three ages of drift are present southwest of the Missouri River and that all three belong to the Wisconsin stage. The two older drifts are early Wisconsin (Iowan and Tazewell respectively) and the third drift is late Wisconsin, probably Mankato. The evidence for these conclusions comes partly from the stratigraphic relations of the deposits in the Knife River area and partly from the tracing of the drift borders between the Knife River area and the North Dakota-South Dakota State line.

STRATIGRAPHIC EVIDENCE

The Pleistocene deposits of the Knife River area have been described. The factors that bear on their dating and correlation can be summarized as follows:

- (1) Three different ages of deposits are differentiated. All three are conformable with the topography that postdates the deepening of the Missouri River trench and are therefore post-Illinoian.

(2) The two older drifts have similar topographic and are separated by a minor unconformity. Both, therefore, are assigned to the early Wisconsin.

(3) The third drift is much less eroded than the other two and is separated from the older deposits by a marked unconformity. This unconformity probably represents the mid-Wisconsin (Tazewell-Cary) interval and the third drift, therefore is thought to be late Wisconsin.

(4) The border of the late Wisconsin drift crosses the Knife River area. Northeast of its margin I have found no evidence, either topographic or stratigraphic, that would indicate a drift border. Quite to the contrary, the young outwash fill in the Knife River valley (Qsd_3) and the outwash in valleys that drain the Max moraine are both graded to the same fill in the Missouri River trench, suggesting that the young drift in the Knife area and the surface drift of the Max moraine are of the same general age. Thus all the drift northeast of the late Wisconsin border seems to be of the same age.

(5) Flint (1951, report in preparation) has shown that the Cary drift has been overlapped by the Mankato in northern South Dakota, and I have found no features that suggest the Cary drift reemerges in southern North Dakota. Therefore, the single late Wisconsin drift in southern North Dakota is probably Mankato.

EVIDENCE FROM THE DRIFT BORDERS

Flint (1951, op.cit.) has shown that all four Wisconsin drifts are present in South Dakota, but that only three can be identified at the North Dakota-South Dakota State line. Near Java, in Walworth County, the Mankato drift crosses the Cary border and the Cary drift is overlapped from here to the State line 25 miles farther north. Therefore, at the State line there are only three Wisconsin drifts, the Iowan, the Tazewell, and the Mankato.

In North Dakota, unfortunately, the drift borders cannot be traced with as much certainty as they can in South Dakota, at least in reconnaissance. There are two reasons for this: (1) In South Dakota the only Wisconsin ice to cross the Missouri River trench was the Iowan; the other three drift borders lie east of the Missouri River. In North Dakota, however, all the known Wisconsin drift borders lie west of the trench. This is an important fact because the Missouri River trench acted as a baffle and removed much of the sediment load of any ice sheet that crossed it. Thus, in many places in southern North Dakota even the late Wisconsin drift consists only of scattered boulders lying on the eroded bedrock surface. The differentiation of such thin drifts is very difficult. (2) In South Dakota the various Wisconsin till sheets are separated by deposits of loess up to several feet thick, and in many exposures the Wisconsin tills can be identified by their stratigraphic positions. The "Peorian" (Iowan plus Tazewell) loess is very persistent, especially east of the Missouri River, and is very helpful in separating early from late Wisconsin tills (Flint, 1951, op.cit.). In North Dakota these loess sheets thin and virtually die out 10 to 15 miles north of the State line, and the thin drifts west of the Missouri River trench are in most places not separated by any intervening deposit.

Nevertheless, despite the difficulties in tracing the drift borders, the following general conclusions can be drawn:

(1) The Iowan drift border is marked by the southwest limit of erratic stones. It can be traced without any large gaps from the South Dakota State line northwest to the Killdeer Mountains.

(2) The Tazewell drift border is too faint to follow in North Dakota.

(3) The Mankato drift border cannot be traced continuously, but can be followed in a general way from the South Dakota State line northwest to the Knife River area, where it coincides with the margin of the third or youngest drift.

(4) The Cary drift has not been identified in southern North Dakota.

Early Wisconsin drifts - Iowan and Tazewell

The early Wisconsin drift sheets crop out in a northwest-trending belt 20 to 30 miles wide in southern North Dakota. Over most of this area the presence of former ice sheets is attested only by the presence of erratic boulders, mostly of granite, with a few of limestone and dolomite. A very few patches of till and ice-contact stratified drift are scattered over this area but these are very minor and do not cover more than one per cent of the total area. Several small deposits of till were found in the bottom of valleys that are graded to the floor of the Missouri River trench. The absence of till over most of the area is due in part to erosion of the drift and in part to nondeposition. Judging from the patches of till after the stagnant tongue of ice in the Missouri trench melted leaving Qsd_3 as a kame terrace. A short time later the ice re-advanced across the Missouri trench in the Stanton quadrangle and deposited the boulder gravels (Qic') on top of the Missouri River gravels near Fort Clark. This is the last Pleistocene event recorded in the Knife River area.

Early Wisconsin gravel deposits

In the southwest part of the Knife River area are small isolated patches of sand and gravel that can not be correlated definitely with any one till sheet or valley fill. Some of these deposits are definitely of glacial origin, some are fluvial origin and still others are indeterminate. I believe them to be of early Wisconsin age because; (1) they lie beyond the late Wisconsin (Mankato) drift border and (2) they have been more extensively eroded than the late Wisconsin deposits to the northeast. On the map these gravels have been divided into three catagories based partly on their lithology and partly on their occurrence.

--Older glacial gravel (Qwg)--

The deposits mapped as Qwg cannot be correlated definitely with either of the early Wisconsin till sheets but are almost certainly of glacial origin and are associated with one of the tills. These deposits are small and comparatively few in number and no attempt was made to discriminate between outwash and ice-contact deposits. Probably the two deposits in secs. 14, and 26, T. 143N., R. 91W., are kames; in contrast probably the small patches in secs. 8, and 17, that are preserved, and from the younger till deposits to the northeast, probably the early Wisconsin drift was deposited as a very thin and patchy blanket.

IOWAN DRIFT BORDER

The outermost drift border in southern North Dakota is drawn along the southwest limit of erratic stones. Although these stones are not everywhere abundant, they are numerous enough in most places to permit the drift border to be traced fairly accurately.

This drift border was first noted by Wood (1904), who mapped a segment of it in southern Dunn and northern Stark counties. Later, Leonard (1916 and 1919) mapped this drift border in reconnaissance from the South Dakota State line northwest to the Montana State line. The drift borders as mapped by Wood and Leonard have been shown on pl. 3. Leonard's version, it can be seen, was extremely generalized; apparently he drew a line tangent to the outermost lobes of erratics and made no attempt to show any of the details.

Western North Dakota today is far more accessible than it was when Leonard examined the glacial deposits, and I was able in a relatively short time to map the drift border from the South Dakota State line to the Killdeer Mountains. As can be seen on the map (pl.3) this line is not, as Leonard had supposed, nearly straight, but rather is very sinuous. In general it shows that the ice front had lobes that extended up the larger valleys and reentrants where it impinged on higher ground.

This drift border crosses the North Dakota-South Dakota State line in the southwestern part of T. 129N., R. 83W., and at this point it coincides with Flint's Iowan drift border. Partly because of this coincidence and partly because the drift northeast of this border shows the same degree of weathering and erosion as the Iowan drift in South Dakota, the outermost drift in North Dakota has been correlated with the Iowan glacial substage.

GRANITE BOULDERS SOUTHWEST OF THE IOWAN DRIFT BORDER

In most places in southern North Dakota the limit of erratic stones is fairly well defined and the drift border can be drawn with moderate confidence. There are, however, a few granite boulders one to several miles beyond and across interstream divides from the general drift border, and I do not believe that these should be included in the Iowan drift. It is possible that these out-lying boulders are relicts of some pre-Wisconsin glaciation. But it has already been noted that the lower part of the White River formation contains a few scattered boulders of granite (p. 95) and it is equally possible that these anomalous granites have been let down onto the present surface by the erosion of the overlying White River sediments. The localities where these anomalous boulders have been found have been shown on the map (pl. 3); the numbers on the map correspond to those in the following discussion:

(1) Boulders in western Morton County. In the northern part of T. 138N., R. 90W., are two occurrences of granite boulders 8 to 10 miles south and west of the Iowan drift border. The drift border in this area is fairly well defined and skirts the edge of a highland area west of Glen Ullen and south of Hebron. The outlying

boulders are in the highland area and are more than 100 feet higher than the edge of the Iowan drift.

The first of these occurrences is questionable; it consists of two granite boulders near each other in a road ditch in a small valley sec. 14. If these boulders were not thrown from a truck, they could be explained by ice rafting in a lake west of the edge of the Iowan ice.

The second occurrence, however, cannot be accounted for either by ice-rafting or by the work of man. In the northeast corner of sec. 14 is a gravel deposit that caps the divide between Heart Butte Creek and one of its tributaries. The gravel consists principally of poorly sorted angular fragments of chert, iron oxidé and sandstone derived from the Fort Union formation, but included also are several cobbles of white sandstone and two small boulders of granite. The sandstone cobbles were derived from the White River formation, the nearest outcrops of which are even today only 10 miles away. The granites must have been derived either from the White River formation or from the erosion of a glacial deposit. If they are of glacial origin these granites must represent some pre-Wisconsin stage, for the topography of this area has been inverted since this gravel deposit was laid down.

(2)Boulder of granodiorite in eastern Stark County. In SW$\frac{1}{4}$, sec. 22, T. 139N., R. 92W., is a single boulder granodiorite or possibly diorite. This boulder is about 8 miles south of the Iowan drift border and on the opposite side of the divide between the Knive and Heart rivers. Stones of similar lithology are found in the glacial drift but have not been noted in the White River formation.

(3) Gravel deposits near Gladstone. Through most of it course in Stark and Morton counties the Heart River is flanked by a terrace 40 to 60 feet above the floodplain and capped with poorly sorted sand and gravel. East of the Iowan drift border these gravels contain pebbles of granite and limestone obviously derived from glacial drift. West of the drift border the gravels consist entirely of stones derived from Fort Union and White River formations, except at the town of Gladstone where several granite boulders have been dug from gravel pits on the terrace. Several other granite erratics were noted in the valleys of the Heart and Green rivers just northwest of Gladstone. These granites, however, are probably derived locally from the erosion of the higher gravel deposits in this area.

Southwest of the Heart River at Gladstone are deposits of sand and gravel up to 200 feet above the present river. These deposits, unlike those capping the terrace, consist principally of well sorted coarse-grained sand with a few stringers of rounded pebbles. The pebbles are principally quartz, quartzite, and vari-colored chert with minor number of red-brown andesite porphyry. Similar deposits of sand and gravel extend for some distance up the valley of Green River in T. 140N., R. 95W., but are not found in the valley of the Heart River upstream from Gladstone. These high level sand and gravel deposits were first noted by Wood (1904, p. 117), and were later described by Leonard (1916, p. 530). Both Leonard and Wood stated that the deposits contained large granite boulders, and inferred therefore that a lobe of the ice sheet had crossed the Heart River at Gladstone. Concerning these gravel deposits Leonard stated: (1916, p. 530):

> "That a lobe of the ice sheet crossed the Heart River at Gladstone is shown by the presence of thick deposits of drift gravels on the upland one to two miles south of the Heart and at an elevation of between 100 and 200 feet above the river level. In places the gravel and sand have a thickness of at least 90 feet, and the deposit contains a number of good-sized granite boulders. A well defined gravel ridge marks the edge of the drift for three or four miles in this area south of the Heart River at Gladstone. This ridge rises 30 to 40 feet above the surface on either side and falls away rather abruptly on the south, while the north slope is more gradual."

Alden also visited the gravel deposits south of Gladstone, and accurately described them as follows (1932, p. 78):

> "In 1921, when the Gladstone deposit was visited by the present writer, sand and gravel were being taken from a small pit near the top of the north slope. South of this is a larger excavation to which a spur track formerly lead from the railway. These pits expose 10 to 30 feet of stratified cross-bedded sand and gravel, the pebbles in which more closely resemble the bench gravel along the Yellowstone River than the glacial drift. These pebbles range from less than an inch to three inches in diameter and consist principally of quartz, quartzite, and chert, with some agate and some dense dark greenish crystalline rocks, diorite, and prophyry. None of the stratified material, so far as is noted, is certainly glacial drift. There were about a dozen boulders of gray and pink granite gathered in a pile on the bottom of the pit, and these are probably of glacial derivation, but they may have rolled down from the surface during excavation of sand and gravel. The deposit appears to cap the ridge for some distance to the south and east. It is possible that this is an erosional remnant of a late Tertiary or early Pleistocene gravel bench similar to the benches of the Yellowstone River. If the granite boulders were actually interbedded with the sand and gravel however as is intimated by Leonard, it is probably a glacial deposit. No glacial drift was seen by the present writer on a traverse extending about nine miles south of Gladstone and thence east and north to Richardton nor along the main road and railway between these two places."

Although as Alden stated, the pebbles in the Gladstone deposits are similar to pebbles in gravels along the Yellowstone River, they resemble even more the gravels of the White River formation in North Dakota. Also, the beds of coarse sand in the Gladstone deposits could have been derived from the lower third of the White River formation, but could not have come from any other local source. Therefore, it seems probable that the Gladstone deposits were made by the erosion and redeposition of materials from the White River formation. Inasmuch as the White River is known to contain at least two granite boulders, not even the granite boulders in the Gladstone deposits need be of glacial derivation.

The reason why the Gladstone gravels were deposited is not apparent. These thick sands are apparently restricted to the valley of the Green River and to the valley of the Heart River just below the mouth of the Green. The easiest way to explain such local aggradation in this part of the world is to invoke an ice dam. However, I have examined the area northeast of these deposits and have found no glacial deposits between Gladstone and the Iowan drift border, 10 miles to the north. The edge of the Iowan drift lies north of the divide between the Knife and Heart river drainages and shows no tendency to be lobate across this divide toward Gladstone. Therefore, if the Gladstone deposits were caused by glacial action, this action probably took place during some pre-Wisconsin advance, and all other traces of this glaciation have now been removed. It is my opinion, however, that the Gladstone deposits are not of glacial origin, because, of all the materials in these deposits, only the granites are even possibly of glacial derivation, and these could equally well have come from the White River beds.

(4) Granite boulders near Dickinson. Wood (1904, pp.116-117) reported several granite boulders on the hillsides in and around Dickinson and several more from the terrace of the Heart River west of Dickinson. Wood thought that these erratics had been rafted up the Heart River valley by bergs calving from the hypothetical Gladstone lobe of the glacier, but I think it more probable that they are relicts of the White River formation.

(5) Granite boulders in southwestern Dunn County. In T. 142N., R. 95 and 96W., are several granite boulders on the dissected north edge of the upland divide between the Heart and Knife river drainages. These boulders are about 3 miles southwest of the Iowan drift border. There is no local evidence whether they are of glacial origin or were derived from the White River formation.

TAZEWELL DRIFT BORDER

Flint (1951, report in preparation) has identified and traced the approximate limits of the Tazewell drift in north-central South Dakota. According to Flint, the Tazewell border is impossible to trace accurately; it apparently lies east of the Missouri River everywhere except in the northern part of the State, where is possibly is west of the river. Extending from northeastern Corson County, South Dakota into southeastern Sioux County, North Dakota is a ridge of poorly sorted boulder gravel that is probably of morainic origin and that may be the feeble terminal moraine of the Tazewell ice sheet.

Traced northwest into Sioux County, North Dakota, this morainic ridge dies out, and from here on to the northwest I could find no suggestion of the Tazewell drift border. Therefore, the best that can be said of the patchy drift that lies between the Iowan and the Mankato drift borders is that it probably includes deposits of both Iowan and Tazewell age, but that these deposits cannot be differentiated.

Late Wisconsin drift - Mankato

Drift of late Wisconsin (Mankato) age covers most of eastern and northern North Dakota. West of the Missouri River this drift crops out in a belt, 25 to 30 miles wide in the Knife River area, that narrows to the south, finally ending about 15 miles north of the South Dakota State line.

Lithologically the Mankato drift is similar to the Iowan and Tazewell drifts, and can be separated from them only on the basis of stratigraphy and differences in topography. In Mercer County the Mankato drift is much less eroded than the early Wisconsin drifts and covers most of the gently rolling uplands in the northern and eastern parts of the Knife River area. Farther south, however, in Morton and Sioux counties, even the Mankato drift has been extensively eroded and over much of its outcrop area is represented only by scattered granite boulders.

MANKATO DRIFT BORDER

Flint's map shows that the Mankato drift border enters North Dakota in southeast Emmons County, in T. 129N., R. 76W. In this area the Mankato drift is separated from the early Wisconsin drifts by an intervening blanket of loess, and the Mankato drift border is drawn at the southwest limit of till or erratic stones on top of this loess. The drift border can be traced from the State line northwest to Westfield, where it enters and is lost in the dissected topography that borders the Missouri River trench.

Between the dangling end of the Mankato drift border near Westfield and the late Wisconsin drift border in the Knife River area are five localities in Sioux, Morton and Oliver counties where deposits or topographic forms suggest presence of a drift border. None of these localities by itself would justify the drawing of a drift border, but the fact that they fall on a nearly straight line connecting the Mankato drift border near Westfield with the late Wisconsin drift border in the Medicine Butte quadrangle makes it seem probable that these five localities are actually representive of the Mankato drift border. These localities have been lettered A through E on the map on pl. 3.

Localities A and B are in northern Sioux County. Locality A is in sec. 19, T. 133N., R. 80W. and is on the upland between the Cannonball River and Porcupine Creek. At this point numerous glacial stones overlie at least six feet of coarse-grained sandy loess. This loess is probably the equivalent of the pre-Mankato loess farther southeast and overlying glacial drift is of late Wisconsin age. Locality B, in sec. 7, T. 133N., R. 81W, consists of several exposures on the north edge of the bluffs of the Cannonball River.

These bluffs, which are composed of sandstones and shales of the Hell Creek formation, are capped by about eight feet of sandy loess, probably the same loess as at locality A. The loess is separated from the Hell Creek formation by a one to two foot thickness of very bouldery till, but no glacial stones were found on top of the loess. Again, if this is the pre-Mankato loess, the underlying glacial drift is early Wisconsin and this locality lies outside the late Wisconsin drift border. The Mankato drift border, therefore, has been drawn between A and B.

Locality C is in southern Morton County a few miles south of Barnes. This locality is not a single outcrop or group of outcrops but a zone several miles long. In this zone there is a northwest-trending line, northeast of which granite boulders are two or three times as numerous as they are southwest of it. Also, northeast of this line several patches of till and a few small dames were noted, whereas to the southwest the drift seems to consist entirely of scattered boulders.

Locality D is in Morton County about six miles east of Almont. Extending north from sec. 11, T. 137N., R. 85W., to the central part of T. 138N., R. 85W., is a series of long linear ridges comprised chiefly of boulder gravel. These ridges probably represent a poorly developed Mankato end moraine.

Locality E is in southwestern Oliver County and consists of a series of small trenches that form a line extending from the eastern part of T. 141N., R. 87W., northwest into the eastern part of the Medicine Butte quadrangle in sec. 25, T. 142N., R. 88W. These trenches range in size from a tenth of a mile long and 50 yards wide to nearly two miles long and a quarter of a mile wide. They all trend southwest and cut through the divides between Beaver Creek and Otter Creek and between Beaver Creek and Brush Creek. Apparently the Mankato ice stood at this position long enough for meltwaters to cut these notches as they spilled over into the drainage of Beaver Creek. Also, northeast of this series of trenches the till cover is thicker and more persistent than it is to the southwest. This series of trenches and the distribution of the till was first noted and correctly interpreted in 1949 by W. D. Johnson Jr. of the Geological Survey, who pointed them out to me in the field.

In the Knife River area the Mankato drift border is located partly by differences in the topography and thickness of the tills and partly by the southwest limit of exposures of till overlying the intermediate fill, Qsd_2.

In the Medicine Butte quadrangle, the Mankato till is much thicker and more extensive than the older drifts and the Mankato drift border is easily traced from the eastern edge of the quadrangle to a point about a mile east of Medicine Butte. Here at locality F (pl. 3) the drift border is marked by a few small ice-contact deposits and also by a trench cut by meltwaters that spilled over from the drainage of Beaver Creek and flowed northwest into the Knife River valley.

Northwest of locality F the Mankato drift border is difficult to trace in detail. It apparently extends up the Knife River valley as far west as locality G (pl. 3), which is in the Broncho quadrangle in the SE$\frac{1}{4}$, sec. 2, T. 142N., R. 90W. At this locality a deposit of fine- to medium-grained sand (probably Qsd$_2$) is overlain by several boulders and cobbles of granite.

West of locality G there is no evidence of Mankato drift in the valley of the Knife River. It is possible that the drift border should be drawn far enough south to include the large patch of till that caps the upland in the northwest part of the Broncho quadrangle, but there is no good evidence either for or against this hypothesis. The drift border has been arbitrarily drawn so that it makes a reentrant around this upland and then extends west of the valley of Spring Creek.

In the Golden Valley quadrangle the Mankato drift extends up the valley of Spring Creek at least as far as locality H and probably as far as Dodge. Locality H, a railroad cut in the east half of sec. 18, T. 144N., R. 90W., shows Mankato till lying unconformably on the intermediate fill, Qsd$_2$. West of this locality the Mankato outwash fill, Qsd$_3$, extends at least to Dodge, but could not be identified west of the Golden Valley quadrangle. Therefore, the Mankato drift border has been drawn just west of Dodge, at which point it leaves the Knife River area.

No attempt was made to trace the Mankato drift border northwest of the Knife River area. It probably continues in a general northwest course and crosses the lower part of the Little Missouri River in eastern Dunn County.

Land forms in the Knife River area

General statement

The land forms of the Knife River area are the result of mass-wasting, fluvial erosion, and glaciation. The major features have already been described in the general discussion of southwestern North Dakota, except that the Oligocene-capped buttes and the late Tertiary planation surface are not present in the Knife River area.

The interstream areas consist largely of a rolling upland with gentle slopes, locally covered with drift. Standing above the upland are a few monadnocks, among which are Medicine Butte and the high hills to the south. The upland seems to be a part of the broad gently-rolling upland surface that comprises much of southwestern North Dakota.

Land forms that are the direct result of glacial deposition include the ground moraine in the northern part of the area, the Krem end moraine, and several mounds of ice-contact gravel; features that are the result of glacio-fluvial erosion and deposition include diversion valleys and the higher terraces; and features that are the result of post-glacial erosion and deposition include the floodplains and lower alluvial terraces, sand dunes, and several types of forms produced by mass-wasting.

Of the various geomorphic features just mentioned, the moraines, the terraces, the floodplains, and the sand dunes have been described elsewhere in the report and will not be discussed here.

Diversion valleys

Both major and minor divides in the Knife River area are crossed by through valleys or trenches, similar to those already described in other parts of the State. The diversion valleys of the Knife River area are divided into two groups. Group No. 1, "major trenches", includes the larger through valleys that cross divides between the major streams and were cut largely by the diverted waters of the principal streams. The floors of these large valleys are covered by post-glacial alluvium. Group No. 2, "minor trenches", includes all the smaller diversion valleys that connect the valleys of the smaller tributaries. Most of the smaller diversion valleys were cut by glacial meltwater. Their floors are not covered by alluvium and they have been shown on both the geologic map (pl. 1) and on the Pleistocene map (pl. 4) by hachured lines.

MAJOR TRENCHES

South Fork and Elm Creek trenches

The largest through valleys or trenches in the Knife River area are in the Broncho and Medicine Butte quadrangles and are occupied by the South Fork of the Knife River and Elm Creek. These two trenches are a part of the long system of diversion valleys that extends from the Killdeer Mountains to Fort Yates (pl. 3). One mile east of Glen Ullen in Morton County they merge and become the Muddy Creek trench, which continues southeast to the Heart River valley.

Both the South Fork and Elm Creek trenches have broad, nearly flat alluvial floors $1\frac{1}{2}$ to $2\frac{1}{2}$ miles wide, and both are cut 200 to 300 feet below the surrounding uplands. The uplands slope toward the trenches, suggesting that these trenches are the sites of previously existing valleys, which were deepened and widened by the diverted waters.

The present divides in the trenches are a few miles south of the Knife River area, and from the divides the alluvial floors slope gently southeast toward the Heart River and gently northwest toward the Knife River. However, for several miles north of the divide in the South Fork trench, the tributary streams enter the trench at right angles or are barbed to it, suggesting that at one time the divide was farther north than it is today. The old divide was probably somewhere in the southwest corner of the Broncho quadrangle, near the middle of T. 141N., R. 91W. The divide in the Elm Creek trench may or may not have shifted; the pattern of the tributary streams is equivocal and could be interpreted in several ways.

Thick alluvial deposits fill both the South Fork and Elm Creek trenches, especially in the divide areas, but the exact thickness of the fills and the altitude of the bedrock divides are unknown. Well data are scanty, for the water table in the trenches is high and most farm wells are less than 25 feet deep. Two wells, however, give minimum figures for the thickness of fill. The first well, in the Northern Pacific Railway Company's stockyards at Hebron in northwest Morton County, penetrated bedrock at a depth of about 70 feet. But even though the well is on the floodplain of the South Fork of the Knife River, it is two miles west of where that stream joins the South Fork trench, and the fill in the trench is certainly thicker. The second well, in sec. 10, T. 141N., R. 89W., is in the Elm Creek trench about 5 miles north of the divide area. According to the driller this well penetrated "... 123 feet of quicksand" before the sides caved in and drilling was abandoned. The evidence from the wells suggests a minimum thickness of 100 feet for the alluvial fill in the South Fork and Elm Creek trenches.

As indicated in the discussion of the Killdeer to Fort Yates diversion valleys (p.175) the South Fork and Elm Creek trenches were probably cut during a pre-Wisconsin glacial stage (Illinoian ?) and were reoccupied and possibly deepened during Wisconsin time.

Goodman Creek and Golden Valley trenches

The Goodman Creek and Golden Valley trenches are in the western part of the Knife River area and extend from the drainage of the Little Missouri River south to the valley of the Knife River in the Medicine Butte quadrangle. Although the two trenches are unlike in appearance their geography suggests that they were originally cut at the same time and that their later histories have been different.

The Goodman Creek trench extends (Fig. 7) the Little Missouri River southeast into the Golden Valley quadrangle and joins the valley of Spring Creek in T. 144N., R. 90W. The northwest part of the trench is occupied by Hans Creek, a northwest-flowing tributary of the Little Missouri River; the southeast part, by Goodman Creek, a tributary of Spring Creek. Except for the 3-mile segment just north of Spring Creek, the uplands on either side slope gently toward the trench, indicating that the trench follows the course of a pre-existing valley. The 3-mile segment north of Spring Creek has steep walls, and the upland on the east side slopes away from the trench. This segment, therefore, may be an ice-marginal channel; and, prior to the cutting of the trench, Goodman Creek may have flowed through the low sag 2 miles north of Golden Valley, joining Spring Creek several miles east of its present mouth. Patches of late Wisconsin till and stratified drift are scattered along the sides of the Goodman Creek trench, indicating that the trench was cut prior to late Wisconsin time.

The Golden Valley trench appears to be a continuation of the Goodman Creek trench. Its western end joins the valley of Spring Creek opposite the mouth of Goodman Creek. From here it extends east about 7 miles into the highland that forms the divide between the Knife River and Spring Creek. Here it turns south to join the Knife River valley in the northwest part of the Medicine Butte quadrangle. The divide in the floor of the trench is in sec. 29, T. 144N., R. 89W., and is 125 to 150 feet above the flood plains of Spring Creek and the Knife River. From the divide the trench floor slopes west towards Spring Creek with a gradient of about 18 feet per mile, and south toward the Knife River with a gradient of about 30 feet to the mile. These gradients are much greater than those of any other trenches in the Knife River area.

The east-west segment of the trench is ½ to 3/4 of a mile wide and is drained by two streams that start in the highland south of the trench and flow north across the trench and through the low hills that divide Golden Valley trench from Spring Creek. The smaller of the two streams crosses the trench in sec. 25, T. 144N., R. 99W., and has cut a narrow coulee 20 to 25 feet into the floor of the trench. Exposures in the coulee show that the floor of the trench is underlain by fine-grained alluvial fill that is probably the equivalent of the Pleistocene fill, Qsd_2 (Tazewell). The contact between this Pleistocene fill and the overlying Recent alluvium is impossible to determine accurately.

The presence of the old alluvial fill (Qsd_2) in the trench provide an explanation to the problem of why the small streams flow across rather than along the floor of the trench. Originally the small streams draining the area flowed north across the site of the trench to Spring Creek. After the initial cutting of the trench the small streams must have turned west down the floor of the trench and joined Spring Creek about 2 miles west of Golden Valley. Later, when the fine-grained fill, Qsd_2 rose to an altitude slightly above the present floor of the trench, the streams spilled out to the north through their former valleys. Once they were reestablished in these northerly courses, the streams had gradients steeper than the west-sloping floor of the Golden Valley trench, and subsequent erosion merely tended to deepen and maintain the new valleys across the trench.

The north-south segment of the trench is comparatively narrow, being only about $\frac{1}{4}$ mile wide, no streams are incised below its alluvial floor and the drainage flows south into the Knife River.

The thickness of alluvial fill (including Qsd_2) in the Golden

Valley trench is unknown, but in the divide area it must be 100 feet or more. The east-west segment of the trench was obviously cut by ponded waters, and the bedrock floor at the west end of the trench is at or below the altitude of Spring Creek. Therefore, unless the small streams flowing west along the original floor of the trench accomplished an exceptional amount of excavation, the bedrock lip of the divide must be at or below the altitude of Spring Creek at the west end of the trench; otherwise, the waters that cut the trench would have had no gradient.

The Golden Valley trench must have cut at or very close to the margin of an ice sheet. Otherwise the diverted waters that cut the trench would have used the lower outlet to the east, around the nose of the divide between Spring Creek and the Knife River.

If the fine-grained fill in the Golden Valley trench has been correctly correlated with the intermediate fill, Qsd_2, the trench must have been cut prior to Tazewell time. The Goodman Creek and Golden Valley trenches together seem to be a diversion route for the Little Missouri River, and were probably cut during the same glacial stage. Therefore, if the Golden Valley trench is pre-Tazewell, the Goodman Creek trench is pre-Tazewell also.

The absence of the fill, Qsd_2, in the Goodman Creek trench is anomolous; but may be due to the following factors: (1) During the deposition of Qsd_2 the small streams of the Golden Valley trench required a steeper gradient than Goodman Creek and built their fill correspondingly higher. Later, during the erosion of Qsd_2, Goodman Creek was able to remove large amounts of the fill whereas the small streams of the Golden Valley trench barely touched it. (2) During the late Wisconsin glacial stage the Goodman Creek trench was probably reused by the diverted Little Missouri River, but there is no evidence that this water flowed through the Golden Valley trench. As soon as the ice front had retreated as far east as Beulah the diverted water could flow from the Goodman Creek trench east down Spring Creek to the valley of the Knife River, and thence west to the north end of the Elm Creek trench. Still later, while the ice front stood at the Krem moraine, the diverted Little Missouri could flow from the Goodman Creek trench down the valleys of Spring Creek and the Knife River to the Missouri River trench at Stanton.

Beulah trench

The Beulah trench is sharply incised across the divide between the Knife and Missouri River drainages and was evidently cut by waters diverted from the Missouri River. The northern end of the trench is in secs. 5 and 6, T. 146N., R. 88W., and joins the valley of Beaver Creek about 2 miles west of where the creek joins the Missouri River. From here the trench extends southeast to a point about 4 miles north of Beulah, where it divides into two branches. The Zap branch trends southwest to the valley of Spring Creek about 3 miles east of Zap; the Hazen branch trends almost due east to the valley of Antelope Creek about 3 miles west of Hazen. The floor of the trench is 1/2 to 3/4 mile wide and is more than 200 feet below the surrounding uplands.

The Beulah trench is crossed by the Krem moraine, which now forms the divide between the Knife and Missouri watersheds. Within the walls of the trench the moraine has not been modified by subsequent erosion, indicating that the Beulah trench was not reused as an outlet for the Missouri River after deposition of the Krem moraine.

North of the Krem moraine the Beulah trench drains into the Missouri River via Beaver Creek. South of the moraine the main trench drains into Antelope Creek through the Hazen branch. The Zap branch drains into Spring Creek but carries only the waters that drain directly into it from the surrounding uplands.

The uplands flanking the trench slope north and south toward the Knife and Missouri rivers, but they also slope east toward a topographic low at the headwaters of Antelope Creek. Thus, to the west the uplands slope toward the trench; to the east, away from it.

When the trench was cut, therefore, the ice front stood very close to the eastern edge; otherwise the diverted waters would have flowed across the low area at the headwaters of Antelope Creek. The walls of the Beulah trench have been dissected into a fairly rugged topography, much more youthful than the topography bordering the South Fork and Elm Creek trenches to the southwest.

The Beulah trench and both of its branches are filled with unknown thicknesses of post-glacial alluvium.

North of the Krem moraine the only Pleistocene deposit in the trench is a large triangular-shaped patch of late Wisconsin outwash in secs. 21 and 28, T. 146N., R. 88W. South of the moraine, however, both the main trench and the Zap branch contain extensive remnants of late Wisconsin outwash (Qwo) unconformably overlying the early Wisconsin fill (Qsd_2). The remnants of the fill Qsd_2 are especially well preserved in the Zap branch where their eroded tops rise up to 55 or 60 feet above the present alluvial floor. The deposits of late Wisconsin outwash, are remnants of an outwash train, extending from the Krem moraine to the valley of Spring Creek. They were deposited on the eroded surface of the early Wisconsin fill, Qsd_2. Post-glacial erosion has dissected the outwash fill, leaving it as a terrace 15 to 20 feet above the modern alluvium.

In contrast to the Zap branch, the Hazen branch contains very few Pleistocene deposits. At its eastern end, where it joins the valley of Antelope Creek, are a few remnants of late Wisconsin outwash and one deposit that appears to be of ice-contact origin. Elsewhere the only Pleistocene deposits in the branch are a few very small patches of till and one small deposit of dirty gravel that was mapped as outwash but could possibly be of post-glacial origin. Deposits of Qsd_2, so numerous in the Zap branch, are missing in the Hazen branch.

The presence and distribution of the fill Qsd_2, indicates that the main trunk and at least the Zap branch of the Beulah trench had been cut by late Tazewell time. On the other hand the youthful topography of the walls suggests that the trench is not pre-Wisconsin. Therefore, the Beulah trench and the Zap branch were probably cut either during the Iowan substage or the early part of the Tazewell substage.

The paucity of glacial deposits in the Hazen branch is difficult to explain. The absence of the early Wisconsin fill, Qsd_2, suggests that the Hazen branch was not cut until post-Tazewell time. Possibly the branch was established during the mid-Wisconsin erosion interval when a tributary of Antelope Creek worked its way headward and captured the drainage of the Beulah trench. The scarcity of late Wisconsin outwash, however, requires another explanation. The few patches of till along its sides indicate that the Hazen branch was cut prior to late Wisconsin time and was in existence while the outwash train was being deposited in the Zap branch. Also, the Hazen branch obviously provides a lower outlet route than the Zap branch, and would have been used by the meltwaters unless it had been blocked, either by a fill or by ice. A sedimentary fill seems out of the question; there are no remnants of such a fill, and the small post-glacial streams could scarcely have removed a fill without leaving some trace. If the branch was blocked by stagnant ice, it is surprising that there are no kames or kame terraces along its sides. Nevertheless, the Hazen branch must have been blocked by something, and the absence of deposits suggests that the blocking agent was ice rather than a sedimentary fill.

MINOR TRENCHES AND NOTCHED DIVIDES

The smaller trenches in the Knife River area transect the divides between tributary streams. Most of these trenches trend south or southwest and most were cut by meltwater with little or no help from the diverted waters of the larger streams. The floors of most trenches are on bedrock except those near the headwaters of Willow Creek in the Broncho quadrangle. The more important of the smaller trenches are as follows:

1. In the southern part of the Broncho quadrangle the wide alluvial flats near the headwaters of Willow Creek are connected with the Elm Creek trench to the east and the South Fork trench to the west by small trenches partly-to completely floored with post-glacial alluvium. The small trenches were probably cut by meltwater that flowed southwest from the ice into the South Fork trench. Like the Elm Creek and South Fork trenches, these small trenches were probably cut during a pre-Wisconsin glacial stage and were again occupied by meltwaters of the Wisconsin ice sheets.

2. In the eastern part of the Medicine Butte quadrangle in secs. 19 and 30, T. 142N., R. 87W., are three small notches in the divide between Brush Creek and a tributary of Beaver Creek. The notches are part of the group of minor trenches that transect the divides between Beaver and Brush creeks and between Beaver and Otter creeks in southwest Oliver County (p.196). All these trenches were cut in late Wisconsin time by meltwater that flowed southwest into the drainage of Beaver Creek. Once in the Beaver Creek drainage, the waters flowed northwest toward the Knife River valley.

3. About 1 mile east of Medicine Butte is a trench, ½ mile long and 200 to 300 feet deep, that connects a tributary of Beaver Creek with a tributary of the Knife River. The trench was cut by the same meltwaters that notched the divides in Oliver County. As these waters flowed northwest down Beaver Creek they were ponded by the edge of the late Wisconsin ice sheet and were forced to rise and spill over the divide east of Medicine Butte. Once across this divide, the waters continued west into the Knife River valley, then west to the Elm Creek trench.

4. In the southern part of the Beulah quadrangle north and west of the Zap branch of the Beulah trench is a series of small trenches and notched divides that records the course of a late Wisconsin meltwater stream. The course extends east from sec. 35, T. 145N., R. 88W., and then south and joins a small tributary of Spring Creek in sec. 7, T. 144N., R. 88W. Ice must have blocked the Zap branch while the meltwater was cutting this course; otherwise the waters would have drained into the Zap branch through the valley in sec. 8, T. 144N., R. 88W. The patch of outwash in secs. 7 and 8, T. 144N., R. 88W is nearly 80 feet higher than the outwash train in the Zap branch, and was deposited by the meltwater stream whose course has just been outlined.

5. In the western part of the Stanton quadrangle, in sec. 36, T. 146N., R. 85W., and sec. 1, T. 145N., R. 85W., is a trench that crosses the divide between a small tributary of the Missouri River and a tributary of the Knife River called Elm Creek (not the Elm Creek that occupies the large trench in the southern part of the area). The north end of the trench is underlain by the early Wisconsin fill, Qsd_2. The trench may have been first cut by meltwater and later partly filled by Qsd_2, or it may have been cut when the Missouri River, flowing on the top of early Wisconsin fill, spilled over the divide into the headwaters of Elm Creek.

Abandoned valley segments

In addition to the trenches that cross divides, there are small to large abandoned valley segments that diverge from the modern valleys only to join them again farther downstream. These abandoned valleys formerly carried the drainage of the modern valley stream; some were abandoned because of glacial diversion, others because of superposition of the streams across bedrock spurs.

1. In the Broncho quadrangle about $\frac{1}{2}$ mile south of the proposed site for the Broncho Dam is an abandoned valley segment or channel connecting the Knife River valley in sec. 17, T. 142N., R. 90W., with the valley of Elm Creek in sec. 9 of the same township. Test holes drilled by the Bureau of Reclamation indicate that the channel is filled with about 115 feet of fine-to medium-grained gray sand, either the intermediate fill, Qsd_2, or the third fill, Qsd_3. The history of this abandoned channel seems to have been as follows: In early Wisconsin time the Knife River agraded its valley up to 50 or 60 feet above the present floodplain. During the dissection of the fill the Knife River was superposed across a bedrock spur and cut a new channel 115 feet deep. Later the Knife River removed the fill from the main valley and resumed its old course. Still later the new channel was filled with the gray sand encountered in the drill holes. The main valley of the Knife River was undoubtedly filled also, but subsequent erosion removed the gray sand from the main valley and did not remove it from the abandoned channel.

2. In the western part of the Medicine Butte quadrangle in secs. 21, 28 and 29, T. 143N., R. 89W., is another abandoned valley segment of the Knife River, similar to the one south of Broncho Dam except that the bedrock floor was cut only about 40 feet below the former land surface. The floor of this channel consists partly of Fort Union formation, partly of till, and partly of gray sand. The

channel is probably the result of superposition of the Knife River from the surface of a Pleistocene fill onto a bedrock spur. Evidently the Knife River did not maintain this course long enough to erode the Fort Union as deeply as in the channel south of the Broncho Dam.

3. In the eastern part of the Medicine Butte quadrangle a major tributary of Beaver Creek abandoned a two mile segment of its former valley. The abandoned segment extends from the eastern half of sec. 22, T. 142N., R. 88 ., across sec. 23 and into the northwest corner of sec. 25. The abandoned valley is comparatively broad, is filled with alluvium, and has gently-sloping grass-covered walls. The present valley parallels the old course about $\frac{1}{2}$ mile to the south, and has a narrow floor and steep walls. The diversion of the stream from the segment of its old valley was probably caused by an ice block.

4. In the Golden Valley quadrangle, a low sag extends from the valley of Spring Creek near Dodge east for about 4 miles to rejoin Spring Creek near the mouth of Goodman Creek. The sag is filled with deposits of the fills Qsd_2 and Qsd_3. Between the ends of the sag the present valley of Spring Creek is narrow and its walls are steeper than they are in the rest of the area. The sag probably represents the former valle y of Spring Creek. The diversion was probably caused by glacier ice- either an active lobe or a stagnant block - that forced Spring Creek out of its old valley and into its present course. The diversion occurred prior to the deposition of the early Wisconsin fill Qsd_2 and is therefore pre-Tazewell, probably

Iowan.

5. In the southern part of the Hazen quadrangle, in secs. 22 and 23, T. 144N., R. 87W., the floodplain of the Knife River narrows to less than ½ mile in width. Bedrock is exposed in both the northwest and southeast valley walls and is overlain in the southeast wall by gray sand (Qsd). The contact between the sand and bedrock dips southeast away from the present valley and disappears below the floodplain in sec. 26. Apparently, the former course of the Knife River was through secs. 26 and 25, and the present course is the result of superposition from the fill across a bedrock spur.

6. In the eastern part of the Hazen quadrangle in secs. 24 and 25, T. 145N., R. 86W., and in sec. 30, T. 145N., R. 85W., are two abandoned valley segments of Coal Creek, one north and one south of the present stream. The floors of these "in-and-out" channels are 30 to 45 feet above the present stream. Whether the channels represent the former valley of Coal Creek or whether they were temporary diversion channels formed during some glacial advance could not be determined.

7. In the Stanton quadrangle east of the Missouri River and sub-parallel to it is a broad topographic sag about 8 miles long and 2 miles wide. Both ends of the sag join the Missouri River trench; the northern end about 3 miles south of Riverdale, and the southern end about 3 miles northeast of Stanton. The sag is largely filled by deposits of stratified drift (Qsd_3) and post-glacial alluvium. The size and geographic position of the sag suggest that it was once the course of the Missouri River. It may mark the original Missouri trench formed by the Illinoian (?) diversion. The sag was

probably blocked by ice during some post-Illinoian glaciation, and the Missouri River was forced to cut its present channel.

Drainage pattern of the Knife River area

ALIGNED DRAINAGE

Many of the tributary streams of Spring Creek and the Knife River have sub-parallel courses that trend northwest or southeast. The tendency for small streams in the Great Plains to be aligned has been noted by numerous workers and several hypotheses have been suggested to explain the phenomenon.

Hypothesis of regional tilt

Pierce (1936, pp.72-73) noted an alignment of the northwest-flowing tributaries in Rosebud and Custer counties, eastern Montana. Other features in the area led Pierce to conclude that the region had been tilted to the northwest and that this tilt favored the development of the northwest-flowing streams.

Hypotheses involving wind action

Russell (1929) noted a strong tendency among the small streams of western South Dakota to be aligned northwest-southeast. From Russell's description and from an examination of aerial photographs of Haakon County, South Dakota, I judge that the aligned drainage of South Dakota is different from that of eastern Montana. In Montana the alignment is crude, merely a tendency for the northwest-flowing streams to be parallel or sub-parallel. In South Dakota, on the other hand, the alignment is remarkably good and affects the southwest-flowing as well as the northwest-flowing tributaries.

Moreover, the streams, besides being aligned, are nearly straight and are spaced at regular intervals.

Russell analyzed several possible explanations for the aligned drainage of western South Dakota and Nebraska and concluded that structural control, regional tilting, or erosion along the strike of differentially resistant beds were all unlikely hypotheses. He suggested that wind action was the probable cause and postulated that western South Dakota had once been covered by a series of southeast-trending longitudinal dunes. Small streams flowing in the interdune depressions incised their drainage into the soft bedrock and have maintained their courses even after the removal of the dune sand.

Baker (1948) agreed with Russell that the aligned drainage in western South Dakota was probably caused by the wind, but proposed an alternative mechanism which he called the yardang process. Baker thought that the prevailing strong winds from the northwest excavated elongate deflation hollows whose long axes trended northwest-southeast, and that the streams had gradually integraded the closed depressions into linear valleys.

Crandell (1951, pp.120-130) studied aligned drainage in the vicinity of Pierre, South Dakota, and concluded that both Russell's and Baker's mechanisms may have operated in that area.

Hypothesis of structural control

Neither wind action nor regional tilt is a likely explanation for the drainage pattern of the Knife River area. First, the pattern of the Knife River drainage does not resemble that of western South Dakota. Although many of the tributaries of the Knife River and Spring Creek are somewhat aligned, they are neither straight nor regularly spaced, and they do not head in uplands that show a striking northwest-southeast pattern of eolian features. Second, although the alignment in the Knife River area superficially resembles that described by Pierce, it differs in that southeast-flowing as well as northwest-flowing streams show the alignment. Third, there are numerous exceptions to the aligned drainage. Several good-sized tributary streams flow southwest, at right angles to the alignment, and any explanation of the drainage pattern must account for these exceptions.

The structure-contour map (pl. 5) shows a definite coincidence between drainage pattern and structure in the Knife River area. Both the major streams and their tributaries appear to be flowing along the axes of synclines. The largest of the synclines trend east-west and are followed by the Knife River and Spring Creek. Most of the smaller "crossfold" synclines trend northwest and are followed by the major tributary streams such as Beaver Creek, and Brush Creek in the Medicine Butte quadrangle. A few synclines trend southwest and are followed by the "exceptions" to the aligned drainage pattern, notably Schaffner Creek in the northwest part of the Broncho quadrangle and a large tributary of Antelope Creek in the central part of the Hazen quadrangle.

Even the Pleistocene diversion valleys have a fairly consistent relation to the structural axes. Those diversion valleys that follow the courses of pre-existing streams, for example the South Fork and Elm Creek trenches, follow the axes of synclines. Those trenches that are thought to be ice-marginal and that do not follow a pre-existing valley, for example the Beulah and Golden Valley trenches, cut across the structure. The northern part of the Goodman Creek trench follows a pre-trench valley and also follows a syncline; the southern 3 mile segment of this trench may be ice-marginal and this segment cuts across a small structural dome.

The coincidence of drainage and structure in the Knife River area is not perfect, but in general the agreement is remarkably close. I suggest, therefore, that the drainage pattern represents an adjustment of streams to the small bedrock structures. The adjustment probably started in the latter part of the Tertiary period, when the Great Plains changed from an area of deposition to one of erosion. As the streams, both large and small, began to carve valleys they encountered beds of varying resistance in the gently folded Tertiary rocks. When a down-cutting stream met the top of one of the more resistant beds - in most cases a sandstone - the stream tended to migrate laterally down dip in accordance with Gilbert's principle of monoclinal shifting. The lateral migration continued until the stream reached the axis of a syncline. Here the stream was trapped and the position of its valley stablized.

CAPTURE OF BARBED TRIBUTARIES

Several of the tributary streams of the Knife River area flow southwest along the axes of synclines. These streams are barbed with respect to the major east-flowing drainage. They are also at a disadvantage with respect to southeast-flowing streams, which join the Knife River farther east and have steeper gradients. As a result, the headwaters of the barbed tributaries are subject to capture by the southeast-flowing streams. Small scale piracy of this sort is taking place today at two localities - at the headwaters of Schaffner Creek in the Broncho quadrangle, and at the headwaters of Coal Creek in the Hazen quadrangle (pl. 1).

Schaffner Creek heads in the upland in the northern part of the Broncho quadrangle and flows southwest down the axis of a small syncline to join the Knife River in sec. 15, T. 142N., R. 91W. The headwaters of Schaffner Creek are actually closer to the Knife River at Broncho damsite than they are to the mouth of Schaffner Creek. Moreover, the Knife River is 40 to 50 feet lower at the damsite than at its junction with Schaffner Creek. Therefore, the southeast-flowing tributaries of the Knife River have steeper gradients than Schaffner Creek and will ultimately behead that stream. A small part of this capture has already been effected in the NE$\frac{1}{4}$, sec. 30, T. 143N., R. 90W., where a southeast-flowing stream has worked its way headward and has captured a 1 mile segment of a tributary of Schaffner Creek.

A similar situation exists in the central part of the Hazen quadrangle about 2 miles northeast of the Dakota Star Mine. The major stream of the area flows southwest along the axis of a syncline and joins Antelope Creek in the western part of the quadrangle. This southwest-flowing stream has a much gentler gradient than Coal Creek, which heads in the same area and flows southeast into the Knife River near the eastern edge of the Hazen quadrangle. Coal Creek has already captured part of the west-flowing drainage, in secs. 10 and 15, T. 145N., R. 86W., and will in the near future completely behead the tributary of Antelope Creek.

Thickness of fill in the major valleys

The bedrock floors of major valleys of the Knife River area have been explored by drill holes at only 3 localities, Garrison dam on the Missouri River, Broncho damsite on the Knife River, and Beulah on the Knife River.

At Garrison dam numerous holes drilled by the U. S. Army Engineers show that the bedrock floor of the Missouri River is 100 to 125 feet below the modern floodplain. Except for a few closed depressions (potholes?) the floor has little relief and seems to be about as wide as the combined widths of the modern floodplain and 40 foot alluvial terrace. Excavations in the terrace show that the fill in this part of the trench consists largely of till and stratified drift of Pleistocene age. Beneath the floodplain, however, an unknown thickness of post-glacial alluvium overlies the Pleistocene deposits. The contact between alluvium and drift is hard to determine from drill hole data, but the alluvium may be as much as 75 feet thick.

At the site of Broncho dam on the Knife River holes drilled by the U. S. Bureau of Reclamation show that across most of the valley the average depth to bedrock is about 115 feet, but near the center the bedrock surface drops about 30 feet and the fill is about 145 feet thick.

No similar deep channel was noted in the drilling at Garrison dam or at Beulah, and the presence of this inner channel at Broncho is therefore anomalous. It is probably a local scour channel. The fill overlying the bedrock floor at Broncho damsite consists of Pleistocene fluvial and glacio-fluvial deposits overlain by Recent alluvium. The contact is hard to pick from the drill hole data, but the Recent deposits are probably not more than 40 feet thick.

A few holes have been drilled in the Knife River valley near Beulah. Two of these were exploratory water wells; the rest were drilled by the Knife River Coal Company in search of buried coal beds. The rather sketchy data from these holes indicate that the bedrock floor of the valley is 100 to 110 feet below the floodplain. No deeper channel was discovered, but the holes are too far apart to eliminate such a possibility.

Mature topography of headwater areas

Several of the larger tributaries of the Knife River flow in valleys that are broader and more mature near their headwater areas than farther downstream. The best examples of this type of valley are Willow Creek in the Broncho quadrangle, Kinneman Creek in the southern part of the Hazen and Stanton quadrangles, and an unnamed tributary of Antelope Creek in the central part of the Hazen quadrangle. All three streams have the following features in common: 1) The lower parts of their valleys have comparatively steep sides and narrow floodplains. 2) The upstream parts of their valleys have gently sloping walls and broad alluvial floors one-eighth to one-half mile wide. 3) The profiles of the alluvial floors appear to coincide with the alluvial terrace in the Knife River valley and with the 40-foot terrace in the Missouri River valley.

The significance of the mature topography in the headwater areas is not clear, and the data at hand are not sufficient to justify any definite conclusions. The following hypothesis seems plausible, but is probably only one of several possible explanations:

The headwater areas may record an erosion cycle during which mature topography was developed over the whole area. Uplift and rejuvenation have enabled the streams to carve a more youthful topography close to the larger valleys, but dissection has not yet reached the headwater areas and there the old topography still persists. The mature topography may have been produced during the development of the transverse broad valley profiles of the major streams, or may post-date this stage.

Mass-wasting process

The picking up and transporting of surficial materials by wind, water, and ice are known as erosion. Surficial material also moves downslope under the dominant influence of gravity aided by the lubricating action of water or ice included in the material. This downslope movement is called mass-wasting.

Sharpe (1938) reviewed all the previous literature on mass-wasting and suggested a new classification. The subdivisions of Sharpe's classification are based, first on the rate of movement of the material, second on the amount of included water, and third on the type of material involved. Sharpe's primary subdivisions, based on the rate of movement, are as follows:

I. Slow flowage phenomena: rock creep, talus creep, soil creep, rock glacier creep, and solifluction.

II. Rapid flowage phenomena: earthflow, mud flow, and debris-avalanche.

III. Sliding: slump, debris slide, debris fall, rockslide and rock fall.

IV. Subsidance: the sinking of ground over mines, caves, etc.

Five types of mass-wasting, embracing all four of Sharpe's categories, have been noted in the Knife River area. These are: subsidance, soil creep, earthflow, and two types of slump.

SUBSIDANCE

Sharpe (1938, p. 88) defines subsidence as "movement in which there is no free slide and the surface material is displaced vertically downward with little or no horizontal component." This type of movement occurs principally over areas where there has been subsurface removal of material, either natural or artificial. In the Knife River area subsidance has occurred over underground mines, where a coal bed has been removed and the roof has collapsed. The largest area of subsidance is over the underground mine 2 to 3 miles north of Beulah. In this area more than 1½ square miles are pockmarked by pits, 10 to 30 yards across and roughly circular in plan, marking places where the thick Beulah-Zap coal bed has been mined out underground. The entire roof of the mine has not collapsed, just certain parts of it and between the pits are zones of uncollapsed strata.

SOIL CREEP

Soil creep is probably the most common and certainly one of the most widely recognized types of mass-wasting. It is the dominant mass-wasting process in all parts of the Knife River area except the small tracts of badlands adjacent to the large rivers, where most of the loose material is removed by slopewash. Material moved by soil creep forms thick deposits of colluvium at the base of some steep valley walls.

EARTHFLOW

An earthflow consists of a mass of sand, silt, and clay, with or without small amounts of coarser rock debris, and fairly well saturated with water. It is the slowest moving of Sharpe's rapid flowage phenomena (1938, p. 50). An area affected by an earthflow can be divided into 3 parts: At the head is a zone of small slump blocks; in the center is a zone of buckled and fissured material; and at the toe is a mass of hummocky material that is the earthflow proper. Failure by earthflow is a common type of mass-wasting in the Knife River area especially on steep sod-covered slopes (pl. 25A).

SLUMP BLOCKS

Sharpe (1938, p. 64) defines landslides as "the perceptible downward sliding or falling of a relatively dry mass of earth, rock, or a mixture of the two." Of Sharpe's various types of landslide the only one in which the material moves more or less as a unit with little tumbling or mixing is the slump. Sharpe's definition of a slump is as follows (p. 65): "...the downward slipping of a mass of rock or unconsolidated material of any size, moving as a unit or as several subsidiary units, usually with backward rotation on a more or less horizontal axis parallel to the cliff or slope from which it descends." The surface of failure and movement of these slump blocks is typically curved and is concave up. In the Pierre area of South Dakota Crandell (1951, p. 232 and 233) observed that the rotational type of slump is very common but that there are also large blocks of material that have moved essentially as a unit and show no rotational effects. He pointed out that a strict interpretation of Sharpe's definitions would leave these blocks unclassified, and proposed that they be included under the term "slump."

Rotational slumps

"Normal" or rotational-type slump blocks are common in the Missouri River trench in places where the river has recently undercut the steep high valley walls. In some places the material has had a free fall and should probably be classified as a debris-fall (Sharpe, 1938, p. 75).

Rockslide slumps

Sharpe defines a rockslide as (p. 76): "...the downward, usually rapid movement of newly detached segments of the bedrock, sliding on bedding, joint, or fault surfaces or on any other plane of separation." Although it is not an essential part of his definition Sharpe's pictures and descriptions of individual rockslides show that he considers this type of movement to involve jumbling and breaking up of the material.

In many of the small tracts of badlands in the Knife River area are examples of a type of landslide block that does not fit into Sharpe's classification. These blocks have moved downslope essentially as a unit with little or no jumbling of the material within the block, and by using Crandell's definition can be classified as a variety of slump. These blocks have slid partly on bedding planes and partly over a previously existing topographic surface and, therefore, they also partly fit Sharpe's definition of a rockslide. In the absence of a more suitable term, I shall call these blocks "rockslide slumps."

A rockslide slump is a landslide in which a block of bedrock detaches itself from a hill and slides as a unit down and away from its original position across a previously existing surface. The end product is a block in which the bedding or other internal structures have remained undisturbed but which has moved downslope and has been rotated away from the parent hillside.

In all the rockslide slumps of the Knife River area the block that moved was originally the nose or end of a badland spur. The surface on which the block slid was partly a bedding plane at the base of the spur and partly a slopewash-covered pediment that surrounded the spur. Apparently the block first moved on the bedding plane and slid out onto the pediment. The bedrock of the spur probably had a slight original dip in the direction of ultimate movement; otherwise the sliding could not start on the bedding plane. Apparently this original dip need not be great, for rockslide slumps have been observed where the bedrock dips at 1° or less.

The rockslide slumps in the Knife River area are thought to develop in the following manner: 1) The edges of the upland or the sides of a comparatively youthful valley are dissected into badlands. Long narrow spurs develop between small steep-sided gullies. As erosion continues, many of the badland spurs become bordered by pediment-like planation surfaces covered with a thin sandy deposit of slopewash. 2) Continued erosion narrows the spurs. As long as the crest line of any spur is not deeply notched no landslide occurs; gradually, however, the crest line is differentially lowered until a notch is cut nearly as deep as the base of the spur. 3) After the end of the spur has been thus isolated, it is able to detach itself and move downslope as a unit block. The block moves first on a bed of saturated clay at or near its base. Then, as it leaves its original position, it rides out across the pediment and is tilted away from the main mass of the badlands. The dip of the strata in the slump block approximately coincides with the slope of the underlying pediment surface.

There are several good examples of rockslide slumps in the Knife River area but only one of these shows anything but the end product, that is a block tilted away from the parent mass and resting on a pediment some distance away from the parent spur. The exception is in the NE¼, SW¼, sec. 34, T. 147N., R. 87W., where a block about 150 feet long and 40 to 50 feet high slid northwest over a pediment surface for a distance of about 100 yards. The beds in the block dip about 10° to the northwest and have been dropped about 25 to 30 feet below their original position. Subsequent erosion has cut below the old pediment surface, and the base of the slump block resting on the surface of the old pediment is now well exposed in cross section. Two photographs of this slump appear in pl. 26. Detailed examination showed that between the block and the undisturbed bedrock below the pediment is a zone, 1 to 1½ feet thick, of jumbled sand, silt and clay, which probably represents the saturated material on which the block slid. The sand was probably derived from the slopewash that covered the pediment and the clay from the saturated clay bed that was the initial surface of movement. Unfortunately this exposure soon will be covered by waters impounded behind Garrison Dam and there will be no further opportunity to study this particular rockslide slump.

STRUCTURE

General statement

Most of western North Dakota is in the Williston Basin, a large shallow structural basin whose only definite boundary is on its southwest flank where it terminates against the Cedar Creek anticline. The general configuration of the Williston Basin in North Dakota can be seen on Ballard's structure contour map (fig. 14), which has generalized contours drawn on top of the Dakota sandstone. This map shows the center of the Williston Basin to be about 50 miles west of the Knife River area, but contours drawn on top of the Tertiary beds will probably show a center farther east. The lowest altitudes of the base of the Golden Valley formation are in the western part of the Broncho quadrangle in the Knife River valley, in the southwestern part of the Golden Valley quadrangle in the valley of Spring Creek, and just northwest of the Knife River area near the town of Elbowoods. These points, all of which are in the bottoms of small synclines, indicate that the center of the Williston Basin as contoured in the Tertiary strata is probably near the northwestern part of the Knife River area.

The general location of the Williston Basin imposes a northward regional dip of 10 to 20 feet to the mile on most of the strata in southern North Dakota. However, superimposed on the regional structure are numerous small domes and synclines that interrupt and in places reverse the regional dip. In no part of the basin are the beds actually flat-lying, although they may appear so in the individual outcrop.

Structure contour map

A structure map of the Knife River area is shown in pl. 5. The contours are drawn on the base of the Beulah-Zap coal bed, which underlies and is intermittently exposed over about two thirds of the area.

Where the Beulah-Zap bed is not exposed because of burial, erosion, or stratigraphic "pinchout", elevations were read on other beds and were corrected to the horizon of the Beulah-Zap bed. The accuracy of the contours varies greatly in different parts of the area. In the places where the Beulah-Zap bed is well exposed the contours are well controlled. Elsewhere, however, the accuracy degenerates because of poor exposures, uncertain correlation of coal beds, or because of known variations in stratigraphic intervals between beds.

Folds

The structure map of the Knife River area shows that the strata are gently folded into small domes and synclines. Neglecting the effect of the small local structures, in the southern part of the area the beds dip north to northwest at an average of about 15 feet to the mile; in the northern part of the area they are nearly flat with perhaps a slight dip to the west.

The larger local structures are synclines and elongated domes whose axes strike nearly due east. The synclines are followed by the valleys of Knife River and Spring Creek. Smaller folds trend in various directions but the majority seem to strike about north 30° to 45° west. The maximum closure on the smaller domes seems to be about 40 to 50 feet.

Faults

Small superficial faults due to the local slumping are common in the badland areas near the major streams but these have not been shown on the map.

Two possible faults are shown on the geologic map of the Broncho quadrangle, but even these may be due to local slumping. The first locality is in secs. 25 and 26, T. 141N., R. 90W. Here a few poor exposures on the northeast side of a small ridge show the Fort Union formation dipping 15° to 45° NE. Whether the dips were produced by landsliding or whether they actually reflect a small fault in the bedrock could not be determined. The second locality is in the NW¼, NW¼, sec. 2, T. 142N., R. 92W., where the beds of the Golden Valley formation have been dropped about 10 to 15 feet on the west side of a small fault. As in the case of the first fault, it was not possible to determine whether this was a local slump block or whether it was truly a bedrock fault.

A third possible fault has been shown on the Stanton quadrangle map, in the southern part of sec. 11, T. 144N., R. 84W. Here the clinker of the Stanton coal bed has been dropped on the south sidd of a hinge fault in which the amount of displacement increases to the west. Again, it was not possible to rule out large scale slumping as a cause for the displacement.

Structures of Paleocene age

Deformed beds at Garrison Dam

In the southern part of sec. 4, T. 146N., R. 84W., the excavation for the spillway of Garrison Dam temporarily exposed in 1949 a zone of faulted and folded Fort Union beds overlain unconformably by flat lying Fort Union strata. The cause for the deformation is not apparent but it clearly took place within the Paleocene epoch.

The deformed zone is 1,000 to 1,200 feet wide; its length was impossible to determine but probably does not exceed 2,000 feet. Although some of the faults go deeper, the intensely deformed strata are only 35 to 40 feet thick. At the edges of the zone the beds are gently folded and offset by faults that strike N. 50 W. to N. 60 W. Near the middle of the zone, the beds are not folded but are so highly fractured and faulted that this part of the zone consists of a jumble of blocks of clay, siltstone, and lignite with no apparent preferred orientation.

The intensely deformed strata rest directly on a 2½ foot lignite bed that is very gently folded and cut by only 2 or 3 faults that have vertical displacements of 6 inches to 2 feet. The deformed strata and the underlying bed of lignite are shown in plates 25A and 27. Closely spaced drill holes indicate that below the highly faulted zone the Fort Union formation has been warped into a shallow basin that has a closure of about 40 feet in 1/4 mile. The long axis of this basin is northeast, nearly at right angles to the strike of the faults. The basin persists at least to a depth of 200 feet, which is the limit of the drill holes.

The upper boundary of the deformed zone is an erosional unconformity, above which are flat-lying silty sandstone beds of the Fort Union formation. The maximum relief of the unconformity is about 6 feet. The silty sandstones are in turn overlain by till with no crumpled beds or other evidence of ice-shove at the contact.

The exposures clearly indicate that, whatever the cause of the folding and faulting, the strata were deformed during the Paleocene epoch. This automatically rules out any mechanism involving ice-shove.

Two possible causes of the deformation, neither of which is entirely satisfactory, are as follows:

(1) Local landsliding along the margins of a Paleocene stream channel. There is no direct evidence in favor of this hypothesis and there are several objections to it. First, no exposures in the spillway cut show any evidence of a deep channel in the Fort Union beds. Second, the movement of the beds seems to have been from both sides toward the center, where the fracturing and faulting are most intense. Third, although the intense deformation affected only about 40 feet of strata, several of the faults extend deeper and cut the underlying 2½ foot lignite bed.

(2) Compressional stresses related to the formation of the underlying synclinal basin. This hypothesis assumes that the basin originated during the Paleocene epoch, but primary cause for the formation of the basin may have been either local sinking due to differential compaction or folding due to horizontal compression. As the basin sank the beds on the limbs were slightly compressed toward the center. Below the 2½ foot lignite bed the strata were confined by the weight of overlying beds and were gently folded. Above the 2½ foot lignite the strata were not confined and were probably saturated, so that they were easily pushed toward the center of the basin. Actually the movement of the beds may have been due partly to compression and partly to down-dip sliding under the influence of gravity. One obvious weakness in this hypothesis is that the strike of the folds and faults is nearly at right angles to the long axis of the basin. Nevertheless, it seems more likely that the deformation was related to the basin-producing forces than to local landsliding.

Subsurface evidence of Paleocene warping

The Cannonball marine formation crops out in the Missouri River trench as far north and west as the Washburn quadrangle, which adjoins the eastern edge of the Stanton quadrangle. At the town of Washburn, about 10 miles east of the Stanton quadrangle, the upper contact of the Cannonball formation has an altitude of 1,740 feet. At the eastern edge of the Stanton quadrangle the top of the Cannonball is below the floodplain of the Missouri River, which has an altitude of 1,685 feet. At Garrison Dam at the north edge of the Stanton quadrangle the core from a drill hole on the west side of the Missouri River shows the top of the Cannonball at 1,430 feet above sea level. There is little chance that the top of the Cannonball formation was misidentified in the drill hole, for the core was in excellent condition and the top of the Cannonball was picked independently by C. R. Golder and G. W. Prescott of the U. S. Engineers and R. W. Brown and myself of the Geological Survey.

Thus, between Washburn and Garrison Dam, a horizontal distance of about 30 miles, the top of the Cannonball drops about 300 feet. The structure map of the Knife River area supplemented by reconnaissance observations in the Washburn quadrangle indicate that the structural relief of the Fort Union beds between Washburn and Garrison does not exceed 125 to 130 feet. Therefore, there is a discrepancy between the dip of the top of the Cannonball formation and the dip of the coal beds in the Fort Union formation that amounts to 175 feet in a distance of about 30 miles.

The discrepancy could be due to marine offlap, and the lower Fort Union beds at Garrison Dam may be the time equivalent of the upper Cannonball beds at Washburn. The discrepancy could also be due to the sinking of a basin during Fort Union time, with the area around Garrison Dam sinking faster than that around Washburn. The latter hypothesis is supported by the following facts:

(1) Ballard's structure map of the Williston Basin (fig. 14) shows about 300 feet of relief on the top of the Dakota sandstone between Washburn and Garrison Dam. This coincides with the dip of the Cannonball-Fort Union contact and suggests that part of this dip had been acquired before the coal beds of the Fort Union formation were deposited.

(2) In the Knife River valley in the eastern part of the Hazen quadrangle the interval between the Beulah-Zap coal bed and the Stanton coal bed is 90 to 100 feet. In the Missouri River valley in the northeastern part of the Beulah quadrangle the interval between the Beulah-Zap coal bed and the Garrison Creek coal bed (which is either the same as the Stanton bed or within 10 feet of the same stratigraphic horizon) is about 165 feet. This indicates a 65-foot northward thickening of the beds between the Beulah-Zap and Stanton-Garrison Creek beds, and is most easily explained by assuming that the northern part of the Knife River area was sinking more rapidly than the southern part during the deposition of the Fort Union formation.

(3) The thickness and character of the Fort Union formation indicates that basin sinking must have occurred during deposition of the beds. The Fort Union formation is thought to have been deposited in coastal plain swamps, yet the formation is between 500 and 1,000 feet thick. Therefore, North Dakota must have been slowly sinking during the Paleocene epoch, and it is unlikely that the amount or rate of this sinking would have been constant over the whole region.

It seems possible, therefore, that many of the subsurface structures were developed during the Paleocene epoch. If this is true, many of the smaller surface structures may be reflections of larger subsurface structures and may increase rather than die out with depth.

Episodes of Tertiary deformation in southwest North Dakota

The relationship between the formations exposed in southwestern North Dakota indicates at least 3 episodes of tilting or local warping in early Tertiary time.

The first episode occurred during the Paleocene epoch. It is recorded by the deformed Fort Union strata at Garrison Dam and is inferred from other data. The deformation consisted of local warping and basin settling accompanied by minor folding and faulting.

The second episode was post-Wasatch (early Eocene) and pre-Oligocene and is recorded by the unconformity at the base of the White River formation. The deformation seems to have been chiefly differential uplift and tilting away from the Black Hills dome, because the White River formation lies on successively older formations when traced from North Dakota south toward the Black Hills.

The third episode occurred after the Oligocene epoch but before the development of the Miocene (?) or Pliocene (?) planation surface. The deformation consisted of the folding of all Tertiary formations into small domes and synclinal basins. Evidence of this episode is most clearly seen in the synclines of the Little Badlands in Stark County and of the Chalky Buttes in Slope County. In these areas White River beds involved in the folding now have dips up to 4° or 5°.

The structural history of the latter part of the Tertiary period and of the Quaternary period includes several pulses of regional uplift, but there is no evidence that any of these pulses was accompanied by folding or involved differential uplift.

GEOLOGIC HISTORY

The geologic history of southwestern North Dakota in general and the Knife River area in particular as read from surface rocks starts in late Cretaceous time and continues to the present. The major events are summarized as follows:

(1) In late Cretaceous time most of North Dakota was covered by marine waters. In these waters were deposited first Pierre shale, then, as the sea gradually shallowed, the Fox Hill sandstone. Further shallowing of the sea gave rise to the brackish water Colgate sandstone member of the Fox Hills formation.

(2) Retreat of the late Cretaceous sea and erosion of the upper surface of the Fox Hills sandstone.

(3) Deposition in latest Cretaceous time of the fluvial Hell Creek formation. The Hell Creek formation was deposited partly in swamps but mostly on floodplains. During this time the sea advanced briefly into southern North Dakota and the brackish water Breien member of the Hell Creek formation was deposited.

(4) A great change in the flora and fauna of the region occurred at the end of Hell Creek deposition. This change marks the end of the Cretaceous and the beginning of the Tertiary period, but was not accompanied in North Dakota by any major physical event.

(5) Deposition, in low-lying coastal plain swamps, of the various members of the Fort Union formation (Paleocene). During early Fort Union time the sea advanced, probably from the northeast, across central North Dakota. In the sea was deposited the

Cannonball marine formation, which intertongues with the lower part of the Fort Union formation. This is the last advance of the sea across North Dakota.

(6) An interval at the end of the Paleocene epoch during which western North Dakota remained low in altitude but received little or no deposits. During the interval the source areas to the west were deeply weathered and deposits of kaolin clay were formed.

(7) Erosion of the kaolin clays to the west and the redeposition of these clays in North Dakota to form the lower member of the Golden Valley formation (early Eocene). This was followed without apparent break by the fluvially deposited upper sandy member of the Golden Valley formation.

(8) A period of uplift and erosion. The uplift appears to have been both regional and differential; the Black Hills dome rose more than the area north and east of it. After the uplift erosion removed large amounts of the Golden Valley and Fort Union formations from North Dakota.

(9) Fluvial deposition of the Oligocene White River formation. Large amounts of reworked volcanic ash in this formation indicate volcanism in the mountains to the west.

(10) A period of folding and warping followed or accompanied by uplift and erosion. Much of the White River formation was removed from southwestern North Dakota and a planation surface capped by 3 to 5 feet of gravel was developed. This planation surface is probably the equivalent of the Flaxville plain in eastern Montana and if so was probably cut during the Pliocene epoch.

(11) Uplift and dissection of the gravel-capped planation surface and the development of the broad, gently rolling plain that today forms the uplands of the interstream divides.

(12) Dissection of the broad upland surface to form the gently sloping broad valley profiles that flank the major stream valleys. By analogy with events in South Dakota this dissection probably occurred in the early Pleistocene, possibly during the Yarmouth interglacial stage.

(13) An advance of some pre-Wisconsin ice sheet (Illinoian?) southwest across the site of the Missouri River trench. The ice sheet diverted the waters of the northeast-flowing streams, turned them southeast, and new channels were cut at or close to the margins of the ice. The major sets of diversion valleys were formed: The first set now abandoned, extends from the Killdeer Mountains in Dunn County southeast to the Missouri River a few miles north of Fort Yates. The second set was incised deeply enough to hold the drainage after the retreat of the ice and became the Missouri River trench.

(14) Deepening of the Missouri River trench and all its tributary valleys to a depth as great or greater than the modern floodplains. This erosion probably took place during the Sangamon interglacial stage.

(15) Advance of the Iowan ice sheet as far southwest as the outermost drift border in North Dakota. Till, ice-contact deposits and the outwash fill, Qsd_1, were deposited in the Knife River area.

(16) A short interval of erosion and weak soil-profile development following the retreat of the Iowan ice.

(17) Advance of the Tazewell ice; deposition of till and of the fine-grained fill, Qsd_2.

(18) Retreat of the Tazewell ice, followed by a period of erosion during which the thick fill, Qsd_2, was dissected to a depth below that of the modern floodplains. During this erosion interval the bedrock floors of the Missouri trench and its tributaries may have been lowered.

(19) The advance of the Cary ice sheet, an event not recorded in southwestern North Dakota.

(20) The advance of the Mankato ice sheet across all but the southwestern part of the Knife River area; deposition of till, stratified drift, and the valley fill, Qsd_3; building of the Krem moraine. As the Mankato ice retreated it left a stagnant body of ice in the Missouri River trench causing deposition of a large kame terrace.

(21) Melting of the ice in the Missouri trench and the deposition of the combined fluvial and glacio-fluvial fill, Qmg.

(22) Readvance of the Mankato ice sheet across the Missouri trench in the Stanton quadrangle; deposition of till and ice-contact gravel, Qic'.

(23) Final retreat of the Mankato ice sheet, followed by an interval of erosion during which the Pleistocene deposits were dissected to depths below that of the modern floodplain.

(24) A period of aggradation during which the streams deposited fine-grained sand and silt and aggraded their courses up to and above the altitudes of the modern floodplains.

(25) Gradual dissection of the older alluvium and development of the modern floodplains of the streams.

ECONOMIC GEOLOGY

The mineral resources of the Knife River area are sand and gravel, ceramic clay, and lignite coal. Of these only the lignite is being extensively exploited. Oil and gas are being produced from other parts of the Williston Basin in North Dakota and the producing formations extend under the Knife River area. Up to the present time, however, the only deep well drilled in the area was a dry hole.

Sand and gravel

Nearly all the deposits of sand and gravel in the Knife River area are of glacial origin. All the larger deposits are in the northern part of the area; in fact most of the southern part of the area is so barren of gravel that outcrops of the clinker or "pseudoscoria" are the chief source of road metal. Even in the northern part of the area most of the sand and gravel deposits are small and the materials are poorly sorted; they have a high silt content and are used principally for road metal. A few small deposits are fairly clean and are used for concrete aggregate by local residents. Most of the deposits in the Knife River area contain some undersirable materials. In addition to silt, these materials are stringers of reworked and weathered coal, pebbles of weak shale, pebbles of chert, and iron oxide. The various Pleistocene fluvial and glacio-fluvial deposits are characteristically different from one another, so that any discussion of the sand and gravel resources of the area must logically be based on the same subdivisions as those shown on the geologic map.

Early Wisconsin gravel deposits (Qwg, Qsg, Qtg, Qsd_1)

With the exception of the outwash fill Qsd_1, the early Wisconsin deposits of sand and gravel are few in number and small in size. They are confined to the southwestern part of the area beyond the border of the Mankato drift. The deposits of undetermined origin, Qsg, and the older glacial deposits, Qwg, are for the most part small in size and very poorly sorted. They contain large amounts of silt and clay and are only used locally for road metal. The deposits of Qtg are a little larger and somewhat better sorted, but these contain a high percentage of chert and flint pebbles, making them unsuitable for some concrete aggregate.

The deposits of the old outwash fill, Qsd_1, are confined to the Knife River valley near Beulah. In general the gravels of Qsd_1 are fairly clean and free of silt. The chief fine-grained impurities are stringers of powdered and weathered lignite and secondary deposits of fine-grained iron oxide. Both of these impurities can probably be removed by washing. A high proportion of the pebbles consist of limestone and dolomite, which may restrict the use of this gravel to certain types of aggregate. A deposit of Qsd_1 is being mined at the Beulah gravel pit and is used both for road metal and for concrete aggregate.

Deposits of the intermediate fill, (Qsd_2)

The intermediate fill, Qsd_2, consists largely of medium- to fine-grained sand and silt. In only a few outcrops does Qsd_2 contain beds of sand and gravel, and even in these places there is usually a great deal of interbedded fine sand and silt. There are no gravel pits in this fill, and there is little chance of discovering any exploitable gravel beds in it.

Deposits of late Wisconsin outwash (Qwo, Qsd_3)

Deposits of late Wisconsin (Mankato) outwash are common in the northern and eastern parts of the Knife River area and there are numerous gravel pits in these deposits. Nearly all of the deposits, however, are poorly sorted and contain small to large amounts of silt and clay. They are mined principally for road metal and would require washing before they would be suitable for concrete aggregate. An exception to this generality is found in the outwash terrace of Qsd_3 in Brush Creek between secs. 9 and 23, T. 143N., R. 88W. where the deposits consist of medium- to coarse-grained sand and gravel, comparatively well sorted, and with very little admixed clay or silt. The pebbles are 60 to 65 percent granite, 20 to 25 percent limestone and dolomite, and 10 to 15 percent basalt, quartzite, sandstone, and iron oxide. The deposits are large and extensive and constitute one of the best potential sources of sand and gravel in the Knife River area.

Ice contact deposits (Qic, Qic')

Several of the large kames in or near the Krem moraine in the northern part of the Knife River area are mined for sand and gravel. The material in most of the kames is fairly well sorted and contains no more silt than most of the outwash deposits. The kames, however, contain a higher percentage of shale pebbles (derived from the Pierre formation) than the outwash deposits.

Missouri River gravels (Qmg)

The Missouri River gravels underlie parts of the 40-foot terrace in the Missouri River trench and consist of coarse-grained sand and gravel derived partly from Canada and partly from the watersheds of the Yellowstone and Little Missouri rivers. In general these extensive deposits are better sorted and cleaner than any other gravel deposits in the area. They contain only small percentages of silt and clay and virtually no powdered coal or limonite. Many of the pebbles consist of chert and agate, undesirable for certain types of concrete aggregate. However, similar gravels are mined from the Missouri and Heart River valleys near Mandan, North Dakota and are used as aggregate after washing and screening. If the Missouri River gravels in the Stanton quadrangle are suitable for aggregate, they are the largest potential source of this commodity in the Knife River area.

Ceramic clay

Some of the beds of plastic clay in the Tongue River member of the Fort Union formation are probably suitable for the manufacture of brick and tile. The beds, however, are discontinuous and much detailed testing would be necessary to determine their extent and potential uses.

The lower member of the Golden Valley formation consists chiefly of kaolinitic clay mixed with varying amounts of quartz and mica. The clay beds are remarkably uniform both in appearance and composition over the entire outcrop area of the formation. They are not being exploited in the Knife River area, but are being mined in Morton County by the Hebron Brick Co. and in Stark County by the Dickinson Pressed and Fire Brick Co. and are used in the manufacture of brick, structural tile, and pottery.

The fourth biennial report of the North Dakota Geological Survey deals with the clay resources of the State and summarizes the results of detailed ceramic tests made on the "...light-colored Tertiary clays" - the Golden Valley formation of this report (Leonard, Clapp, and Babcock, 1906, pp. 132-190). The tests showed that nearly every sampled outcrop of the Golden Valley kaolin beds contains clay suitable for some ceramic use. Most of the sandy clays are suitable for fire brick; the silty to non-silty clays are suitable for brick and tile; and a few beds of plastic clay are suitable for pottery. Therefore the lower member of the Golden Valley formation is a potential source of ceramic clay whenever the formation is present and the Golden Valley-Fort Union contact can be used to estimate the extent and location of deposits of ceramic clay in southwest North Dakota.

Oil and gas possibilities

Until the spring of 1951 North Dakota was one of the marginal areas that had not produced any oil or gas. Paleozoic and Mesozoic rocks that have yielded oil in Wyoming, Montana, and Canada were known to underlie much of the State, but the few scattered wildcat wells had produced nothing but salt water. In March, 1951, the Amerada Petroleum Corporation discovered oil near Tioga, a small town about 25 miles east of Williston. The discovery well is on the north end of the Nesson anticline, the largest known structural dome in the Williston Basin. The producing horizon is apparently in strata of Devonian age, but later holes in the same area have encountered oil in the Madison limestone (Mississippian) as well. The discovery of oil in the Tioga well has stimulated exploration in other parts of the Williston Basin, and more producing fields will probably be discovered in the future.

In addition to the structural traps, which so far are the only basis for the wildcat wells in North Dakota, there is a possibility that oil in the Paleozoic formations may occur in reefs or on stratigraphic traps. Future drilling will probably determine whether any of these non-structural traps exist in the Williston Basin.

The small structures that are superimposed on the gentle regional dip of the beds in the Knife River area are probably too small to warrant much optimism for oil discoveries unless they reflect larger buried structures. Drilling in other parts of the Williston Basin in the near future will undoubtedly indicate whether some of the small structures increase with depth. If they do, the small domes of the Knife River area may well be the targets for wildcat wells.

In the summer of 1950 the Plymouth Oil Company drilled a well, the Kelley-Leutz # 1 well, in the northern part of sec. 28, T. 142N., R. 89W., Mercer County. The hole started in the Fort Union formation about 10 feet below the base of the Golden Valley formation, and was drilled 12,526 feet, ending in rocks of Cambrian age. The well was abandoned as a dry hole. Detailed information of the formations encountered in this hole is not available, but a driller's log with the approximate tops of some of the formations is given in the appendix. The structure contour map of the Knife River area (pl. 5) shows that the Kelley-Leutz well is not on one of the larger structures in the area so that this particular well should not be the cause of too much pessimism regarding future possibilities in the area.

Coal beds

The coal beds are the chief resource of the Knife River area and are being extensively mined. All of the valuable beds are in the Tongue River member of the Fort Union formation; a few small beds occur in the Golden

Valley formation but are not persistent or thick enough to warrant development.

Physical properties

All of the coal in the Knife River area is of lignitic rank and is similar to the lignites described from other parts of North Dakota (see fig. 1). The fresh lignite is tough and compact. Most of it appears black in gross aspect, but the powder or streak is dark brown. Some of the fresh lignite has a woody or fibrous texture and a dull lustre. Other fresh lignite is compact, black, and has a vitreous lustre. Some of the more fibrous layers are quite soft and porous and resemble charcoal. Carbonized logs and plant stems are common in most of the beds. Some of these have a woody texture; others are massive and shiny. The black shiny lignites in general break easier than the woody fibrous varieties.

On exposure to the air the lignite loses considerable part of its high moisture content. This causes shrinking and cracking and the coal soon degenerates into fine black powder. This characteristic makes it almost impossible to ship lignite in open cars to distant markets. The tendency of the lignite to weather to fine powder also makes it difficult in some places to estimate the true thickness of the beds, because the pressure of the overlying beds squeezes the powder out into the zone of soil creep. This causes an apparent thinning of the lignite bed at the outcrop: in many places a bed 4 to 5 feet thick will appear on the weathered outcrop to be only 2 or 3 feet.

This lignite contains several types of impurities, the most common of which is silt or clay that forms ash when the coal is burned. Other impurities present in minor amounts are iron sulfide (probably marcasite), sulfur, and gypsum. The latter two are probably formed by the disintegration of the iron sulfide. Parts of some of the lignite beds have been silicified to form a hard, non-combustible black substance which the miners call "bone."

Chemical composition

Numerous samples of lignite have been collected from various mines in the Knife River area and have been analyzed in the chemical laboratory of the U. S. Bureau of Mines at Pittsburg, Pennsylvania. A representative sample of these analyses is given in Table 1. For the purposes of comparison, a few analyses of coals from nearby fields have been included, as well as one analysis of Pittsburgh bituminous coal.

Distribution and correlation of beds

BEULAH-ZAP BED

The most important coal bed in the Knife River area is the Beulah-Zap bed. Mercer County is currently the largest lignite-producing county in the United States and all the larger mines are in this bed; in the calendar year 1950 the three large mines near Zap, Beulah, and Hazen produced 1,184,893 short tons. The bed was named and mapped near the towns of Beulah and Zap by Leonard and Dove (1925, pp. 125-130).

Except where it has been removed by erosion, the Beulah-Zap bed underlies the Medicine Butte quadrangle, all but the southwest part of the Broncho quadrangle, the eastern part of the Golden Valley quadrangle, all the Beulah quadrangle, and the western half of the Hazen quadrangle. To the west in the Broncho and Golden Valley quadrangles the bed thins and probably pinches out. To the south and southeast it extends for unknown distances into Morton and Oliver counties. To the east it thins and probably disappears in the eastern part of the Hazen quadrangle. To the northeast it thins and may or may not extend into the Minot area; if it does it is probably Andrews' bed B, 90 feet above the Minter bed (Andrews, 1931, p. 72). To the north and northwest it extends into the southern part of the Fort Berthold Indian Reservation, where it was mapped as bed 2 by Pishel and bed EE by Bauer and Herold. *

*The bed mapped as "EE" near the mouth of the Little Missouri River in Dunn County is probably not the same as bed "EE" in the extreme eastern part of the Fort Berthold Indian Reservation, where it correlates with the Beulah-Zap bed.

In the Knife River area the Beulah-Zap bed is less than 5 feet thick only in the Broncho quadrangle; elsewhere it is much thicker, reaching a maximum of 25 feet in the center of the Beulah quadrangle. Measured sections of the Beulah-Zap bed are shown in figs. 15 - 20 .

The Beulah-Zap bed is the most persistent in thickness and quality of all coal beds in the Knife River area and it is the best key horizon in the Fort Union formation. Even where outcrops are poor, the bed has been extensively burned and the clinker is readily traceable. The correlation of the other coal beds is much more difficult. Much of the area consists of smooth grass-covered slopes with few or no outcrops. Because of the great variability in the lateral persistence of the beds correlation across these grass-covered slopes is difficult and uncertain at best. In some places the accuracy of correlation is good; in others, little more than a reasonable guess. All beds that have been correlated, however, are probably close to the same stratigraphic horizon. For example, the Schoolhouse bed in the southern part of the Knife River area is actually several beds, all close to the same horizon, but separated by intervening areas of no coal.

COAL BEDS ABOVE THE BEULAH-ZAP BED

The principal beds stratigraphically above the Beulah-Zap bed are the Schoolhouse and Twin Buttes beds in the Fort Union formation, and the Alamo Bluff and Schaffner beds in the overlying Golden Valley formation. All these beds are restricted to the southwestern part of the area.

Schoolhouse bed

The Schoolhouse bed was named for an exposure in a small mine near a rural school in the southern part of sec. 27, T. 142N., R. 89W. The bed persists over most of the Broncho and Medicine Butte quadrangles, and has been tentatively identified in the southern parts of the Golden Valley and Beulah quadrangles. It persists southeast of the Knife River area and may correlate with the thick bed whose burned out portions form the clinker cap of the hills near Glen Ullen in Morton County.

The Schoolhouse bed is 45 to 50 feet above the Beulah-Zap bed in the eastern part of the Medicine Butte quadrangle. The interval increases westward to about 80 feet near Broncho damsite and 100 feet in the western part of the Broncho quadrangle. In the vicinity of Broncho damsite the Schoolhouse bed splits into 2 parts which gradually diverge westward. In the vicinity of the South Fork of the Knife River, they are separated by 25 to 30 feet of sandy shale and clay. Only in the southeastern part of the Medicine Butte quadrangle is the bed consistently thick and of good quality.

Twin Buttes bed

The Twin Buttes, named for exposures near a pair of small conical buttes in sec. 28, T. 143 N., R. 90W., is 130 to 150 feet above the Beulah-Zap bed. Over most of the Broncho and Medicine Butte quadrangles the Twin Buttes bed is a thin impure lignite 1 to 3 feet thick with a persistent clay parting near the middle. Locally, as in the vicinities of Medicine Butte and Schaffner Creek, it thickens and is a bed of good quality 5 to 7 feet thick. In the southern and eastern parts of the Medicine Butte quadrangle the Twin Buttes bed grades laterally in a very short distance into brown carbonaceous shale. The Twin Buttes bed persists north in the southern part of the Golden Valley quadrangle where it is as much as 6 or 7 feet and is locally mined.

Alamo Bluff bed

The kaolin clay beds of the lower member of the Golden Valley formation are characteristically capped by a thin impure lignite or carbonaceous shale, which locally thickens to a coal bed 2 to 6 feet thick. In the Broncho quadrangle this has been called the Alamo Bluff bed. The Alamo Bluff bed was named for an exposure in a small escarpment near the ruins of an adobe house, facetiously called "the Alamo" by the Knife River party, in the northeast corner of sec. 28, T. 143N., R. 90W. The bed is too variable in thickness and quality to permit an accurate estimate of its reserves, but it probably has little or no commercial value. The local small pits 2 to 3 miles northeast of Dodge in the Golden Valley quadrangle are probably in the Alamo Bluff bed, but these pits were slumped in and a section of the bed could not be obtained.

Schaffner bed

The Schaffner bed, named for exposures near Schaffner Creek, is a small lenticular bed of coal in the upper member of the Golden Valley formation. It occurs about 30 feet above the Alamo Bluff bed and is best developed in the northwestern part of the Broncho quadrangle. As its average thickness is only 2 to 2½ feet, it probably has no commercial value.

COAL BEDS BELOW THE BEULAH-ZAP BED

Thick coal beds below the Beulah-Zap bed are exposed only in the northeastern part of the Knife River area. Some of these are fairly persistent; others which are locally thick and of good quality, lense out in short distances. Therefore, correlation across areas of poor exposures is difficult and many beds have been given local names, even though detailed drilling might show that they correlate with other beds a few miles away. The following discussion will be organized on the basis of local geography.

Beulah area

Several coal beds crop out below the Beulah-Zap bed in the vicinity of Beulah. Of these only the Spaer bed and the Hazen B bed appear to persist over any great area.

Spaer bed

The Spaer bed, about 60 feet below the Beulah-Zap bed, persists over parts of the Medicine Butte, Beulah and Hazen quadrangles. The Spaer bed was named from exposures at the Spaer ranch in the NE¼, sec. 12, T. 143N., R 89W. In this part of the Knife River valley the bed is 2 to 4 feet thick and is easily identified by a thin cap of silicified carbonaceous shale. Silicified shale also caps the Spaer bed just northwest of the Dakota Collieries' strip mine near Zap; but east of the mine the Spaer bed has no silicified cap, whereas two local beds, one 35 feet above and one 30 feet below the Spaer, are overlain by a silicified carbonaceous shale.

The Spaer bed was not observed in the Knife River valley east of Beulah. In the Zap and Hazen branches of the Beulah trench a bed 55 to 60 feet below the Beulah-Zap bed has tentatively been correlated with the Spaer bed.

Hazen "B" bed

The Hazen "B" bed, named for exposures near the town of Hazen, crops out on the north side of the Knife River valley as far west as the town of Beulah. Between Beulah and Hazen it is 2 to 5 feet thick and about 110 to 115 feet below the base of the Beulah-Zap bed. It is quite variable both in thickness and the presence of clay partings.

In addition to the Spaer and Hazen "B" beds there are 3 or 4 local beds that do not persist laterally for more than a mile or two.

Subsurface beds

Drill holes and an old mine shaft at Beulah reveal the existence of two thick beds that underlie the area but that do not crop out at the surface. Both of these beds were formerly mined underground by the old Beulah Coal Company; the access shaft was near the present power house at the east end of the town.

The upper of the two beds is about 10 feet thick and is 180 to 190 feet below the Beulah-Zap bed. In the shaft the base of this bed has an altitude of 1,751 feet, putting it about 40 feet below the Knife River floodplain. Although this bed is nearly 10 feet thick at the shaft, drill holes indicate that it underlies less than 2 square miles on the north side of the Knife River and is not present on the south side.

The lower bed is at an altitude of 1,633 feet, or about 200 to 210 feet below the Beulah-Zap bed. Drill holes show that this bed is 8 to 10 feet thick and is present on both north and south sides of the Knife River valley.

Hazen area

Hazen "A" bed

The lowest bed that crops out near Hazen is called the Hazen "A" bed. It is about 4 to 5 feet thick, and lies 155 to 160 feet below the Beulah-Zap bed. The Hazen "A" bed was traceable only on the north side of the river, and extends from the Gallagher Mine 1½ miles northwest of Hazen (locality 357) east to sec. 31, T. 145N., R. 86W. On the south side of the Knife River the bed exposed at locality 370 in sec. 12, T. 144N., R. 86W. is probably the Hazen "A" bed.

Hazen "B" bed

The Hazen "B" bed, about 40 feet above the Hazen "A" bed, was identified on both sides of the Knife River valley. It is 4 to 6 feet thick and of good quality. East of Hazen poor exposures on both sides of the Knife River valley prevent an accurate tracing and correlation of this bed, but it seems to be at about the same horizon as the Coal Creek bed.

Star bed

A poorly exposed bed 25 to 40 feet above the Hazen "B" bed and 75 to 95 feet below the Beulah-Zap bed has been named the Star bed. The bed was penetrated by the water well at the Dakota Star Mine, where it is about 10 feet thick. Except for this drill hole the Star bed is exposed only at two other places. Its thickness is apparently quite variable and its lateral persistence questionable. It is possibly the lateral equivalent of the Stanton bed to the east.

Stanton area

The Beulah-Zap coal bed pinches out north of the Knife River somewhere between Hazen and Stanton. From Hazen east, therefore, it is more difficult to relate the beds to the horizon of the Beulah-Zap bed. Several coal beds were mapped in the southern part of the Stanton quadrangle, but of these only the Stanton bed can be definitely traced over all of the area.

Coal Creek bed

The Coal Creek bed, named for exposures along the creek of the same name, was traced on the north side of the Knife River valley in the eastern part of the Hazen and the western part of the Stanton quadrangles. It is probably present also on the south side of the river, but except in the valley of Kinneman Creek it is buried by the late Pleistocene glacial fluvial deposits. Where it has been mapped, the Coal Creek bed varies from about 2½ to 4 feet in thickness. It is 35 to 40 feet below the Stanton bed and may be the lateral equivalent of the Hazen "B" bed.

Stanton bed

The Stanton bed was named for its development in the high hills 4 to 6 miles south of Stanton. The bed has been traced from the eastern part of the Hazen quadrangle across the southern half of the Stanton quadrangle. Although it is laterally persistent the thickness and quality of this bed are quite variable. It is thickest in the high hills a few miles south of Stanton, being 8 to 11 feet thick in the vicinity of the Kamin

Mine in sec. 13, T. 144N., R. 85W. West of Stanton in the Knife River valley the Stanton bed is 4 to 8 feet thick and has a thick roof of soft yellow-gray sand. East of the Missouri River the Stanton bed is 4 to 6 feet thick and of good quality. It has been traced to the eastern margin of the Knife River area, and apparently persists for several miles eastward into the Washburn area.

The Stanton bed is very close to the same stratigraphic horizon as the Garrison Creek bed a few miles to the north. It was not possible, however, to definitely correlate these two beds. On the west side of the Missouri River the Stanton bed pinches out to the north and the Garrison Creek pinches out to the south, and there is a gap between them in secs. 5 and 8, T. 145N., R 84W. On the east side of the Missouri River the east-central part of the Stanton quadrangle is covered with thick deposits of till and stratified drift, and the beds cannot be traced across this covered area without the aid of drill holes.

Knoop bed

The Knoop bed was named for exposures on the Knoop Ranch on the west side of the Missouri River in secs. 8, 9, 16, and 17, T. 145N., R. 85W. At its type locality the Knoop bed consists of two beds or "benches" of coal separated by 3 to 4 feet of shaly clay. Traced to the north the upper bed thins and dies out, but the lower bed persists and can be traced as far as sec. 13, T. 146N., R. 85W. Over most of the area in which the Knoop bed is exposed the Stanton bed is either missing or its covered by glacial drift so that it is not possible to measure the interval between them. The best estimate is that the Knoop bed is 85 to 95 feet below the

Stanton bed near the Knife River, but this interval appears to increase northward. In sec. 30, T. 146N., R. 84W., the Knoop bed is 95 to 100 feet below the Garrison Creek bed, and at its northernmost outcrop in sec. 13, T. 146N., R. 85W., it is 110 to 115 feet below the Garrison Creek bed. If this interval continues to increase to the north it is possible that the Knoop bed may correlate with the Wolf Creek coal bed, which crops out near river level at the site of Mannhaven.

Hancock bed

In the bluffs on the east side of the Missouri River in secs. 26 and 35, T. 145N., R. 84W., are numerous abandoned adits and small pits in a bed that appears to be 6 to 9 feet thick. The bed could not be traced beyond these two sections. One of the old adits in the northwest corner of sec. 35 was known as the Hancock Mine, and from this the bed takes its name. The Hancock bed is 150 to 160 feet below the Stanton bed, which crops out higher in the bluffs. If the 85 to 95 foot interval between the Stanton and Knoop beds on the west side of the Missouri River is correct, the Hancock bed is probably not the equivalent of the Knoop bed across the river. If these two beds do not correlate, then the Knoop bed does not persist as far east as the east side of the Missouri River trench in the southern part of the Stanton quadrangle.

Local bed 50 feet above the Stanton bed

In the high hills north of the Missouri River trench in the south-eastern part of the Stanton quadrangle is a lignite bed 2 to 3 feet thick and 50 to 55 feet above the Stanton bed. This bed could not be traced out of this part of the Knife River area and could not be correlated with any other bed.

Garrison area

Three coal beds have been mapped in the northern part of the Stanton quadrangle near Garrison Dam. Two of these, the Wolf Creek and Garrison Creek beds, can be traced northward into the Minot area where they were named and mapped by Andrews (1939, pp. 70-72).

Wolf Creek bed

In the northern part of the Stanton quadrangle, the Wolf Creek coal bed lies at or slightly below the altitude of the Missouri River, and the only natural outcrop of this bed is in the cutbank of the river about one mile south of the former town of Mannhaven. The only other exposures of this bed in the area are in the abandoned mine at Mannhaven and in the excavations at Garrison Dam. The bed at Mannhaven described by Wilder (1905, p. 37) and Smith (1908, p. 23) is the Wolf Creek coal bed. Excavations on the western side of the Missouri River at Garrison Dam show that the Wolf Creek coal bed consists of two beds each 5 to 6 feet thick and separated by several feet of shaly clay. The upper split is the one that was formerly mined at Mannhaven. On the east side of the Missouri River excavations and drill holes show that the two splits come together to form one bed about 11 feet thick with only a minor shale parting of 1 to 2 inches in the middle. Northward the two splits of the bed diverge again and near the mouth of Wolf Creek in the Minot area are about 20 feet apart. Andrews (1939, pp. 69-70) called the upper split the Wolf Creek coal bed and the lower split a local coal bed which is 23 feet below the Wolf Creek bed.

Smith (1908) suggested that the Wolf Creek and the Hancock beds were probably one and the same; but inasmuch as several miles separate the known outcrops of these beds and inasmuch as it is known that beds 8 to 10 feet thick can pinch out in less than half a mile, all that can be safely said is that the two beds appear to be near the same stratigraphic horizon.

Garrison Creek bed

The Garrison Creek bed can be traced from the type locality in the Minot area south into the Knife River area. In the Stanton quadrangle the Garrison Creek bed is exposed in the west abutment of Garrison Dam, where it consists of two beds 3.5 and 2.2 feet thick, separated by nearly 3 feet of gray clay. Traced to the south the interval between the beds increases until, at locality 393, sec. 24, T. 146N., R. 85W., they are about 15 feet apart. South of this locality both beds thin rapidly and apparently pinch out before reaching the northern boundary of T. 145N., R. 84W. On the east side of the Missouri River near Garrison Dam the splits of the Garrison Creek are much closer together and the shale parting is a few inches to 2 feet thick. The Garrison Creek bed could not be traced south of sec. 22, T. 146N., R. 84W.

Kruckenberg bed

The Kruckenberg was named for exposures on the Kruckenberg farm in sec. 2, T. 146N., R. 85W. It is about 50 feet above the Garrison Creek bed and was mapped on both sides of the Missouri River trench in the northern part of the Stanton quadrangle. West of the river the bed is 2 to 2½ feet thick; east of the river, 3 to 4 feet thick. It could not be traced north of the Knife River area.

Possible thick local bed

In the summer of 1949 numerous water wells were drilled in the northern and eastern parts of the Knife River area. Two of those wells apparently penetrated a very thick coal bed. One, in the NW¼, sec. 2, T. 146N., R. 85W. reported a lignite bed 36 feet thick about 60 feet below the Garrison Creek bed. The other well, about 1/2 mile north in the Garrison quadrangle in sec. 35, T. 147N., R. 85W. reported about 14 feet of coal at the same horizon. Two miles to the east in secs. 1 and 12, T. 146N., R. 85W., the approximate stratigraphic horizon of this thick lignite bed is marked only by two to three feet of brown carbonaceous shale. Thus if the well logs are reasonably accurate this very thick lignite bed pinches out in less than 2 miles.

Blackwater-Emmett area

In order to fill in a gap between the maps of the Fort Berthold Indian Reservation, the Minot area, and the six quadrangles of the Knife River area, the maps of the Beulah and Hazen quadrangles were extended north to include the southeast corner of the Blackwater and the southern edge of the Emmett quadrangles. This added area together with the northern parts of the Beulah and Hazen quadrangles will be called for convenience the Blackwater-Emmett area. Several coal beds, including the Beulah-Zap bed were mapped in this area. In the western part of the Blackwater-Emmett area, the eastern end of the Fort Berthold Indian Reservation is underlain by three coal beds, the Beulah-Zap bed (bed "EE" of Bauer and Herold), and beds "CC" and "DD". The two latter beds were originally mapped by Bauer and Herold and the current mapping is in essential agreement with their earlier work.

Three beds of coal, the Garrison Creek bed, a local bed, and the Beulah-Zap bed, were mapped in the eastern part of the Blackwater-Emmett area. Of these only the Beulah-Zap beds correlate with the beds of the Fort Berthold Indian Reservation.

Bed "CC"

Bed "CC" is 125 to 140 feet below the Beulah-Zap bed and can be traced intermittently across most of the northwest corner of the Beulah quadrangle. It is 5 to 6 feet thick and appears to be of uniformly good quality. Many of the small pits in which Bauer and Herold were able to measure sections of this bed are now filled in and grassed over, so that the information on this bed is more complete in their older report than in this report. East of the edge of the Indian Reservation in the Beulah quadrangle is a zone about 4 miles long in which there are few or no bedrock outcrops. Bed "CC" apparently does not persist across this area and it could not be identified in the northeastern part of the Beulah quadrangle.

Bed "DD"

In the northern part of the Beulah quadrangle Bauer and Herold have apparently mapped two different lignites as bed "DD". In the center of sec. 12, T. 146N., R. 89W. they found some blocks of lignite in a swampy area and correlated this with their bed "DD" farther to the northwest (1921, p. 170). This locality (which is not shown on the Beulah quadrangle) is only about 50 feet below the clinker of the Beulah-Zap bed, whereas in T. 146N., R. 88W., the bed mapped "DD" is 80 to 90 feet below the Beulah-Zap bed. It is this lower bed that has been shown as "DD" on the Beulah quadrangle.

Garrison Creek bed

The Garrison Creek bed was traced by Andrews between Garrison and the Blackwater-Emmett area. In the southwest corner of the Emmett quadrangle it consists at locality 331 of two beds of coal 4.3 and 2.5 feet thick separated by 1.5 feet of gray clay. Traced to the west both parts of the bed thin, and at locality 327 in the southeast corner of the Blackwater quadrangle the Garrison Creek bed consists of two beds each less than 2 feet thick separated by 10 to 12 feet of clay. The bed continues to thin to the west and pinches out altogether in sec. 32, T. 147N., R. 87W. The Garrison Creek bed in the Blackwater-Emmett area is 160 to 165 feet below the Beulah-Zap bed, or about 20 to 30 feet below the stratigraphic horizon of Bed "CC" in the Fort Berthold Reservation.

Local bed 110 feet above Garrison Creek bed

In the eastern part of the Blackwater-Emmett area is a local bed, 2 to 3½ feet thick, 45 to 50 feet below the Beulah-Zap bed, and 110 to 115 feet above the Garrison Creek bed. This bed could not be traced out of this small area, and is probably local.

Correlations with beds in adjoining coal fields

Four different surveys of coal beds meet in the Blackwater-Emmett area. These are: the maps of the Knife River area, Andrews' map of the Minot area (1939), Bauer and Herold's map of the Fort Berthold Indian Reservation south of the Missouri River (1921), and Pishel's map of the Fort Berthold Indian Reservation north of the Missouri River (1912). Correlation of the coal beds among these four surveys is difficult partly because some of the beds appear to pinch in this area and partly because Bauer and Herold made little attempt to correlate their mapping with that of Pishel. As a result of the mapping of the Knife River area, the following correlations seem probable:

Pishel identified 3 coal beds north of the Missouri River and called them 1A, 2, and 3. Of these, bed 1A probably consists of two different lignites. East of a large segment of a terrace that Pishel calls Armstrong Flats his bed 1A is the Garrison Creek bed and is about 160 feet below bed 2. West of Armstrong Flats, bed 1A is only 125 to 130 feet below bed 2 and is probably the equivalent of Bauer and Herold's bed "CC".

Pishel's bed 2 is the Beulah-Zap bed of the Knife River area, Bauer and Herold's bed "EE", and possibly Andrews' bed "B". Pishel's bed 3 has not been identified in any of the other areas.

Andrews' suggested that the Wolf Creek coal bed was Pishel's bed 1A, but this is incorrect. The Wolf Creek bed goes below the level of the Missouri River just east of the Blackwater-Emmett area and does not crop out in either the Fort Berthold Indian Reservation or the Knife River area.

Andrews' Minter bed apparently does not persist southwest out of the Minot area and is not represented by any beds in the other areas.

Bauer and Herold's bed "DD" does not persist to the north or east and was not mapped by Pishel.

Mining and development

The mining of the lignite beds in the Knife River area probably started before the beginning of the 20th century when the early settlers dug coal for their own use. By about 1910 several small underground mines were in operation mining coal near Beulah and Zap, but the first large mine in the area seems to have been the Lucky Strike Mine at Zap, which was opened in June, 1918. This mine is now abandoned. By 1925 the old Beulah Coal Company (now the Knife River Coal Company) had abandoned its attempt to mine the beds below the level of the Knife

River at Beulah and had started work on the now large underground mine in the Beulah-Zap bed about 2 miles north of town. At about this same time the large strip mine southeast of Zap was started. The newest large mine in the area was Truax-Traer's Dakota Star Mine, about 5 miles north of Hazen. This mine, which is the largest producer in the area, was begun in 1944, and its production has made Mercer County the number one lignite-producing county of North Dakota and of the United States.

Table 3, which was compiled from the annual report of the coal mine inspector of North Dakota shows the production of the various mines in Mercer County for the year 1950. All of the mines listed in this table take their coal from the Beulah-Zap bed. The only mine active in recent years that produced from any other bed was the Kamin Mine south of Stanton, which mined the Stanton coal bed. This operation was abandoned in 1948. Some of the other beds in the area are mined privately for use by the individual ranchers and farmers.

All of the production from the numerous small mines in the Knife River area is purchased locally for domestic use. A small percentage of the output of the three large mines is bought by local consumers, but most of their production is for commercial users. The output of the Knife River Coal Company at Beulah is used largely in the power plant of the Montana-Dakota Utilities Company at Beulah. The output from Dakota Collieries' strip mine at Zap and the Dakota Star Mine near Hazen is shipped to Bismarck and to the larger cities of eastern North Dakota and Minnesota.

Recently the Bureau of Mines has conducted experiments in the storing of lignite excavated during the construction of the Garrison Dam. A pile of lignite dumped on the ground as a result of normal mining operations will rapidly weather and air slake to a fine black powder several feet into the pile. Also the inner part of the pile is apt to catch on fire by spontaneous combustion. The Bureau's experiments showed, however, that if the lignite is broken up into small lumps and is compacted with a sheep's foot roller every time one or two feet is added to the pile that the danger of spontaneous combustion is materially reduced.

The continued mining development of the thick lignite beds of North Dakota seems assured for some time to come. In addition to the present uses, which are almost sure to continue, it is likely that North Dakota lignite will soon be in demand for use in the manufacture of synthetic petroleum products.

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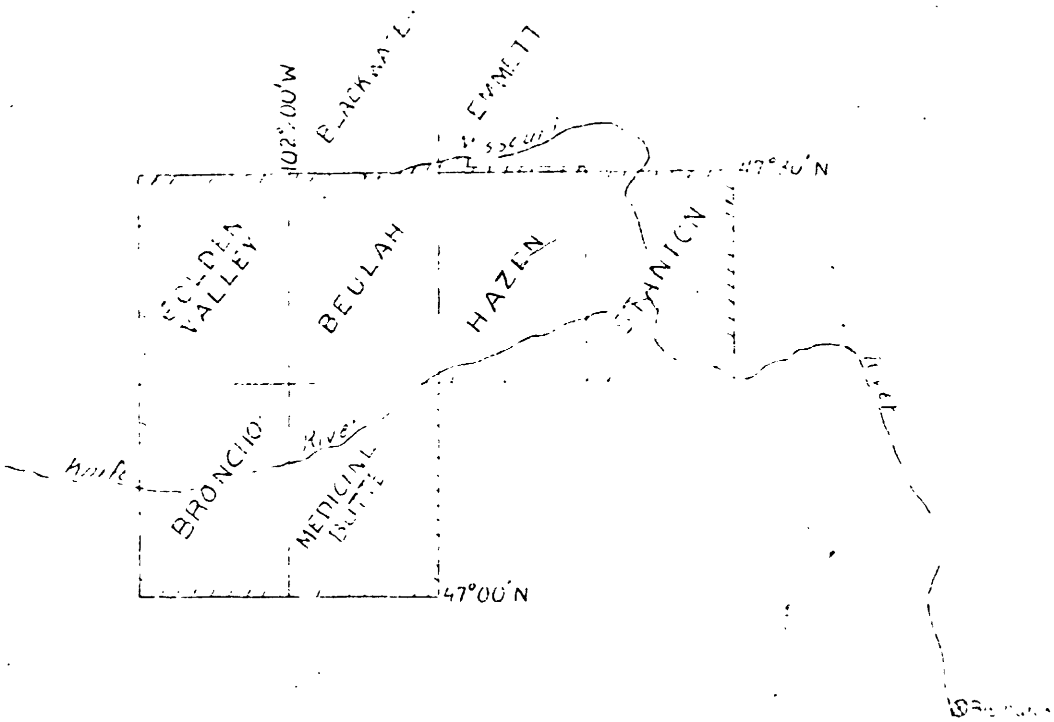


Fig. 2. Sketch map of Knife River area showing position of quadrangles.

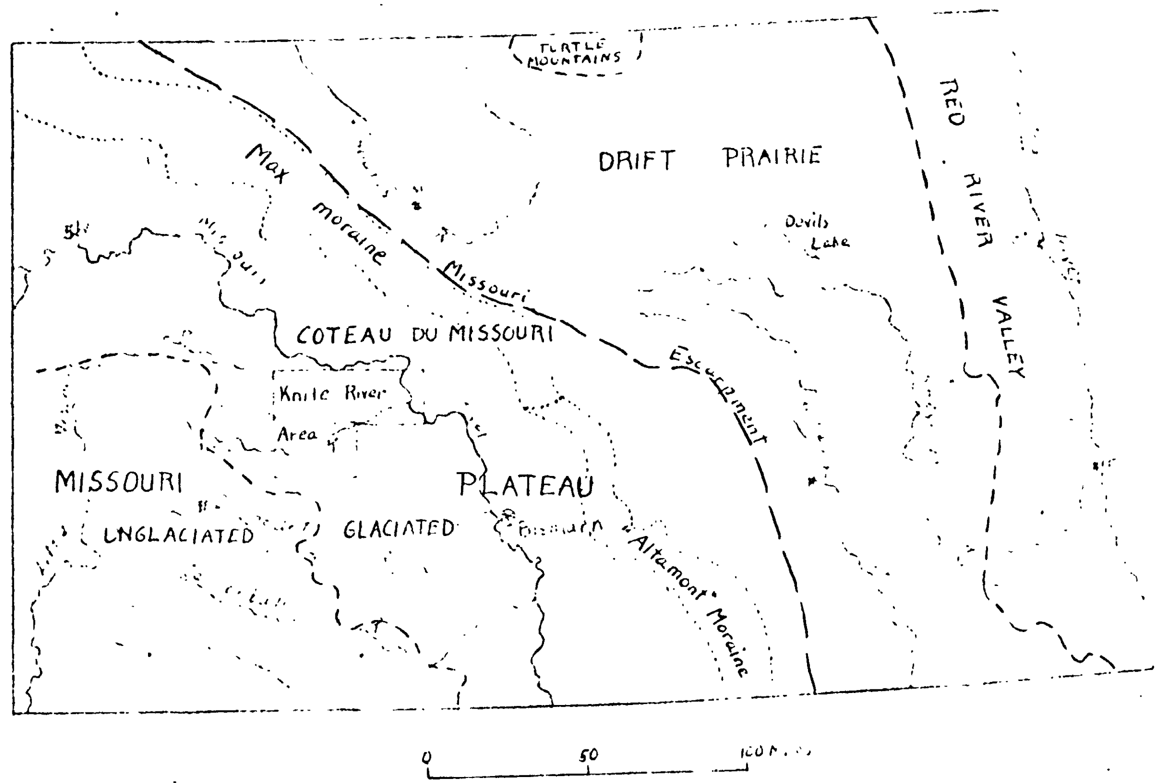


Fig. 3. Sketch map showing physiographic divi ions of North Dakota.

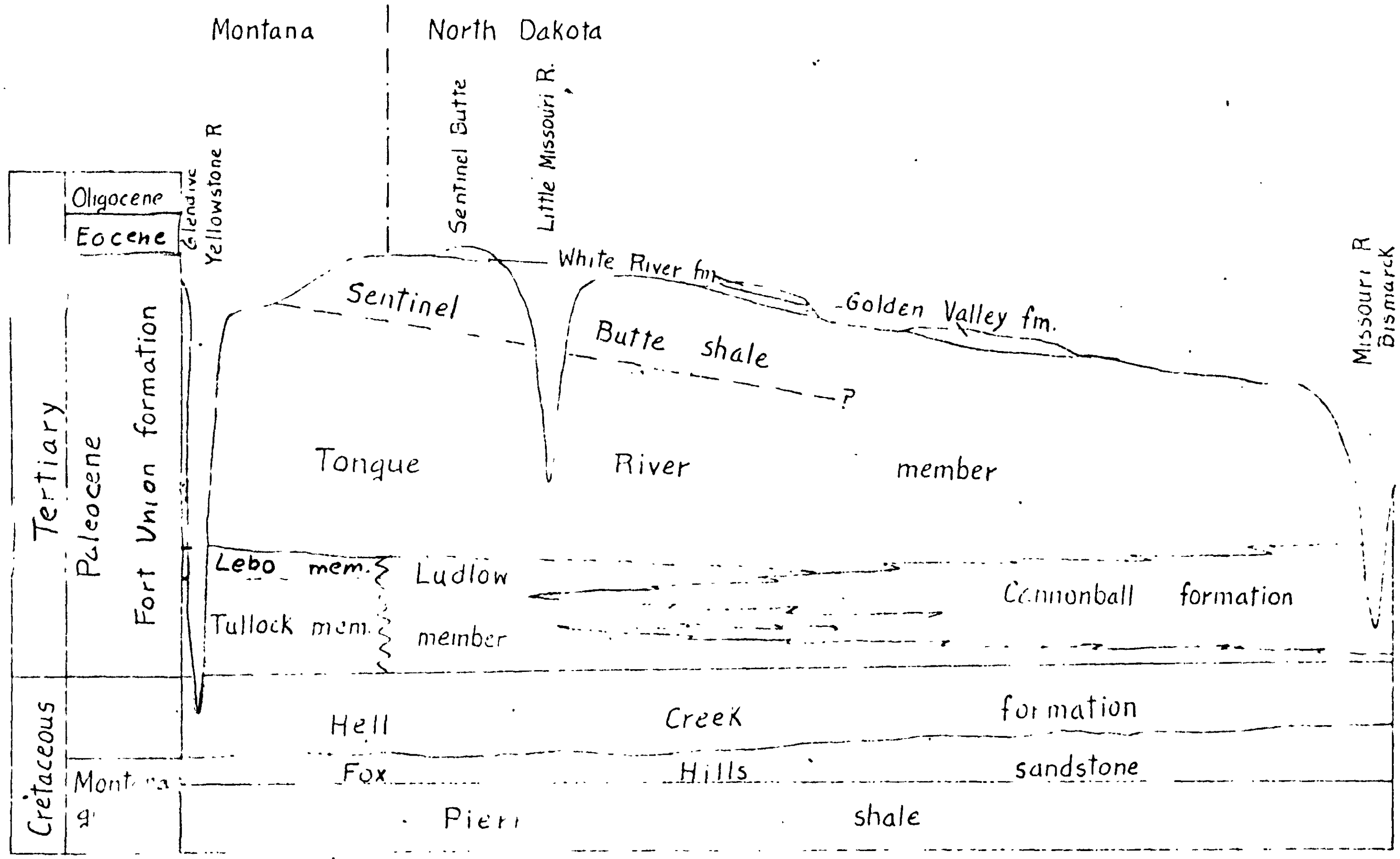
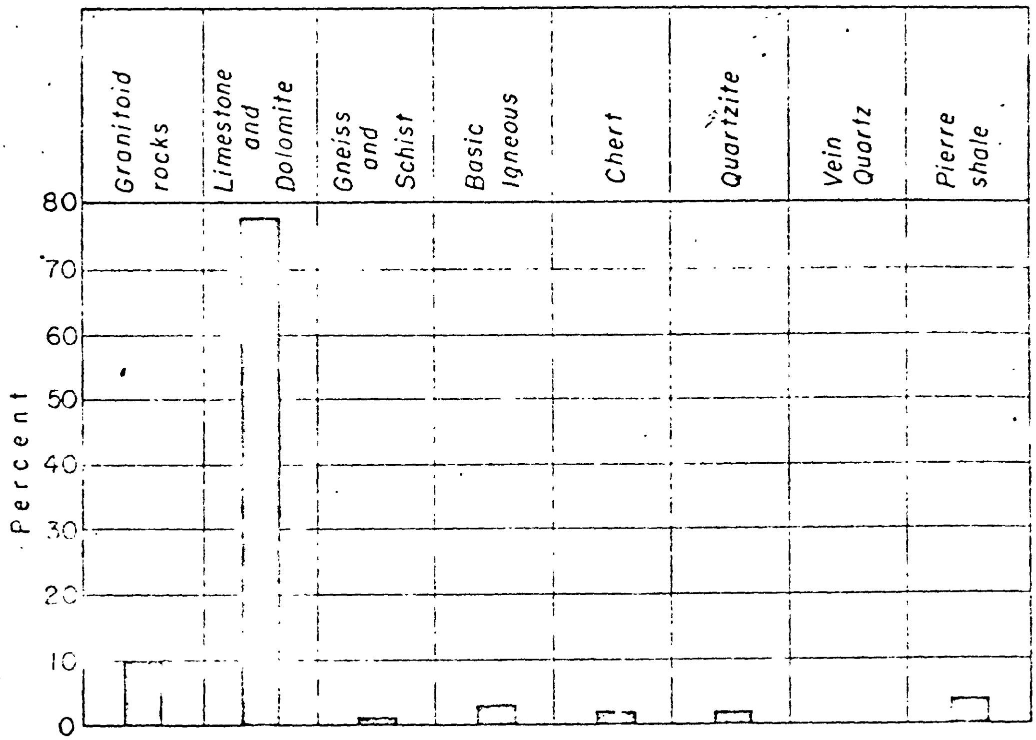


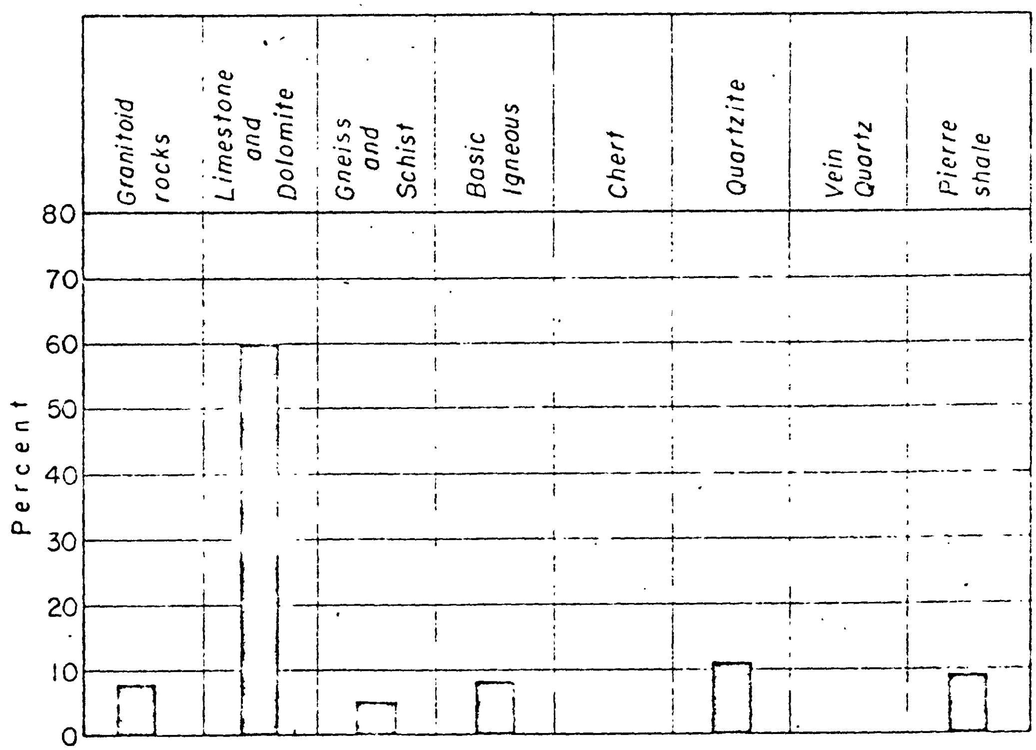
Fig. 5. Idealized stratigraphic section of Upper Cretaceous and Tertiary formations between Glendive, Montana and Bismarck, North Dakota.

Fig. 6. Graphs (on following 6 pages) show percentages of different types of erratic stones in till in the Knife River area. Stones larger than 6" and less than $\frac{1}{2}$" in diameter were excluded.

Fig. 6 continued

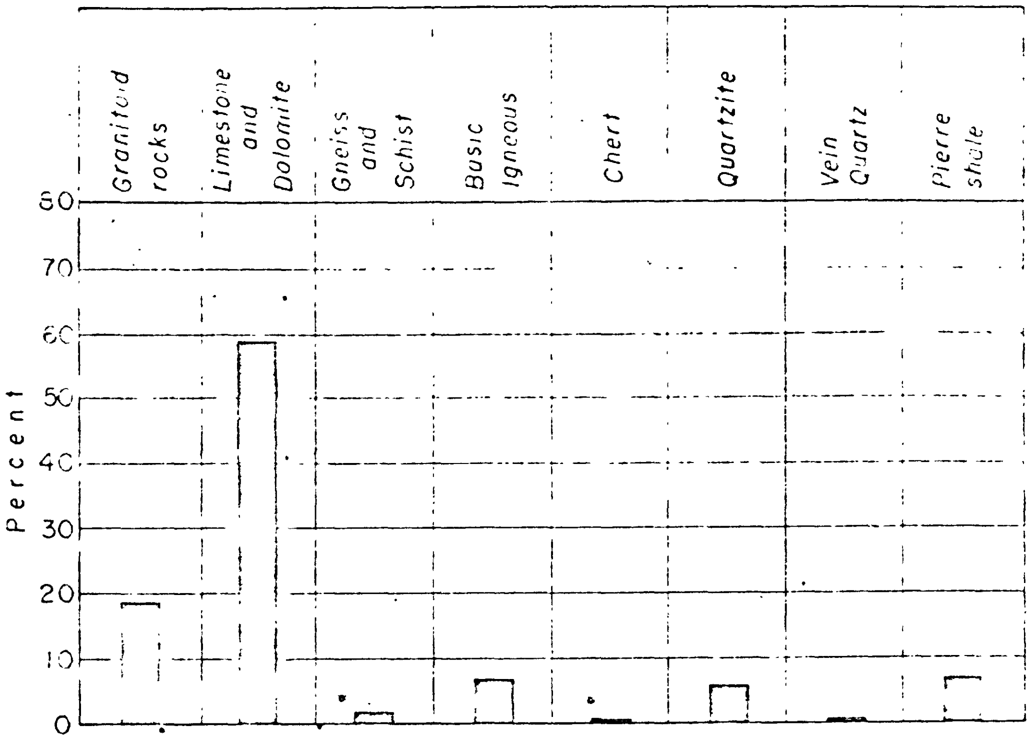


(1) NE¼, NE¼, sec. 28, T. 143 N., R. 89 W.

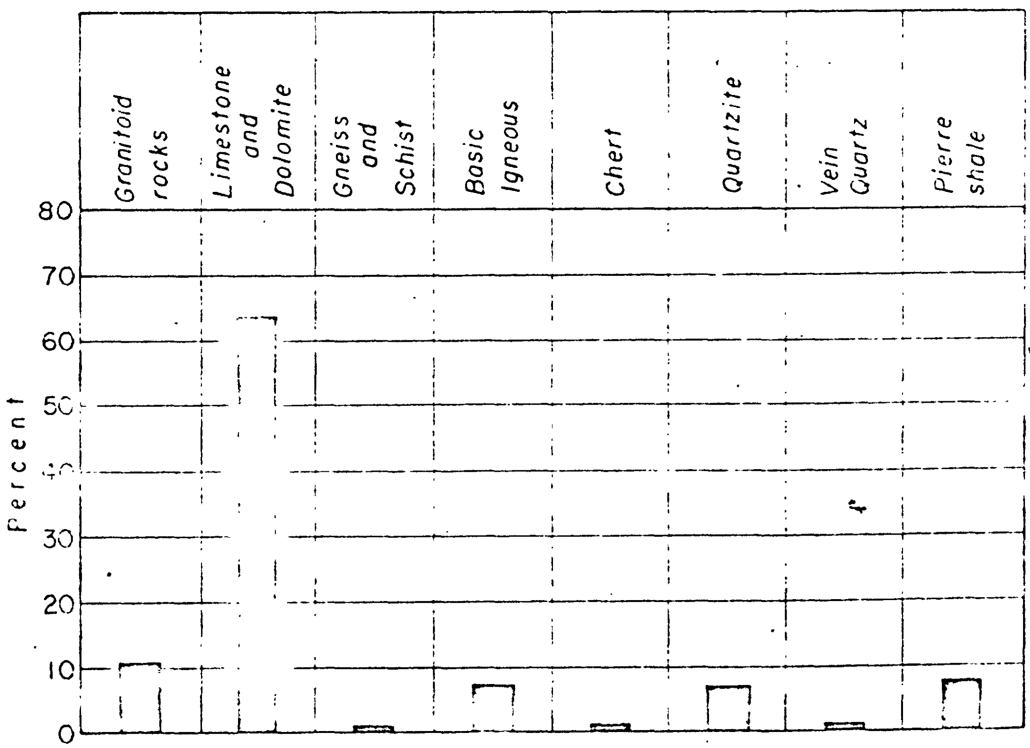


(2) SW¼, SW¼, sec. 22, T. 143 N., R. 90 W.

Fig. 6 continued

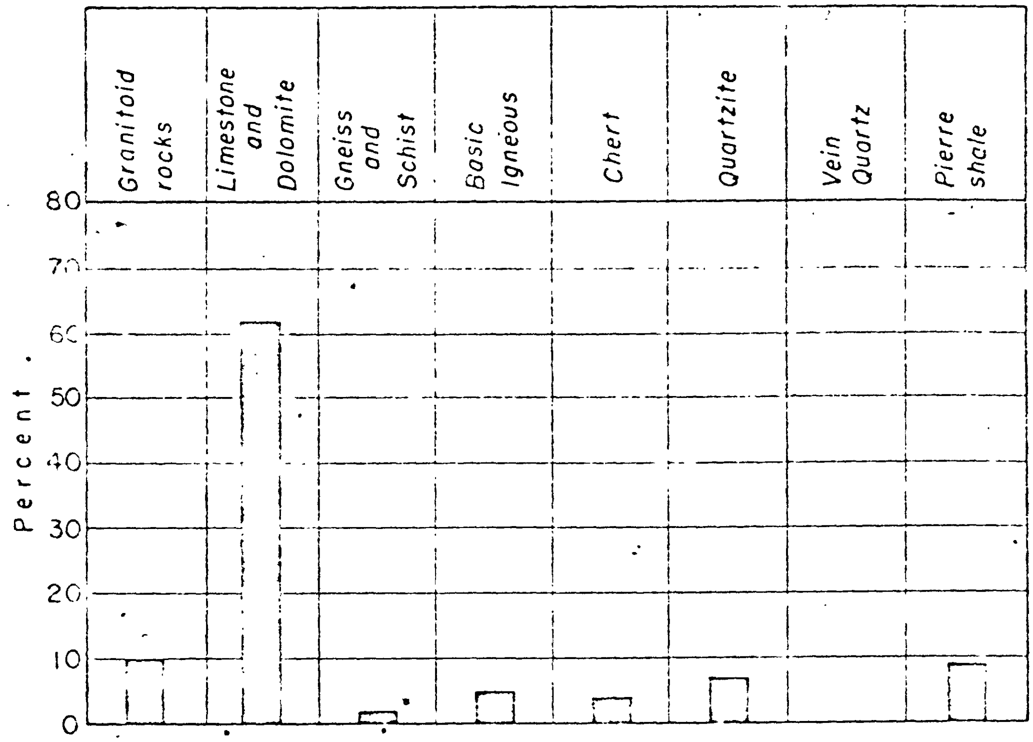


(3) NE¼, SE¼, sec. 5, T. 141 N., R. 91 W.

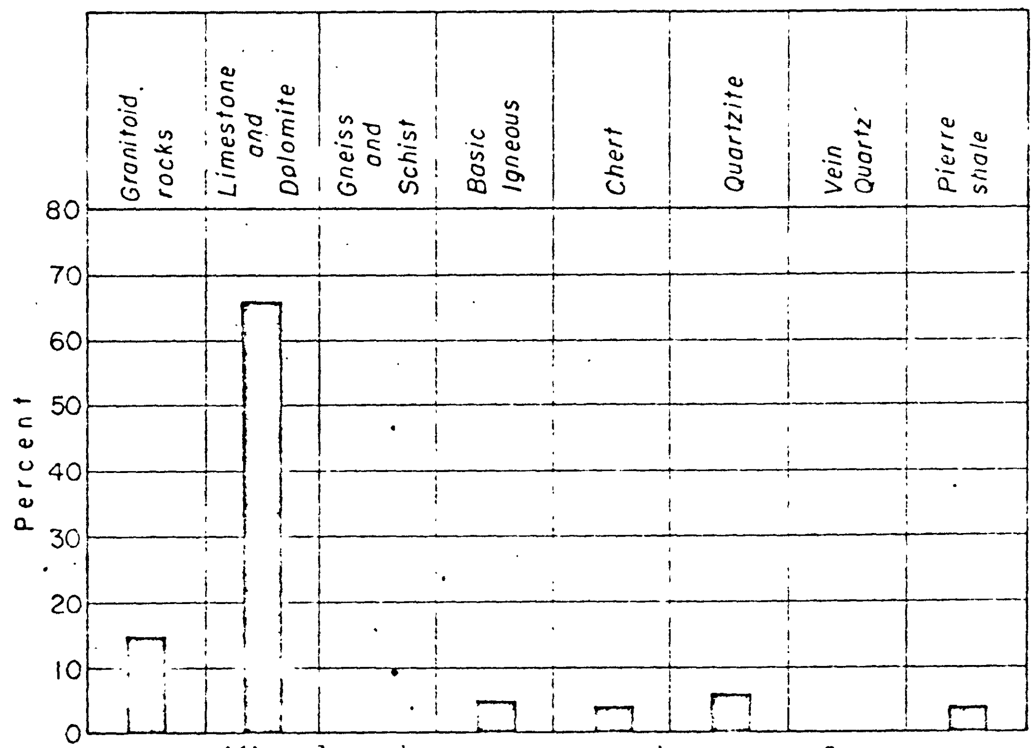


(4) NW¼, NW¼, sec. 25, T. 142 N., R. 91 W.

Fig. 6 continued

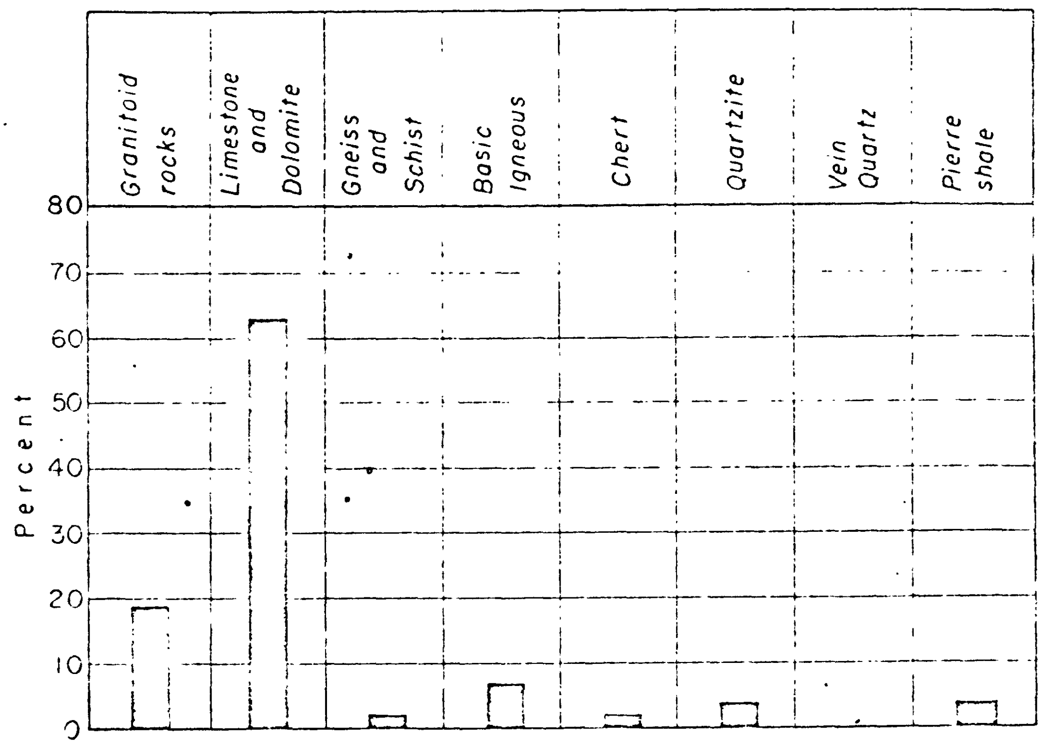


(5) NE¼, NE¼, sec. 30, T. 143 N., R. 90 W.

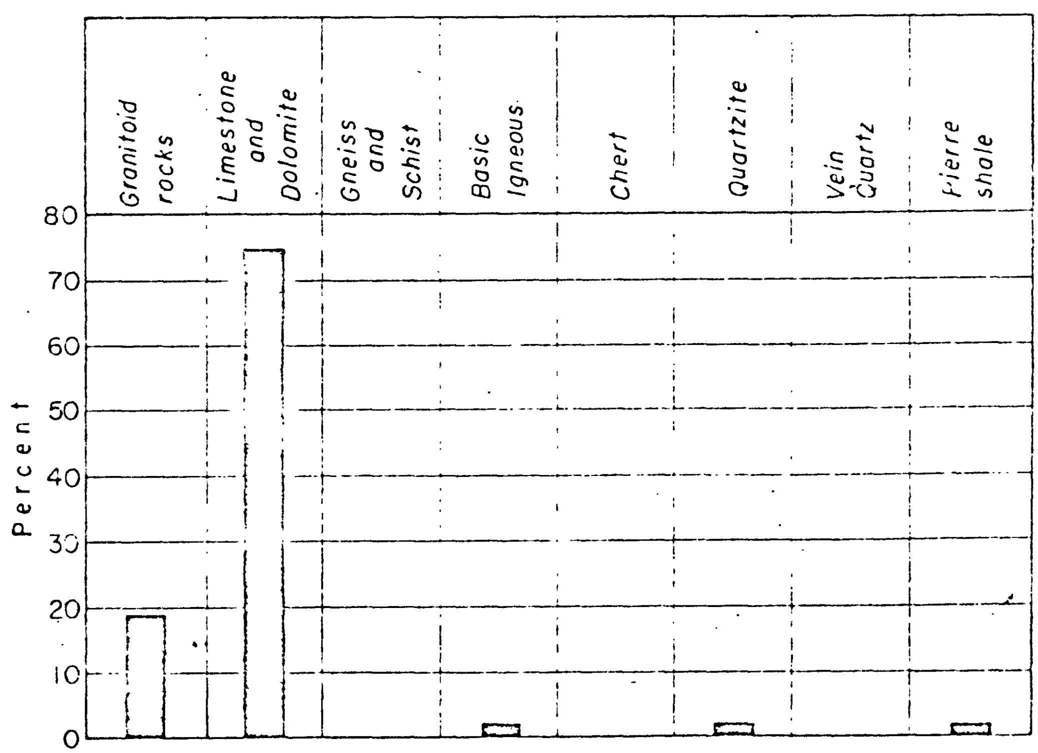


(6) SW¼, NW¼, sec. 12, T. 142 N., R. 89 W.

Fig. 6 continued

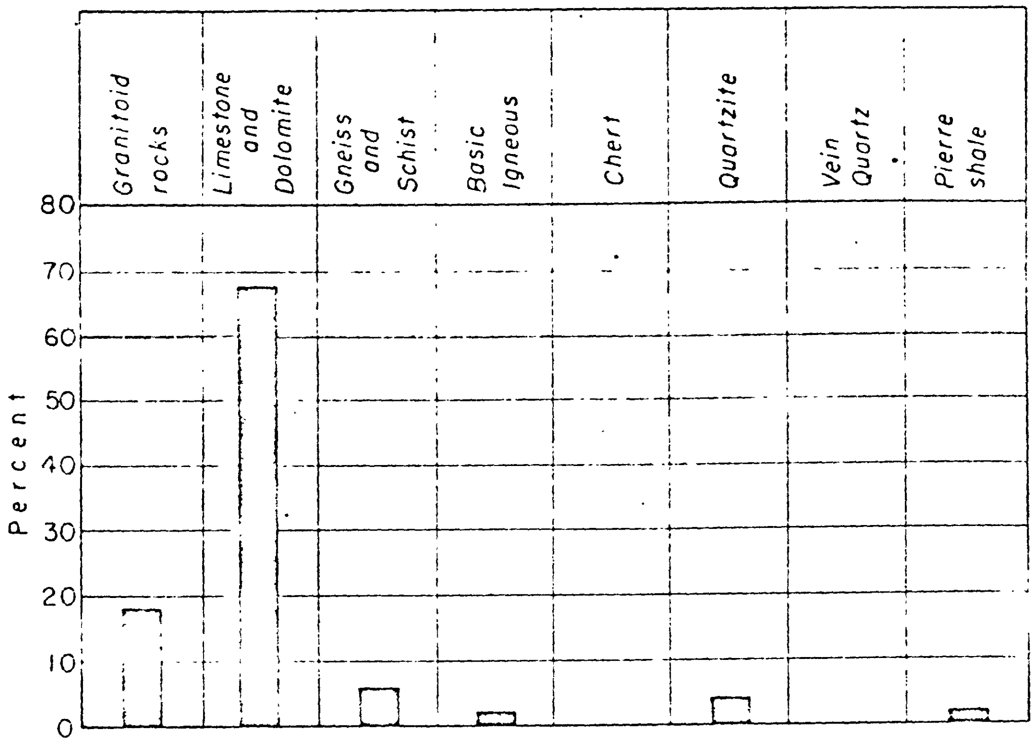


(7) SE¼, SW¼, sec. 8, T. 143 N., R. 88 W.

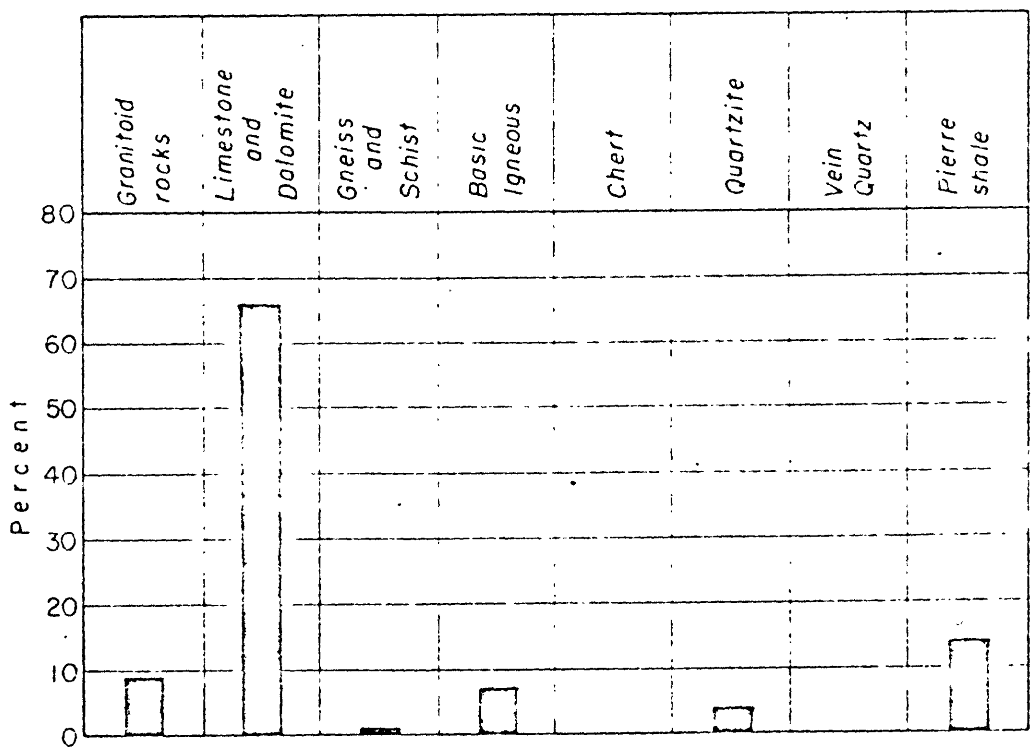


(8) SE¼, SW¼, sec. 15, T. 143 N., R. 88 W.

Fig. 6 continued

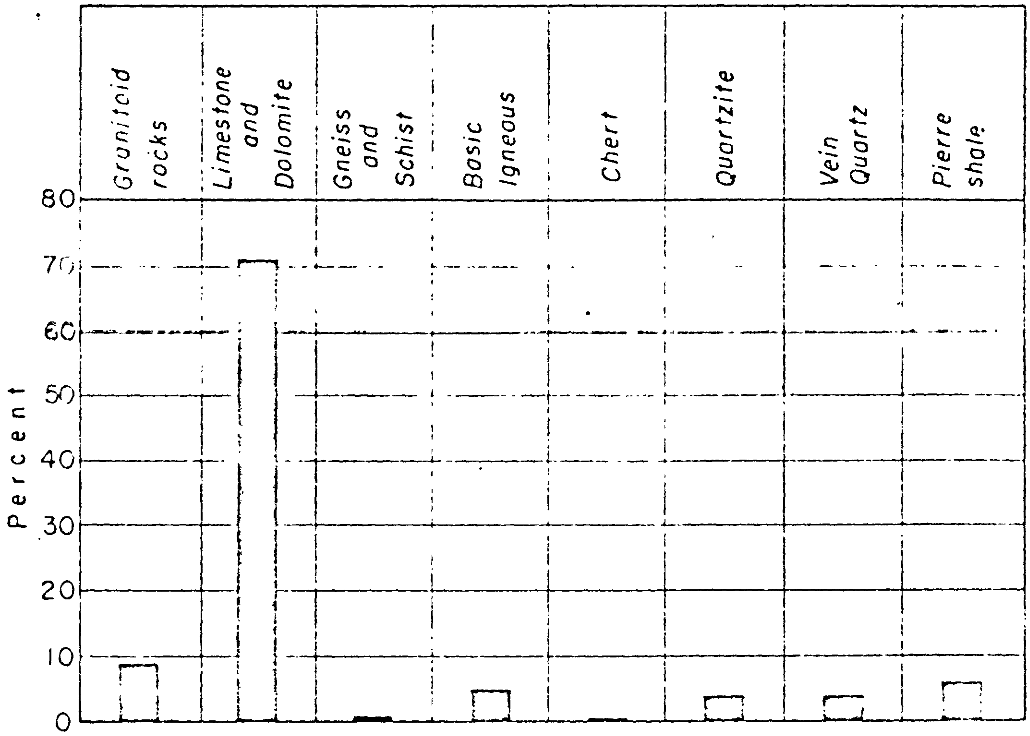


(9) NW$\frac{1}{4}$, SE$\frac{1}{4}$, sec. 11, T. 143 N., R. 88 W.



(10) SW$\frac{1}{4}$, SE$\frac{1}{4}$, sec. 6, T. 145 N., R. 88 W.

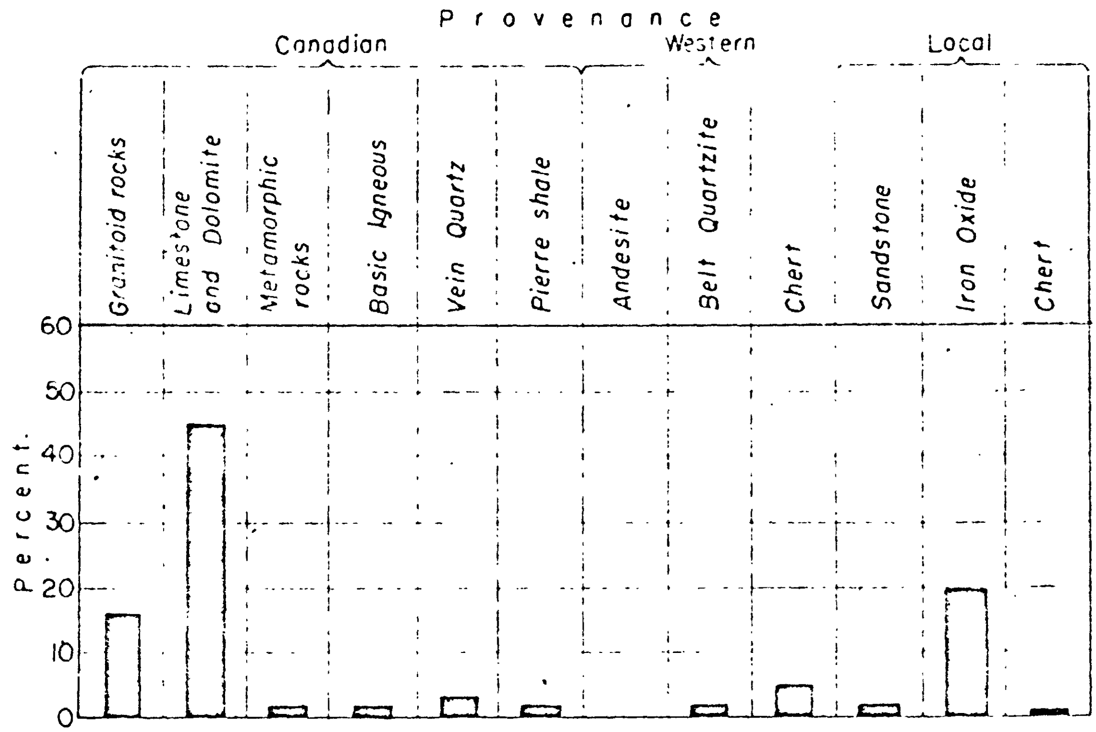
Fig. 6 continued



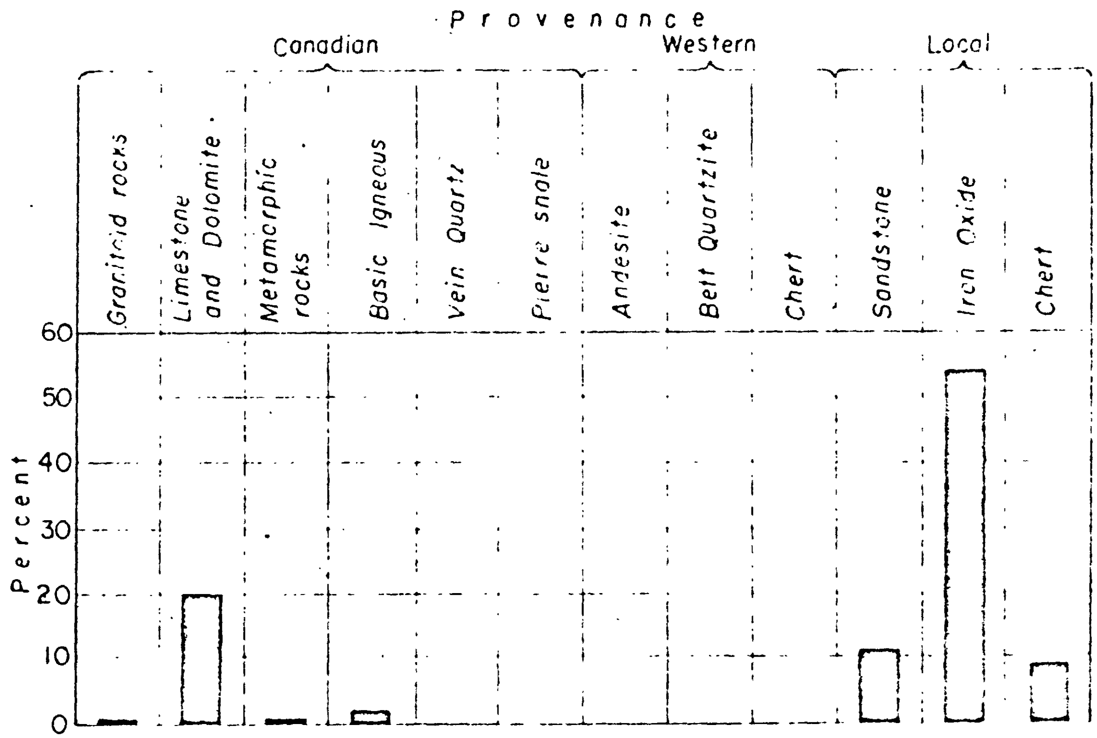
(11) NW$\frac{1}{4}$, NE$\frac{1}{4}$, sec. 13, T. 146 N., R. 86 W.

Fig. 7. Graphs (on following 6 pages) show percentages of various types of stones in the gravel deposits in White River [illegible]. Stones larger than 6" and smaller than $\frac{1}{4}$" in diameter were excluded from the counts.

Fig. 7 continued

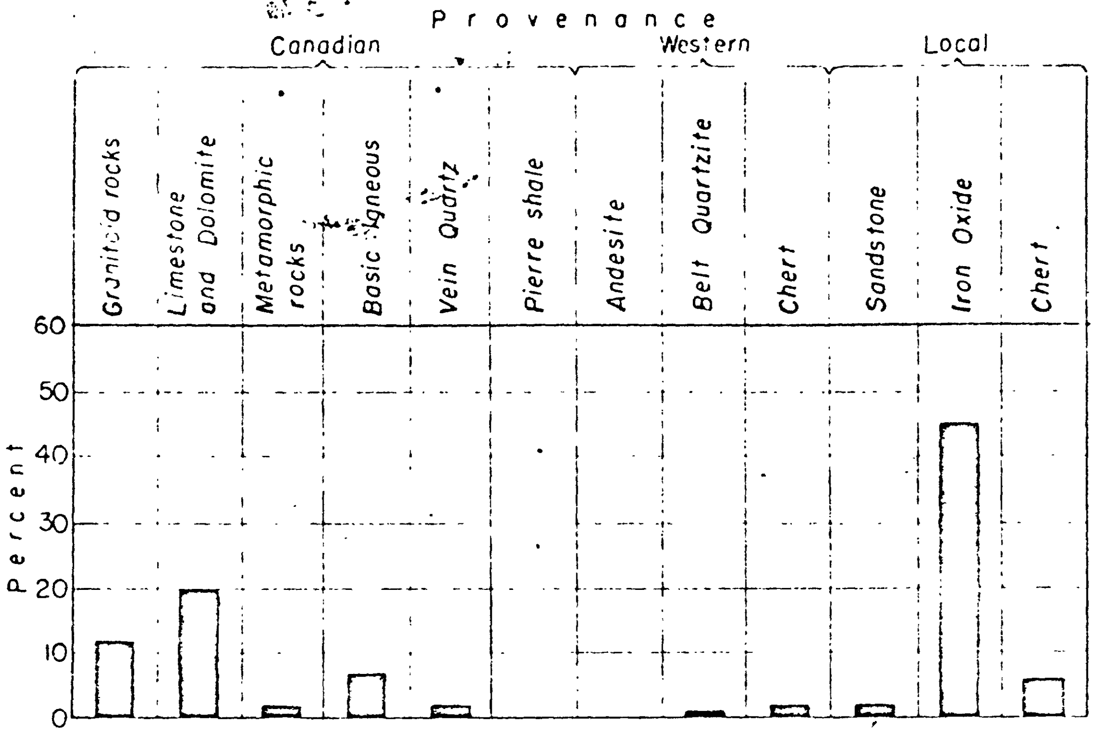


(1) Qsd$_1$; NE$\frac{1}{4}$, NW$\frac{1}{4}$, sec. 36, T. 144N., R. 88W.

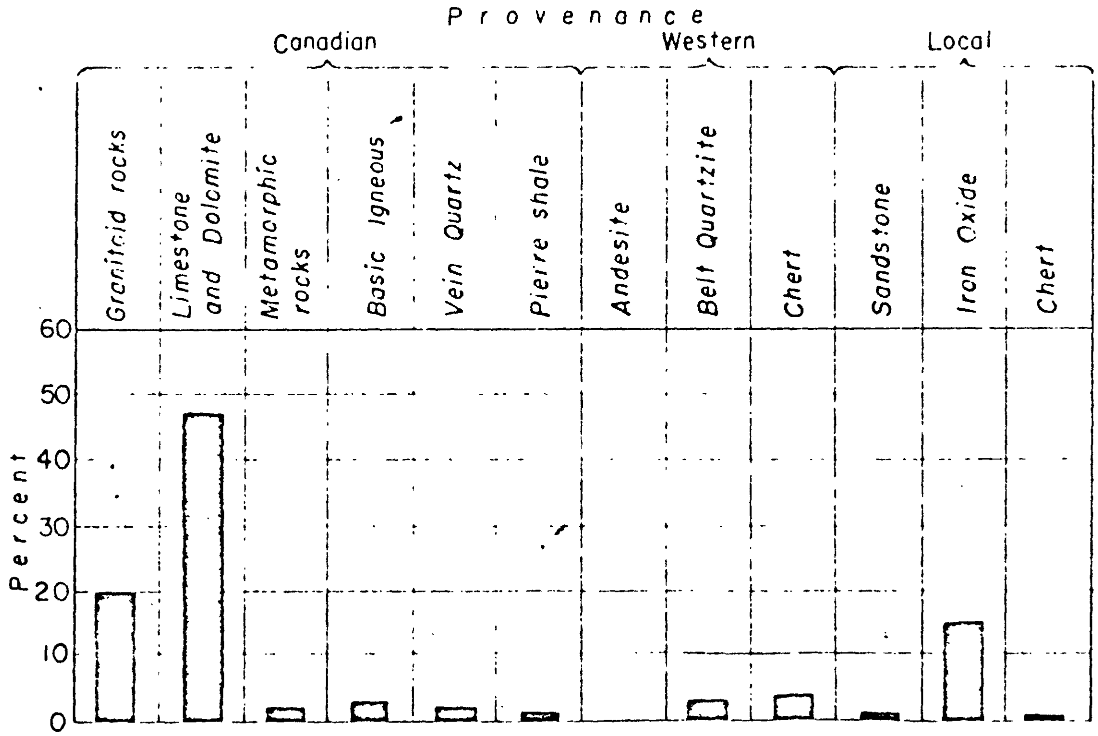


(2) Qtg; NW$\frac{1}{4}$, SW$\frac{1}{4}$, sec. 10, T. 142N., R. 91W.

Fig. 7 continued

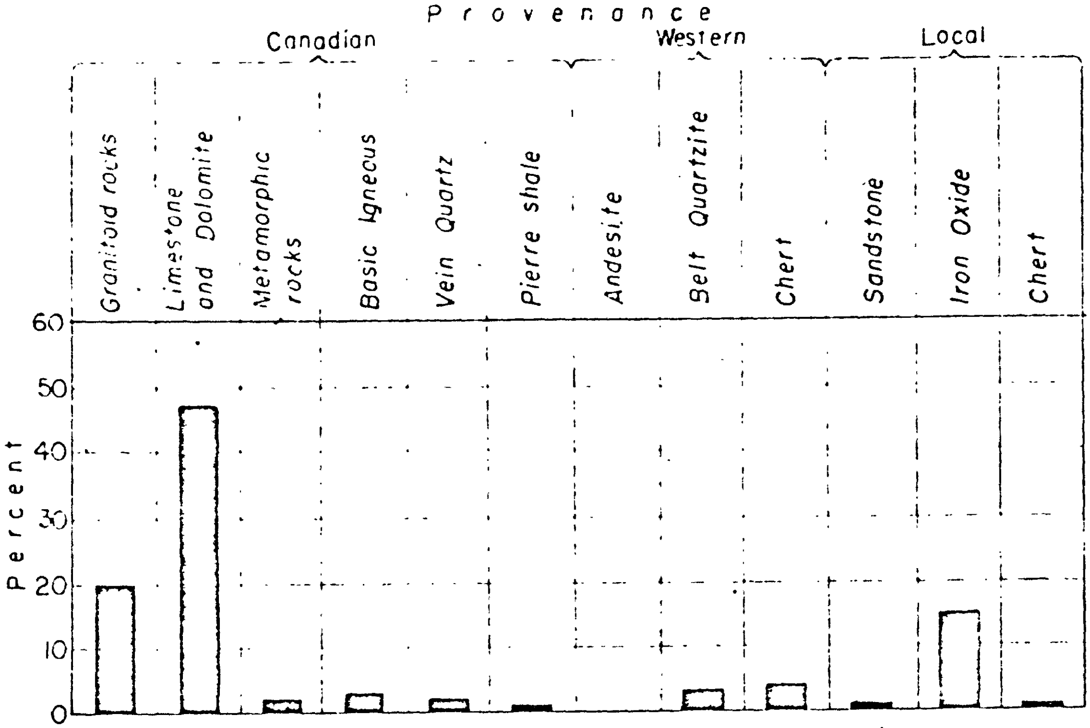


(3) Qsd_2; SW$\frac{1}{4}$, NW$\frac{1}{4}$, sec. 14, T. 144N., R. 89W.

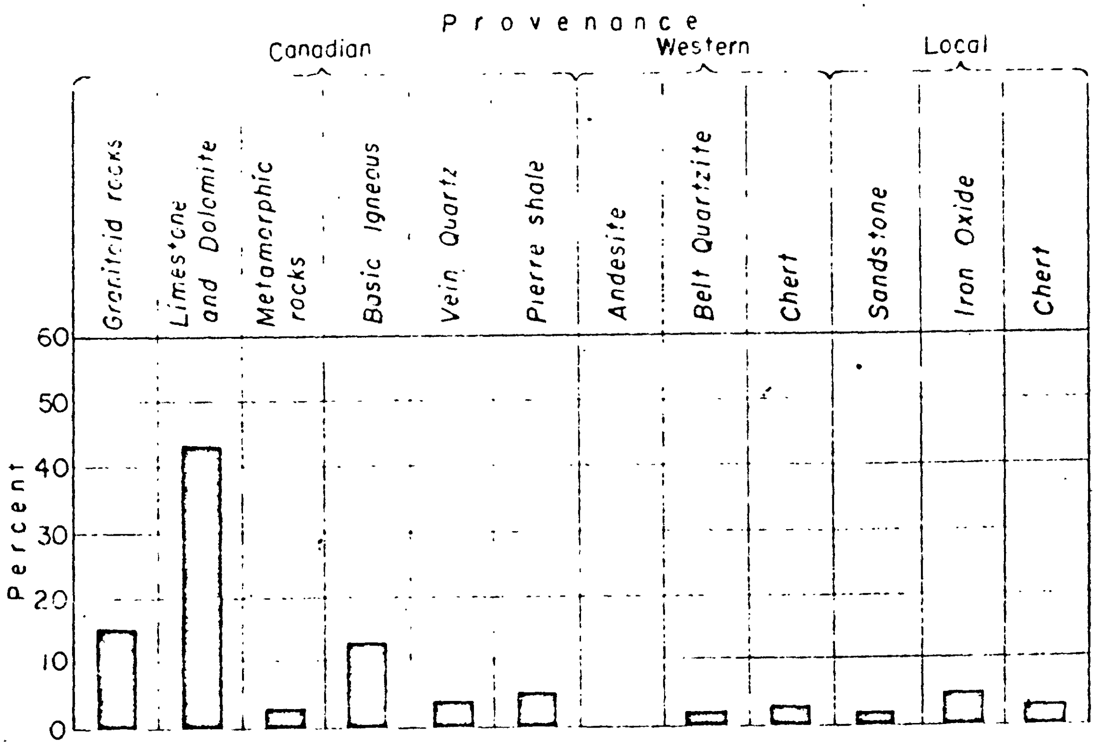


(4) Qsd_3; NW$\frac{1}{4}$, NW$\frac{1}{4}$, sec. 23, T. 143N., R. 88W.

Fig. 7 continued

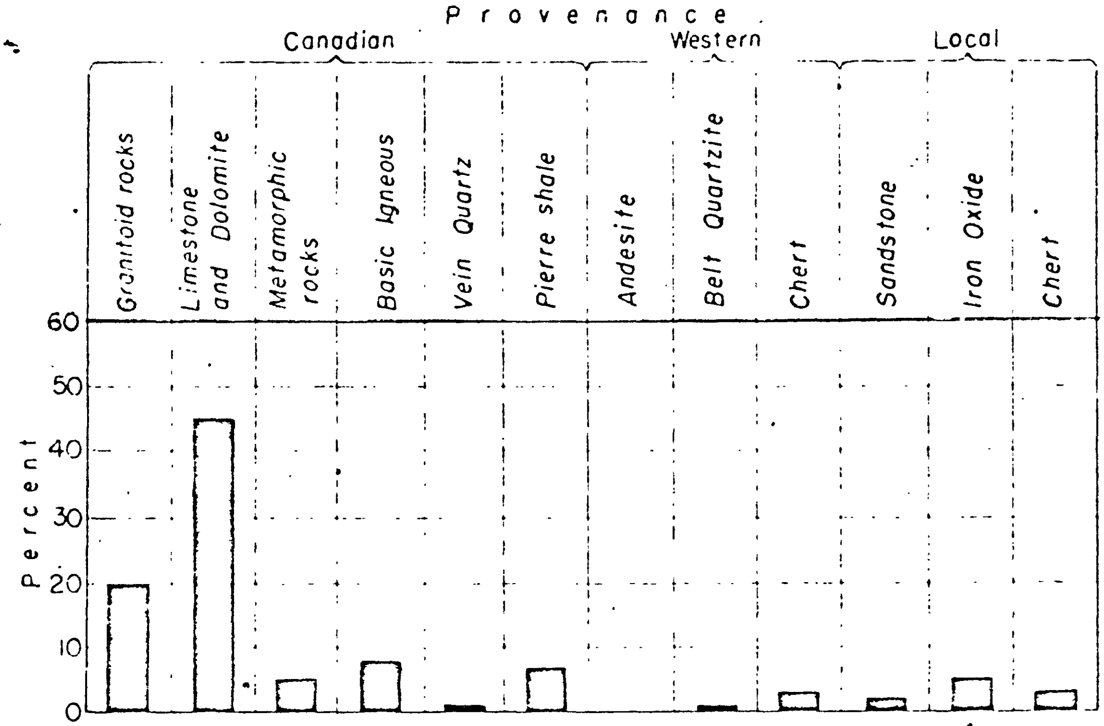


(5) Qsd_3; NW¼, NW¼, sec. 25, T. 144N., R. 88W.

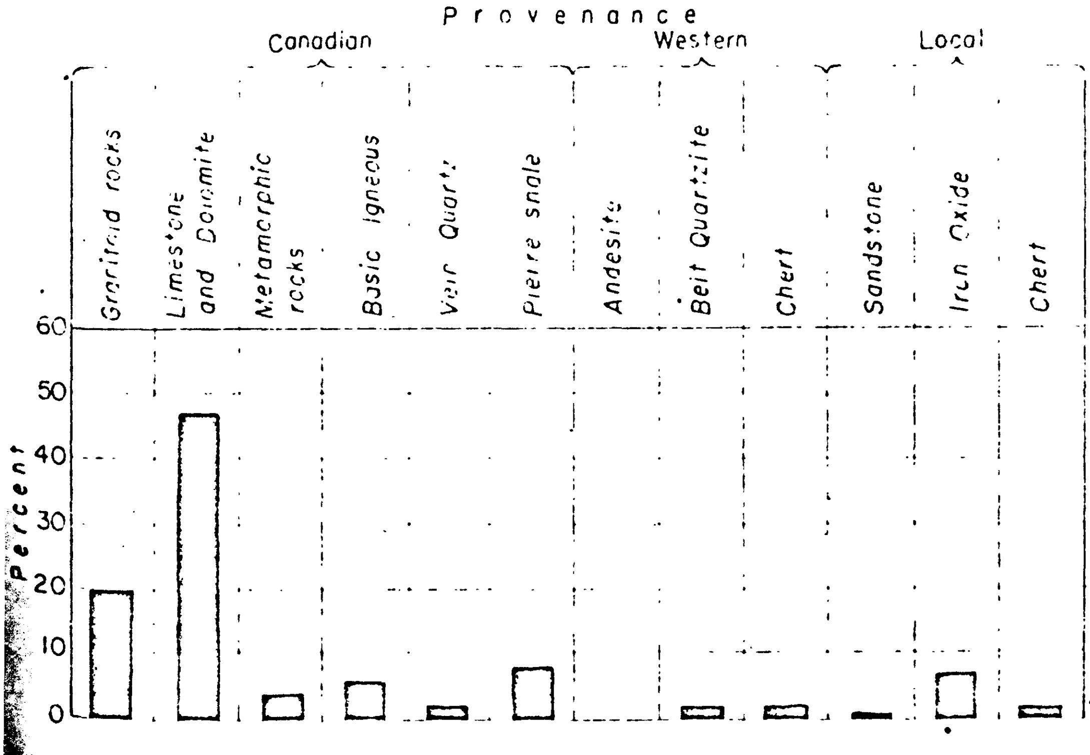


(6) Qsd_3; NW¼, SE¼, sec. 11, T. 144N., R. 87W.

Fig. 7 continued

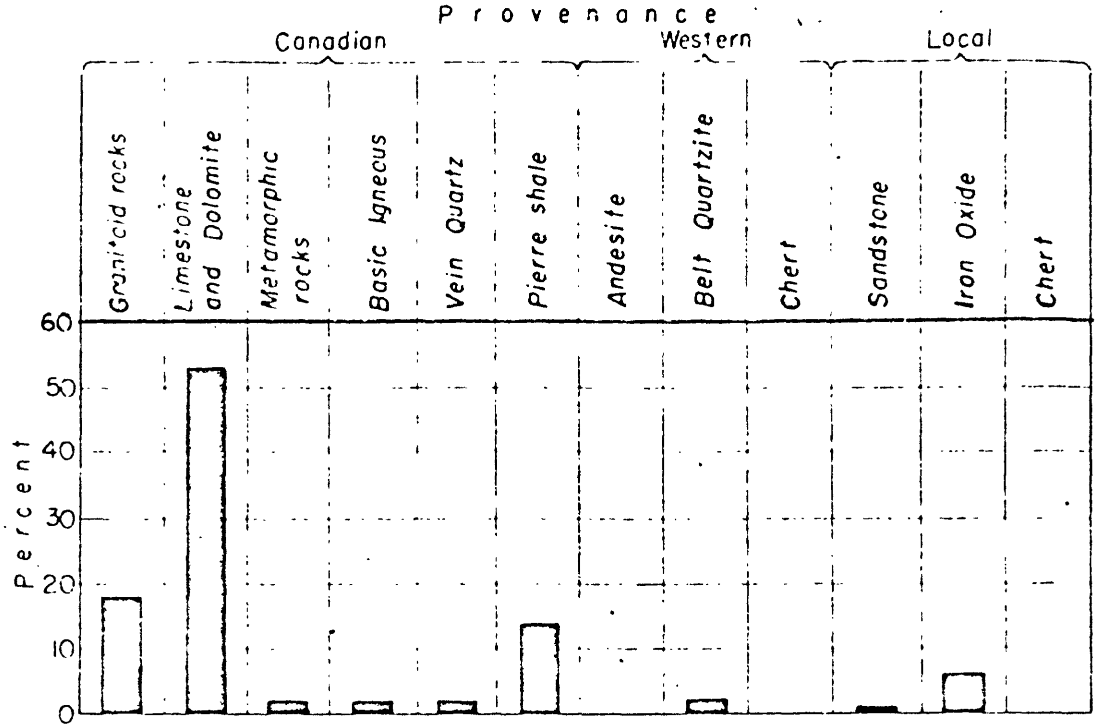


(7) Qsd$_3$; SE¼, NW¼, sec. 21, T. 146N., R. 84W.

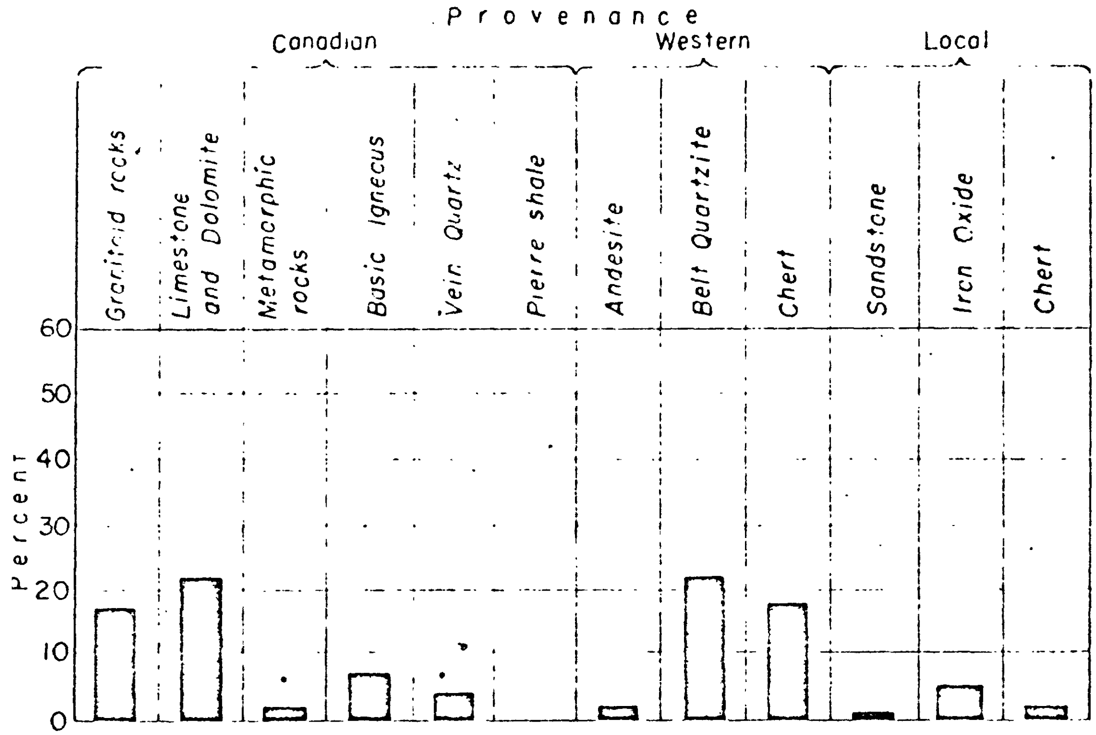


(8) Qwo; NE¼, NW¼, sec. 9, T. 145N., R. 85W.

Fig. 7 continued

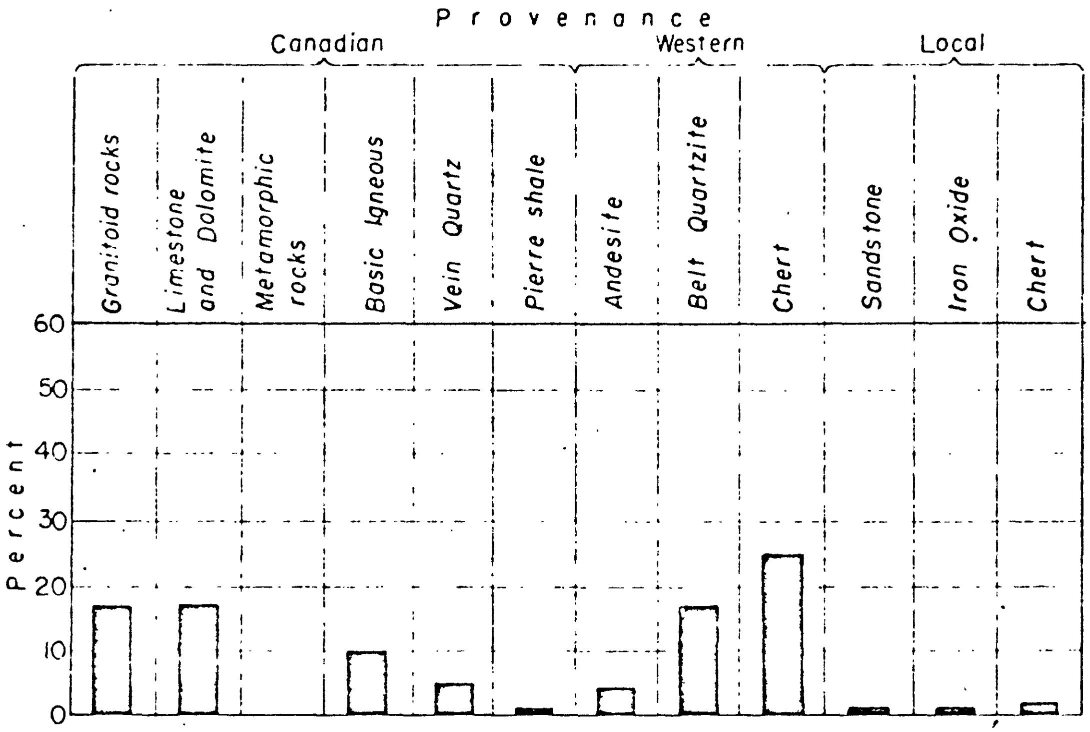


(9) Qic; SW¼, SW¼, sec. 1, T. 145N., R. 88W.



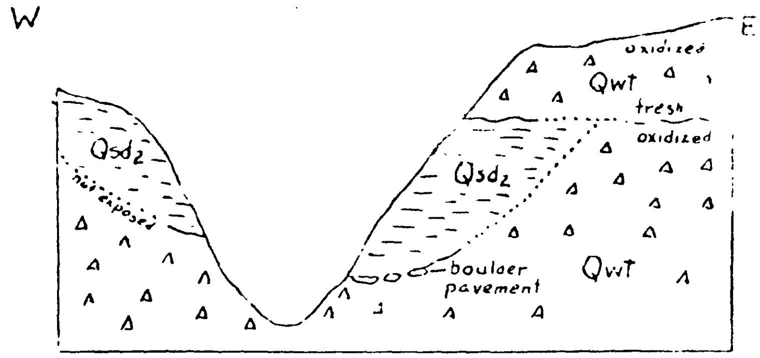
(10) Qmg; SW¼, SE¼, sec. 26, T. 144N., R. 84W.

Fig. 7 continued

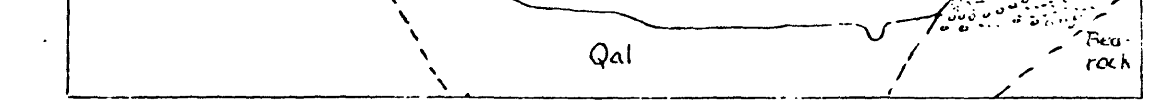


(11) Qmg; SW$\frac{1}{4}$, SW$\frac{1}{4}$, sec. 32, T. 147N., R. 84W.

Fig. 9



A. Cross section showing relations between Pleistocene deposits in NE1/4, NE1/4, sec. 18, T. 146N., R. 86W.



B. Idealized cross section of Knife River valley at west edge of Beulah.

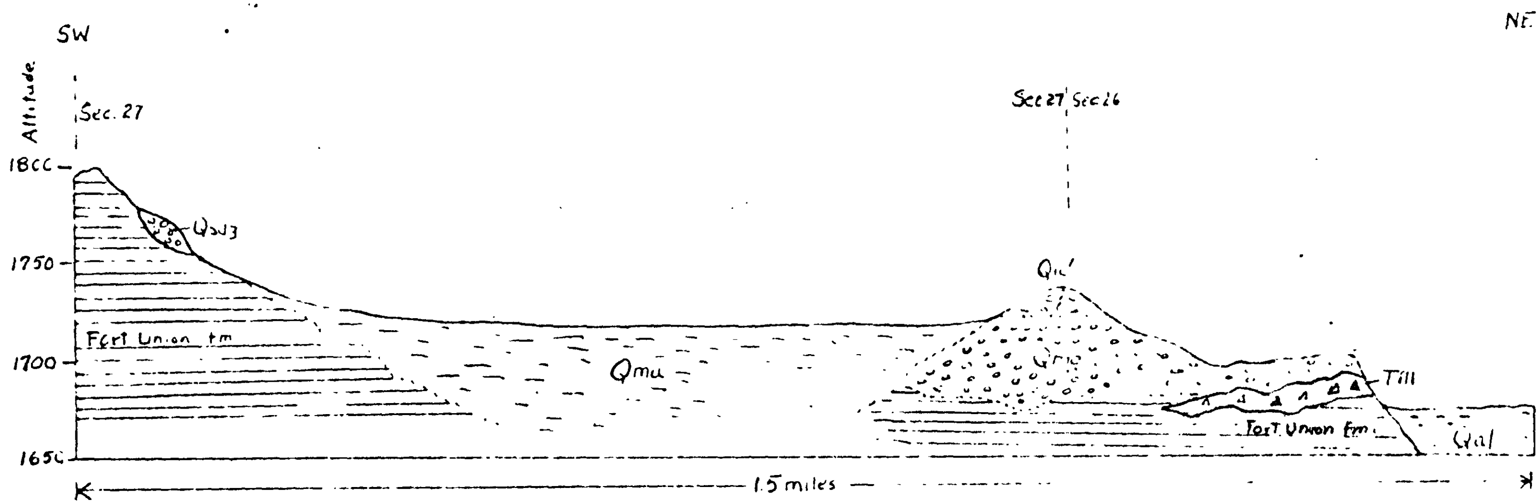


Fig. 10. Cross section of "40 foot terrace" of Missouri River about 1 mile northwest of Fort Clark, secs. 26 and 27, T. 144N., R. 84W., showing relations of Missouri River gravel (Qmg) to older Pleistocene deposits and to Recent alluvium (Qma) on the terrace.

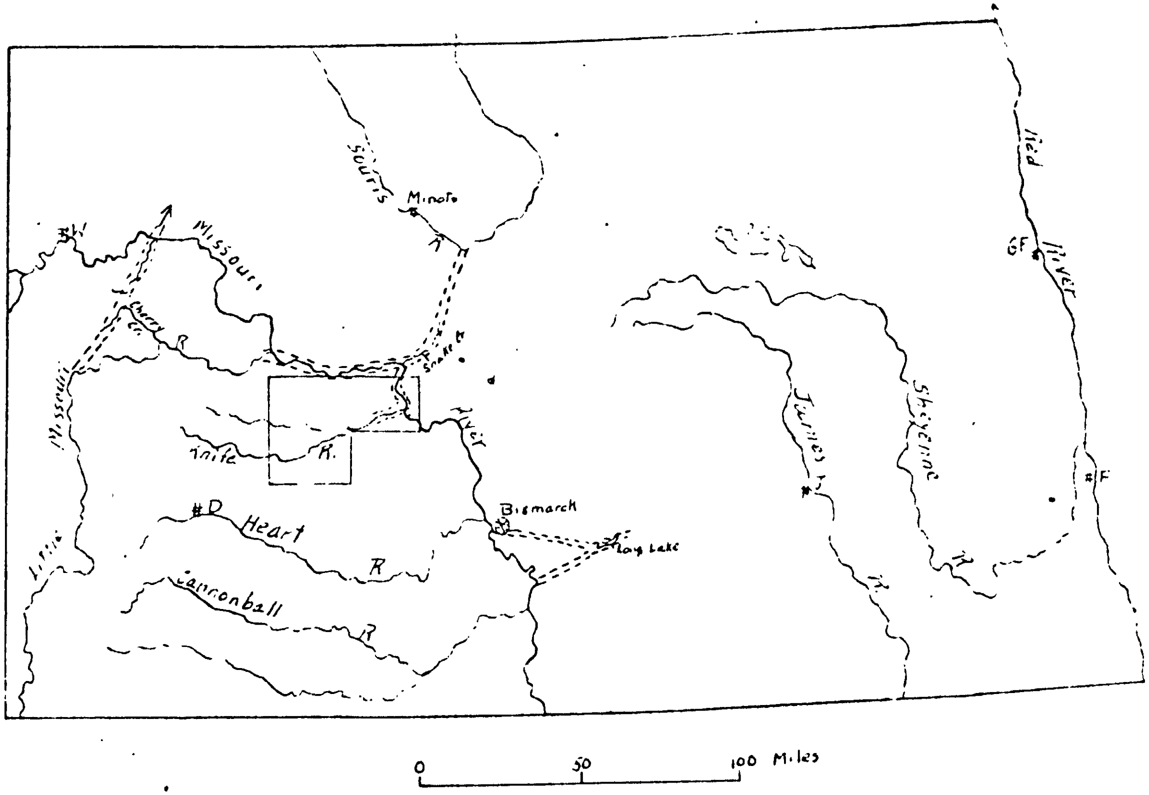


Fig. 11. Former drainage of North Dakota as inferred by Todd.

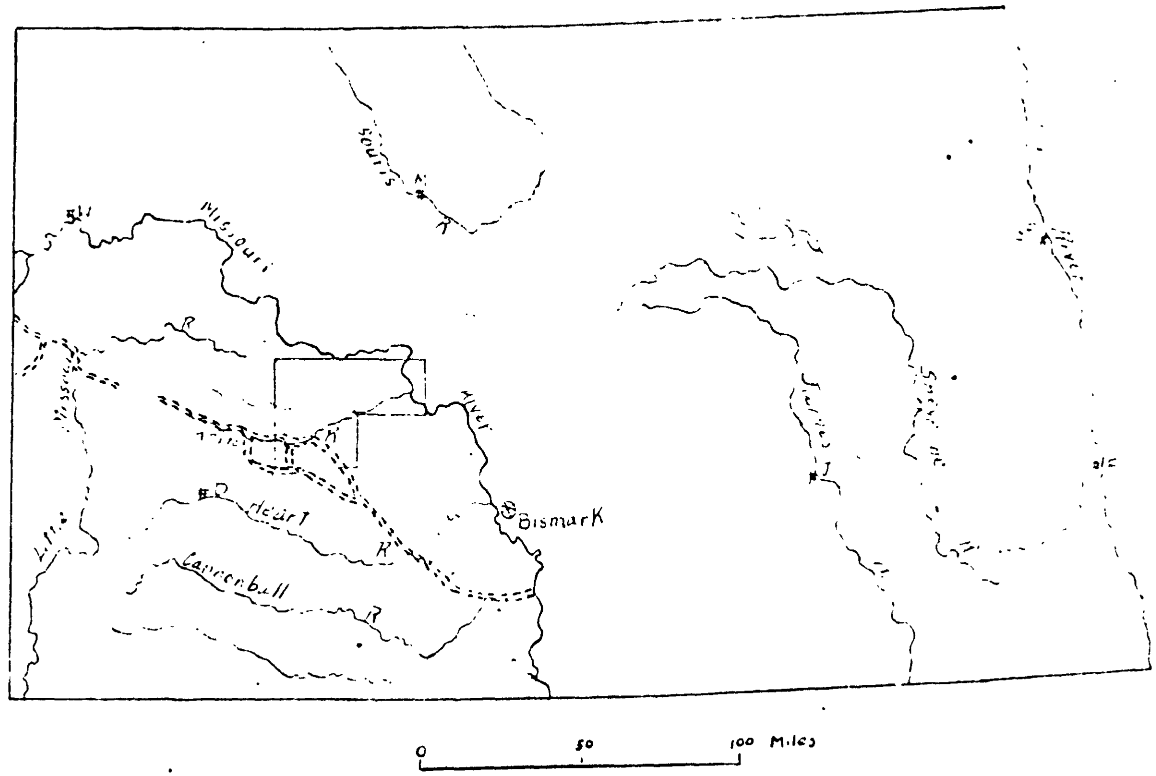


Fig. 13. Pleistocene diversion valleys as mapped by Leonard and Alden.

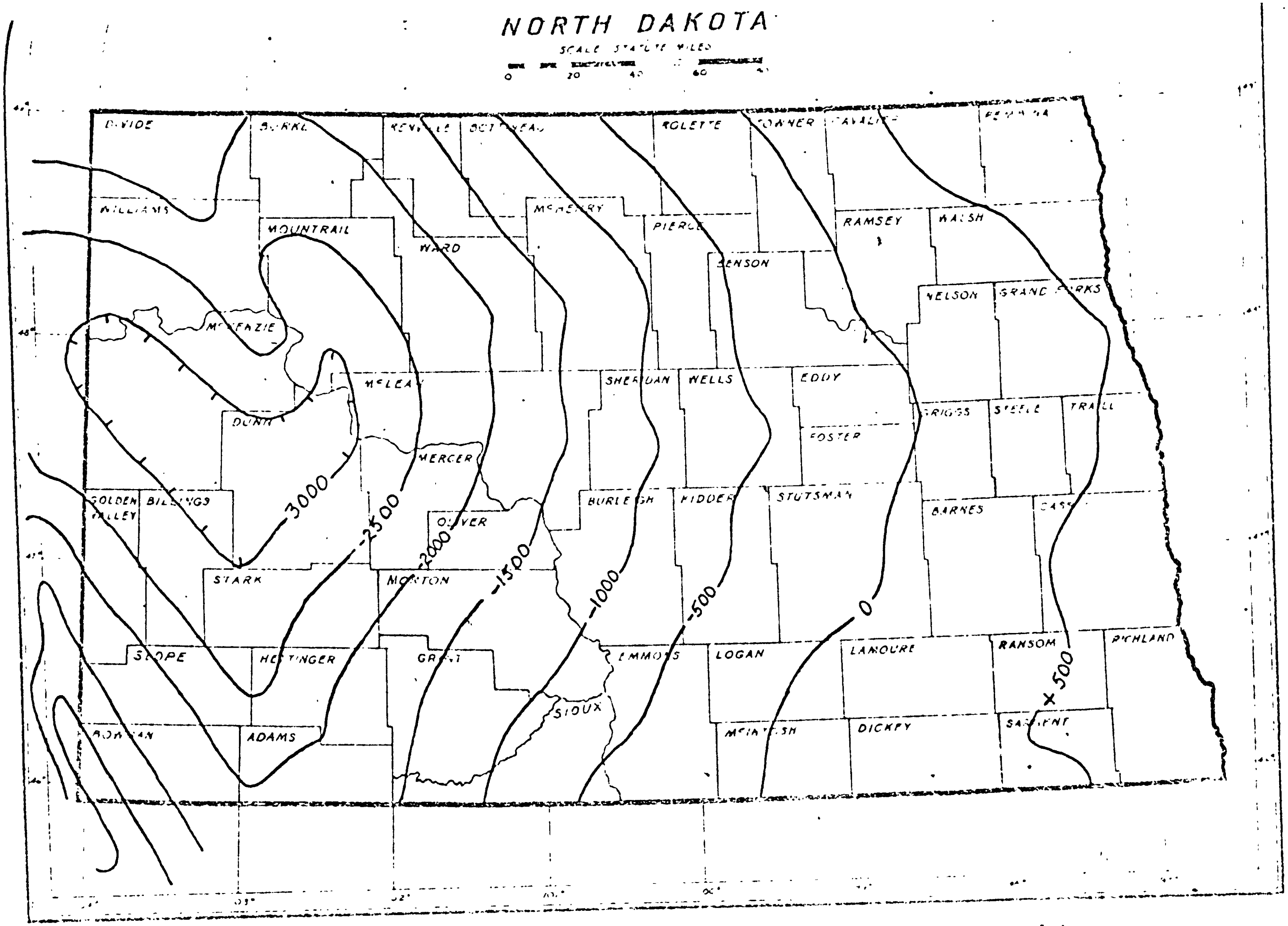


Fig. 14. Generalized structure map of North Dakota, contoured on top of Dakota sandstone. After Ballard (1942).

Location	Lab. No.	Form of Analysis	Proximate				Ultimate					Heating Value	
			Moisture	Volatile Matter	Fixed Carbon	Ash	Hydrogen	Carbon	Nitrogen	Oxygen	Sulphur	Calories	B. T. U.
Dakota Star Mine, Sec. 21, T. 145 N., R. 86 W. Mercer Co.	D-2574	A	37.1	27.0	30.8	5.1	6.8	41.9	0.6	45.1	0.5		6,930
		C	—	42.9	49.0	8.1	4.2	66.5	0.9	19.5	0.8		11,020
		D	—	46.6	53.4	—	4.6	72.4	1.0	21.1	0.9		11,980
Smith Mine, Sec. 23, T. 144 N., R. 85 W. Mercer Co.	33067	A	37.37	28.0	29.0	5.7	6.9	40.1	0.6	45.3	0.7	3,823	6,881
		C	—	44.7	46.3	9.0	4.4	65.3	1.0	19.2	1.1	6,104	10,987
		D	—	49.1	50.1	—	4.8	71.7	1.1	21.1	1.2	6,709	12,076
Knife River Coal Min. Co. Beulah, Mercer Co.	A-68042	A	35.6	26.2	32.6	5.6	6.7	42.3	0.6	44.1	0.7	3,961	7,130
		C	—	40.7	50.6	8.7	4.3	65.7	0.9	19.3	1.1	6,144	11,060
		D	—	44.6	55.4	—	4.7	72.0	1.0	21.1	1.2	6,733	12,120
Harnisch Mine, Sec. 8, T. 140 N., R. 90 W. Morton Co.	A-45879	A	32.9	27.3	34.5	5.3	6.7	45.7	0.7	41.0	0.6	4,356	7,840
		C	—	40.6	51.6	7.8	4.5	68.1	1.0	17.7	0.9	6,489	11,680
		D	—	44.1	55.9	—	4.9	73.9	1.1	19.1	1.0	7,039	12,670
Lucky Strike Mine, Sec. 26, T. 144 N., R. 89 W. Mercer Co.	A-45881	A	33.6	27.1	33.2	6.1	6.9	44.5	0.7	41.0	0.8	4,272	7,690
		C	—	40.9	49.9	9.2	4.7	67.1	1.1	16.6	1.3	6,439	11,590
		D	—	45.0	55.0	—	5.2	73.8	1.2	18.4	1.4	7,089	12,760
Republic Mine (Dakota Collieries) Sec. 24, T. 144 N., R. 89 W. Mercer Co.	A-45883	A	32.0	28.0	35.5	4.5	6.8	47.0	0.7	40.6	0.4	4,400	7,920
		C	—	41.1	52.3	6.6	4.7	69.1	1.0	18.0	0.6	6,467	11,640
		D	—	44.0	56.0	—	5.1	74.0	1.1	19.1	0.7	6,928	12,470
Steven Bros. Coal Co. Garrison, McLean Co. Sec. 19, T. 148 N., R. 84 W.	A-45983	A	33.1	29.6	32.7	4.6	6.7	43.6	0.7	44.0	0.4	4,128	7,430
		C	—	44.3	48.3	6.9	4.6	65.2	1.1	21.6	0.6	6,178	11,120
		D	—	47.6	52.4	—	4.9	70.1	1.2	23.2	0.6	6,639	11,950
Northwestern Improvement Co., Colstrip, Montana	A-46852	A	25.6	27.2	40.2	7.0	6.3	51.5	0.8	33.8	0.6	4,939	8,890
		C	—	36.5	54.1	9.4	4.7	69.2	1.1	14.8	0.8	6,633	11,940
		D	—	40.3	59.7	—	5.2	76.4	1.2	16.4	0.8	7,322	13,180
Pittsburgh Coal, Fayette Co., Penn.	23097	A	2.5	35.7	53.6	8.2	5.2	76.2	1.5	7.2	1.8	7,385	13,650
		C	—	36.6	55.0	8.4	5.0	78.1	1.5	5.1	1.8	7,780	14,000
		D	—	40.0	60.0	—	5.5	85.3	1.7	5.6	2.0	8,490	15,290

Forms of Analysis: A—as received; C—moisture-free; D—Moisture-and ash-free.

Analyses by U. S. Bureau of Mines, Pittsburgh Laboratory

295A (page 319 follows)

Table [illegible]. Yearly Coal Production of North Dakota from 1925 thru 1950

Year	Shipped	Produced
1925	1,[illegible],[illegible]42	1,357,408
1926	1,04[illegible],457	1,3[illegible],302
1927	1,1[illegible]1,569	1,5[illegible],154
1928	1,43[illegible],[illegible]	1,[illegible],624
1929	1,497,029	1,902,593
1930	1,3[illegible],[illegible]78	1,[illegible]49,144
1931	1,155,[illegible]04	1,552,242
1932	1,2[illegible],[illegible]71	1,743,053
1933	1,474,[illegible]24	1,372,381
1934	1,[illegible]9,[illegible]10	1,74[illegible],226
1935	1,35[illegible],196	1,828,213 +
1936	1,251,[illegible]5 +	1,704,933
1937	1,551,7[illegible] +	2,184,927 +
1938	1,45[illegible],[illegible]3	2,14[illegible],061
1939	1,545,140	2,176,841
1940	1,5[illegible],[illegible]23	2,1[illegible],131
1941	1,[illegible]28,035	2,347,258
1942	1,7[illegible],[illegible]47	2,474,006
1943	2,019,024	2,694,600
1944	1,910,[illegible]19	2,515,823
1945	1,898,434	2,485,469 +
1946	2,[illegible]4,352 +	2,610,544 +
1947	2,212,619 +	2,817,768 +
1948	2,359,[illegible]5 +	2,954,363 +
1949	2,385,035 +o	2,970,300 +
1950	2,[illegible]6,[illegible] +	2,[illegible]12,534 +

Name of Mine	Kind of Mine	Address	Tons Produced	Output Value
Bauers Coal Mine	Slope	Beulah	2,000	5,500.00
Reick Coal Mine	Drift	Zap	763	2,2[illegible].00
Dakota Collieries	Strip	Zap	191,143	474,234.33
Dakota Star Mine	Strip	Hazen	575,455	1,286,658.12
Elder Coal Mine	Strip	Hebron	250	625.00
Grishkowsky Coal Mine	Strip	Beulah	2,348	6,691.30
Knife River Coal Mine Co.	Drift	Beulah	418,295	881,230.51
Krause Coal Mine	Strip	Zap	704	1,761.70
Link Coal Mine	Strip	Beulah	65	112.50
Mittelsteadt Mine	Strip	Hazen	125	21[illegible].50
Moxley & Erickson Mine	Slope	Beulah	633	1,399.00
Voegele Coal Mine	Strip	Glen Ullin	159	333.90
Walker Coal Mine	Strip	Zap	156	429.00

Table 3. Lignite Production of Mercer County for fiscal year 1950

Driller's log of Keller - Leutz No. 1 Well

Mercer County, North Dakota

[illegible]: Center NW/4 NW/4 Sec. 2[illegible], T-[illegible]-N, R-[illegible]

[illegible]: 6-15-50 [illegible]: 9-2[illegible]-50

[illegible]: Dry & Abandoned

[illegible]: [illegible]'

0-60	shale, gray	Fort Union, Cannonball and Hell Creek formations
60-70	lignite	
70-130	shale, gray	
130-150	shale, gray	
150-193	shale, gray	
193-205	lignite	
205-240	shale, gray	
240-250	lignite	
250-265	shale, gray	
265-270	lignite	
270-1140	shale, gray	
1150-1460	sandy shale	Fox Hills sandstone
1460-1600	sand & shale inter-bedded	
1600-1620	shale, bentonitic	Pierre shale, Niobrara fm., Benton group
1620-1650	dolomite	
1650-1700	lime	
1700-3430	shale, gray	
3430-3460	black lignitic shale	
3460-3940	shale, bentonitic	
3940-3950	black lignitic shale	
3950-4220	gray shale	
4220-4230	black shale	
4230-4690	gray shale --------Top of Dakota ss----------4689	
4690-4800	shale & sand stringers	
4800-4830	sand	
4830-5040	sandy shale --------Top of Morrison -----------4889	
5040-5110	shale w/sand stringers----Top of Sundance--------5094	
5110-5140	shale	
5140-5170	sandy shale	
5170-5230	gray-green shale	
5230-5270	shale	
5270-5360	gypsiferous sand	
5360-5540	gray shale	
5540-5580	green shale	
5580-5600	gray shale	
5600-5630	green shale	
5630-5670	dense gray limestone	
5670-5750	red and green shale	
5700-5730	dense tan limestone	
57[illegible]-5800	dense pink dolomite	
[illegible]-5870	green & gray dense limestone	
5870-5950	red shale	

Driller's log of Kelley - Leutz No. 1 Well

Mercer County, North Dakota

5950-5970	anhydrite	
5970-6040	red shale & anhydrite——Top of Triassic ——————	6004
6040-6070	anhydrite limestone	
6070-6110	red & green shale & anhydrite	
6110-6220	black shale	
6220-6310	red shale & anhydrite	
6310-6380	black shale	
6380-6405	sand ——————————Top of Amsden ——————————	6399
6405-6430	gray-green shale	
6430-6620	anhydrite dolomite	
6620-6740	red shale & anhydrite ————Big Snowy ———————	6599
6740-6810	gray limestone	
6810-6850	sandy red shale	
6850-6870	tan dense limestone	
6870-7015	red & green sandy shale	
7015-7145	vari-colored shales w/sand	
7145-7240	white & gray limestone	
7240-7310	red shale	
7310-7390	brown dense limestone	
7390-7620	anhydrite w/limestone inclusions	
7620-7740	brown dense limestone	
7740-7856	anhydrite & red shale ———Top of Madison ——————	7849
7856-7920	tan limestone w/anhydrite inclusions	
7920-8020	tan fine crystalline limestone	
8020-8210	buff & light green fossiliferous limestone	
8210-8250	gray crystalline limestone, anhydrite inclusions	
8250-8790	gray crystalline limestone	
8790-8972	gray dense limestone w/gray shale stringers ——— Top of Englewood —————	8970
8972-9000	black greasy shale	
9000-9025	tan fossiliferous limestone ——Top of Devonian —————	9000
9025-9220	tan dolomite & red dolomitic shale	
9220-9470	buff sucrosic limestone w/dolomite stringers	
9470-9550	gray brown dense limestone	
9550-9740	buff & tan dense limestone	
9740-9780	white fine granular dolomite	
9780-9798	buff, tan & brown limestone	
9798-9800	white fine light sand	
9800-10,260	brown & tan crystalline, dense limestone ——— Top of Silurian——————	10,129
10,260-10,940	white coarse crystalline porous dolomite	
10,940-10,980	white sandy dolomite	
10,980-11,040	brown & gray limestone & dolomitic sand	
11,040-11,090	tan fine granular dolomite ——Top of Ordovician ———	11,054
11,090-11,320	gray & brown dense fossiliferous limestone w/anhydrite inclusions	
11,320-11,360	tan very fine grained dolomite w/anhydrite	
11,360-11,380	tan & brown dense limestone	
11,380-11,400	tan very fine grained dolomite w/anhydrite	
11,400-11,899	buff, tan & brown fine-grained limestone ———— Top of Winnepeg ————	11,855
11,899-12,060	green splintery shale w/sand inter-bedded	
12,060-12,080	brown dense limestone	

[illegible] log of Keller - Lentz No. 1 Well

[illegible] County, North Dakota

[illegible]-12,170	green shale w/sandy dolomite interbedded
[illegible]-12,230	brown crystalline limestone
[illegible]-12,275	green shale w/included sand
[illegible]-12,340	fine angular quartz sand, tight, dolomitic
[illegible]-12,400	tan & brown fossiliferous limestone ———
	Top of Cambrian (?)——— 12,3[illegible]
[illegible]-12,526	white, tan, gray, dense, slightly sand limestone ([illegible])

T.D. 12,526'

* Coal fields whose locations are shown in Fig. 1

No.	Field	Bulletin
1	Scobey	751-E
2	Fort Peck	381-A
3	McCone County	905
4	Richey-Lambert	847-C
5	Culbertson	471-D
6	Williston	531-E
7	Nesson Anticline	691-G
8	Fort Berthold	726-D
9	Fort Berthold	381-A, 471-C
10	Minot	906-B
11	Washburn	381-A
12	New Salem	726-A
13	Cannonball River	541-G
14	Standing Rock and Cheyenne River	575
15	Northwestern South Dakota	627
16	Marmarth	775
17	Sentinel Butte	541-A
18	Sidney	471-D
19	Glendive	471-D
20	Terry	471-D
21	Baker	471-D
22	Ekalaka	751-F
23	Mizpah	906-C
24	Miles City	341-A
25	Little Sheep Mountain	531-F
26	Ashland	831-B
27	Rosebud	847-B
28	Forsyth	812-A
29	Tullock Creek	749
30	Pine Ridge	541-H
31	Bull Mountain	647
32	Big Horn County	856
33	Northward extension of Sheridan	806-B
34	Sheridan	541-B
35	Buffalo	381-B
36	Barber	351-I
37	Pumpkin Buttes	806-A
38	Sussex	471-F
39	Glenrock	341-B
40	Lost Spring	471-F
41	Gillette	796-A
42	Powder River	381-B
43	Little Powder River	471-A
44	Coalwood	973-B
45	This report	

53-21

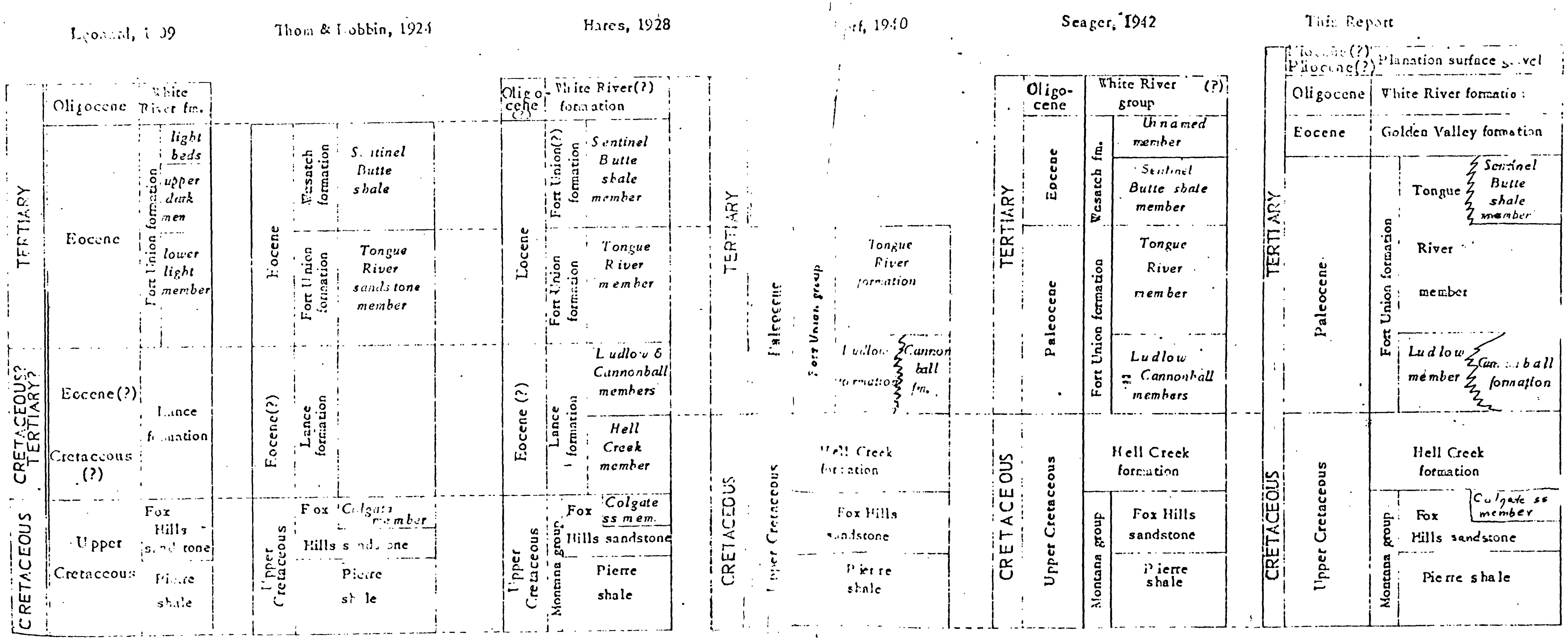


Fig. 4. Former correlations and proposed revision of formations in southwest North Dakota