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GEOLOGY OF THE WILLISTON BASIN, NORTH DAKOTA, MONTANA, AND SOUTH DAKOTA, WITH REFERENCE TO SUBSURFACE DISPOSAL OF RADIOACTIVE WASTES

By Charles A. Sandberg

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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ILLUSTRATIONS

GEOLOGY OF THE WILLISTON BASIN, NORTH DAKOTA, MONTANA, AND SOUTH DAKOTA, WITH REFERENCE TO SUBSURFACE DISPOSAL OF RADIOACTIVE WASTES

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ABSTRACT

The southern Williston basin, which underlies about 110,000 square miles in North Dakota, South Dakota, and eastern Montana, is part of a large structural and sedimentary basin. Its surface is a flat to gently rolling plain, standing about 1,500 to 3,500 feet above sea level and locally studded by a few high buttes. The sedimentary sequence that fills the basin has a maximum thickness of about 16,700 feet and rests on Precambrian metamorphic rocks at depths of 500 to 13,900 feet below sea level. It contains rocks of every geologic system from Cambrian to Quaternary. Rocks of Middle Cambrian through Middle Ordovician age are largely shale and sandstone, as much as 1,200 feet thick; rocks of Late Ordovician through Pennsylvanian age are largely limestone and dolomite, as much as 7,500 feet thick; and rocks of Permian through Tertiary age are predominantly shale and siltsone, as much as 8,000 feet thick. Pleistocene glacial drift mantles the northern and eastern parts of the area.

Rocks of the Williston basin are gently folded and regional dips are 1° or less from the margins to the basin center. Dips on the flanks of the major anticlinal folds, the Nesson and Cedar Creek

anticlines and the Poplar and Bowdoin domes, generally are about 1° to 3° except on the steep west limb of the Cedar Creek anticline. The basin was shaped by Laramide orogeny during latest Cretaceous and early Tertiary time. Most of the present structural features, however, were initiated during the Precambrian and reactivated by several subsequent orogenies, of which the latest was the Laramide.

The most important mineral resource of the area is oil, which is produced predominantly from the Paleozoic carbonate sequence and largely on three of the major anticlinal folds, and lignite, which is present near the surface in Paleocene rocks.

The subsurface disposal of radioactive wastes at some places in the Williston basin appears to be geographically and geologically feasible. Many sites, at which large quantities of wastes might be injected with minimal danger of contamination of fresh-water aquifers and oil-producing strata, are available. The strata and types of reservoirs that deserve primary consideration for waste disposal are the Winnipeg Formation of Middle Ordovician age as a deep salaquifer, the Permian to Jurassic salt beds as moderately deep units in which solution cavities might be created for storage, the thick Upper Cretaceous shale beds as shallow hydraulically fractured shale reservoirs, and the Newcastle Sandstone of Early Cretaceous age as a shallow shale-enclosed sandstone reservoir.

INTRODUCTION

This geologic summary of the Williston basin is one of a series of reports on the sedimentary and structural basins of the United States, prepared by the Geological Survey for the Division of Reactor Development, U.S. Atomic Energy Commission. These reports summarize the geology of several major basins and make preliminary generalized evaluations of the possibilities for the subsurface disposal of radioactive wastes.

This report evalutes four possible types of subsurface reservoirs for radioactive wastes in the Williston basin: (a) permeable sandstone and carbonate beds at moderate to great depths in the central part of the basin but at or near the surface on the margins, (b) salt beds which are present only at moderate to great depths, (c) thick beds of shale at shallow depths, and (d) permeable sandstone beds at shallow depths. (Shallow is here used for depths less than 5,000 feet; moderate, for depths between 5,000 and 10,000 feet; and great, for depths more than 10,000 feet.)

Area of report

The Williston basin, one of the largest structural basins in North America, underlies approximately 200,000 square miles in North Dakota, northern and central South Dakota, eastern and north-central Montana, southern and central Saskatchewan, and southwestern Manitoba. This report considers only the southern or United States part of the

Williston basin, which constitutes more than half of this large area or about 110,000 square miles. The southern part of the Williston basin (fig. 1) is hereafter referred to simply as the Williston basin. The deepest part of the basin, designated on figure 1 the Central Williston basin, occupies about one-fifth of the report area and underlies about 22,000 square miles of northwestern North Dakota and northeastern Montana.

The eastern and southern limits of the Williston basin are outlined by a belt in which the edges of Paleozoic and Mesozoic rocks onlap the Precambrian basement rocks. For this report, the eastern limit is arbitrarily placed between the -500-foot and -1,000-foot structure contours drawn at the base of Mississippian rocks (fig. 1). The southwestern and western limits of the basin are placed at the northeast flanks of the Black Hills uplift and an unnamed arch that connects the Black Hills and Central Montana uplifts; the north flank of the Central Montana uplift, and the east flanks of the Little Rocky and Bearpaw Mountains (fig. 1).

Geologic setting

Rocks at the surface in the Williston basin generally are flat lying or dip only a few degrees. They comprise predominantly nonmarine Tertiary rocks and predominantly marine Cretaceous rocks (fig. 2). North and east of the Missouri River, shown as a sinuous line of county boundaries that passes through Pierre, S. Dak.,

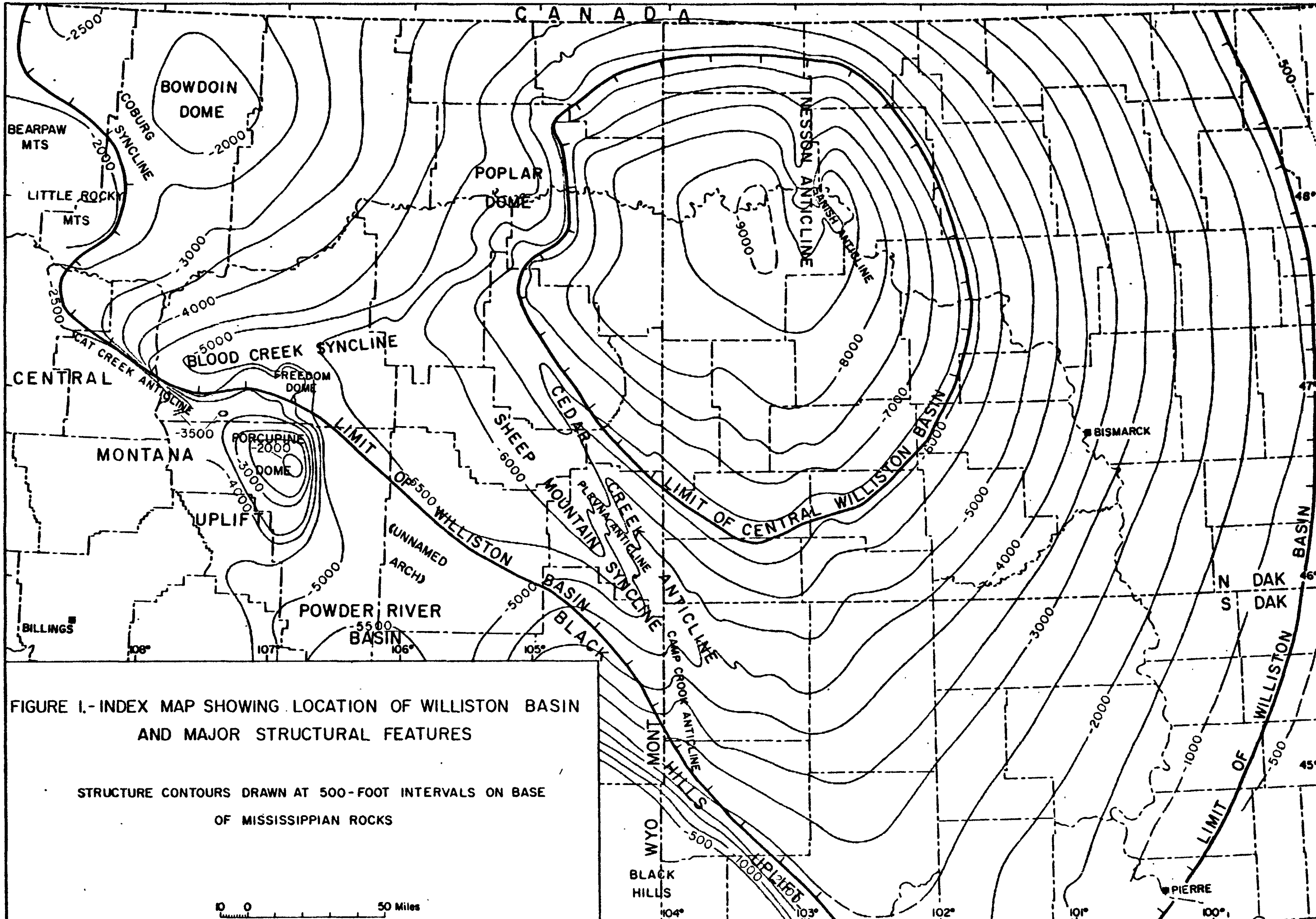

FIGURE I.- INDEX MAP SHOWING LOCATION OF WILLISTON BASIN AND MAJOR STRUCTURAL FEATURES

STRUCTURE CONTOURS DRAWN AT 500-FOOT INTERVALS ON BASE OF MISSISSIPPIAN ROCKS

10 0 50 Miles

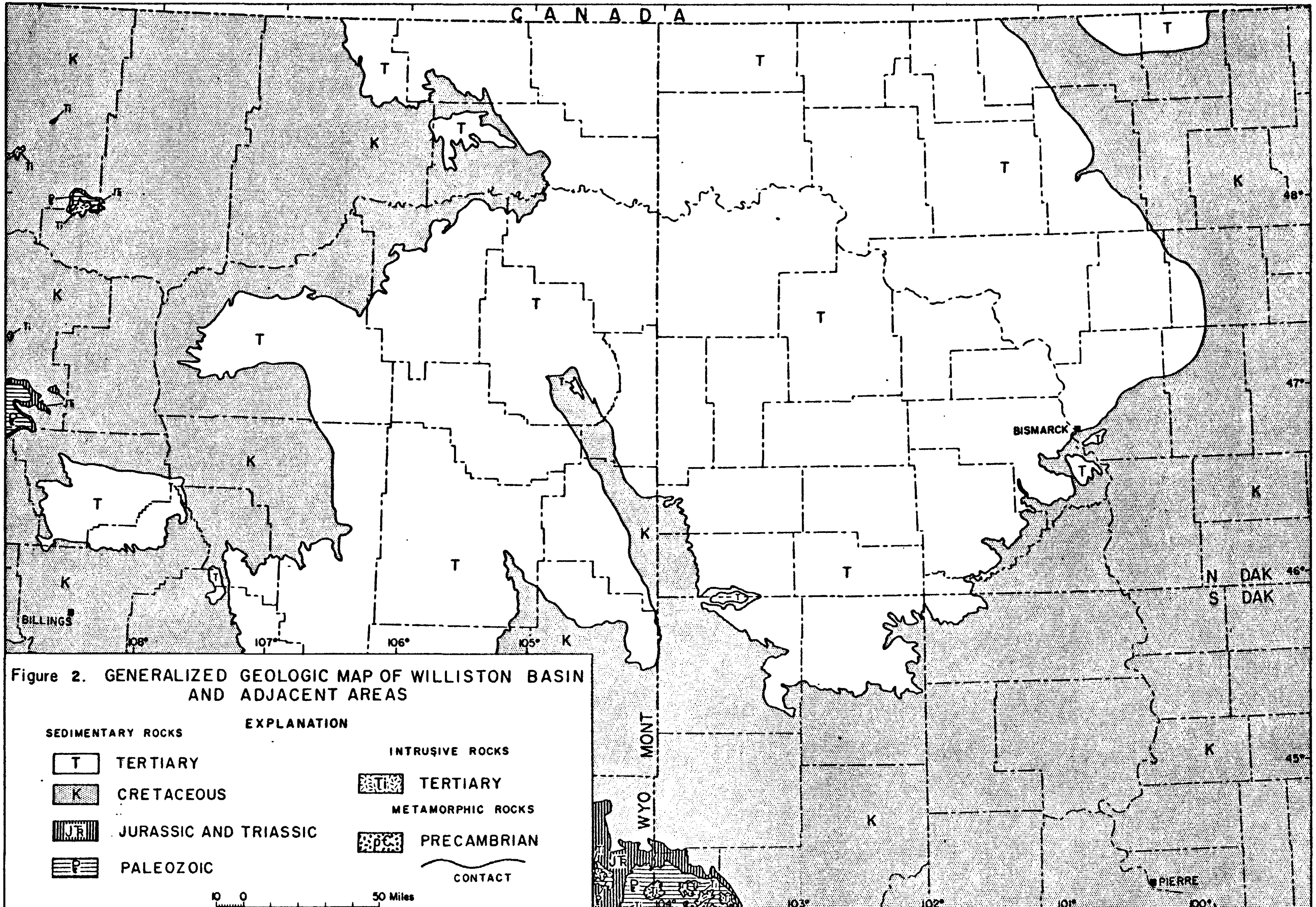

Figure 2. GENERALIZED GEOLOGIC MAP OF WILLISTON BASIN AND ADJACENT AREAS

Bismarck, N. Dak., and thence northwestward (fig. 2), the bedrock is mantled at most places by thick glacial drift. The thickness of this drift averages 200 feet but locally may be as much as 500 feet.

Beyond the southwestern and western limits of the Williston basin Jurassic, Triassic, and Paleozoic rocks crop out on the flanks of the Black Hills, the Big Snowy Mountains of the Central Montana uplift, and the Little Rocky Mountains (figs. 1 and 2). Tertiary intrusive rocks are exposed in the Black Hills and the Little Rocky and Bearpaw Mountains (figs. 1 and 2). Precambrian metamorphic and granitic rocks form the core of the Black Hills.

During the Paleozoic and early Mesozoic, the Williston basin area was at times an intracratonic basin or a shelf area that bordered a miogeosyncline much farther west. At other times the area was flooded by seas that followed a trough extending eastward from the miogeosyncline across the area of the Central Montana uplift and the Central Williston basin. For short intervals the entire Williston basin area was above sea level and subjected to subaerial erosion; infrequently thin continental deposits were laid down.

In Cretaceous time, the Williston basin area was part of a huge epicontinental seaway that extended southward through Canada and the western conterminous United States. As the sea periodically transgressed westward and regressed eastward within this trough, some continental deposits were laid down largely in the western part of the area. Most Cretaceous deposition in the eastern part of the area was marine.

During and following Laramide orogeny in latest Cretaceous and Tertiary time, the area of the Williston basin was for the most part above sea level and received continental deposits of sandstone, shale, and lignite.

Sedimentation in the Williston basin area has been either continental or in shallow epicontinental seas, whose depths probably were never much greater than 300 feet. Nevertheless, because of intermittent but continuing downwarping, a considerable thickness of sedimentary rocks has accumulated. The accumulation is greatest in the Central Williston basin. There the maximum thickness of sedimentary rocks is about 16,700 feet beneath the Killdeer Mountains, 20 miles directly south of the Nesson anticline (fig. 1), in northwestern North Dakota.

Geographic setting

The Williston basin area occupies the northern part of the Great Plains. The land surface is flat to gently rolling, but in places it is hilly or studded by solitary buttes. The glaciated area north and east of the Missouri River contains many small saline lakes. Rugged breaks or badlands occupy narrow belts along many major streams and in a few places, such as along the Little Missouri River in North Dakota, wider belts of badlands are present. The general land surface is 1,500 to 3,500 feet above sea level. Several isolated buttes in western South Dakota and southeastern Montana rise to a little more than 4,000 feet, but the elevation of the highest butte in North Dakota is 3,468 feet. Local relief exceeds 500 feet at only a few localities.

The report area is drained principally by the eastward- and southward-flowing Missouri River, its major tributaries, the Yellowstone and Little Missouri Rivers, and its many smaller tributaries. The Missouri River enters the west edge of the area at an elevation of about 2,300 feet, drops 900 feet in approximately 700 miles, and leaves the south edge at an elevation of about 1,400 feet. The streams in north-central North Dakota flow northward into Canada.

Almost all parts of the Williston basin, except for the badlands and some swampy glaciated areas, are traversed by a large network of improved and unimproved roads. The area is served largely by east-west routes of the Great Northern, Northern Pacific, and Chicago, Milwaukee, St. Paul, and Pacific railroads. Parts of North Dakota and South Dakota are served also by the Minnesota, St. Paul, and Sault Ste. Marie and by the Chicago and Northwestern railroads.

The population of the Williston basin (fig. 1), as compiled from the 1960 Census of Population, is about 525,000 persons, of whom about two-thirds live in North Dakota. This population is predominantly rural and the average population density is about 4.7 persons per square mile. The principal cities and their populations are: Bismarck, capital of North Dakota, 28,000; Minot, N. Dak., 31,000; and Pierre, capital of South Dakota, 10,000. Several major business and railroad centers with populations of 35,000 to 53,000 lie within a hundred miles of the outside limits of the Williston basin. These cities are Billings, Mont., Fargo and Grand Forks, N. Dak., and Rapid City, S. Dak.

The climate is semiarid and subject to severe diurnal and seasonal temperature changes. Hot dry summers generally have many days with temperatures higher than 95°. Long cold winters may have several periods, as long as two weeks, of subzero temperatures, and readings of -20° to -40° are common. Cool wet springs commonly prevent heavy trucks from leaving the hard-surfaced roads.

The economy has long been agricultural and is based largely on dryland wheat farming and stock grazing. However, since 1951, the Williston basin has been subjected to intensive petroleum exploration and petroleum exploration, production, and refining have become important economic factors. In 1960, oil production in the Williston basin was almost 40 million barrels from about 30 oilfields in Montana, about 70 oilfields in North Dakota, and 1 oilfield in South Dakota (fig. 3). Significantly, three-quarters of the oil production came from oilfields located on only three major structural features, the Cedar Creek and Nesson anticlines and the Poplar dome (fig. 1).

Acknowledgments and sources of data

This report draws heavily on the author's background in the stratigraphy of the Williston basin. His experience was acquired during work since 1954 on the Geological Survey's Williston basin Oil and Gas Investigations project, a part of the Interior Department's program for development of the Missouri River basin. The cross section, correlation chart, stratigraphic section, and most maps

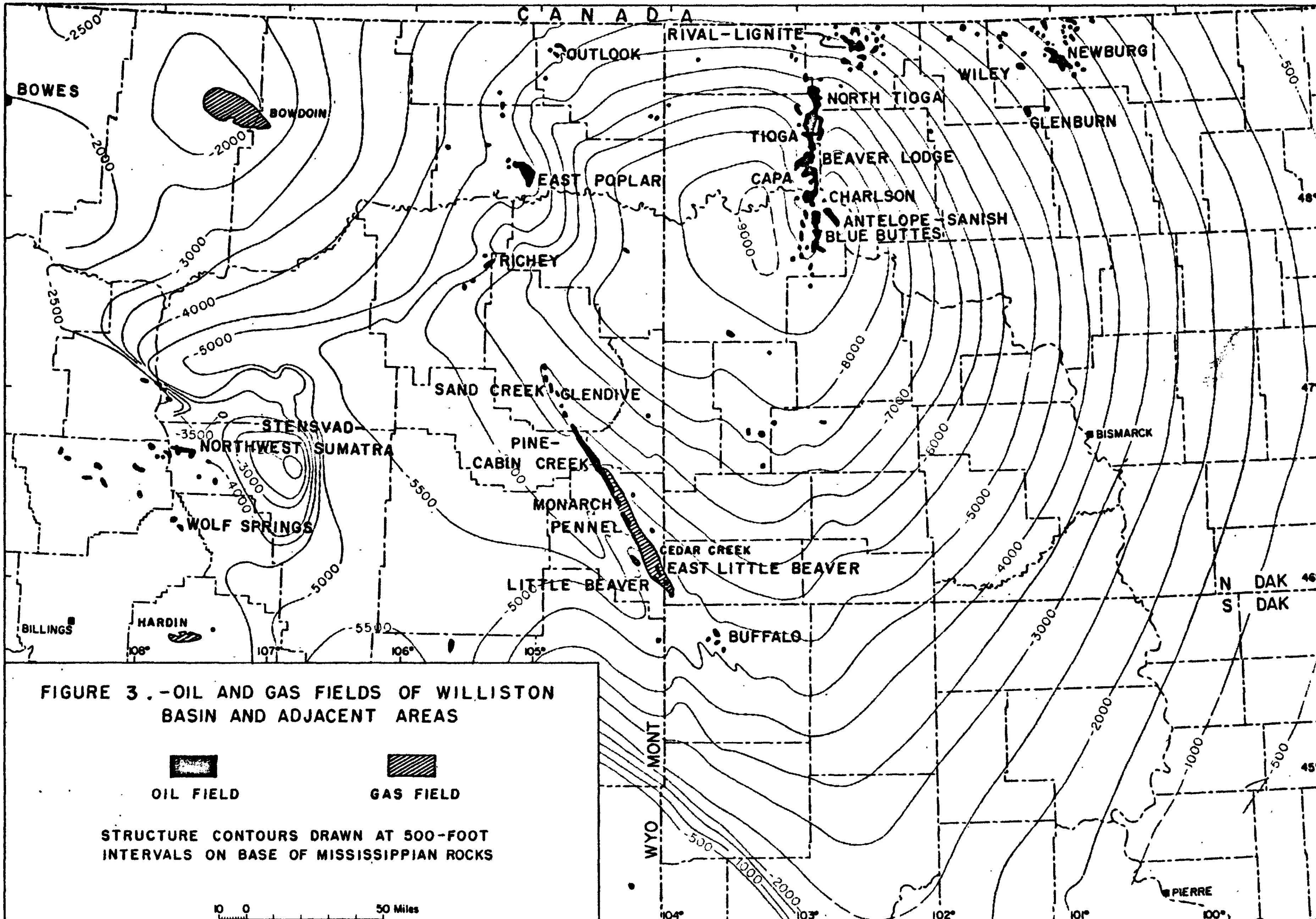

FIGURE 3. -OIL AND GAS FIELDS OF WILLISTON BASIN AND ADJACENT AREAS

STRUCTURE CONTOURS DRAWN AT 500-FOOT INTERVALS ON BASE OF MISSISSIPPIAN ROCKS pertaining to lower and middle Paleozoic rocks were compiled largely from heretofore unpublished data. However, time did not permit original compilation of the entire report; many of the other maps are from several published and unpublished sources. Some maps were modified to incorporate more recent data or to conform to the author's personal interpretations; others were not changed except by adapting their formats.

The generalized geologic map (fig. 2) is based on state geologic maps of Montana (Ross and others, 1955), North Dakota (Hansen, 1956), South Dakota (Petsch, 1953a), and Wyoming (Love and others, 1955). The oil and gas fields map (fig. 3) was compiled from maps by Dorothy Sandberg (1959) and Petroleum Information Corp. (1960), and subsequently has been updated from various reports published by Petroleum Information Corp. and articles and reports in the periodicals, Williston Basin Oil Review and Montana Oil and Gas Journal. All other maps, unless original to this report, are credited directly below their titles. Where only the name and date of the source are stated, the map is essentially unmodified.

Several colleagues on the Geological Survey kindly permitted use of their unpublished maps. N. M. Denson and J. R. Gill furnished a structure contour map of the Precambrian surface between the 102° and 106° meridians and between the 45° and 49° parallels. E. K. Maughan furnished a map of Permian formations in the Williston basin.

Special thanks are expressed to Barlow, Hammond, and Haun, Geologists, Inc., who gave permission (written communication, May 21, 1961) to use parts of four unpublished Cretaceous isopach maps. Without this assistance, an adequate discussion of the Cretaceous rocks could not have been prepared in the short time available.

STRATIGRAPHY

The sedimentary rocks that fill the Williston basin attain a maximum thickness of about 16,700 feet and include parts of every geologic system from Cambrian to Quaternary. This thick sequence rests on an erosion surface of Precambrian metamorphosed igneous rocks at elevations ranging from 500 feet to about 13,900 feet below sea level (fig. 4). The sequence comprises three distinct lithologic assemblages. Rocks of Middle Cambrian through Middle Ordovician age are about 1,200 feet thick in the Central Williston basin and consist of clastic rocks, largely shale and sandstone, containing interbeds of limestone and limestone-pebble conglomerate. Rocks of Late Ordovician through Pennsylvanian age comprise a carbonate sequence about 7,500 feet thick there. They consist largely of limestone and dolomite but include one thick salt bed, seven thinner salt beds, and several thin beds of shale. Rocks of Permian through Tertiary age are about 8,000 feet thick in the Central Williston basin and consist predominantly of shale, containing interbeds and lenses of sandstone and siltstone in the lower and upper parts, and near the base,

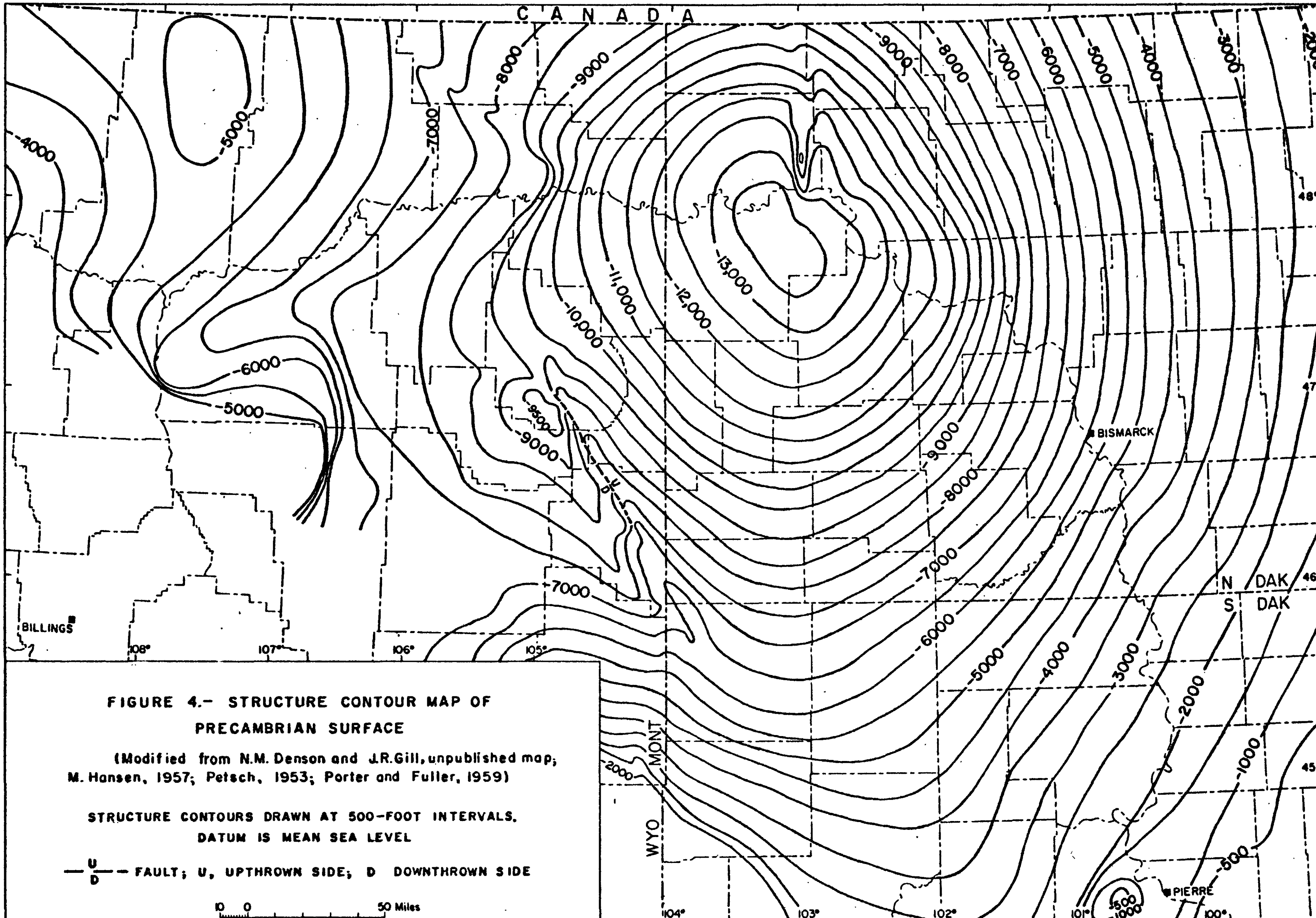

FIGURE 4.- STRUCTURE CONTOUR MAP OF PRECAMBRIAN SURFACE

(Modified from N.M. Denson and J.R. Gill, unpublished map; M. Hansen, 1957; Petsch, 1953; Porter and Fuller, 1959)

STRUCTURE CONTOURS DRAWN AT 500-FOOT INTERVALS. DATUM IS MEAN SEA LEVEL

—U/D— FAULT; U, UPTHROWN SIDE; D DOWNTHROWN SIDE

10 0 50 Miles

three salt beds. North of the Missouri River, this shale sequence is thinner but it is mantled by Pleistocene glacial drift which has an average thickness of 200 feet. A stratigraphic section (fig. 5), showing only major lithologies, gives the nomenclature, age, and thickness of sedimentary rocks in the Central Williston basin.

The sedimentary formations are not considered individually in this report but have been grouped into 17 convenient subdivisions for discussion. The names of these stratigraphic subdivisions, their thickness in the Central Williston basin, and the figure numbers of corresponding isopach maps are shown on figure 5.

Many of the formations present in the Central Williston basin extend throughout the entire basin. Some, however, are absent locally or are very thin and others are not differentiated in other parts of the basin. Conversely, some sandstones of Cretaceous age underlie adjacent parts of the basin but grade into shale outside the Central Williston basin. Consequently, formation names and their usage differ slightly in various parts of the basin. The correlation of pre-Tertiary formations between north-central Montana, eastern Montana, North Dakota, and South Dakota is shown by a chart (fig. 6), whereon unconformities are indicated by wavy lines and absent parts of the stratigraphic columns are shown by vertical shading.

The correlations and age assignments of formations in this report reflect recent work by the author and petroleum geologists and paleontologists familiar with the Williston basin. Several subsurface units that have no outcropping equivalents in the United States are designated in this report by informal names (fig. 6). Although these subsurface units are in widespread usage by the petroleum industry, their names, as well as some new age assignments, do not conform with nomenclature currently accepted by the Geological Survey for areas of outcrop adjacent to the Williston basin.

Precambrian rocks

Preliminary consideration of the Precambrian rocks of the Williston basin is important to a discussion of the stratigraphy of the overlying sedimentary rocks. The thickness and distribution of many formations of Paleozoic and Mesozoic age were controlled in part by the intermittent movement of structural features ancestral to those formed during Laramide orogeny, which produced the present structure of the Williston basin. Some of these ancestral features were already in existence at the close of the Precambrian.

The Precambrian of the Williston basin is composed largely of metamorphosed igneous rocks. Many Precambrian cores and rotary drilling samples appear to be gneissic granite or related types of medium- to coarse-grained intrusive rocks; the remainder are amphibolite and other types of metamorphosed mafic to intermediate igneous rocks (Tullis, 1952). Unfortunately, the distribution of rock types is not well known because of a lack of well data. Except along the eastern and southeastern margins, where the elevation of the Precambrian surface is higher than 4,000 feet below sea level (fig. 4), fewer than 15 wells have penetrated Precambrian rocks in the Williston basin. Of these wells, 4 are located on the Nesson anticline, 1 on the Sanish anticline, and 3 on the Cedar Creek anticline (fig. 1); the remainder are widely scattered.

The Precambrian erosional surface in some parts of the basin is underlain by a granite wash, as much as 50 feet thick, whose presence is revealed by cores. Consequently, many wells that reportedly bottomed in granite on the basis of cuttings may not have penetrated unweathered Precambrian rocks.

The only metasedimentary rocks known in the Williston basin are assigned to the Sioux Quartzite. They are present west of Pierre, S. Dak., in the small area shown as a dome on figure 4. This area appears to be a monadnock or butte of quartzite that overlies and rises sharply above the surrounding granitic terrain. The monadnock of quartzite is overlain by the upper beds of the Minnelusa Formation of Pennsylvanian and Permian age, whereas Precambrian granitic rocks nearby are overlain by Ordovician, Devonian, and Mississippian rocks as well as the lower beds of the Minnelusa Formation. This suggests that the monadnock was an island during much of Paleozoic time. This monadnock lies near the northwest end of an extension of the Sioux uplift, which probably was a plateau of flat-lying quartzite on the Precambrian surface. Future drilling along the southeastern margin of the Williston basin may disclose similar monadnocks projecting into the Paleozoic rocks.

Flanking the southwestern margin of the Williston basin, other Precambrian metasedimentary rocks assignable to the Belt Series underlie most of the Central Montana uplift (fig. 1). Part of this area may have formed a low plateau on the Precambrian surface.

Deadwood Formation and related rocks

The Deadwood Formation of the northern Black Hills is about 450 feet thick and is largely of Late Cambrian age, but the upper few feet is of earliest Ordovician age. Correlation of the Deadwood Formation northward into the Williston basin reveals several hundred feet of additional beds in both the upper and lower parts there. The age of the Deadwood in the subsurface of North Dakota, South Dakota, and eastern Montana ranges from Middle Cambrian well into Early Ordovician.

Rocks related to and continuous with the Deadwood Formation at the west side of the Williston basin in north-central Montana have a slightly different lithologic character. Knechtel (1956) proposed that rocks previously assigned to the Deadwood Formation in the Little Rocky Mountains (fig. 1) be divided into two formations, but these rocks are not named nor readily differentiated in the subsurface (fig. 6). For convenience in this discussion, the related rocks in north-central Montana will be considered simply as Deadwood Formation.

The Deadwood Formation rests unconformably on an irregular erosion surface of Precambrian metamorphic rocks and is unconformably overlain by the Winnipeg Formation of Middle Ordovician age except in north-central Montana where the Winnipeg is absent. There the Deadwood is unconformably overlain by the Red River Formation of Late Ordovician age.

The Deadwood Formation is as much as 1,300 feet thick (fig. 7) on the west side of the Williston basin in north-central Montana, but it thins progressively eastward to the eastern margin, where it forms only a veneer. The Deadwood is not present in eastern North Dakota or southeast of Pierre in South Dakota.

Despite its general eastward thinning, the Deadwood Formation appears to be slightly thicker, on the basis of sparse well control, in a trough (fig. 7) extending from the Central Montana uplift through the deepest part of the Williston basin. This greater thickness resulted in part from accelerated accumulation along an axis of subsidence and in part from pre-Winnipeg erosion of areas on the north and south. The trough is interrupted by a large area of anomalous thinning, possibly caused by retarded subsidence of what may well have been the ancestral Porcupine dome (figs. 1 and 7). The Deadwood thins abruptly from about 1,000 feet to less than 70 feet in thickness in a small area (fig. 7) near the end of the trough. Thinning in this area is interpreted as the result of deposition over a high monadnock of Precambrian rocks. This monadnock probably was structurally controlled by a positive element that is here interpreted as the ancestral Nesson anticline. Carlson (1960) discussed this area in detail and made a similar interpretation. Other anomalously thin

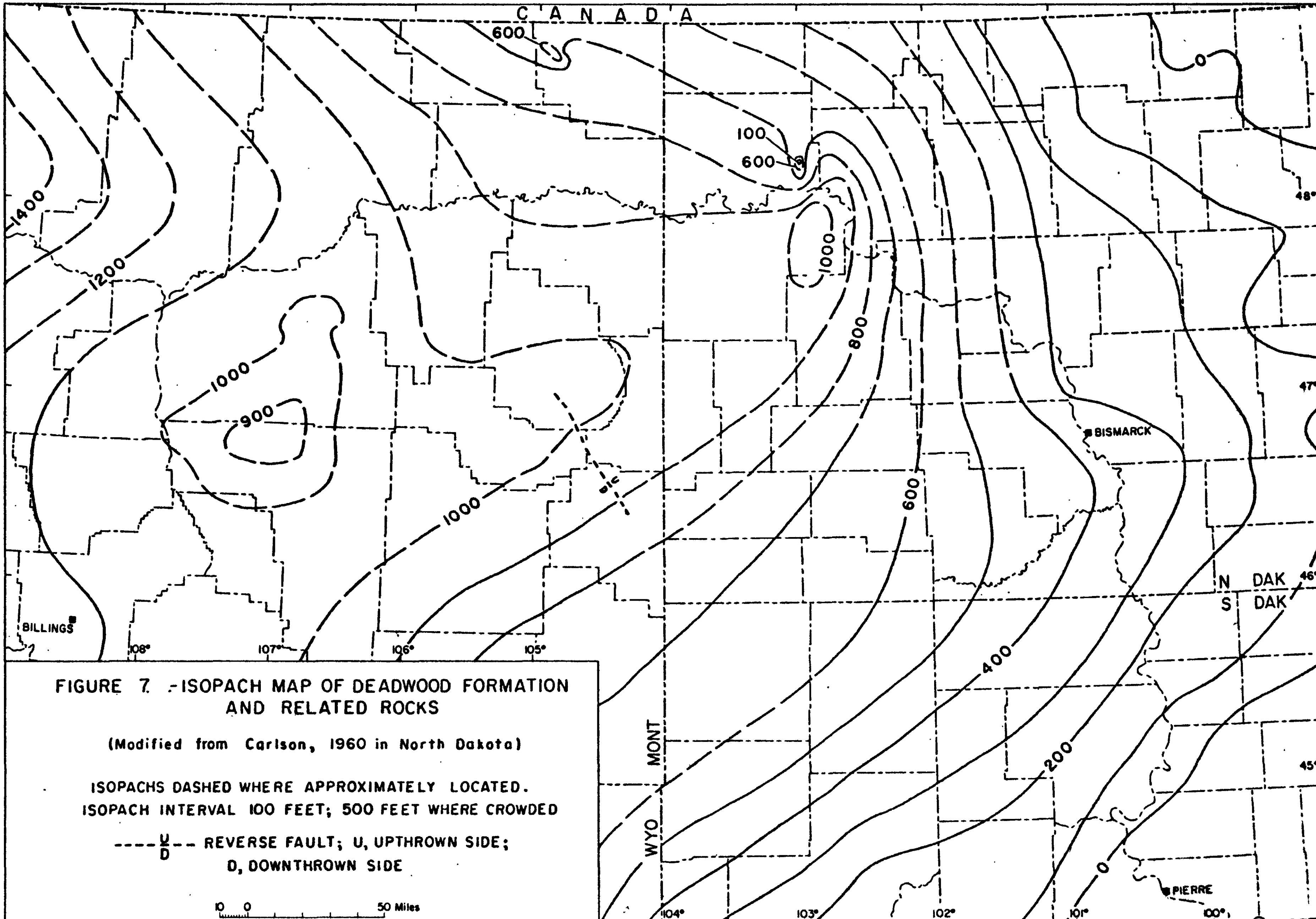

FIGURE 7. -ISOPACH MAP OF DEADWOOD FORMATION AND RELATED ROCKS

(Modified from Carlson, 1960 in North Dakota)

ISOPACHS DASHED WHERE APPROXIMATELY LOCATED.
ISOPACH INTERVAL 100 FEET; 500 FEET WHERE CROWDED

----U/D-- REVERSE FAULT; U, UPTHROWN SIDE; D, DOWNTHROWN SIDE

10 0 50 Miles

areas that reflect buried topography of the Precambrian surface may be revealed by future drilling.

The lithology of the Deadwood Formation cannot be described in detail, because the formation has been penetrated by only a few wells outside of eastern North Dakota. However, the basal bed appears to be a widespread grayish-red conglomeratic quartzitic sandstone, 30 to 200 feet thick, that grades downward locally to granite wash. This bed probably is continuous with the lithologically similar Flathead Quartzite of Middle Cambrian age, the basal Cambrian formation of the mountains west of the Williston basin. The lithology of the rest of the Deadwood Formation consists of interbedded greenish-gray and gray shale, gray limestone and limestone-pebble conglomerate, and light-gray, grayish-red, and brownish-red sandstone and siltstone.

East-west facies changes characterize the Deadwood Formation. In general, beds of limestone are thicker and constitute a greater proportion of the formation at the west side of the basin. Many beds of limestone probably thin eastward, however, and lens out between beds of shale. The beds of limestone in eastern Montana are concentrated in the upper part of the formation. Much of the shale grades into or interfingers with siltstone and sandstone eastward in North Dakota and South Dakota, but beds of limestone commonly are present near the top of the formation. Sandstone appears to constitute most of the formation along the eastern and southern margins of the basin. The facies of the Deadwood Formation probably parallel those of correlative Middle Cambrian to Lower Ordovician rocks, which are illustrated in a diagrammatic east-west cross section of southern Montana and northern Wyoming by Hansen (1957).

During Cambrian and Early Ordovician time, the Williston basin area was not a sedimentary basin but part of a broad shelf that bordered the Cordilleran miogeosyncline in western Montana and Idaho. The continuity of the Flathead Quartzite of Middle Cambrian age and the lower conglomeratic beds of Late Cambrian age in the Deadwood Formation suggests that they are the initial deposits of a sea that transgressed eastward from the miogeosyncline across this shelf during Middle to Late Cambrian time. The lithology of these beds suggests reworking of a granitic regolith on the irregular Precambrian surface. Facies in the remainder of the Deadwood Formation suggest a changing depositional pattern and passage of time as the shoreline moved eastward. Sandstone was deposited near the shorline, siltstone and shale farther from shore, and limestone at some distance from shore. The abundance of sandstone in eastern North Dakota and South Dakota is attributed to erosion of a landmass composed of the Sioux Quartzite. The age of the top beds of the Deadwood and correlative formations ranges from Late Cambrian in western Montana to Early Ordovician in the central part of the report area.

Winnipeg Formation

The Winnipeg Formation of Middle Ordovician age is correlated throughout the Williston basin from outcrops in southwestern Manitoba. In the subsurface, it generally comprises three units that have dissimilar distribution and are not everywhere present: a basal sandstone, a medial shale, and an upper dolomitic sandstone. These units were named as members of the Winnipeg in North Dakota by Carlson (1958) and were described in detail by Carlson (1960). The formal names are not used here, however, because the members cannot be everywhere differentiated. Moreover, the basal sandstone of the subsurface can be only tenuously correlated (Fuller, 1961, p. 1339) with the outcropping sandstone, from which its name is derived.

In the Williston basin, the Winnipeg Formation generally overlies the Deadwood Formation unconformably. However, in areas along the eastern margin, where the Deadwood is absent, the Winnipeg rests unconformably on Precambrian metamorphic rocks. Along the southwestern margin of the Williston basin, a bed of sandstone that underlies the Winnipeg Formation is here tentatively identified as the thin northern wedge of the Harding Sandstone of Middle Ordovician age (fig. 6). The Winnipeg is conformably overlain by the Red River Formation of Late Ordovician age or by correlative beds in the Whitewood Dolomite (fig. 6). In places the contact between the Winnipeg and Red River is gradational. Transitional beds that are considered part of the Winnipeg by Carlson (1958 and 1960) and the author are included at the base of the Red River Formation by Fuller (1961).

The Winnipeg Formation underlies all but the extreme western part of the Williston basin in north-central Montana (fig. 8). However, it is absent and probably was not deposited over the monadnock of Sioux Quartzite west of Pierre, S. Dak. The Winnipeg attains a maximum thickness of about 350 feet in northwestern North Dakota between the deepest part of the Williston basin and the south end of the Nesson anticline. From this area, it thins uniformly toward its western limit which trends northward through the central part of Montana. Sparse well control, however, prevents the location of isopachs (fig. 8) close to this limit. Thinning in a southeastward direction is interrupted by an arcuate trough that extends westward across southern North Dakota and southwestward across South Dakota (fig. 8).

A small area of slight thinning that may have resulted both from retarded subsidence and differential compaction marks the ancestral Nesson anticline (fig. 8) in northwestern North Dakota. The Precambrian monadnock there had been covered only by the uppermost beds of the Deadwood Formation prior to deposition of the Winnipeg. A broader area of thinning in western South Dakota and southeastern Montana (fig. 8) accentuates the west side of the trough that lies on the east near the Black Hills. The east side of this area of thinning marks the southwestern limit of the lower sandstone, which trends northward just inside South Dakota and northwestward in southeastern Montana. Retarded subsidence, which probably controlled

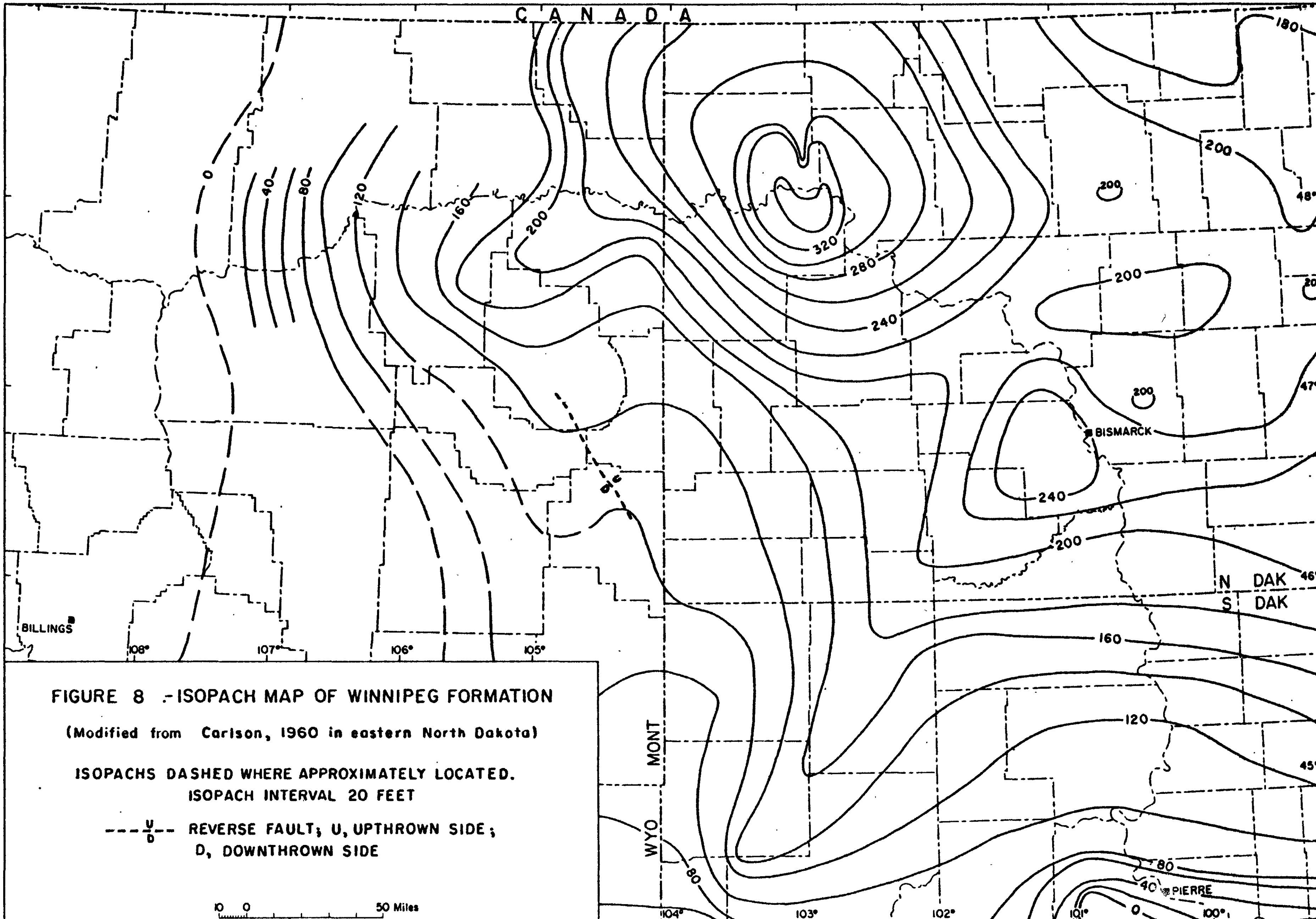

FIGURE 8 .-ISOPACH MAP OF WINNIPEG FORMATION

(Modified from Carlson, 1960 in eastern North Dakota)

ISOPACHS DASHED WHERE APPROXIMATELY LOCATED.
ISOPACH INTERVAL 20 FEET

---U/D-- REVERSE FAULT; U, UPTHROWN SIDE; D, DOWNTHROWN SIDE

10 0 50 Miles

that limit, is the first indication of vertical movement in the area of the ancestral Cedar Creek anticline.

The lithology of the lower unit of the Winnipeg Formation is light-gray to white, very fine to medium-grained, quartzose sandstone. The sandstone is well rounded, friable, well sorted, and clean in eastern North Dakota, but rounded to subangular, firmly cemented, poorly sorted, and silty or argillaceous near its center of maximum accumulation (Carlson, 1960). The middle unit generally consists of greenish-gray waxy noncalcareous shale. In southeastern Montana, South Dakota, and southern North Dakota, the upper unit commonly consists of light-gray dolomitic sandstone and siltstone that locally grade to sandy dolomite. However, according to Carlson (1960), the sandstone and siltstone grade northward in North Dakota to greenish-gray, in part silty, calcareous shale and the area of coarser clastics coincides with the area of maximum accumulation of the upper unit in the south-central part of the state. Fuller (1961) considered the shale facies of the upper member as part of the overlying Red River Formation.

The lower sandstone of the Winnipeg Formation is a discrete unit that rarely intertongues with the overlying green shale in the area east of a line connecting the Camp Crook and Cedar Creek anticlines and extending northwestward past the west side of the Poplar dome (fig. 1). Its thickness is generally only 10 to 50 feet, except within the 220-foot isopach of the Winnipeg Formation (fig. 8) in northwestern North Dakota and northeastern Montana. There its thickness increases abruptly to 100 feet or more and reaches a maximum of about 165 feet just east of the Nesson anticline.

The medial shale is a mappable unit in North Dakota, South Dakota, and eastern Montana. In North Dakota, it exceeds 100 feet in thickness in all but the southwestern and northwestern corners of the state. Its maximum thickness is about 170 feet in the area where the formation is thickest south of the Nesson anticline.

The upper unit has a different distribution from that of the lower two units of the Winnipeg Formation. It is thicker in the southern part of the Williston basin and the arcuate trough in southern North Dakota and western South Dakota is the axis of its thickest accumulation. The upper unit attains a maximum thickness of about 80 feet west of Bismarck, N. Dak., where the thickness of the formation exceeds 240 feet (fig. 8). From there it thins northward and it is absent in the northwest corner of North Dakota and in northeastern Montana.

Between the 105°30' and 106° meridians in Montana, the Winnipeg Formation undergoes an abrupt facies change and the medial shale disappears westward apparently by interfingering with sandstone. Because the upper unit is absent in northern Montana, the medial shale appears to interfinger westward with the lower sandstone there. However, because the lower unit is absent west of the Cedar Creek anticline, the medial shale appears to interfinger with the upper sandstone in southern Montana. Thus, the medial shale is a facies of both the upper and lower sandstones. Consequently, the exclusion from the Winnipeg by Fuller (1961) of beds above the green shale is untenable in eastern Montana. West of the 106° meridian in Montana, the Winnipeg Formation is a sandstone containing thin lenses of shale and none of the units present in North Dakota is recognizable.

Middle Ordovician strata furnish the first evidence for the existence of a sedimentary Williston basin (Sandberg and Hammond, 1958, p. 2329). The initial basin in northwestern North Dakota and northeastern Montana first centered around an area just south of the Nesson anticline (fig. 8). Later, during deposition of the upper sandstone the center of accumulation shifted southeastward to the area west of Bismarck, N. Dak. The Winnipeg Formation, in contrast to the underlying Deadwood Formation, was not connected with deposits in the Cordilleran geosyncline on the west. The Winnipeg was deposited in a shallow epicontinental sea that extended much farther east and south than the limits of the Williston basin, as demonstrated by Fuller (1961).

Red River and Stony Mountain Formations

The Red River Formation and the conformably overlying Stony Mountain Formation are of Late Ordovician age. They are correlated throughout the Williston basin from outcrops along its east edge in southwestern Manitoba. Many workers would prefer to assign a Middle

Ordovician age to all or part of the Red River, but, according to Ross (1957), there is insufficient paleontologic evidence at present for such an assignment. Stratigraphic considerations favoring a Middle Ordovician age are summarized by Fuller (1961, p. 1354-1358).

The Red River Formation conformably overlies the Winnipeg Formation. However, it unconformably overlies rocks related to the Deadwood Formation in north-central Montana where the Winnipeg is absent. Throughout most of the Williston basin, the Stony Mountain is conformably overlain by the Stonewall Formation of Late Ordovician age, but where the Stonewall is eroded, one of several younger formations rests on the Stony Mountain or Red River. The Souris River Formation of Late Devonian age rests unconformably on a narrow belt of the Stony Mountain in north-central Montana and on progressively older beds of the Red River farther west. The Duperow Formation of Late Devonian age rests unconformably on the Stony Mountain or Red River in most of South Dakota, but the Souris River, which locally underlies the Duperow, rests on the Stony Mountain in part of north-central South Dakota. The Englewood Limestone of Early Mississippian age truncates the Duperow Formation and unconformably overlies the Red River near the Black Hills.

The Red River Formation underlies the entire Williston basin except for the area of the small monadnock west of Pierre, S. Dak., but the overlying Stony Mountain Formation is less widespread (fig. 9). The combined thickness of the Red River and Stony Mountain is

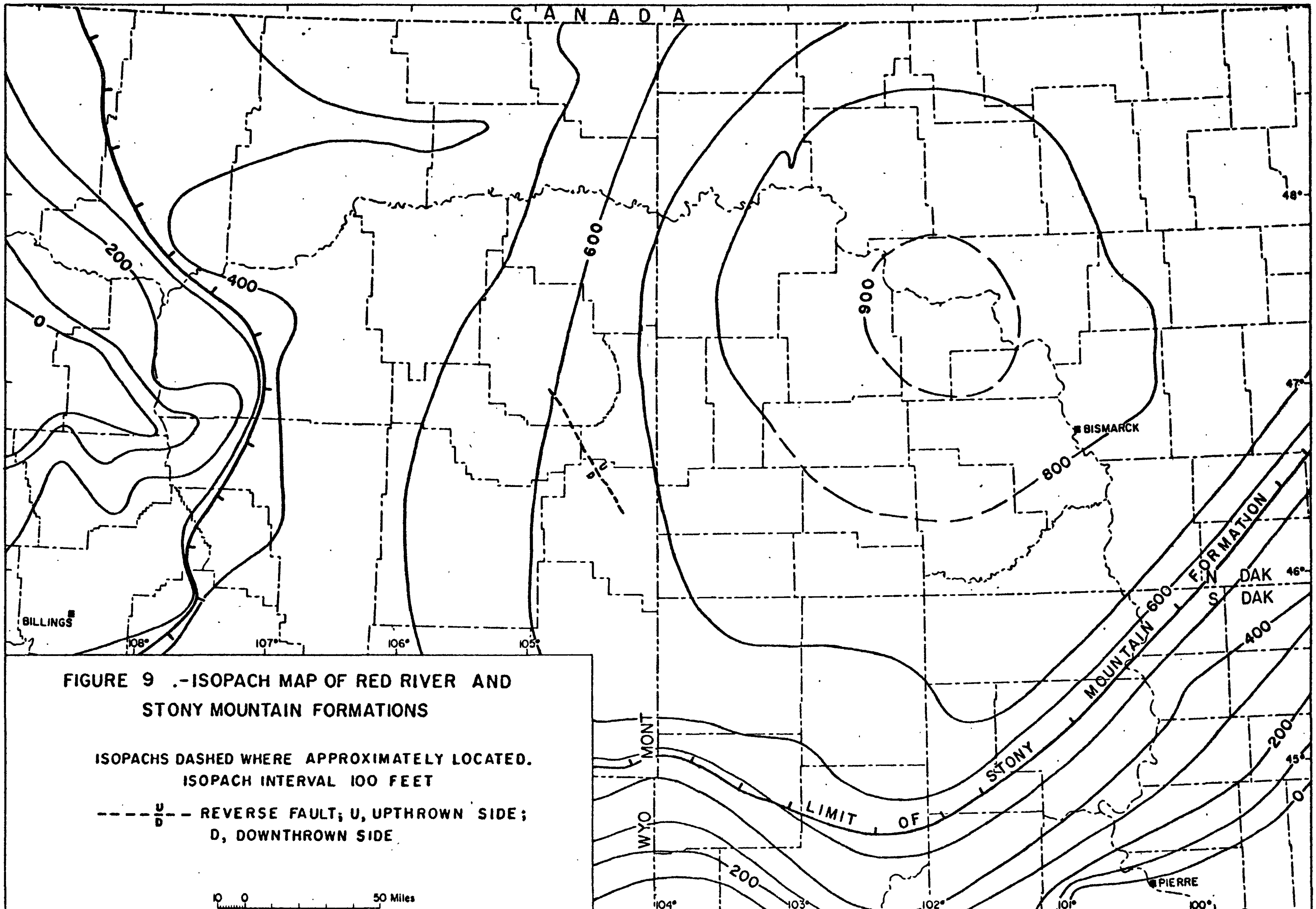

FIGURE 9 .-ISOPACH MAP OF RED RIVER AND STONY MOUNTAIN FORMATIONS

ISOPACHS DASHED WHERE APPROXIMATELY LOCATED.
ISOPACH INTERVAL 100 FEET

---U/D-- REVERSE FAULT; U, UPTHROWN SIDE; D, DOWNTHROWN SIDE remarkably uniform except along the western and southern margins of the basin. Thicknesses range from about 550 feet west of the Cedar Creek anticline and from 675 feet in north-central South Dakota to about 850 feet in east-central North Dakota. A thickness greater than 870 feet is known in only one well. The formations are only about 15 feet thinner in an elongate area in north-central Montana than in adjacent areas.

The Stony Mountain and Red River were protected from pre-Devonian erosion by the overlying Stonewall Formation, whose limit is parallel to and just inside the limit of the Stony Mountain. Beyond the limit of the Stonewall, the Stony Mountain was truncated in a belt about 25 miles wide. Beyond the limit of the Stony Mountain, the Red River was thinned greatly, as indicated by the close spacing of isopachs in central Montana and northern South Dakota (fig. 9). It was completely removed by pre-Devonian erosion on the Central Montana uplift and southeast of Pierre, S. Dak. Slight thinning of the Red River and Stony Mountain in the area of the ancestral Nesson anticline suggests that subsidence was slightly retarded.

The Red River Formation ranges from 410 to about 700 feet in thickness in the Central Williston basin, but it thins to about 300 feet where it is uneroded in north-central Montana. It consists largely of gray and brownish-gray slightly argillaceous fossiliferous limestone in the Central Williston basin but grades to very light gray, white, and mottled yellowish-gray and light-gray largely unfossiliferous dolomite on the margins. The basal beds are generally sandy or silty. The upper part of the Red River contains interbeds of anhydrite, and, according to Fuller (1961), it represents three complete evaporitic cycles.

The Stony Mountain Formation ranges only from 140 to about 200 feet in thickness in the Central Williston basin, but it thins to 90 feet in eastern Montana where it is abruptly truncated westward. It generally comprises three units in the Central Williston basin. The lower unit is gray to brownish-gray highly argillaceous limestone grading to calcareous shale. The contact between this unit and the much purer carbonate of the underlying Red River generally provides one of the most easily recognized horizons, on mechanical and lithologic well logs, in the Williston basin. The medial unit is yellowish-gray and brownish-gray dolomitic limestone containing bedded anhydrite at the top. The upper unit, which is much thinner than either of the lower units, is gray shaly and sandy limestone interbedded with calcareous shale.

The middle unit of the Stony Mountain Formation grades westward to dolomite that is lithologically similar to dolomite in the underlying Red River in eastern Montana. The upper and lower units thin abruptly westward in the same area. In north-central Montana, the lower unit of the Stony Mountain is absent and the Red River and Stony Mountain Formations are difficult to differentiate. Along the southwestern margin of the Williston basin, the lower unit is represented by a thin bed of dolomite that is lithologically similar to underlying and overlying beds and is distinguishable from them only by its higher radioactivity as shown by gamma-ray logs.

The Red River and Stony Mountain Formations merge southwest of the report area to form the Bighorn Dolomite of Late Ordovician age, which is described in detail by Richards and Nieschmidt (1961). However, the Bighorn Dolomite in the Little Rocky Mountains and the Whitewood Dolomite of Late Ordovician age in the Black Hills represent only the lower beds of the Red River (fig. 6).

During Late Ordovician time the Williston basin was an intracratonic basin that apparently had no direct western connection with a Cordilleran geosyncline. The Williston basin was covered by the shallow waters of a huge epicontinental sea that encompassed most of the interior United States and probably extended into northern Canada. Deposition in the slightly deeper waters of a basin is suggested for the dark-gray argillaceous limestone facies of the Red River and Stony Mountain in North Dakota, whereas deposition on a shelf is suggested for their light-gray dolomite facies in Montana and South Dakota. The thickest accumulation of these formations is in east-central North Dakota (fig. 9). Thus, during Late Ordovician time the basin center migrated about 60 miles northwest of its position during the deposition of the upper member of the Winnipeg, whereas the sea transgressed much farther westward across the shelf area in Montana.

Stonewall and Interlake Formations

The Interlake Formation was defined from outcrops in southwestern Manitoba as a group consisting of the thin Stonewall Formation at the base and four overlying informal "members," designated by letters. It was anticipated that the upper unnamed part of the group might later be divided into formations corresponding to the informal "members," but subsurface studies have not produced any mappable subdivisions. Therefore, in current informal subsurface usage, which is followed herein, the Stonewall Formation is retained but assigned a Late Ordovician age, and the Interlake Formation of Silurian age is restricted to the previously unnamed beds. Ross (1957) included the Stonewall in the Stony Mountain Formation because it seemed to be "assignable to the Upper Ordovician"; he proposed Bighorn Group to include the Red River and the redefined Stony Mountain Formation in the Williston basin. However, this classification is not used herein because the Stonewall and Interlake cannot be everywhere differentiated, whereas the Stonewall and Stony Mountain are separated by a sharp contact. The distribution of the Stonewall closely parallels that of the lithologically similar and conformably overlying Interlake and, unlike the underlying Stony Mountain and Red River Formations, the Stonewall is not equivalent to any part of the outcropping Bighorn Dolomite.

The Stonewall Formation conformably overlies the Stony Mountain Formation. The Interlake Formation generally is unconformably overlain by the Elk Point Group of Middle Devonian age and beyond the limit of the Elk Point Group by the Dawson Bay Formation of Middle Devonian age. Around the margins of the basin, the Interlake, or the Stonewall in areas where the Interlake is absent, is unconformably overlain by either the Souris River or Duperow Formation. Locally on domes of the ancestral Cedar Creek anticline, the Interlake is unconformably overlain by the Madison Group of Mississippian age.

The Stonewall and Interlake are largely confined to the Williston basin, but they extend a short distance into the northern Powder River Basin (fig. 10). They attain a maximum combined thickness of about 1,200 feet at the south end of the Nesson anticline in northwestern North Dakota, whence they thin radially toward their limits.

Slight thinning of the Stonewall and Interlake Formations on the ancestral Nesson anticline (fig. 10) was caused by further retarded subsidence. The irregular configuration of isopachs in east-central Montana (fig. 10) resulted from earliest Mississippian folding, faulting, and erosion of the ancestral Cedar Creek anticline. A greater thickness of the formations was preserved from erosion on the downthrown west side of a high-angle reverse fault that offset the steep west limb of the ancestral anticline. The five areas of thinning east of the fault resulted in part from earliest Mississippian erosion of domes, from which the overlying Devonian rocks were

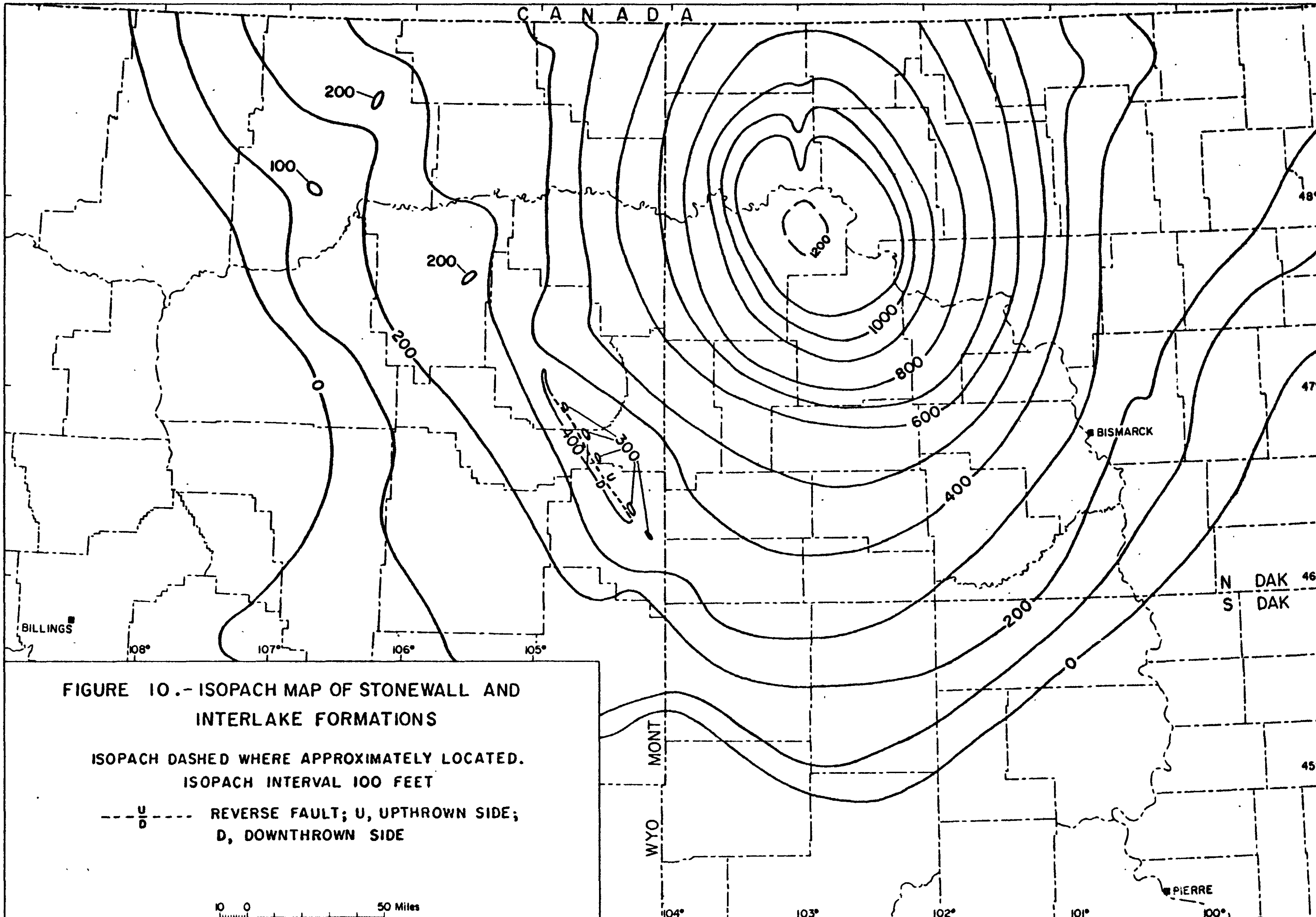

FIGURE 10.- ISOPACH MAP OF STONEWALL AND INTERLAKE FORMATIONS

ISOPACH DASHED WHERE APPROXIMATELY LOCATED.
ISOPACH INTERVAL 100 FEET

---U/D---- REVERSE FAULT; U, UPTHROWN SIDE; D, DOWNTHROWN SIDE stripped, along the crest of the ancestral anticline. Small areas of thinning in east-central and north-central Montana are channels cut into the Interlake during Early Devonian time.

The Stonewall Formation ranges in thickness from 50 to 100 feet where it was protected from erosion by the overlying Interlake Formation. The lithology of the Stonewall is predominantly dolomite that is brownish gray to light brownish gray in the Central Williston basin and yellowish gray to white in surrounding areas. The basal 10 to 20 feet is commonly sandy and about 5 to 10 feet near the middle is locally shaly.

The Interlake Formation ranges from 300 to about 1,100 feet in thickness in the Central Williston basin where it consists of interbedded brownish-gray, yellowish-gray, and light-gray to white dolomite and dolomite breccia. Many of the dolomite beds are anhydritic and thin beds of anhydrite may be found locally in any part of the formation. On the margins of the basin the Interlake is predominantly very light gray to white dolomite. The formation is characterized by many minor facies changes and few if any beds are widespread. Near the Nesson anticline, however, a locally persistent bed of grayish-red shaly dolomite grading to shale is present about 500 feet above the base.

During latest Ordovician and Silurian time, the Williston basin was a deeply subsiding intracratonic basin surrounded by a wide, stable shelf. The size and shape of the basin was suggested by the close spacing and regularity of isopachs within the 400-foot isopach (fig. 10). The shelf area, indicated by the widely spaced isopachs, lay outside the 400-foot isopach. In the basin the Stonewall and Interlake Formations contain both light- and dark-colored dolomite but on the shelf the dolomite is predominantly very light colored.

The absence of facies indicative of shoreline deposition at or near the present limits and stratigraphic evidence for one to three episodes of intense erosion during the Devonian suggest that the Interlake was originally thicker and extended much farther east, south, and west. As sedimentation was continuous from Ordovician to Silurian time in the Williston basin, it is suggested that the dimensions of the Silurian sea may have approached those of the Orodvician sea. The thickest accumulation of the Stonewall and Interlake Formations (fig. 10) is about 60 miles northwest of the thickest accumulation of the Red River and Stony Mountain Formations (fig. 9). Thus, the depositional center of the Williston basin migrated a total distance of 120 miles northwestward during nearly continuous deposition from late Middle Ordovician through the close of Silurian time.

Devonian rocks

Rocks of Devonian age underlie the entire Williston basin except for the area of the small monadnock west of Pierre, S. Dak., where they were not deposited, and several small areas along the crest of the ancestral Cedar Creek anticline (fig. 11). They attain a maximum thickness of about 2,000 feet along the international boundary in northwestern North Dakota, whence they thin southward toward their erosional limit in South Dakota and southeastern Montana. An area of thinning, caused by retarded subsidence marks the ancestral Nesson anticline, which is indicated by the indentation of the 1,600-foot isopach (fig. 11). This ancestral feature trended northwestward during the Devonian, whereas an earlier ancestral anticline in this area had trended northward during the early Paleozoic (figs. 7-10). The ancestral Nesson anticline and several other ancestral structural features, whose intermittent uplift influenced the pattern of sedimentation, are prominent on isopach maps of Devonian formations (Sandberg, 1961a).

Lower, Middle, and Upper Devonian rocks are present in the Williston basin. Each series generally overlies an unconformity, but in the Central Williston basin deposition was continuous between the Middle and Upper Devonian. Discontinuous deposits at the base of the Devonian System were tentatively referred to the Beartooth Butte Formation of Early Devonian age by Sandberg (1961). The Middle Devonian series is divided into the Winnipegosis and Prairie Formations of the Elk Point Group and the overlying Dawson Bay Formation. The Prairie is divided into a lower member and an upper, salt member. The Upper Devonian Series is divided, in ascending order, into the Souris River Formation, the Jefferson Group, consisting of the Duperow

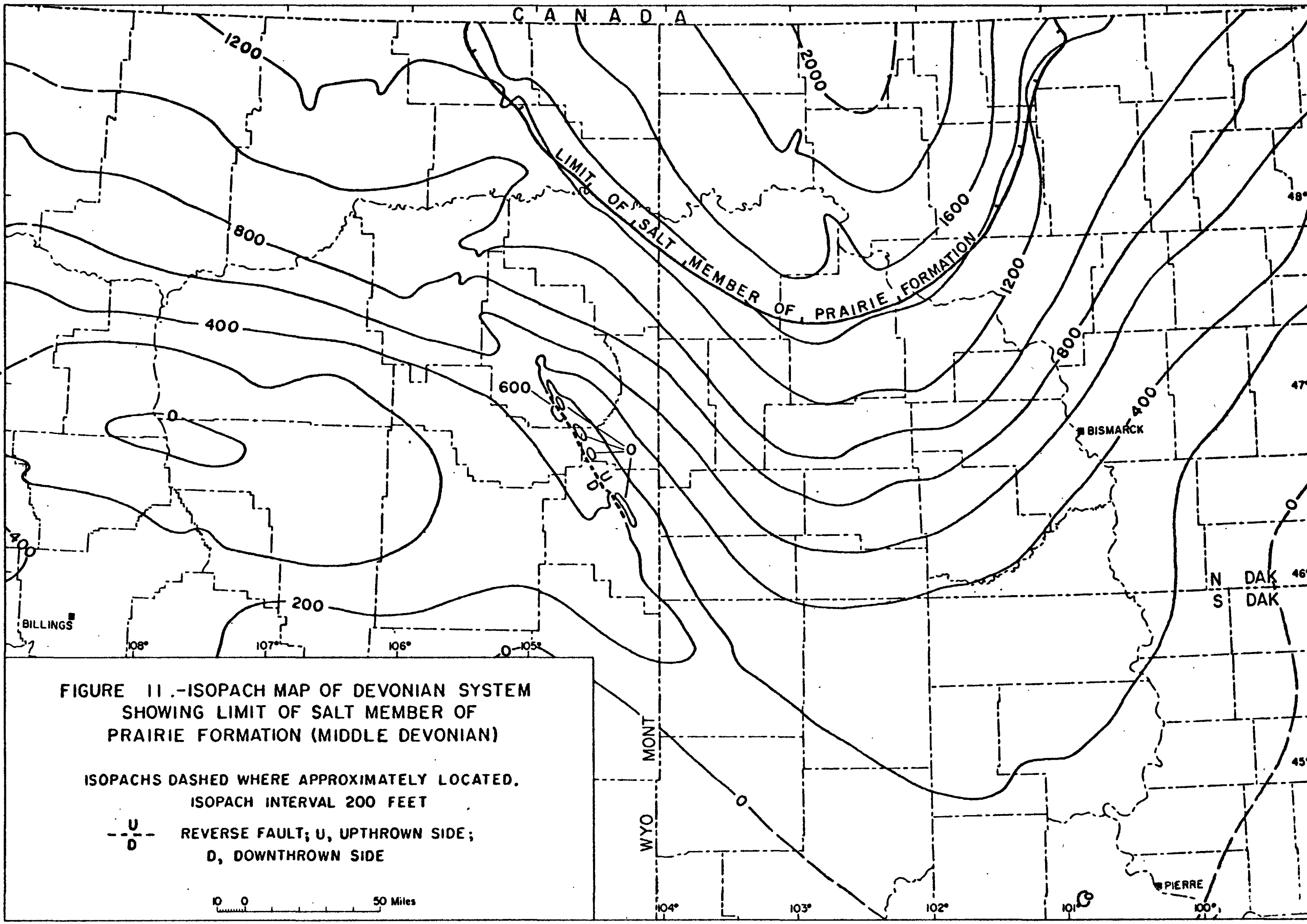

FIGURE 11.-ISOPACH MAP OF DEVONIAN SYSTEM SHOWING LIMIT OF SALT MEMBER OF PRAIRIE FORMATION (MIDDLE DEVONIAN)

ISOPACHS DASHED WHERE APPROXIMATELY LOCATED.
ISOPACH INTERVAL 200 FEET

--U/D-- REVERSE FAULT; U, UPTHROWN SIDE; D, DOWNTHROWN SIDE and Birdbear Formations, and the Three Forks Formation. The derivation of this nomenclature and the detailed stratigraphy of the formations are discussed by Sandberg and Hammond (1958).

The Beartooth Butte(?) Formation, generally less than 50 feet thick, consists of grayish-red dolomitic siltstone or shale and dolomite breccia or conglomerate. It fills channels or sinkholes in any pre-Devonian rocks directly underlying Middle or Upper Devonian rocks.

The Elk Point Group attains a maximum thickness of about 700 feet east of the Nesson anticline, and extends only a short distance outside the Central Williston basin. Its basin facies is separated from the surrounding shelf facies approximately by a line parallel to and a few miles outside the limit of the salt member of the Prairie Formation (fig. 11).

The Winnipegosis Formation of the Elk Point Group ranges from 0 to 300 feet in thickness. In the Central Williston basin, the lower three-fifths of the formation is grayish-red and dark-gray dolomitic siltstone and highly argillaceous limestone and the upper two-fifths is brownish-gray and dark-gray fossil-fragmental limestone. The shelf facies of the Winnipegosis is predominantly light-gray dolomite underlain by a thin bed of grayish-red silty dolomite.

The Prairie Formation of the Elk Point Group underlies the deepest part of the Williston basin and ranges in thickness from 0 to about 525 feet. It is divided into a lower member that is mostly anhydrite and dolomite locally interbedded with shale and halite and a salt member that is predominantly halite containing some sylvite and a few thin beds and stringers of shale. A more complete discussion of the stratigraphy of the Prairie Formation was presented by Sandberg in TEI-725 (Pierce and Rich, 1958).

The salt member, which is more restricted but much thicker than the lower member, ranges from 0 to about 400 feet in thickness (fig. 12). The depth of the top of the salt member ranges from 6,000 to 12,100 feet below the surface. The salt member has been partly or completely dissolved in some areas, such as northeastern Montana (fig. 12), and indirect evidence suggests that solution is presently taking place in other areas.

The Dawson Bay Formation ranges in thickness from 0 to 185 feet and is more widespread than the Elk Point Group. The limit of the Dawson Bay is parallel to and about 100 miles outside the limit of the salt member of the Prairie Formation (fig. 11). The Dawson Bay is divided into an argillaceous member overlain by a carbonate member, which constitutes most of the formation in the Central Williston basin. The argillaceous member consists of grayish-red silty dolomite. The basin facies of the carbonate member is brownish-gray dolomitic limestone, whereas the shelf facies is light-gray dolomite.

The Souris River Formation ranges in thickness from 0 to 340 feet and is more widespread than the Middle Devonian formations. It was cyclically deposited during minor fluctuations of a transgressive sea.

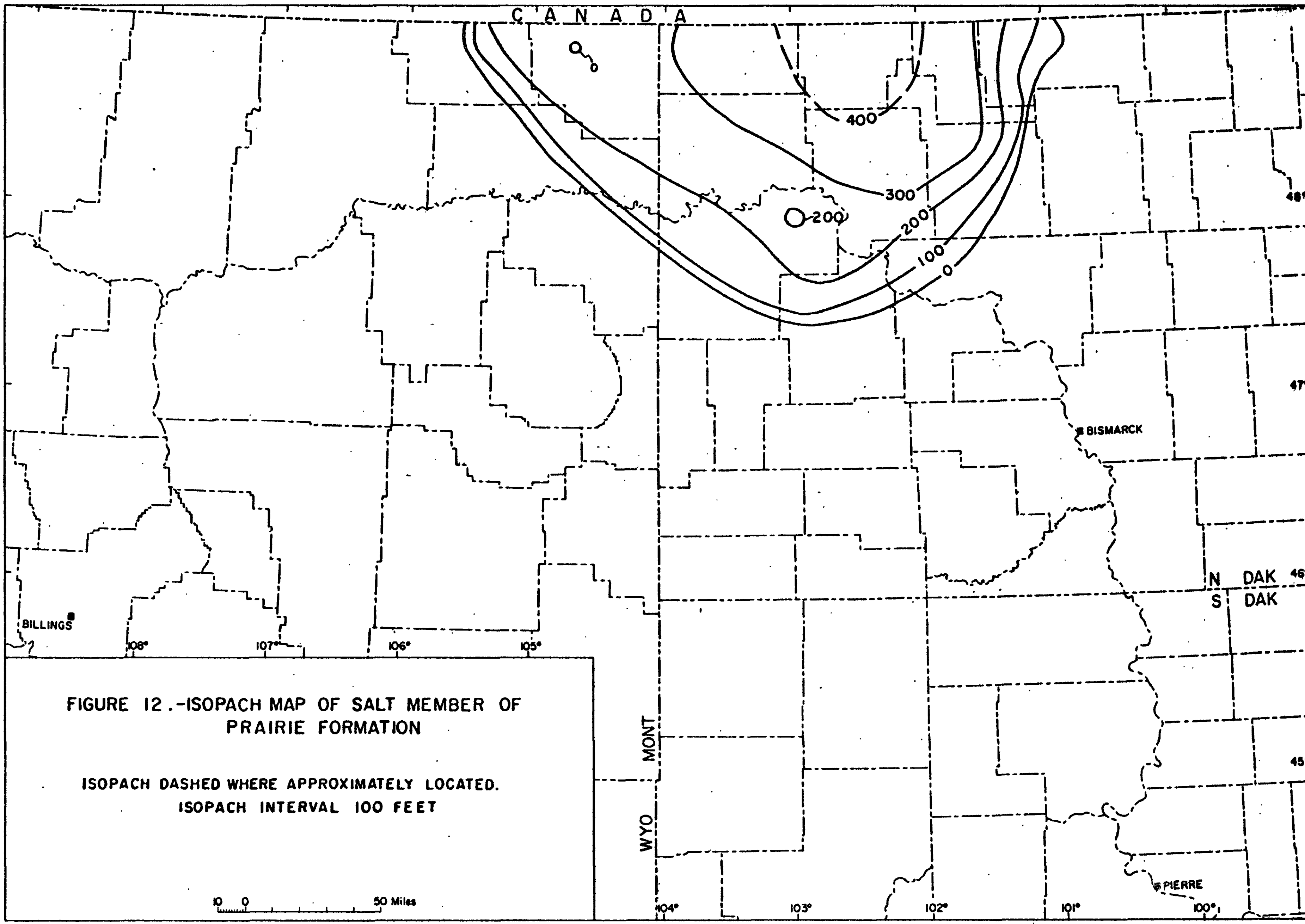

FIGURE 12.-ISOPACH MAP OF SALT MEMBER OF PRAIRIE FORMATION

ISOPACH DASHED WHERE APPROXIMATELY LOCATED.
ISOPACH INTERVAL 100 FEET

The Souris River consists of gray, greenish-gray, and brownish-gray thinly interbedded shaly dolomite, argillaceous limestone, shale, siltstone, and anhydrite.

The Jefferson Group reaches a maximum thickness of 725 feet in north-central Montana, but it does not exceed 570 feet in thickness in the Central Williston basin. From the international boundary it thins progressively southward in the report area.

The Duperow Formation of the Jefferson Group ranges in thickness from 0 to 600 feet and is the most widespread Devonian formation. Its limit generally coincides with the limit of the Devonian System (fig. 11). It was cyclically deposited during major fluctuations of a trangressive sea. The Duperow consists of gray, brownish-gray, and yellowish-gray limestone, dolomitic limestone, dolomite, and anhydrite interbedded with thinner beds of greenish-gray shale and siltstone.

The Birdbear Formation of the Jefferson Group ranges from 0 to 125 feet in thickness, but it is almost everywhere 75 to 115 feet thick. It was deposited during the later part of a single major sedimentary cycle. The Birdbear consists uniformly of light-gray to medium brownish-gray dolomite and limestone. The upper quarter is anhydritic dolomite or anhydrite.

The Three Forks Formation ranges in thickness from 0 to 240 feet and is thickest in the Central Williston basin, east and south of the Nesson anticline. It was deposited in a slightly regressive sea. The Three Forks generally consists of greenish-gray, grayish-orange, and grayish-red dolomitic siltstone and shale, but its color is predominantly grayish red along the eastern margin of the basin.

Middle Devonian rocks rest unconformably on the Interlake Formation in the Central Williston basin. The Souris River or the more extensive Duperow Formation unconformably overlies the Interlake, Stonewall, Stony Mountain, or Red River Formations on the margins. Upper Devonian rocks are disconformably overlain by the Bakken Formation of Late Devonian(?) and Early Mississippian age. Beyond the limit of the Bakken, Upper Devonian rocks are overlain unconformably by the Englewood or Lodgepole Limestone of Early Mississippian age along the southern and eastern margins of the basin. In northeastern North Dakota, Jurassic rocks locally truncate the Lodgepole Limestone and rest unconformably on Upper or Middle Devonian rocks.

During Early Devonian time most of the Williston basin area was a landmass, and the pre-Devonian formations, which were at the surface, were deeply weathered and eroded.

During Middle Devonian time a sea transgressed southeastward from northern Alberta and occupied an intracratonic basin in northwestern North Dakota and northeastern Montana. This basin was centered near the international boundary east of the Nesson anticline, about 60 miles northeast of the depositional center of the Stonewall and Interlake Formations (fig. 10). Slight regional uplift accompanied by accelerated subsidence of the basin contracted the depositional area and resulted in precipitation of the evaporites of the Prairie Formation. Near the end of Middle Devonian time rapid expansion of the seas caused a strong influx of red mud, which capped the Prairie and prevented its dissolution when normal salinity was re-established.

At the beginning of Late Devonian time when the Souris River Formation was deposited, the sea spread southward and westward from the restricted Middle Devonian basin across shelf areas in South Dakota and Montana. The Williston basin gradually lost its identity as a depositional center and during deposition of the Jefferson Group, the entire report area was part of a huge shelf across which the sea transgressed southward.

A restriction of the seas that began during deposition of the upper part of the Birdbear Formation continued intermittently into latest Devonian time when the Three Forks was deposited. In the Central Williston basin deposition was essentially continuous between the Three Forks and the overlying Bakken Formation, but along the western margin it was abruptly terminated by regional uplift.

Intense uplift followed by erosion of ancestral structural features that previously had been subjected only to slight movement or to retarded subsidence is evidenced by several areas of thinning, shown on the isopach map (fig. 11). Devonian rocks in north-central Montana thin southward as a result of earliest Mississippian erosion toward the ancestral Central Montana uplift, where they were completely removed. In an area 120 miles long and 10 miles wide in east-central Montana, Devonian rocks were thinned from an original thickness of as much as 650 feet to less than 200 feet by earliest Mississippian erosion of the ancestral Cedar Creek anticline. They were completely removed from several domes along the crest. An inferred high-angle reverse fault (figs. 4, 7-11), about 1 to 3 miles west of the crest of the ancestral Cedar Creek anticline, resulted from compressive forces and offset the steep west limb (Sandberg, 1961a).

Bakken Formation

A thin sequence of shale and dolomite that lies between the Three Forks Formation and the Madison Group was named the Bakken Formation in the area of the Nesson anticline. The Bakken Formation is of Late Devonian(?) and Early Mississippian age and is disconformable with underlying and overlying strata.

The Bakken Formation underlies the northern part of the Williston basin and reaches a maximum thickness of about 140 feet on the central part of the Nesson anticline (fig. 13). It is thicker than 60 feet in a basin that trends northwestward in northwestern North Dakota and westward for a short distance into northeastern Montana. Elsewhere, its thickness is generally less than 40 feet. However, anomalous isopachs adjacent to the re-entrant in its eastern limit (fig. 13) suggest that a pre-Madison erosional valley cut across a secondary center of accumulation there.

Although it may be partly latest Devonian, the Bakken was considered to be the basal formation of the Mississippian System in the northern Williston basin for the purpose of structure contouring. The base of the Bakken is as much as 9,000 feet below sea level in the Central Williston basin and about 2,000 to 2,500 feet below sea level on the margins (fig. 14).

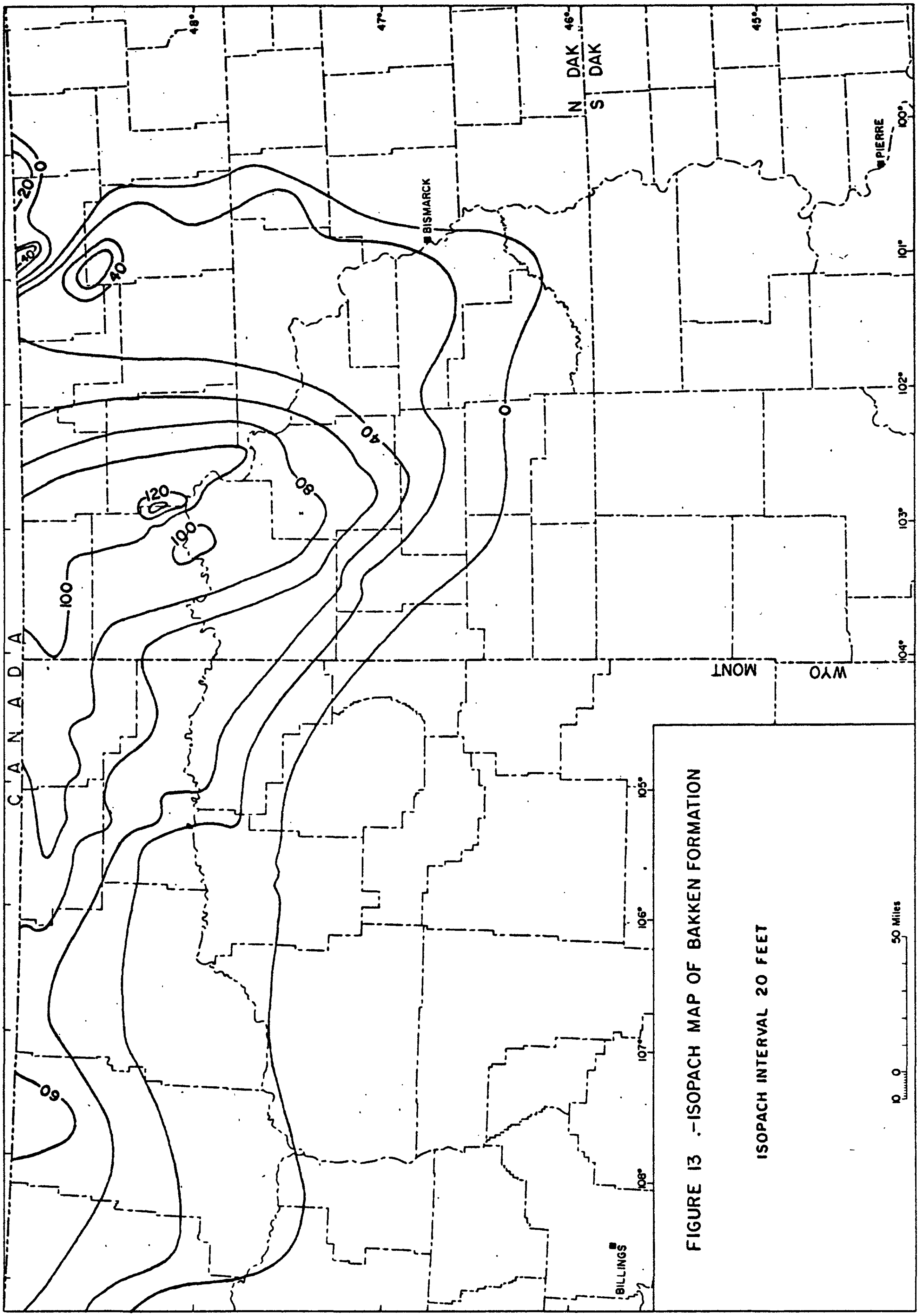

FIGURE 13 .–ISOPACH MAP OF BAKKEN FORMATION

ISOPACH INTERVAL 20 FEET

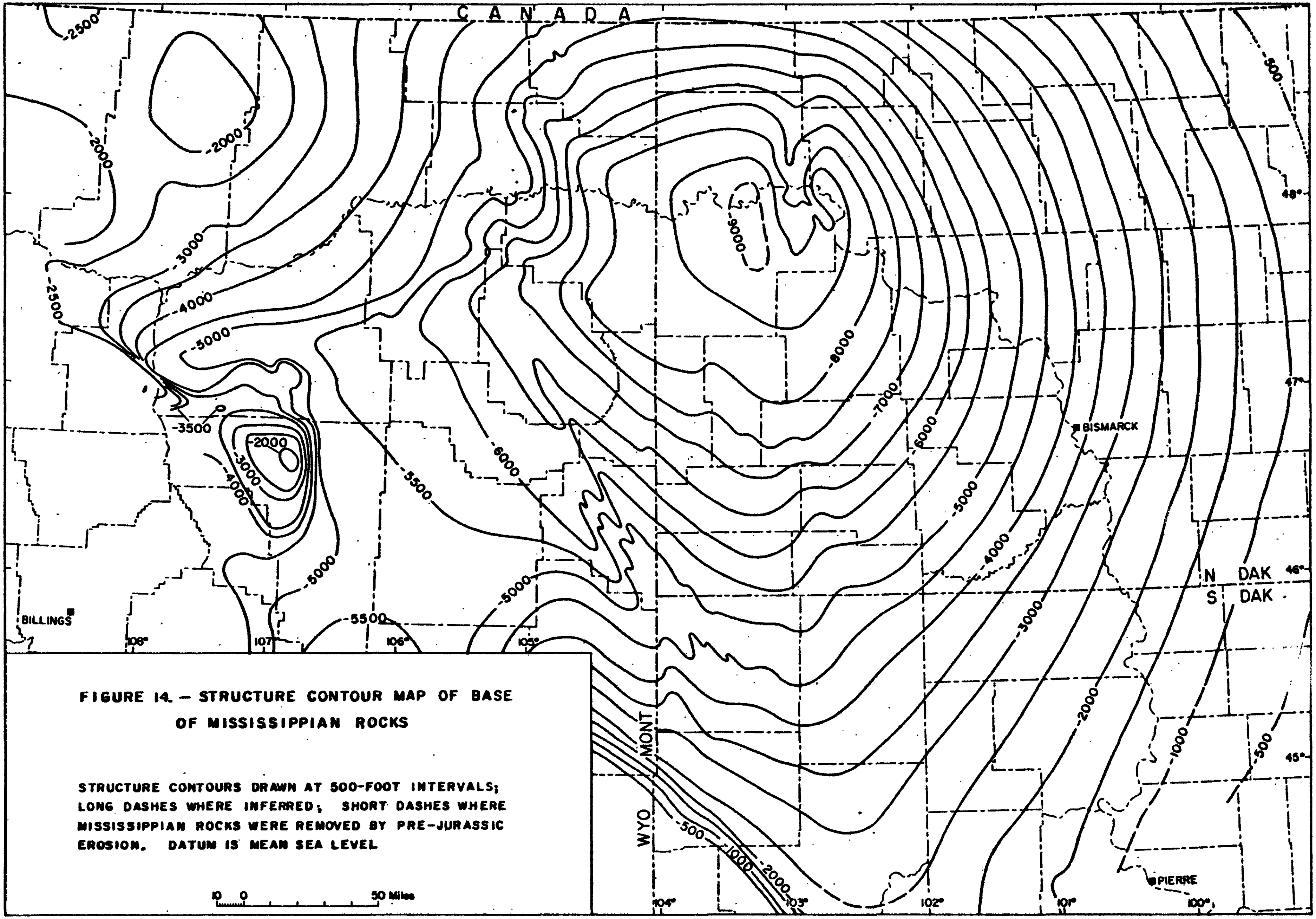

FIGURE 14. — STRUCTURE CONTOUR MAP OF BASE OF MISSISSIPPIAN ROCKS

STRUCTURE CONTOURS DRAWN AT 500-FOOT INTERVALS; LONG DASHES WHERE INFERRED; SHORT DASHES WHERE MISSISSIPPIAN ROCKS WERE REMOVED BY PRE-JURASSIC EROSION. DATUM IS MEAN SEA LEVEL

The Bakken Formation consists of two radioactive black noncalcareous shales separated by light-gray dolomitic siltstone and sandstone or silty dolomite. The lower black shale is thicker but less extensive than the upper. In east-central and north-central Montana and west-central North Dakota, first the lower black shale and then the medial siltstone thins southward and disappears by onlap. The upper black shale is truncated by pre-Madison erosion at the limit of the formation.

Penecontemporaneously with the deposition of the Bakken Formation in the northern part of the Williston basin, the lithogenetically related Englewood Limestone was deposited in the southern part of the Williston basin and in the area of the Black Hills (fig. 6). Although the Englewood has been considered to be of Early Mississippian age, recent paleontologic evidence (G. Klapper and W. M. Furnish, written communication, Sept. 10, 1961) and regional correlation by the author indicate that it is in part of Late Devonian age.

In latest Devonian(?) and earliest Mississippian time, the margins of the Williston basin were partly above sea level. The Bakken Formation was deposited in a restricted basin while the ancestral Central Montana uplift, Cedar Creek anticline, and other structural features were being intermittently uplifted and eroded. During episodes of lessened or no uplift, the Bakken Formation was deposited as far south as the northern part of the ancestral Cedar Creek anticline. During the same episodes the Englewood Limestone was deposited as far north as the southern part of the anticline. Although the two depositional basins may have been joined locally and briefly, renewed uplift tilted the most extensive beds of each formation and resulted in erosion which truncated them in the vicinity of the ancestral Cedar Creek anticline. Evidence of this tectonic activity is seen at a few localities in the northern Black Hills, where an angular unconformity separates the Englewood Limestone from the overlying Pahasapa Limestone of Early Mississippian age.

Madison Group

The Madison Group is correlated throughout the Williston basin from outcrops in southwestern Montana, where it was originally named the Madison Limestone. In the Williston basin, the Madison Group is divided, in ascending order, into the Lodgepole and Mission Canyon Limestones of Early Mississippian age and the Charles Formation of Late Mississippian (Meramec) age. These formations are successively conformable and difficult to differentiate in some areas where the Mission Canyon is in part a facies of the Lodgepole or of the Charles.

The Madison Group disconformably overlies the Bakken Formation in the northern part of the Williston basin. In South Dakota, the Madison or its outcropping equivalent, the Pahasapa Limestone, disconformably or unconformably overlies the Englewood Limestone. Elsewhere, the Madison generally overlies one of four Upper Devonian formations (Sandberg, 1961a). On several domes of the ancestral Cedar Creek anticline, where Devonian rocks are absent, the Madison Group unconformably overlies the Interlake Formation. The Madison Group generally is conformably overlain by the Big Snowy Group of Late Mississippian (Chester) age. Beyond the limits of the Big Snowy Group, the Madison is unconformably overlain by the Minnelusa Formation of Pennsylvanian and Permian age in central North Dakota and in South Dakota and by Jurassic rocks in north-central and northeastern Montana and in eastern North Dakota.

The Madison Group underlies the entire Williston basin and is absent only from the summit of the small monadnock west of Pierre, S. Dak., where it probably was not deposited (fig. 15). Its thickness is greater than 1,600 feet in a trough that extends about N. 70° E. from the Central Montana uplift toward the deepest part of the Williston basin and culminates in a broad, roughly circular basin in northeastern Montana and northwestern North Dakota. An area of deep pre-Jurassic erosion in north-central Montana, where the Madison thins from 1,600 to about 800 feet, accentuates the north side of the trough. The limit of the salt beds (fig. 15), which are mostly in the Charles Formation, approximately outlines the Madison depositional basin. The center of maximum accumulation of the Madison Group is on the southern part of the Nesson anticline, where it attains a thickness of about 2,350 feet.

Thinning of the Madison Group along the ancestral Cedar Creek anticline (fig. 15) resulted from retarded subsidence there during deposition of the Lodgepole Limestone. An area of slight thinning on

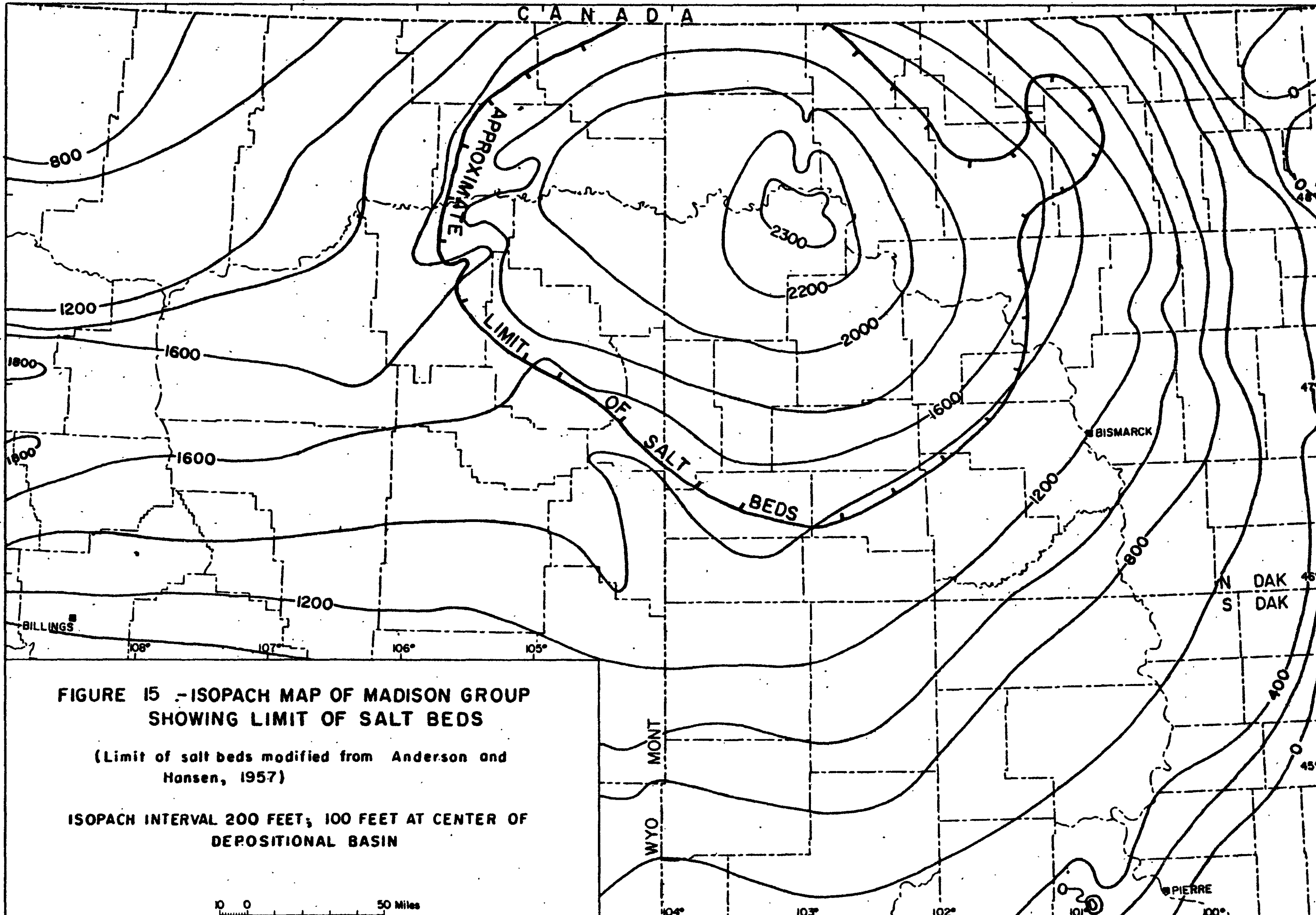

FIGURE 15 .-ISOPACH MAP OF MADISON GROUP SHOWING LIMIT OF SALT BEDS

(Limit of salt beds modified from Anderson and Hansen, 1957)

ISOPACH INTERVAL 200 FEET; 100 FEET AT CENTER OF DEPOSITIONAL BASIN the ancestral Nesson anticline resulted from retarted subsidence during deposition of the Lodgepole and Mission Canyon Limestones. Two areas of thinning, indicated by indented isopachs, near the Poplar dome suggest slightly positive areas. There the Madison is thinner because salt beds in the Charles Formation are thin or absent owing to solution or nondeposition. Elsewhere the Madison thins uniformly from its depositional center toward its eastern and southern limits largely by pre-Pennysylvanian and pre-Jurassic erosion of the upper beds.

The Lodgepole Limestone generally exceeds 525 feet in thickness in the Central Williston basin and its maximum thickness there is about 850 feet. It consists of thin-bedded gray argillaceous limestone that is in part crinoidal, cherty, or shaly. The basin facies is dark-colored organic limestone and shale, whereas the shelf facies is light-colored fragmental limestone (Nordquist, 1953). Many minor facies changes characterize the Lodgepole. It may locally contain mounds of algal and crinoidal debris in the subsurface, as evidenced by outcropping bioherms, several hundred feet thick, at its base on the Central Montana uplift. An argillaceous facies, here informally termed the Englewood facies, is sporadically present at or near the base of the formation in north-central South Dakota and south-central and eastern North Dakota. The Englewood facies is as much as 90 feet thick, but it grades abruptly into less argillaceous limestone of the Lodgepole (fig. 6). The facies consists of interbedded dark-gray highly argillaceous limestone and calcareous shale or siltstone where it overlies the Bakken Formation in North Dakota, but elsewhere it consists of shale that is grayish red or greenish gray speckled with grayish red. Previous correlation of this facies on the southern and eastern margins of the basin with the Englewood Limestone of the Black Hills (Sandberg and Hammond, 1958, p. 2328) is now uncertain because the Englewood Limestone appears to be of the same age as the Bakken Formation, which underlies the facies in some areas.

The Mission Canyon Limestone generally is thinner than the Lodgepole and its thickness ranges from 350 to 775 feet in the Central Williston basin. Although the shelf facies is differentiated by its coarser and more fragmental texture and massive bedding from the shelf facies of the Lodgepole, the basin facies of the Mission Canyon is similar to that of the Lodgepole. The Mission Canyon, like the overlying Charles, is characterized by many facies changes. Bioherms in the Mission Canyon were recognized by Lewis (1959), who discussed the detailed stratigraphy of their core and flank facies. Thin beds of anhydrite locally are present in the Mission Canyon. In north-central North Dakota, the lowest of seven salt beds in the Madison Group is termed the "X" salt bed by Anderson and Hansen (1957) and appears to lie within the Mission Canyon (fig. 5). This thin salt bed is about 3,600 feet below the surface and is present in the area shown by the protuberance of the eastern limit of the salt beds (fig. 15).

The contact between the Mission Canyon and Lodgepole is gradational, and there is little agreement as to where the contact should be placed regionally. However, in a single well the contact is arbitrarily placed at the horizon where mechanical logs indicate a slight change from more argillaceous and thinner bedded limestone below to less argillaceous and thicker bedded limestone above.

The contact between the Mission Canyon and Charles is commonly placed at the base of the lowest thick bed of salt or anhydrite in the Charles Formation. Because the evaporite beds in the Charles are not coextensive, however, the contact ranges vertically through several hundred feet of beds so that the upper half of the Mission Canyon is a facies of the Charles (fig. 6).

The Charles Formation ranges in thickness from 525 to 725 feet in the Central Williston basin. It is less widely distributed than the other formations of the Madison Group and is absent from north-central Montana, eastern North Dakota, and central South Dakota because of pre-Pennyslvanian and pre-Jurassic erosion. The Charles consists of cyclically interbedded limestone, dolomite, anhydrite or salt (halite), and shale. The carbonate rocks generally are less fragmental than those of the Mission Canyon. The detailed stratigraphy of the Charles and the complex informal terminology of its oil-producing zones are discussed by Fish and Kinard (1959). The base of the Charles in east-central Montana is a bed of dark-gray shale, informally termed the Richey Shale. Elsewhere, however, the correlative horizon of this bed lies well above the base.

Although anhydrite is the more common evaporite of the Charles Formation on the margins, salt (halite) is predominant in the Central Williston basin. There six beds of salt, designated by the letters

"A" to "F" in descending order by Anderson and Hansen (1957), constitute about 30 to 45 percent of the Charles Formation. The thickness of these salt beds aggregates 100 feet or more in an area of about 18,000 square miles and attains a maximum of 350 feet (fig. 16). The salt beds in the Charles lie between 1,500 and 2,500 feet above the base of Mississippian rocks (fig. 14) or about 6,000 to 9,000 feet below the surface. The thickest salt bed, "A", has a maximum thickness of 150 feet, whereas the most extensive salt beds, "D" and "F", have maximum thicknesses of 60 and 90 feet, respectively (Anderson and Hansen, 1957).

The framework of the Williston basin area changed greatly as a result of earliest Mississippian orogeny. During deposition of the Madison Group, the Central Williston basin was again the center of an intracratonic basin, but for the first time since the Early Ordovician the basin was directly connected with the Cordilleran geosyncline on the west. The trough that extends through the Central Montana uplift (fig. 15) probably was the axis of subsidence that permitted the eastward transgression of seas across a shelf area, but the connection between the intracratonic basin and geosyncline was much wider. Some of the more active areas of earliest Mississippian orogeny, such as the ancestral Cedar Creek anticline, subsided more slowly than adjacent areas during the early part of Madison deposition. Later, during deposition of the Charles Formation, renewed intermittent activity along an extended Cedar Creek trend (fig. 15) may have

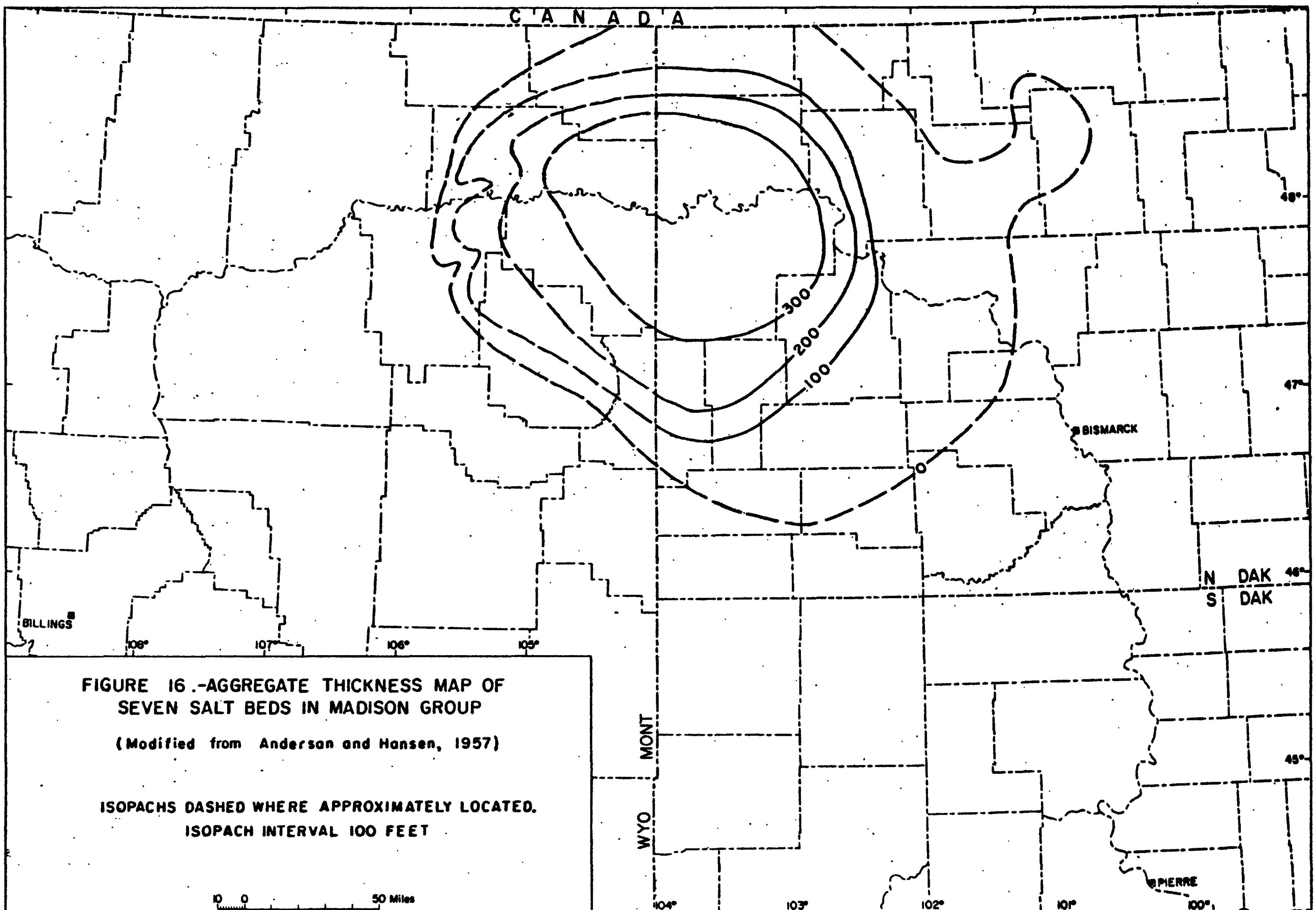

FIGURE 16.-AGGREGATE THICKNESS MAP OF SEVEN SALT BEDS IN MADISON GROUP

(Modified from Anderson and Hansen, 1957)

ISOPACHS DASHED WHERE APPROXIMATELY LOCATED.
ISOPACH INTERVAL 100 FEET

temporarily barred or at least reduced the flow of water into the basin. This periodically produced a highly restricted marine environment in which halite was precipitated.

Big Snowy Group

The Big Snowy Group is correlated throughout the western part of the Williston basin from the adjacent Big Snowy Mountains of the Central Montana uplift. In the subsurface, the group consists, in ascending order, of the Kibbey Sandstone and the Otter and Heath Formations. These formations are successively conformable and are of Late Mississippian (Chester) age. The upper limit of the outcropping Big Snowy Group was revised by Gardner (1959) to include two new formations of Mississippian or Pennsylvanian age and one of Pennsylvanian age. This revised terminology is untenable in the subsurface, however, and is not employed here. The proposed formations as well as the upper part of Gardner's Heath Formation are not related to the Big Snowy Group but can be correlated with the lower (Pennsylvanian) part of the Minnelusa Formation, which truncates the Big Snowy Group. This correlation, illustrated by Foster (1960), is supported by faunal evidence (Willis, 1959) for the Early Pennsylvanian age of the upper part of Gardner's Heath Formation, which is approximately equivalent to the Tyler Formation of informal subsurface usage (fig. 6).

The Kibbey Sandstone of the Big Snowy Group conformably overlies the Charles Formation of the Madison Group. The Heath Formation is unconformably overlain by the Tyler Formation. Where the Heath is absent, the Otter Formation or Kibbey Sandstone is unconformably overlain by the Tyler or by the Minnelusa Formation, where the Tyler is not present (fig. 6). Beyond the limit of the Minnelusa Formation in northeastern Montana and northwestern North Dakota, the Otter and Kibbey are unconformably overlain by Jurassic rocks.

The distribution of the Big Snowy Group is similar to that of the Charles Formation, but the Big Snowy was more restricted by pre-Pennsylvanian and pre-Jurassic erosion owing to its higher stratigraphic position. The Big Snowy Group underlies a roughly circular area that encompasses northeastern and east-central Montana, all of western North Dakota except for the north-central part, and northwestern South Dakota and a 100-mile wide belt that extends westward from this circular area through central Montana. The thickness of the Big Snowy exceeds 600 feet in a trough extending N. 70° E. from the Central Montana uplift across the north end of the Cedar Creek anticline into the southern part of the Central Williston basin (fig. 1). The group has a maximum thickness of about 725 feet at the western limit of the basin adjacent to the Central Montana uplift. Its thickness does not exceed 610 feet in the Central Williston basin.

The Kibbey Sandstone, which is the most widespread formation, has the same distribution as the Big Snowy Group. The Kibbey has a maximum thickness of about 275 feet in the Central Williston basin. It consists of grayish-red siltstone, sandstone, and shale interbedded with limestone, dolomite, and anhydrite. The formation is divided into three units on the basis of a medial unit, which is informally called the Kibbey Limestone. The Kibbey Limestone generally consists of limestone or dolomite, although it may consist of sandstone or anhydrite in some areas, according to Nordquist (1953). Despite these lithologic changes, the Kibbey Limestone is readily recognized on mechanical well logs and consequently is one of the best marker beds in the upper part of the Paleozoic sequence.

The Otter Formation underlies central and east-central Montana and west-central North Dakota and has a maximum thickness of about 225 feet in the report area. It consists predominantly of greenish-gray but also of gray, purple, and black shale with interbeds of gray and yellowish-gray earthy argillaceous limestone and dolomite. The upper part of the formation is darker in color and the contact between the Otter and Heath Formations commonly is gradational.

The Heath Formation underlies central and east-central Montana and extends a short distance into west-central North Dakota. It is only about 100 feet thick in the Central Williston basin but is 300 feet thick adjacent to the Central Montana uplift. The Heath consists of interbedded dark-gray to black marine petroliferous shale and limestone.

The framework of the Williston basin during Big Snowy deposition resembled that during Madison deposition. A shallow intracratonic basin in east-central Montana and west-central North Dakota was connected by a trough to the Cordilleran geosyncline on the west. The connection probably was narrower than at most times during Madison deposition, as suggested by the predominance of clastic over carbonate sediments.

The Kibbey Sandstone was deposited in a restricted marine environment that was transitional between the highly restricted environment of the underlying Charles and the normal marine environment of the overlying Otter. This suggests that the sea gained access to the basin from the trough during Kibbey deposition. The sea in which the Otter Formation was deposited became slightly restricted probably because of narrowing of the trough, as evidenced by the upward gradation from greenish-gray to dark-gray shale. Further narrowing of the trough resulted in a greater influx of muddy sediments during deposition of the Heath Formation. Although slightly restricted, the sea nevertheless teemed with organisms, which upon death were incorporated in the sediment and imparted the dark color to the Heath. Regional uplift ended Big Snowy deposition and was followed by slight folding of the group and by erosion of the upper beds.

Minnelusa Formation and related rocks

The Minnelusa Formation of Pennsylvanian and Permian age is correlated into the Williston basin from the adjacent Black Hills (fig. 1). It is divided in the subsurface into a lower member and an upper member (fig. 17), which appear to be unconformable and to correspond approximately to the Pennsylvanian and Permian parts, respectively. In eastern and central Montana and western North Dakota, two other Pennsylvanian units, the Tyler Formation of informal subsurface usage and the overlying Amsden Formation, are differentiated and correlated with the lower part of the lower member of the Minnelusa Formation (fig. 6).

The Minnelusa Formation and related rocks successively truncate and unconformably overlie all formations of the Big Snowy and Madison Groups. However, the Minnelusa unconformably overlies the Sioux Quartzite of Precambrian age on the monadnock west of Pierre, S. Dak., where the older Paleozoic rocks are absent. The Minnelusa generally is overlain unconformably by the Opeche Formation of Permian age (fig. 17), but beyond the limits of the Opeche, the Minnelusa Formation and related rocks are unconformably overlain by the Spearfish Formation of Permian and Triassic age or by Jurassic rocks.

The Minnelusa Formation and related rocks underlie the Central Williston basin, central and southeastern Montana, and almost all of the Williston basin in South Dakota. Their northern and eastern limits follow a line parallel to and about 20 to 45 miles north or east of the Missouri River. Their northwestern limit coincides approximately with the -5,000-foot structure contour, drawn at the base of Mississippian rocks, between the west side of the Poplar dome and the Blood Creek syncline (fig. 1). Their southern and western limits lie far outside the report area. The Minnelusa Formation and related rocks exceed 500 feet in thickness in west-central and northwestern South Dakota and southwestern North Dakota. They attain a maximum thickness of 760 feet at the south edge of the report area (fig. 17, col. 4).

The lower member (Pennsylvanian) of the Minnelusa Formation has a maximum thickness of about 500 feet in the southern part of the Williston basin, where it commonly can be divided into four units. The basal unit, according to McCauley (1956), consists of grayish-red to white sandstone interbedded with grayish-red silty shale; it is generally 10 to 20 feet thick but locally attains a thickness of about 100 feet. The overlying unit has a maximum thickness of about 150 feet and consists of light-gray argillaceous limestone with thin interbeds of red and green shale (McCauley, 1956). It is overlain by an argillaceous unit, about 100 to 150 feet thick, consisting of greenish-gray and grayish-red shale with thin interbeds of dolomite. The uppermost unit is largely dolomite and has a maximum thickness of about 250 feet. It consists of light-gray or pink dolomite interbedded with anhydrite, sandy and silty dolomite, sandstone, and black shale.

The Tyler Formation, as revised for informal subsurface usage by Mundt (1956), has an average thickness of 100 feet but locally may be as much as 300 feet thick. It is divided into two parts, which are separated by a limestone tongue in central Montana. The lower part consists predominantly of black carbonaceous shale interbedded with thin seams of coal and locally thick lenses of sandstone. Although included in the outcropping Heath Formation by Gardner (1959), the

Tyler contains in the subsurface brackish-water ostracodes that are considered to be of Early Pennsylvanian age (Willis, 1959). The upper part of the Tyler grades upward from black to grayish-red shale by interfingering of beds (Mundt, 1956). The upper part of the Tyler is equivalent to the lower member of the Amsden Formation of Nieschmidt (1953), which was renamed the Cameron Creek Formation by Gardner (1959). The Tyler Formation occupies the same stratigraphic position as the lower three units of the lower member of the Minnelusa Formation and tentative correlations have been suggested by McCauley (1956) and Foster (1960).

The Amsden Formation, as employed in the western part of the Williston basin, has an average thickness of 100 to 200 feet. It consists of light-gray to pink limestone overlain by light-gray to pink partly cherty dolomite containing thin interbeds of sandy dolomite, sandstone, and greenish-gray and grayish-red shale. It is equivalent to the middle and upper members of the Amsden Formation of Nieschmidt (1953), which were renamed the Alaska Bench Limestone and the Devils Pocket Formation, respectively, by Gardner (1959). The Amsden Formation is here correlated with the uppermost, dolomite unit of the lower member of the Minnelusa Formation.

The upper member (Permian) of the Minnelusa Formation has a maximum thickness of about 280 feet. It is largely confined to South Dakota and North Dakota by pre-Opeche erosion, but it extends a short distance into southeastern Montana (fig. 17, col. 1). At the base of the upper member in many areas is a grayish-red shale, about 30 feet thick. Where present, this bed serves as a marker for dividing the Minnelusa. The remainder of the upper member was correlated with the Broom Creek "Group" of the Hartville Formation by McCauley (1956), who described it as consisting of light-gray to pink anhydritic dolomite with interbeds of anhydrite and white to red sandstone in South Dakota and light-gray to pink sandstone with interbeds of sandy dolomite in North Dakota.

During the Pennsylvanian, the Williston basin area was part of a large, shallow intracratonic basin. Sediments were deposited in an environment that fluctuated between normal and restricted marine. The center of accumulation probably was near the southwest corner of South Dakota, where Gries and Tullis (1955) reported nearly 1,300 feet of Pennsylvanian rocks. The sea that covered the Williston basin area probably was part of a large epicontinental sea that occupied much of the interior United States. During the early phase of deposition, marginal marine and near-shore marine conditions prevailed in central and east-central Montana and west-central North Dakota, where the lithology of the lower part of the Tyler Formation suggests reworking of the uplifted Heath and Otter Formations. Later, the Kibbey Sandstone was eroded and reworked in a near-normal marine environment, as suggested by the lithologies of the upper part of the Tyler and the lower part of the Minnelusa Formation. The many beds of sandstone in the Minnelusa suggest that the area of Sioux

Quartzite in southeastern South Dakota may have been a landmass. After a brief cessation of deposition followed by a minor episode of erosion, the upper member of the Minnelusa Formation was deposited during early Permian time in the slightly restricted environment of a smaller basin.

Opeche Formation and Minnekahta Limestone

The Opeche Formation and the conformably overlying Minnekahta Limestone, both of Permian age, are correlated throughout the central part of the Williston basin from outcrops in the adjacent Black Hills. The Opeche Formation unconformably overlies the Minnelusa Formation. The Minnekahta Limestone generally is conformably overlain by the Spearfish Formation of Permian and Triassic age. Beyond the limits of the Spearfish, the Minnekahta and Opeche are unconformably overlain and successively truncated by the Saude Formation (Jurassic) of informal subsurface usage or in central South Dakota (fig. 17) by the Sundance Formation of Jurassic age.

The Opeche Formation and Minnekahta Limestone underlie the Central Williston basin, adjacent parts of southeastern Montana and southwestern North Dakota, and all of western South Dakota (fig. 18). They reach a maximum combined thickness of about 475 feet south of the Missouri River in west-central North Dakota, whence they thin abruptly to the northwest, north, and northeast owing to pre-Jurassic erosion. They thin gradually toward the south and southwest. A fault

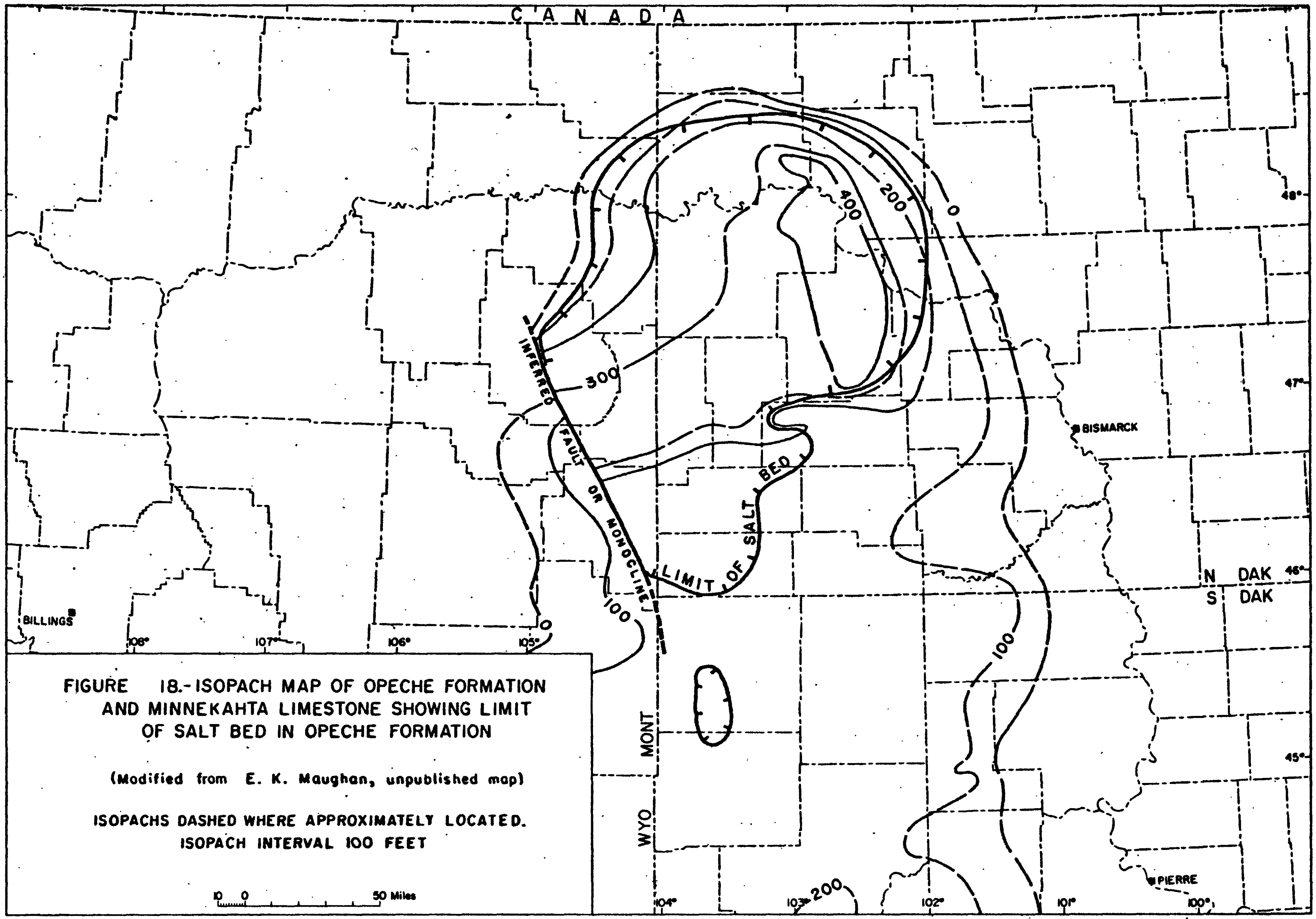

FIGURE 18.- ISOPACH MAP OF OPECHE FORMATION AND MINNEKAHTA LIMESTONE SHOWING LIMIT OF SALT BED IN OPECHE FORMATION

(Modified from E. K. Maughan, unpublished map)

ISOPACHS DASHED WHERE APPROXIMATELY LOCATED.
ISOPACH INTERVAL 100 FEET

or monocline along the west flank of the ancestral Cedar Creek anticline (fig. 18) has been inferred by E. K. Maughn (oral communication, May 1961) on the basis of abrupt depositional thinning of the Opeche east of this feature. The west side of this feature apparently was uplifted or upthrown because the formations are further thinned by pre-Jurassic erosion on the west.

The Opeche Formation ranges in thickness from 0 to about 425 feet and commonly is divided into two units. The lower unit, 0 to 375 feet thick, is reddish-orange and pink silty shale and siltstone with interbeds of dolomite and anhydrite. A thick bed of salt (halite) is present within this unit in the Central Williston basin and in a smaller area in northwestern South Dakota (fig. 18). This salt bed, termed the Permian "A" salt by Anderson and Hansen (1957), has a maximum thickness of about 180 feet and lies about 5,700 to 7,700 feet below the surface (Pierce and Rich, 1958). A second bed of salt, about 30 feet thick, is locally present beneath the "A" salt in west-central North Dakota. This salt occurs at or near the base of the Opeche Formation and was termed the Permian "B" salt by Anderson and Hansen (1957). The upper unit, 0 to 50 feet thick, consists of grayish-red and reddish-orange shale. McCauley (1956) ascribed a continental origin to the lower unit, which he tentatively correlated with the Cassa "Group" of the Hartville Formation; he ascribed a marine origin to the upper unit, to which he restricted the name Opeche Formation. In accordance with widespread subsurface usage, however, both units are here included in the Opeche Formation.

The Minnekahta Limestone ranges in thickness from 0 to 50 feet, but it is uniformly 30 to 50 feet thick where uneroded. It consists of purple, pink, or white dolomitic limestone and anhydrite.

During deposition of the lower part of the Opeche Formation, much of the Williston basin area was a landmass. A shallow, highly restricted marine basin in west-central North Dakota probably was connected by a narrow trough that extended southwestward, as suggested by the 300-foot isopach (fig. 18), toward the main seaway in Wyoming. Intermittent activity of the inferred fault or monocline (fig. 18) probably reduced the flow of normal marine water into the basin and resulted in the precipitation of salt there. Little or no salt is found in the Opeche on the west side of this feature. During the deposition of the upper part of the Opeche and Minnekahta Limestone, much of the area continued to be emergent, but access of the sea to the basin was restored and slightly restricted marine conditions prevailed.

Spearfish and Saude Formations

The Spearfish Formation of Late Permian and Early Triassic age is correlated from the adjacent Black Hills into the Williston basin, where it is unconformably overlain and truncated by the Saude Formation of Zieglar (1956) of informal subsurface usage. Although the Saude Formation, as proposed by Zieglar (1955), is a widespread mappable unit, it has not as yet been adequately defined according to the Code of Stratigraphic Nomenclature (American Commission of Stratigraphic Nomenclature, 1961). The Saude was tentatively considered to be of Jurassic(?) age by Zieglar (1955, 1956) and of Early Triassic(?) age by Goldsmith (in McKee and others, 1959, p. 11). The Saude is here considered to be of Middle Jurassic age, because it is conformable with and has a similar distribution to the overlying Middle Jurassic strata, whereas it overlies a major unconformity. This assignment does not preclude the possibility that it may be in part of Early Jurassic age. Despite differences in their age and distribution, the Spearfish and Saude both consist predominantly of red beds; hence, they are considered together in this report.

The Spearfish Formation conformably overlies the Minnekahta Limestone. The Saude Formation truncates the Spearfish as well as the underlying Minnekahta Limestone and Opeche Formation and rests unconformably on the Minnelusa Formation and related rocks in eastern Montana. In north-central North Dakota, the Saude also truncates the Minnelusa, and farther east it unconformably overlies and truncates all the formations of the Madison Group and locally all the Upper and Middle Devonian formations. The Saude is conformably overlain by Middle Jurassic evaporitic beds, variously assigned to the Nesson Formation of informal usage, the Dunham Salt of informal usage, or the Gypsum Spring Formation in different parts of the Williston basin (fig. 6). Where the Saude is absent in South Dakota, the Gypsum

Spring Formation or the Sundance Formation rest unconformably on the Spearfish (fig. 17).

The Spearfish and Saude Formations underlie the entire Williston basin except for parts of north-central Montana, south-central North Dakota, and north-central and central South Dakota (fig. 19). Their combined thickness exceeds 700 feet in extreme southwestern North Dakota and also adjacent to the Black Hills in South Dakota, where it attains a maximum of 775 feet. The Spearfish and Saude are thicker than 300 feet in a narrow belt that trends N. 15° E. through western South Dakota and North Dakota and coincides approximately with the area, wherein the Spearfish contains a salt bed (fig. 19), informally termed the Pine Salt by Zieglar (1955). On either side of this belt the formations thin gradually toward their eastern and western limits.

The Spearfish Formation consists of reddish-orange, light-brown, and moderate-red siltstone, mudstone, and sandstone, containing a thick bed of salt (halite) and thin lenses and inclusions of white anhydrite or gypsum. It has a maximum thickness of about 775 feet at the southwestern margin of the Williston basin near the northern Black Hills. Where the Pine Salt is present, it commonly divides the Spearfish into three members (fig. 17). The lower member ranges in thickness from 60 to 190 feet but commonly is about 100 feet thick. Its present distribution is similar to but slightly more restricted than the distribution of the Opeche Formation and Minnekahta Limestone (fig. 18). It is predominantly siltstone and mudstone with inclusions of anhydrite or gypsum. The middle member, the Pine Salt of

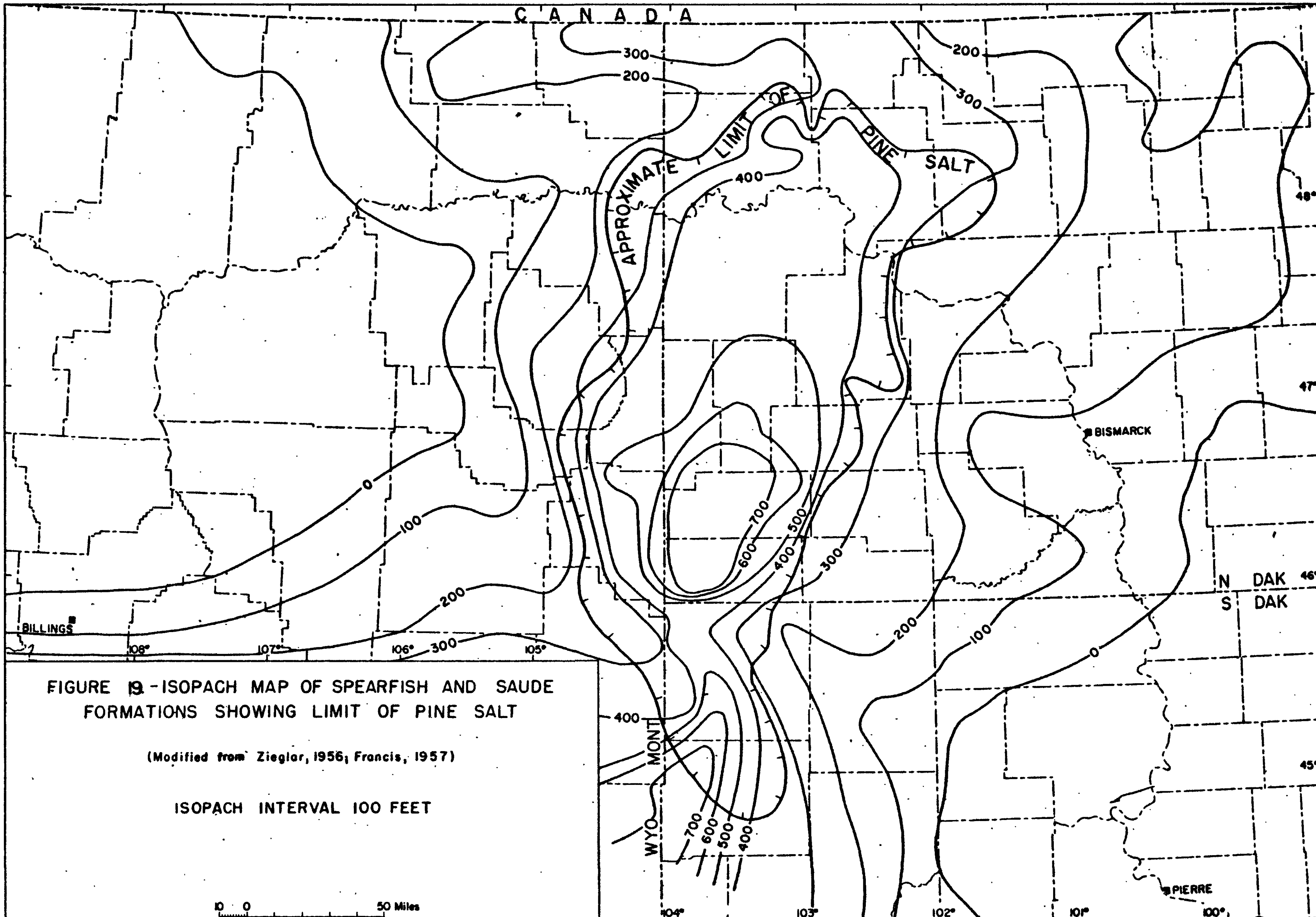

FIGURE 19 -ISOPACH MAP OF SPEARFISH AND SAUDE FORMATIONS SHOWING LIMIT OF PINE SALT

(Modified from Zieglar, 1956; Francis, 1957)

ISOPACH INTERVAL 100 FEET

informal usage, has a maximum thickness of about 380 feet and a north-south extent of about 250 miles (fig. 20). It is about 4,000 to 7,500 feet below the surface. The lower two-thirds of the Pine Salt commonly is a thick bed of halite with interbeds of shale and anhydrite. The upper third is reddish-orange siltstone capped by a bed of anhydrite, 20 to 30 feet thick, that locally contains halite (Zieglar, 1956). The upper member is predominantly siltstone and mudstone with stringers of dolomite and anhydrite or gypsum. It is restricted by pre-Saude erosion to the southwestern margin of the Williston basin, where it locally attains a thickness as great as 290 feet.

The Pine Salt was believed to be of Jurassic(?) age by Zieglar (1955, 1956), who restricted the Spearfish Formation to the beds between it and the Minnekahta Limestone. The Pine Salt was termed the Triassic "B" salt by Anderson and Hansen (1957), who included all beds between the Piper Formation of Middle Jurassic age and the Minnekahta in the Spearfish Formation. Goldsmith (<u>in</u> McKee and others, 1959, p. 11), however, correlated the Pine Salt with evaporitic beds in the Permian part of the Spearfish Formation in the Black Hills and therefore considered the Pine Salt to be Permian. Although the Pine Salt is here considered an integral part of the Spearfish Formation, there is no evidence for its Permian age in the Williston basin and it may straddle the Permian-Triassic boundary (fig. 17). In general, however, the lower member of the Spearfish may be considered

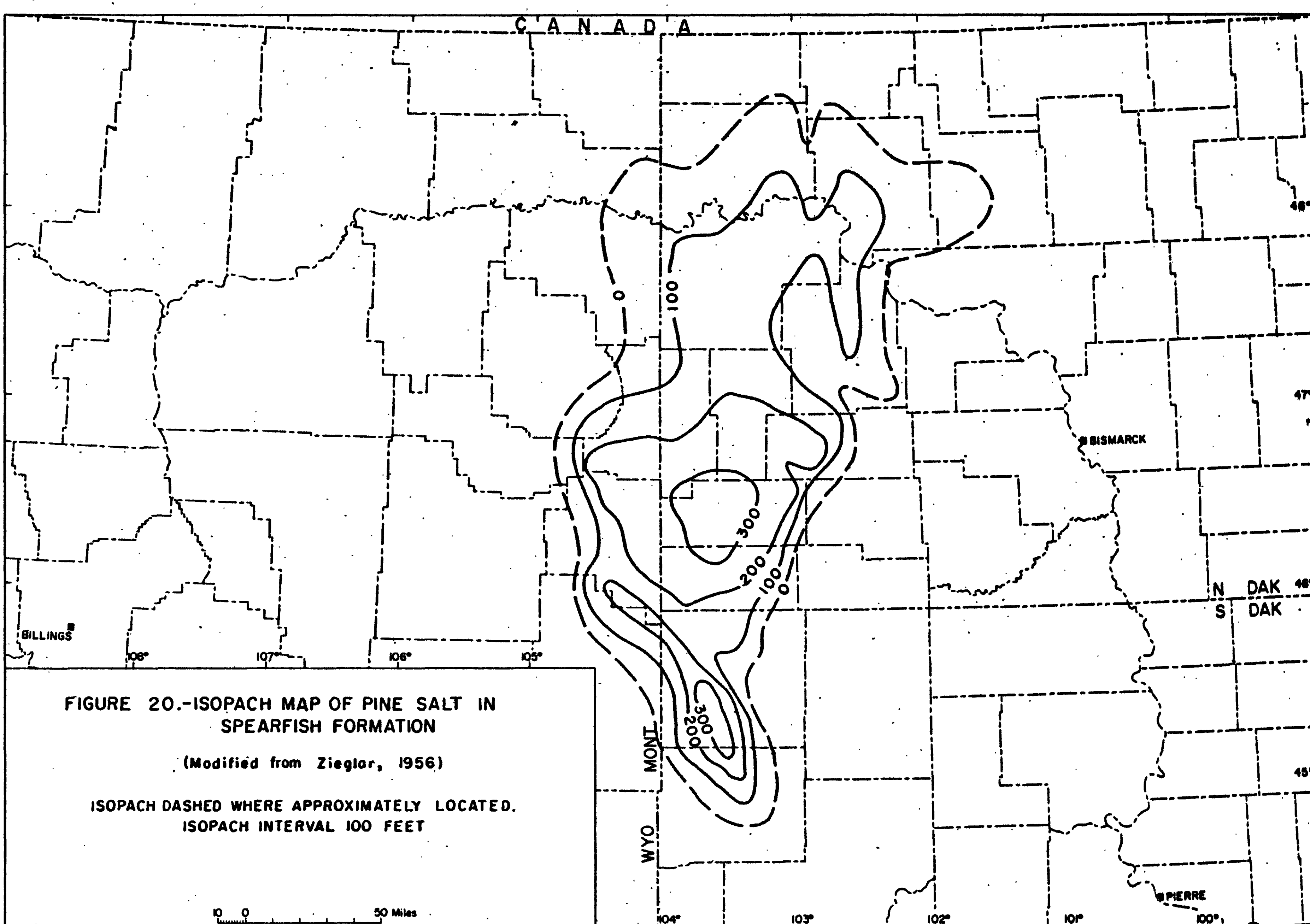

FIGURE 20.-ISOPACH MAP OF PINE SALT IN SPEARFISH FORMATION

(Modified from Zieglar, 1956)

ISOPACH DASHED WHERE APPROXIMATELY LOCATED.
ISOPACH INTERVAL 100 FEET

to be of late Permian age and the upper member to be of Early Triassic age.

The Saude Formation underlies North Dakota and eastern Montana, but it may extend into northwestern South Dakota (fig. 17). It generally ranges in thickness from 100 to 300 feet in North Dakota, where it attains a maximum thickness of about 325 feet. The thickness changes abruptly in short distances, however, because the Saude overlies and fills in an irregular erosion surface. The Saude consists predominantly of reddish-orange siltstone and sandstone, which locally are conglomeratic.

During deposition of the lower member of the Spearfish Formation in Late Permian time, less of the Williston basin area was emergent than during deposition of the Minnekahta Limestone and Opeche Formation. A shallow, slightly restricted sea, connected by a trough in western South Dakota to the main seaway in Wyoming, probably covered eastern Montana, western North Dakota, and western South Dakota. Siltstone and mudstone were laid down in fluctuating near-shore and marginal marine environments. Later, intermittent uplift just west of the Cedar Creek trend reduced the influx of normal saline water from the southwest. Halite was precipitated along the ancestral Cedar Creek anticline and in areas to the northeast, whereas anhydrite was deposited in a less restricted environment in the Black Hills area. As tectonic activity lessened in Early Triassic time, siltstone and mudstone of the upper member of the Spearfish were laid down in fluctuating marginal marine and continental environments. Regional uplift ended Spearfish deposition and the tectonic framework of the basin area changed greatly during the ensuing episode of emergence and erosion, which largely removed the upper part of the Spearfish from the Williston basin area.

During deposition of the Saude Formation in Jurassic time, the sea apparently entered the Central Williston basin area from the northwest and then transgressed eastward, southward, and southwestward. It reworked the post-Triassic regolith that had developed on the Spearfish and older formations and the Saude Formation was laid down on an irregular erosion surface.

Post-Saude Jurassic rocks

The most complete sequence of post-Saude Jurassic rocks is in eastern Montana. There the Middle Jurassic Series comprises the marine Nesson Formation of informal subsurface usage and the overlying Piper Formation, and the Upper Jurassic Series comprises, in ascending order, the marine Rierdon and Swift Formations and the nonmarine Morrison Formation. The Nesson, Piper, and Rierdon Formations are successively conformable, but the Swift Formation is separated from the underlying Rierdon and the overlying Morrison by unconformities. The Piper, Rierdon, and Swift Formations constitute the Ellis Group in north-central Montana.

A bed of salt, informally termed the Dunham Salt by Zieglar (1955), underlies the Central Williston basin (fig. 21) and is equivalent to the basal part of the Nesson. Where the Dunham Salt is present in North Dakota, usage of the term Piper is extended downward to include beds equivalent to the upper part of the Nesson; elsewhere in the state the Piper is used for all strata between the Saude and Rierdon Formations (fig. 6).

In South Dakota, the Gypsum Spring Formation of Middle Jurassic age, a partial equivalent of the Nesson Formation, is unconformably overlain by the Sundance Formation. However, the unconformity becomes less pronounced and disappears northward. The Sundance Formation is generally considered to be of Late Jurassic age and to be equivalent to Rierdon and Swift Formations (McKee and others, 1956). In north-central South Dakota, however, the Sundance appears to be correlative with part of the Piper Formation, as used in North Dakota, and thus may be in part of Middle Jurassic age (fig. 6).

Post-Saude Jurassic rocks conformably overlie the Saude Formation but where the Saude is absent they transgress and unconformably overlie rocks ranging in age from Triassic to Mississippian. The Morrison Formation commonly is overlain unconformably by the Lakota or Kootenai Formations of Early Cretaceous age. However, the unconformity is almost indiscernible in some areas where deposition probably was continuous.

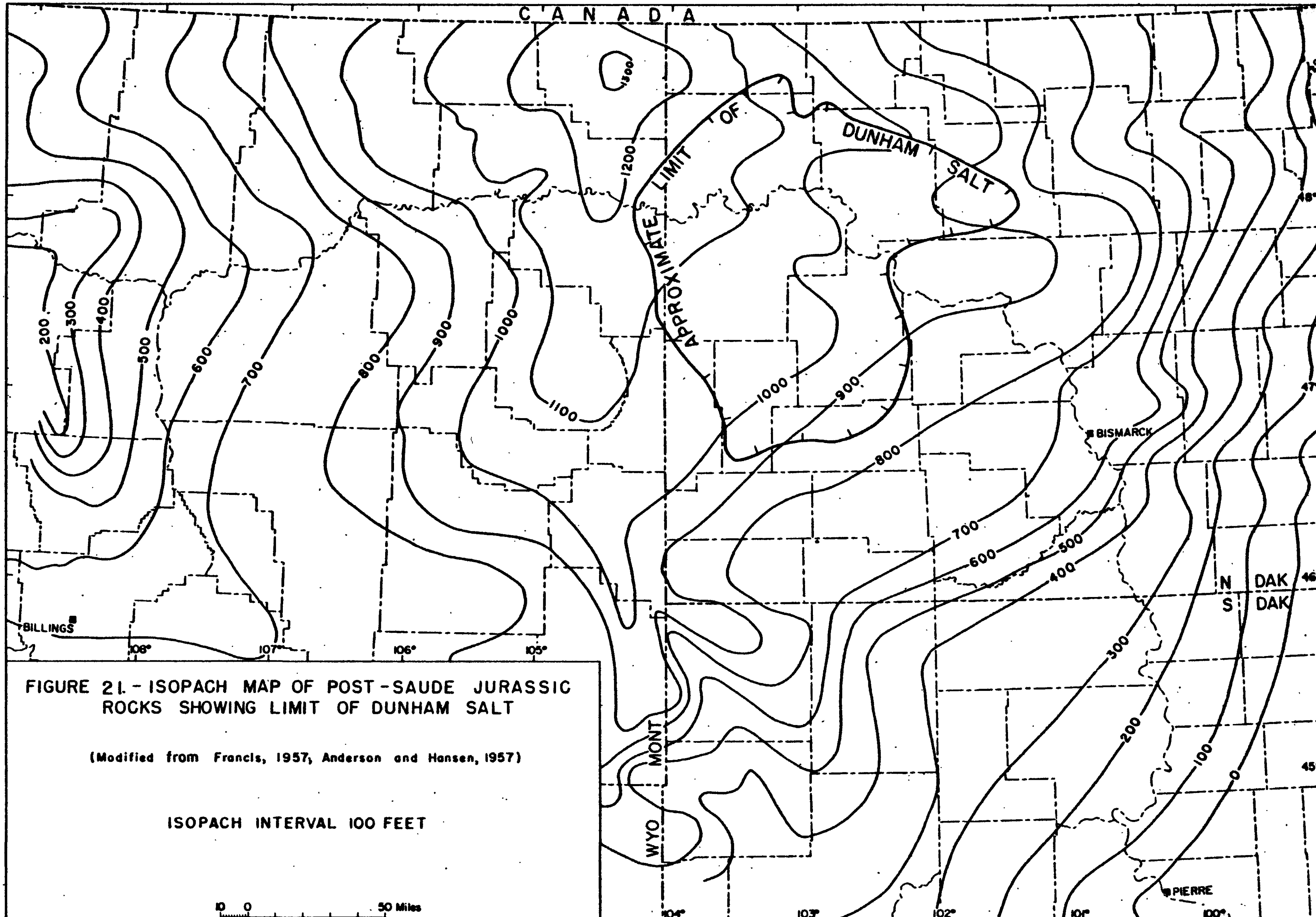

FIGURE 21. - ISOPACH MAP OF POST-SAUDE JURASSIC ROCKS SHOWING LIMIT OF DUNHAM SALT

(Modified from Francis, 1957, Anderson and Hansen, 1957)

ISOPACH INTERVAL 100 FEET

Post-Saude Jurassic rocks underlie the entire Williston basin and have a maximum thickness of about 1,300 feet in northeastern Montana (fig. 21). They are widely distributed and their western and southern limits lie far outside the report area. Post-Saude Jurassic rocks thin uniformly toward the margins of the Williston basin owing largely to the trangressive onlap of the marine formations. Thinning toward the eastern margin of the basin, however, is caused in part by pre-Createceous erosion. Most anomalous isopachs, such as those that indicate an area of thinning trending northwestward in northwestern South Dakota, result from variations in thickness of the nonmarine Morrison Formation. Thinning in central Montana (fig. 21), however, is toward an area, termed Belt island by Imlay and others (1948). There most of the marine formations are very thin or absent because of nondeposition.

The Nesson Formation of informal usage was proposed by Nordquist (1955) for a sequence of rocks, 200 to 300 feet thick, that underlies the Piper Formation in the northern Williston basin. The Nesson comprises three members, named the Poe Evaporite, Picard Shale, and Kline, in ascending order. The Poe consists of interbedded grayish-red shale and white to pink gypsum or anhydrite, containing interbeds of grayish-red dolomite or limestone, and a basal bed of salt. The Picard consists uniformly of grayish-red and greenish-gray shale. The Kline generally consists of light-gray to brownish-gray limestone overlain by light-gray to white dolomite.

The Dunham Salt of informal usage has also been called the Triassic "A" salt by Anderson and Hansen (1957), who included it in the Spearfish Formation. The Dunham Salt underlies an area of about 13,000 square miles. It has a maximum thickness of 142 feet east of the Nesson anticline, according to Anderson and Hansen (1957), but it is thin or absent in several areas on the anticline (fig. 22). The Dunham is stratigraphically the highest salt bed in the Williston basin, but it is present only in the deepest part. It lies 5,000 to 7,000 feet below the surface or about 300 feet below the middle member of the overlying Piper Formation, whose structural configuration is shown on figure 23.

The Gypsum Spring Formation consists of white anhydrite or gypsum with interbeds of grayish-red shale overlain by light-gray and yellowish-gray limestone interbedded with grayish-red shale.

The Piper Formation generally consists of three members (Nordquist, 1955; Sandberg, D., 1959), of which the middle is informally termed the Piper Limestone. The lower member is dark-gray or greenish-gray shale with interbeds of limestone, gypsum, sandstone, and red shale (Nordquist, 1955). The middle member generally is yellowish-gray limestone in Montana but grades to interbedded limestone, siltstone, and sandstone in North Dakota (Sandberg, D., 1959). The upper member commonly is greenish-gray and grayish-red shale with interbeds of limestone. Nordquist (1955) proposed that the members of the Piper Formation be named the Tampico Shale, Firemoon Limestone,

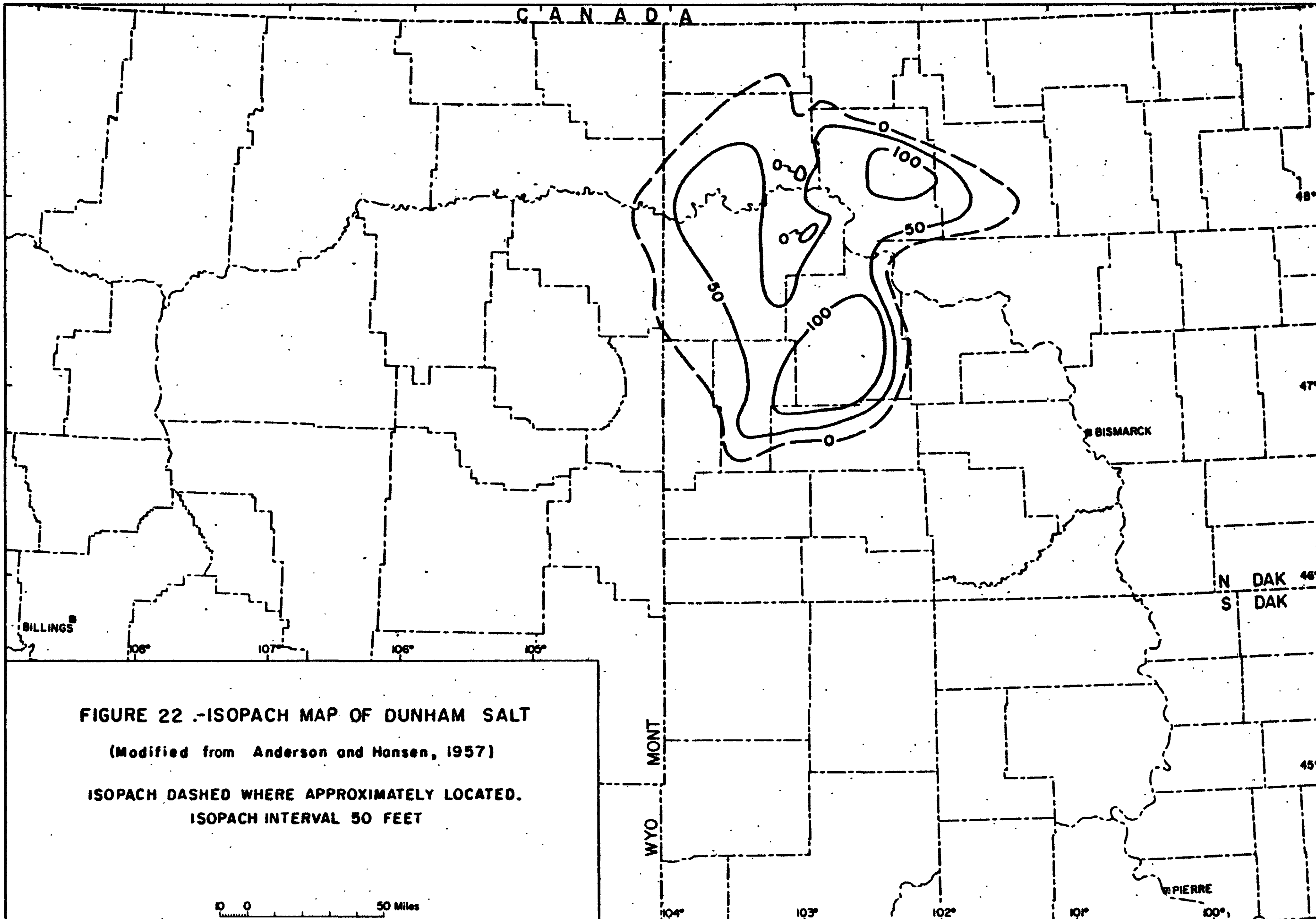

FIGURE 22.-ISOPACH MAP OF DUNHAM SALT

(Modified from Anderson and Hansen, 1957)

ISOPACH DASHED WHERE APPROXIMATELY LOCATED.
ISOPACH INTERVAL 50 FEET

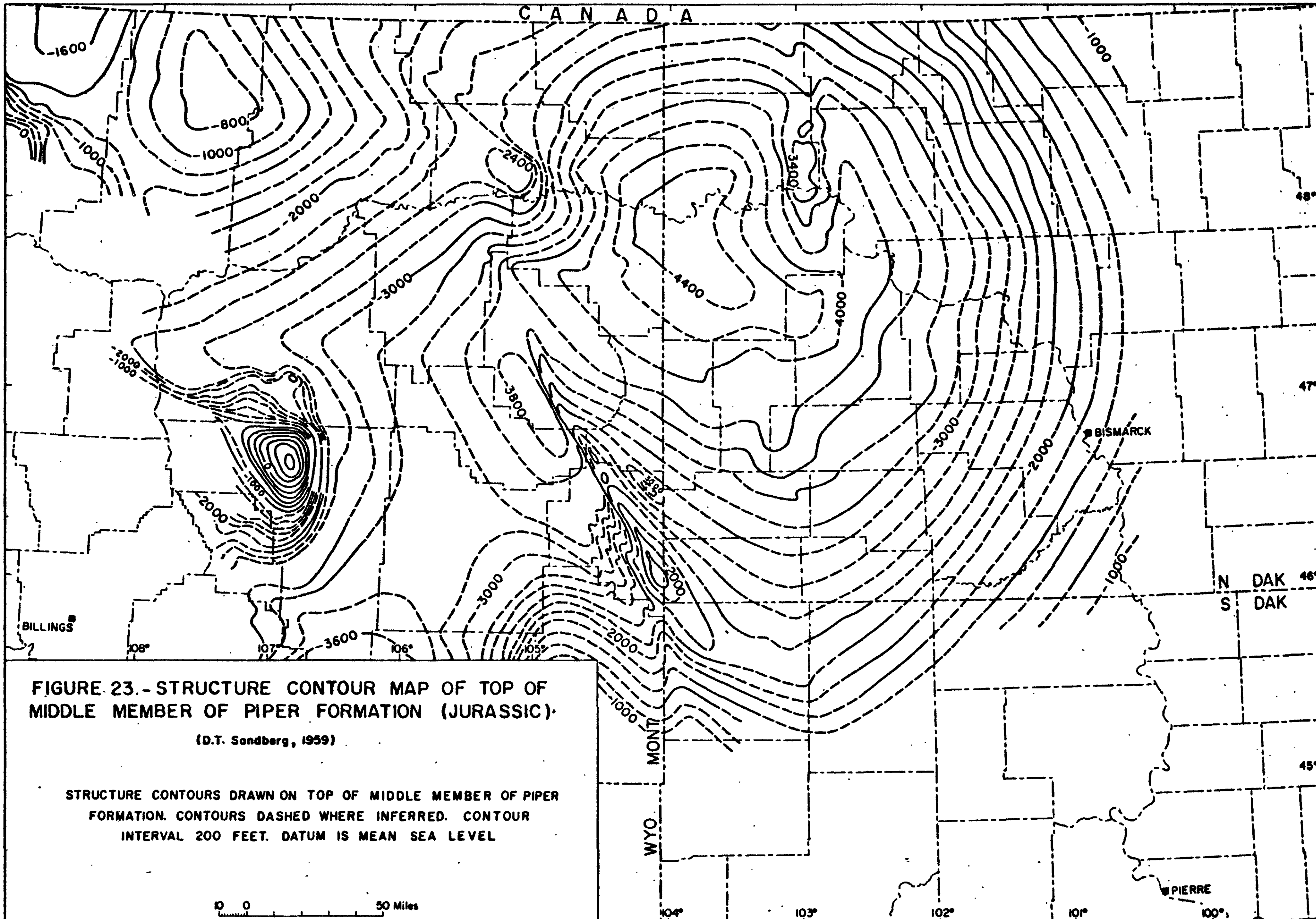

FIGURE 23.- STRUCTURE CONTOUR MAP OF TOP OF MIDDLE MEMBER OF PIPER FORMATION (JURASSIC).

(D.T. Sandberg, 1959)

STRUCTURE CONTOURS DRAWN ON TOP OF MIDDLE MEMBER OF PIPER FORMATION. CONTOURS DASHED WHERE INFERRED. CONTOUR INTERVAL 200 FEET. DATUM IS MEAN SEA LEVEL and Bowes, in ascending order, but these formal names have not found widespread usage. Some workers (Schmitt, 1953; Towse, 1954; Peterson, 1957) did not separate from the Piper the beds that Nordquist (1955) assigned to the Nesson Formation, and their usage generally is employed in North Dakota.

The Rierdon Formation consists predominantly of greenish-gray calcareous shale, which in places grades to argillaceous limestone near the top of the formation (Francis, 1956). This appears to be the most widely accepted description of the Rierdon, although some workers include an overlying sequence of noncalcareous shale, and Peterson (1957) included a still higher sequence of sandy shale and sandstone in the Rierdon. Thus, although most workers agree that an unconformity separates the Rierdon from the overlying Swift Formation, they disagree on its stratigraphic position. These differences in interpretation arise because both the upper part of the Rierdon and the lower part of the Swift contain several hundred more feet of beds in the Williston basin than they do in their type area.

The Swift Formation consists of greenish-gray interbedded slightly calcareous shale and siltstone overlain by glauconitic fine-grained quartzose sandstone, which is interbedded with and gradational to greenish-gray slightly calcareous shale and siltstone. On the eastern margin of the Williston basin, the sandstone unit is absent owing to post-Swift erosion and the lower part of the shale unit is sandy (Peterson, 1957). Shale at the top of the Swift generally is distinguished by its glauconitic content from superficially similar shale at the base of the overlying Morrison in some areas.

The Sundance Formation consists of interbedded shale, siltstone, and sandstone, lithologically similar to beds in the Rierdon and Swift Formation. In north-central South Dakota, however, it includes in its lower part limestone similar to that of the basal Piper Formation of North Dakota. Usage of the term Sundance in the Williston basin generally is restricted to South Dakota, where the Swift-Rierdon contact is not readily discernible. Francis (1956, 1957) suggested that Ellis Group terminology--the Piper, Rierdon, and Swift Formations--be restricted to the western part of the Williston basin and that usage of the term Sundance be extended into southeastern Montana and all but extreme northwestern North Dakota. This suggestion, however, has not been widely accepted.

The Morrison Formation is a discontinuous and heterogeneous assemblage of nonmarine claystone, siltstone, sandstone, variegated shale, and thin lenses of coal. The thickness of the formation and of its component beds changes abruptly in short distances. The Morrison is absent in eastern North Dakota and South Dakota and in parts of northeastern and north-central Montana. In some areas of the Williston basin, sandstone in the upper part of the Morrison is indistinguishable from sandstone at the base of the overlying Dakota Group of Early Cretaceous age. Elsewhere, red shale in the Morrison is not readily distinguished from red shale in the Kootenai Formation of Early Cretaceous age. Although some workers (McKee and others, 1956; Francis, 1957) attempted to isopach the Morrison Formation separately, they apparently were unable to completely exclude beds of Cretaceous age in some areas. D. E. Hansen (1958) postulated that the Jurassic-Cretaceous contact is gradational rather than unconformable in North Dakota. The combined thickness and distribution of the Morrison Formation and Dakota Group are shown on figure 24. The random pattern of the isopachs suggests many erratic changes in the thickness of these units.

A slowly subsiding intracratonic basin occupied the Williston basin area during most of Middle and Late Jurassic time. The shallow sea had a wide connection across a shelf area with deeper waters of the Cordilleran geosyncline in western Montana. Belt island probably was alternately a broad submarine platform or low isthmus at the west side of the shelf area rather than an island (Peterson, 1957). It extended northeastward from southwestern to north-central Montana, and the access of normal marine waters to the intracratonic basin was controlled by its intermittent activity.

In early Middle Jurassic time, the sea was restricted following deposition of the Saude Formation and widespread precipitation of halite and anhydrite took place. The resulting deposits are the Poe Evaporite Member of the Nesson Formation, the Dunham Salt, and the lower part of the Gypsum Spring Formation.

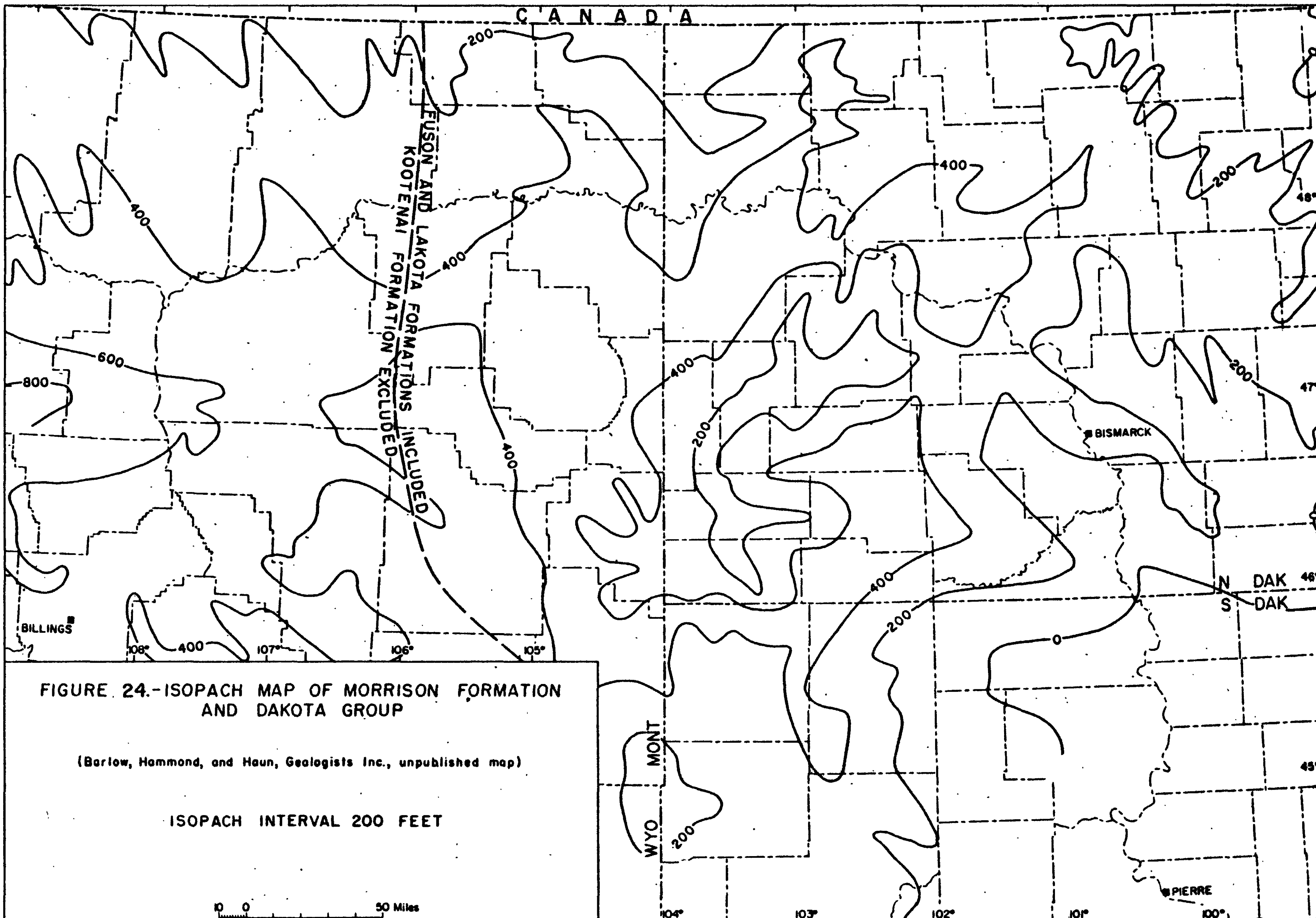

FIGURE 24.-ISOPACH MAP OF MORRISON FORMATION AND DAKOTA GROUP

(Barlow, Hammond, and Haun, Geologists Inc., unpublished map)

ISOPACH INTERVAL 200 FEET

Later in the Middle Jurassic, access of the sea to the basin was restored and the upper part of the Nesson Formation, the lower part of the Piper Formation of North Dakota, and the upper part of the Gypsum Spring Formation were deposited during a transgressive marine cycle.

In late Middle Jurassic time, a slight regression of the sea followed by a widespread transgression with minor fluctuations resulted in deposition of the Piper Formation of Montana, the upper part of the Piper Formation of North Dakota, and the basal part of the Sundance Formation in north-central South Dakota.

In early Late Jurassic time, the Rierdon Formation and lower part of the Sundance were deposited over a large area during minor fluctuations of the sea.

Regional uplift in the Williston basin area ended Rierdon deposition and was followed by an episode of erosion. This uplift probably accompanied the beginning of Nevadan orogeny farther west (Peterson, 1957). However, deposition between the Rierdon and Swift and between the lower and upper parts of the Sundance locally may have been continuous in the deeper part of the basin in North Dakota and north-central South Dakota.

In middle Late Jurassic time, the Swift Formation and the upper part of the Sundance were laid down during the most widespread transgression of Jurassic seas, while Belt island was apparently inactive (Peterson, 1957). Coarseness of the clastics suggests their western source, probably from the area of Nevadan orogeny (Peterson, 1957).

In latest Jurassic time, the sea regressed, leaving a low landmass in most of the Williston basin area. Deposition locally was transitional from marine to nonmarine, but over a wide area the Swift was slightly eroded and in some places deeply channeled. The discontinuous deposits of the lower part of Morrison Formation were laid down in many different continental environments and perhaps locally in marginal marine environments. The close of the Jurassic, however, was marked by simultaneous deposition of continental, marginal marine, and near-shore marine deposits in different parts of the Williston basin.

Dakota Group and related rocks

The Dakota Group of Early Cretaceous age comprises the Lakota, Fuson, and Fall River Formations, in ascending order, in most of the Williston basin. Inyan Kara Group, however, is used for equivalent rocks in South Dakota, where the Fuson Formation thins southward and becomes indistinguishable because of a facies change. In the Black Hills area, the Lakota Formation was redefined by Waagé (1959) to include beds previously assigned to the Fuson. In central South Dakota, the Lakota is difficult to differentiate and Fall River Formation commonly is used for all rocks equivalent to the Inyan Kara Group. In north-central Montana, the Kootenai Formation is equivalent to the Lakota and Fuson Formations and the First Cat Creek Sand of informal subsurface usage is equivalent to the Fall River Formation.

The term Dakota Group is employed here because of widespread usage, although it would be more expedient to use Inyan Kara Group throughout the Williston basin in view of many other conflicting applications of the name Dakota. The type Dakota Sandstone, from which the name Dakota Group originated is present just south of the Williston basin (fig. 17, col. 6).

Both the Fall River Formation of central South Dakota and a stratigraphically higher sandstone, which is separated from the Fall River by the Skull Creek Shale, were shown by Gries (1954) to be equivalent to the type Dakota Sandstone. Although Gries (1954) tentatively correlated the higher sandstone with the Newcastle Sandstone, he applied the name Dakota to it. The term Newcastle Sandstone is here used in accordance with current widespread usage for the higher sandstone. However, the Newcastle is equivalent to a large part of the type Dakota Sandstone, as shown diagrammatically on figure 6 and by well-log cross section on figure 17. An informal term, Dakota Sand, is used by drillers for either the Fall River Formation of the Newcastle Sandstone, depending on which is present or thicker in a particular well. An informal term, Dakota Silt, is used by drillers and geologists for persistent silty beds at the base of the Colorado Group, which overlies the Dakota Group. Another application of the term Dakota is that of D. E. Hansen (1955), who proposed that usage of Dakota Group be extended upward to include the Skull Creek Shale, Newcastle Sandstone, and Mowry Shale. However, this usage is not widely accepted, and most workers retain these formations in the Colorado Group.

The Dakota Group and related rocks unconformably overlie the Morrison Formation but apparently are conformable with it in part of North Dakota. They unconformably overlie the older Jurassic rocks where the Morrison is absent. Along the eastern and southern margins of the Williston basin, they rest unconformably on rocks ranging in age from Pennsylvanian to Precambrian. The Dakota Group and related rocks are conformably overlain by the Skull Creek Shale or Thermopolis Shale of the Colorado Group.

The Dakota Group and related rocks underlie the entire Williston basin except for parts of central and eastern South Dakota, north of the type area of the Dakota Sandstone (fig. 24). Thier northern, western, and southern limits lie far outside the report area. They have a maximum thickness of about 500 feet in north-central Montana. The combined thickness and distribution of the Dakota Group and the Morrison Formation is shown on figure 24. This map largely portrays the thickness and distribution of sandstone in both units because the Kootenai Formation, a predominantly argillaceous unit, is arbitrarily excluded from the Dakota Group west of a north-south line in eastern Montana.

The Lakota Formation consists of white and light-gray, medium- to coarse-grained sandstone with laminae of gray shale (Hansen, D. E., 1955). It has a maximum thickness of about 125 feet in the Central Williston basin. The Lakota commonly is conglomeratic and in some areas it contains rounded, polished chert pebbles. Its lithologic character is highly varied in the Black Hills, where the formation consists of sandstone, claystone, and siltstone and locally is coal bearing (Waagé, 1959).

The Fuson Formation of North Dakota is medium dark-gray to grayish-black shale with interbeds of quartzose sandstone (Hansen, D. E., 1955). It has a maximum thickness of about 125 feet in the Central Williston basin. The Fuson commonly contains rounded, medium- to coarse-grained pellets of siderite. It grades to sandstone in southeastern North Dakota and north-central South Dakota and becomes indistinguishable from the underlying Lakota. The correlation of the Fuson Formation of North Dakota with the type Fuson of the Black Hills is uncertain.

The Fall River Formation consists of light-gray fine- to coarse-grained quartzose sandstone interbedded with gray sandy shale (Hansen, D. E., 1955). It generally is the thickest formation of the Dakota Group and has a maximum thickness of about 200 feet in the Central Williston basin. In some areas, the Fall River can be divided into three units on the basis of a medial shaly sandstone (Hansen, D. E., 1955).

The Kootenai Formation has a maximum thickness of about 400 feet in north-central Montana. It consists largely of grayish-red, greenish-gray, and gray shale with interbeds of sandstone and a basal sandstone, informally termed the Third Cat Creek Sand. This sandstone, which locally is conglomeratic, is correlated with the Lakota Formation. The upper, argillaceous part of the Kootenai is correlated with the Fuson Formation of North Dakota. In central Montana, a sandstone in the argillaceous part of the Kootenai locally is about 100 feet thick and is informally termed the Second Cat Creek Sand.

The First Cat Creek Sand of informal usage is a white to light-gray fine- to coarse-grained sandstone with laminae of gray shale. It is lithologically similar to but thinner than the correlative Fall River Formation.

The contacts between the Kootenai Formation and First Cat Creek Sand in Montana and between the so-called Fuson Formation and Fall River Formation in North Dakota constitute a single widespread horizon. The structure contour maps (Dobbin and Erdmann, 1955; Hansen, D. E., 1957), on which figure 25 is based, were drawn at this readily discernible horizon. Because of the southward disappearance of the Fuson Formation of North Dakota, however, the structure contours (fig. 25) could be extended only a short distance into South Dakota.

The tectonic framework of the Williston basin area remained relatively unchanged from latest Jurassic time to earliest Cretaceous time. Much of the area probably was a landmass, but in some parts a shallow sea continued to regress despite slight transgressive interruptions. The Lakota, Fuson, and Kootenai Formations were deposited in fluctuating continental and marginal marine environments. Later, during deposition of the Fall River Formation and First Cat Creek Sand, a shallow Early Cretaceous sea transgressed southward from Canada through the Williston basin area. As the sea continued its southward transgression, it spread eastward and possibly slightly westward and covered the entire report area as well as a large part of the western United States.

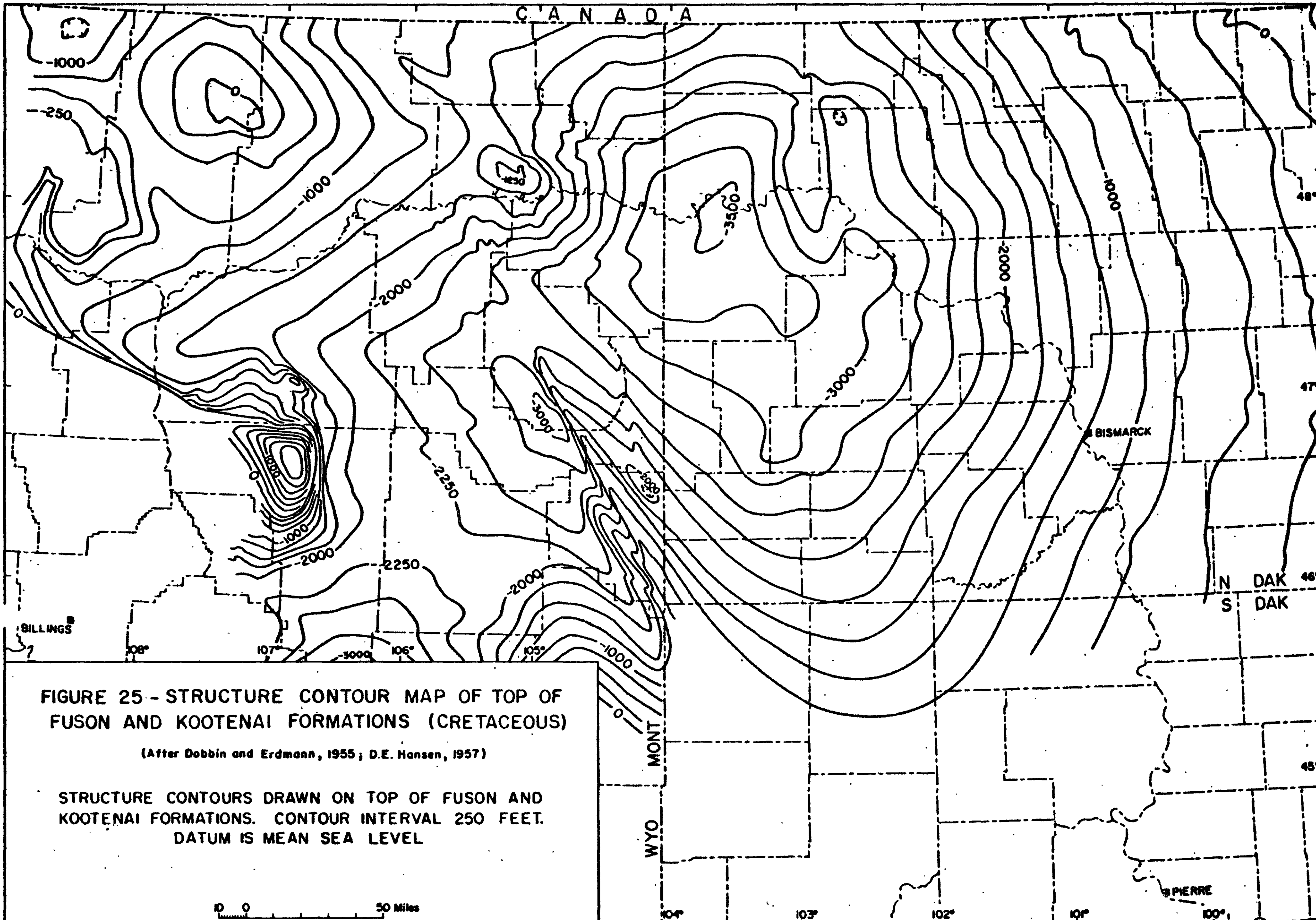

FIGURE 25 - STRUCTURE CONTOUR MAP OF TOP OF FUSON AND KOOTENAI FORMATIONS (CRETACEOUS)

(After Dobbin and Erdmann, 1955; D.E. Hansen, 1957)

STRUCTURE CONTOURS DRAWN ON TOP OF FUSON AND KOOTENAI FORMATIONS. CONTOUR INTERVAL 250 FEET. DATUM IS MEAN SEA LEVEL

10 0 50 Miles

Lower part of Colorado Group

In the Central Williston basin the lower part of the Colorado Group includes, in ascending order, the Skull Creek Shale, Newcastle Sandstone, and Mowry Shale. These formations are successively conformable and are of Early Cretaceous age. In Montana, the Thermopolis Shale of Early Cretaceous age at the base of the Colorado Group is equivalent to the Skull Creek Shale, Newcastle Sandstone, and lower part of the Mowry Shale of North Dakota. The Newcastle Sandstone is considered a member of the Thermopolis in eastern Montana, but it is absent in north-central Montana. In central and eastern South Dakota, two tongues of sandstone in the lower part of the Mowry Shale are informally designated, in descending order, the D Sand and Upper J Sand, whereas the Newcastle is correlated with the Lower J Sand of informal usage in the Denver-Julesburg basin of Nebraska and Colorado. These three beds of sandstone--the D Sand, Upper J Sand, and Lower J Sand--form the upper part of the type Dakota Sandstone (fig. 6).

The Skull Creek Shale or the Thermopolis Shale conformably overlies the Fall River Formation or the First Cat Creek Sand of informal usage. The Mowry Shale is conformably overlain by the Belle Fourche Shale of Late Cretaceous age.

The lower part of the Colorado Group underlies the entire Williston basin area and has a maximum thickness of about 500 feet. It is widely distributed and its northern, western, and southern limits lie far outside the report area.

The Skull Creek Shale is medium-gray to black marine bentonitic shale. The basal beds commonly consist of interbedded shale, siltstone, and sandstone. These beds, which are informally termed the Dakota Silt, commonly are gradational with the underlying Fall River Formation. The contact with the overlying Newcastle Sandstone also is commonly gradational because of interbedding of sandstone and shale. The Skull Creek is about 200 to 300 feet thick in the Central Williston Basin, but it thins eastward and is only about 40 feet thick in eastern North Dakota (Hansen, D. E., 1955). The Skull Creek thins southward and lenses into the type Dakota Sandstone in south-central South Dakota (fig. 17, col. 5-6).

The Newcastle Sandstone consists of light-gray fine-grained shaly and silty quartzose sandstone with interbeds of gray shale (Hansen, D. E., 1955). In some areas it contains carbonized plant fragments and thin seams of lignite. The Newcastle occurs as thin discontinuous lenses and pods of sandstone (fig. 26), which grade abruptly into the enclosing marine shales by intertonguing. It has a maximum thickness of 120 feet in the Central Williston basin but is absent from most of central North Dakota, north-central South Dakota, and north-central Montana (fig. 26). Along the southeastern margin of the Williston basin, the Newcastle includes the Upper J Sand and D Sand of informal usage and is about 275 feet thick. However, these beds of sandstone pinch out northwestward into the overlying Mowry Shale (fig. 26).

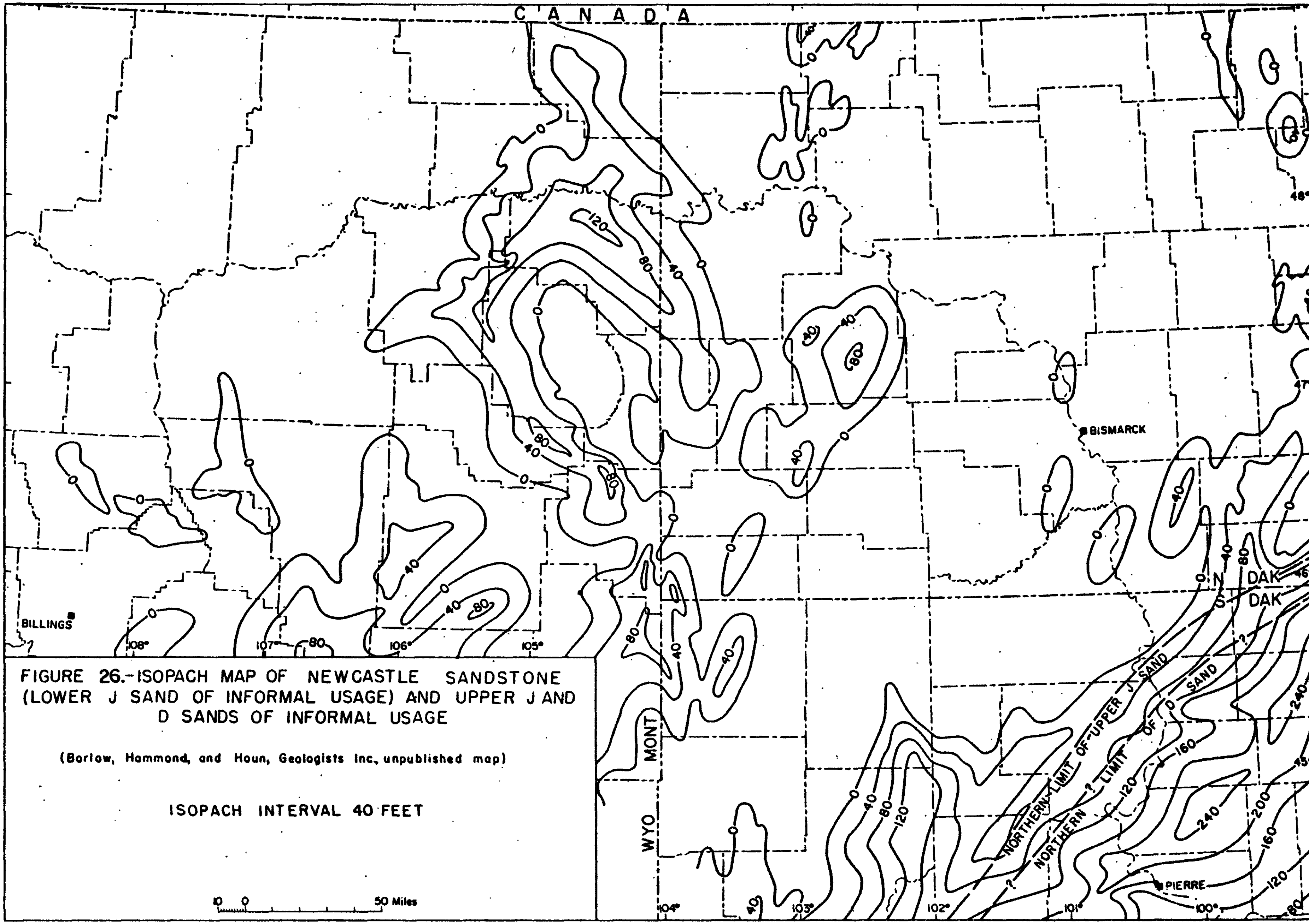

FIGURE 26.-ISOPACH MAP OF NEWCASTLE SANDSTONE (LOWER J SAND OF INFORMAL USAGE) AND UPPER J AND D SANDS OF INFORMAL USAGE

(Barlow, Hammond, and Houn, Geologists Inc., unpublished map)

ISOPACH INTERVAL 40 FEET

The Newcastle Sandstone lies about 300 to 500 feet above the top of the Fuson and Kootenai Formations (fig. 25) or about 1,500 to 5,000 feet below the surface.

The Thermopolis Shale consists predominantly of dark-gray marine bentonitic shale and is lithologically similar to the Skull Creek Shale. Its thickness ranges from 300 to a maximum of about 625 feet in north-central Montana. The Newcastle Sandstone Member near the middle of the formation is overlain by about 150 to 250 feet of dark-gray shale. In north-central Montana, a thin shaly sandstone at about the same horizon in the Thermopolis as the Newcastle farther east has been termed the Cyprian Sandstone Member by Knechtel (1959).

The Mowry Shale, which conformably overlies the Thermopolis Shale, consists of medium- to dark-gray siliceous shale with thin interbeds of bentonite and shaly sandstone. Its outcrops are characterized by barren slopes covered by light-gray or silvery-gray chips of shale. In the subsurface, however, it commonly is difficult to differentiate from the overlying Belle Fourche Shale (fig. 17). In North Dakota and South Dakota, where the term Thermopolis is not employed, usage of the term Mowry is extended downward to the top of the Newcastle Sandstone, and the lower part of the Mowry consists of beds of nonsiliceous shale equivalent to the upper part of the Thermopolis. The Mowry Shale ranges in thickness from 50 to 200 feet in the Central Williston basin. It thins eastward to extinction in eastern North Dakota (Hansen, D. E., 1955).

In late Early Cretaceous time, the Williston basin area lay in the eastern half of a long, wide seaway that extended southward through western Canada and the western conterminous United States. Shale was deposited in relatively shallow water in a normal marine environment, as evidenced by abundant fish remains. Ash falls accompanied deposition of the lower part of the Colorado Group but occurred most frequently during deposition of the Mowry Shale. These ash falls not only formed the bentonites that are interbedded with the shales but contributed sediments to the shales, especially the siliceous Mowry (Rubey, 1929). Circulating currents intermittently concentrated coarser clastics as sand bars. A major episode of sand-bar development probably resulted in deposition of the widespread Newcastle Sandstone, as suggested by its distribution pattern (fig. 26). Some of the larger sand bars probably were built above sea level and supported vegetation, as suggested by the plant remains in the Newcastle. The thick accumulation of the Newcastle and related sandstones in central South Dakota suggests that this area may have been close to a landmass from which the coarser sediments were derived.

Belle Fourche Shale, Greenhorn Formation, and Carlile Shale

The lower part of the thick marine shale sequence of Late Cretaceous age (fig. 5) includes the successively conformable Belle Fourche Shale, Greenhorn Formation, and Carlile Shale of the Colorado Group, in ascending order. In the Little Rocky Mountains of north-central Montana, they are lumped with the Niobara Formation, the uppermost formation of the Colorado Group, as the Warm Creek Shale (Gries, 1953). The Belle Fourche conformably overlies the Mowry Shale and the Carlile is conformably overlain by the Niobrara Formation.

The Belle Fourche Shale, Greenhorn Formation, and Carlile Shale underlie the entire Williston basin and are generally thicker than 500 feet except in a small part of northeastern Montana and northwestern North Dakota (fig. 27). They attain a maximum thickness of about 1,200 feet at the southwestern margin of the basin. They are thickest in two poorly defined troughs. A major trough extends northeastward from northeastern Wyoming toward north-central North Dakota and is crossed in southwestern North Dakota by a secondary trough trending southeastward from central Montana to north-central South Dakota (fig. 27). From these areas of thickening, the formations thin erratically toward the margins of the basin.

The Belle Fourche Shale consists of medium dark-gray to dark-gray micaceous bentonitic shale with interbeds of white to light-gray bentonite (Hansen, D. E., 1955). Its maximum thickness is about 500 feet at the southwestern margin of the Williston basin. The Belle Fourche ranges in thickness from about 150 to 450 feet in the Central Williston basin. It becomes silty eastward in North Dakota and thins to a thickness of about 100 feet at the eastern margin of the basin (Hansen, D. E., 1955). The contact between the Belle Fourche and the underlying Mowry commonly is gradational, but in North Dakota it is placed at the base of a bed of silty bentonitic shale (Hansen, D. E.,

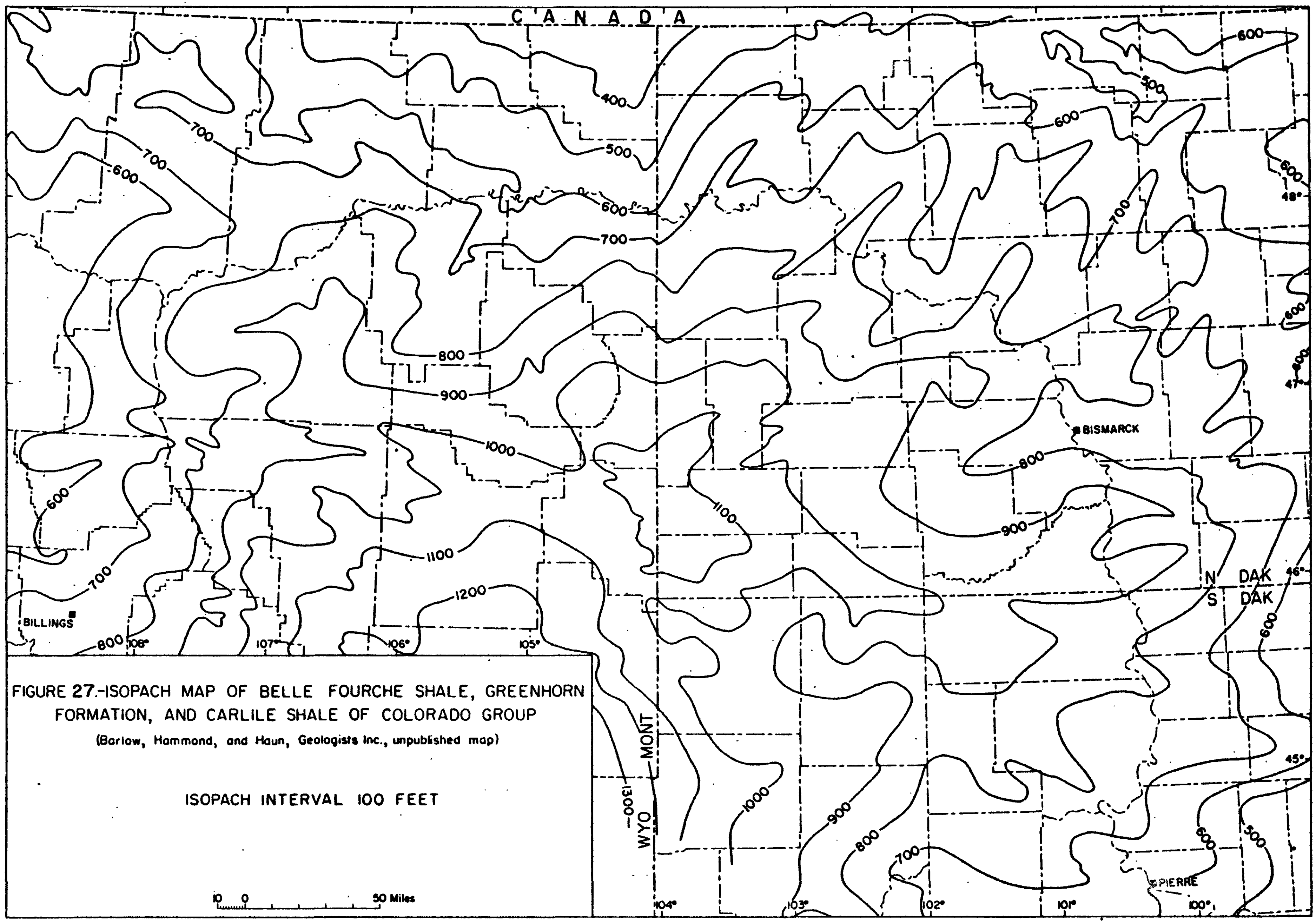

FIGURE 27.-ISOPACH MAP OF BELLE FOURCHE SHALE, GREENHORN FORMATION, AND CARLILE SHALE OF COLORADO GROUP

(Barlow, Hammond, and Haun, Geologists Inc., unpublished map)

ISOPACH INTERVAL 100 FEET

1955). The contact between the Belle Fourche and the overlying Greenhorn Formation generally is sharp.

The Greenhorn Formation consists of dark-gray speckled calcareous shale interbedded with shaly limestone. It is a thin but widespread unit that is readily differentiated from the overlying and underlying shales on lithologic and mechanical well logs (fig. 17). The Greenhorn ranges in thickness from 15 to 200 feet in the report area, but its thickness in North Dakota ranges only from 120 to 150 feet (Hansen, D. E., 1955).

The Carlile Shale is dark-gray shale with thin interbeds of sandy shale or shaly sandstone near the middle. It commonly is divided into three members along the southwestern margin of the Williston basin. The Carlile attains a maximum thickness of about 600 feet at the southwestern margin of the basin, but its thickness is about 200 to 500 feet in the Central Williston basin. The contact between the Carlile and the underlying Greenhorn is sharp. However, the contact with the overlying Niobrara Formation commonly is gradational and some geologists do not differentiate the Carlile from the Niobrara.

The tectonic framework of the Williston basin area in early Late Cretaceous time was unchanged from that of late Early Cretaceous time. Shale continued to be the predominant sediment in the relatively shallow water of a slowly subsiding trough. Ash falls occurred intermittently, but they were less frequent than during deposition of the

Mowry Shale. The major source of sediments probably lay far southwest of the report area, as evidenced by the thickening of deposits in that direction at the southwestern margin of the basin (fig. 27). Currents only infrequently carried in coarser clastics to be deposited as interbeds of shaly sandstone or sandy shale.

Niobrara Formation and Pierre Shale

The upper part of the thick marine shale sequence of Late Cretaceous age (fig. 5) includes the Niobrara Formation of the Colorado Group and the conformably overlying Pierre Shale of the Montana Group in the eastern two-thirds of the Williston basin. The Niobrara Formation conformably overlies the Carlile Shale. Because the Niobrara-Pierre contact is difficult to pick consistently, the Niobrara is here considered with the Pierre rather than with the upper part of the Colorado Group. The Pierre Shale is conformably overlain by the Fox Hills Sandstone, the uppermost formation of the Montana Group.

The arbitrary western limit of usage of the Pierre Shale is a line that denotes the eastern limit of the easternmost bed of sandstone interbedded with marine shale (fig. 28). West of this line, the Pierre Shale is equivalent to the Telegraph Creek Formation, Eagle Sandstone, Claggett Shale, Judith River Formation, and Bearpaw Shale of the Montana Group, in ascending order (fig. 6).

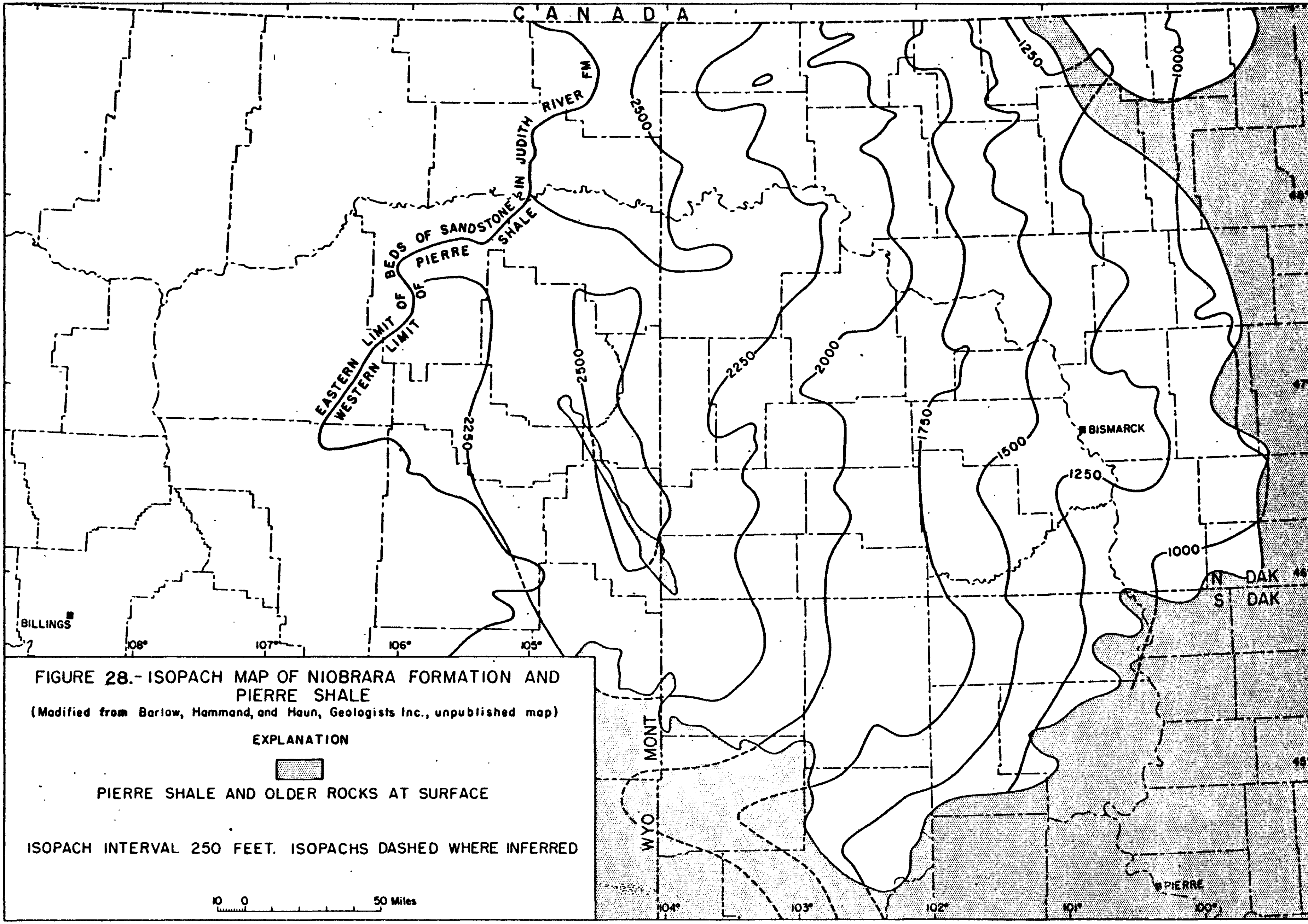

FIGURE 28.- ISOPACH MAP OF NIOBRARA FORMATION AND PIERRE SHALE

(Modified from Barlow, Hammand, and Haun, Geologists Inc., unpublished map)

EXPLANATION

PIERRE SHALE AND OLDER ROCKS AT SURFACE

ISOPACH INTERVAL 250 FEET. ISOPACHS DASHED WHERE INFERRED

10 0 50 Miles

The Niobrara Formation and Pierre Shale have a maximum thickness of about 2,500 feet in east-central and northeastern Montana (fig. 28). They are thickest in a trough that extends southward through western North Dakota and eastern Montana. They thin gradually eastward and have a thickness of about 1,000 feet near the outcrop of the Pierre Shale in central North Dakota (fig. 28). The Pierre is exposed on the eastern and southern margins of the Williston basin and on the Cedar Creek anticline.

The Niobrara Formation consists of medium- to dark-gray partly speckled calcareous shale interbedded with thin beds of argillaceous limestone, chalk, and bentonite. Its thickness in the Central Williston basin ranges from about 100 to 200 feet.

The Pierre Shale consists of medium-gray to black bentonitic shale with thin interbeds of light-gray and yellowish-gray bentonite. Zones of silty or sandy shale in the Pierre probably were deposited contemporaneously with equivalent beds of sandstone farther west. The Pierre generally is not subdivided in the Williston basin, although as many as eight members are mapped in outcrops on the margins. Its thickness ranges from about 900 feet in central North Dakota to 2,300 feet in the Central Williston basin.

Rocks of the Montana Group equivalent to the Pierre Shale are exposed in most of north-central Montana and on the Central Montana uplift. There they are several hundred feet thicker than the Pierre is in the Central Williston basin. However, they appear to thin westward in most areas because of present-day erosion of the flat-lying Bearpaw Shale.

The marine Telegraph Creek Formation, about 100 to 200 feet thick, consists of interbedded yellowish-gray thin-bedded sandstone, siltstone, and sandy shale. Its contacts are gradational and its lithologic character is transitional between the underlying Niobrara Formation and the overlying Eagle Sandstone.

Both the Eagle Sandstone, about 100 to 300 feet thick, and the Judith River Formation, about 350 to 500 feet thick, consist in part of marine yellowish-gray and gray sandstone and siltstone and in part of marginal-marine and continental claystone, carbonaceous shale, and lignite. Each was deposited during an episode of eastward regression followed by westward transgression of the sea.

The marine Claggett Shale, about 400 to 500 feet thick, and the marine Bearpaw Shale, about 700 to 900 feet thick, are lithologically similar to and depositionally continuous with corresponding parts of the Pierre Shale. They were deposited during episodes of maximum western extent of the Late Cretaceous sea.

During deposition of the Niobrara Formation and Pierre Shale, the tectonic framework of the Williston basin area remained essentially unchanged from that of late Early Cretaceous time. However, the western shoreline twice migrated back and forth across the western third of the Williston basin area (Weimer, 1960). Deposition of marine shale in the eastern two-thirds of the area was not interrupted, although silty or sandy shale was laid down there during the shoreline migrations. Ash falls continued intermittently throughout the area.

Rocks between top of Pierre Shale and surface

Rocks of Late Cretaceous to Pleistocene age, locally as thick as 2,800 feet, overlie the Pierre Shale and its equivalents in part of the Williston basin area. Their thickest accumulation is in the Killdeer Mountains, 20 miles directly south of the Nesson anticline (fig. 1) in the Central Williston basin. Rocks between the top of the Pierre Shale and the surface comprise, in ascending order, the Fox Hills Sandstone and Hell Creek Formation of Late Cretaceous age, the Fort Union Formation of Paleocene age, the Golden Valley Formation of Eocene age, the White River Formation of Oligocene age, the Arikaree Formation of Miocene age, the Flaxville Gravel of Miocene or Pliocene age, and glacial drift of Pleistocene age. The Fort Union Formation comprises the Ludlow, Cannonball, Tongue River, and Sentinel Butte Members, in ascending order. The White River is considered to be a group, comprising the Chadron and Brule Formations, in ascending order, by some geologists. All post-Pierre strata, except for the Fox Hills Sandstone, a thin tongue in the Hell Creek Formation, and the Cannonball Member of the Fort Union Formation, are continental.

The Fox Hills Sandstone consists largely of marine yellowish-gray and light-gray shaly bentonitic sandstone and silty or sandy shale. Its thickness ranges from about 100 to 350 feet in the Central Williston basin. The Fox Hills is absent northeast of the Porcupine dome (fig. 1). The Fox Hills was deposited during the southward and eastward regression of the Late Cretaceous sea from the Williston basin area.

The Hell Creek Formation, which disconformably overlies the Fox Hills Sandstone, consists of a highly varied assemblage of nonmarine gray and yellowish-gray mudstone, siltstone, and sandstone (Cobban, 1952). It is 100 to 550 feet thick in the Central Williston basin. In some areas the lower part of the formation contains carbonaceous shale and lignite (Brown, 1952). The Hell Creek is continental except for a brackish-water tongue near the base in south-central North Dakota (Laird and Mitchell, 1942). This tongue was deposited during a very minor marine transgression after the sea had largely withdrawn from the Williston basin area.

The Fort Union Formation, as much as 2,000 feet thick, conformably overlies the Hell Creek Formation. The Fort Union consists largely of gray and yellowish-gray shale, claystone, and sandstone interbedded with lignite. In some areas it is divided into three members on the basis of the different average shade of rather indefinite stratigraphic zones. The Ludlow Member at the base is dark colored; the overlying Tongue River Member generally is lighter in color; the uppermost member, the Sentinel Butte, is dark colored. These three members of the Fort Union are continental, but the Cannonball Member which interfingers with the Ludlow Member in parts of North Dakota and South Dakota, is marine. The Cannonball Member has a maximum thickness of about 300 feet in North Dakota, but it thins westward to extinction in easternmost Montana. It consists of gray and yellowish-gray sandstone and shale, which were deposited during a minor transgression of the sea into the southern part of the Williston basin area.

The continental Golden Valley Formation, about 175 feet thick, conformably overlies the Fort Union Formation in southwestern North Dakota. It is found in isolated erosional remnants between the Missouri River, at Bismarck, N. Dak., and the Montana line (Brown, 1952). It consist of interbedded purplish-gray carbonaceous shale and yellowish-orange and white claystone overlain by interbedded fine- to coarse-grained sandstone, shale, and claystone (Benson, 1949).

The White River Formation, as much as 400 feet thick, unconformably overlies Eocene and older strata. It is present on high divides and isolated buttes in southeastern Montana, southwestern North Dakota, and western South Dakota (Denson and others, 1959). It consists of very light gray and pinkish-gray tuffaceous sandstone, conglomerate, claystone, and limestone and probably was deposited on flood plains and in lakes.

The continental Arikaree Formation, as much as 300 feet thick, unconformably overlies the White River Formation on some of the highest divides and buttes. The Arikaree consists largely of yellowish-gray tuffaceous sandstone overlying a basal conglomerate.

The Flaxville Gravel caps some of the highest divides in north-central and northeastern Montana but probably is not present in North Dakota. Its thickness generally is 30 feet or less. It was deposited on a flood plain and consists of unconsolidated or locally cemented sand and rounded gravel.

Glacial drift mantles Tertiary and Cretaceous rocks north and east of the Missouri River in northern Montana, northern and eastern North Dakota, and eastern South Dakota (fig. 2). Its thickness averages about 200 feet but locally may be as much as 500 feet.

Thin unconsolidated Quaternary deposits, including alluvium, colluvium, terrace gravel, landslide debris, and some sand dunes, are widely distributed.

The Late Cretaceous sea withdrew southward and eastward from the Williston basin area during deposition of the Fox Hills Sandstone. During the latest Cretaceous and Tertiary the Williston basin area was alternately subjected to continental deposition and erosion, except for two brief marine incursions into the southern part in latest Cretaceous and early Paleocene time. The Continental Glacier periodically covered the northern and eastern parts of the area during the Pleistocene. Since its retreat, the Williston basin area has been subjected to widespread erosion accompanied by minor local deposition.

STRUCTURE

The Williston basin is a large, relatively shallow elliptical basin, lying partly in midwestern Canada and partly in the conterminous United States. Its axis trends about N. 10° W. in the southern part of the basin, the area considered in this report (figs. 1, 4, 14, 23, and 25). Rocks at the surface generally appear to be flat-lying because regional dips from the margins to the basin center are 1° or less. Most of the major folds are on the west side of the basin; the east and south sides contain only minor wrinkles. Dips on the flanks of major folds generally are about 1° to 3°, but dips on folds in the basin interior do not exceed 2°. The only known dips steeper than 3° in the Williston basin are adjacent to the uplifts and mountains bordering the western margin and on the west limb of the Cedar Creek anticline (fig. 1).

The dominant structural grain trends N. 30° W., and secondary structural grains trend N. 55° to 60° E. and N. 2° E. Many linear structural features within the Williston basin trend roughly in one of these three directions.

Folds

The major folds in the Williston basin are the Cedar Creek and Nesson anticlines, the Poplar and Bowdoin domes, and the Sheep Mountain and Blood Creek synclines (fig. 1). The important secondary folds are the Camp Crook, Plevna, and Sanish anticlines, the Freedom dome, and the Coburg syncline (fig. 1).

The Cedar Creek anticline is a 125-mile long, northwest-plunging asymmetrical anticline with a steep west limb. It trends N. 30° W. from northwestern South Dakota to east-central Montana (fig. 1). Dips on its west limb range from about 4° to 30° SW., but locally the surface rocks are nearly vertical where they reflect a subsurface fault. The Plevna anticline branches from the Cedar Creek anticline and parallels its west limb. The Sheep Mountain syncline borders the Plevna and Cedar Creek anticlines on the west. The Camp Crook anticline connects the southern part of the Cedar Creek anticline with the Black Hills uplift.

Two small anticlines have been inferred west of the Plevna anticline, and two or more small anticlines have been inferred east of the Cedar Creek anticline (fig. 14). These anticlines also trend about N. 30° W. and probably are related to the Cedar Creek anticline.

The Nesson anticline is a 75-mile long, 15-mile wide anticline that plunges southward just east of the basin center. It trends about N. 2° E. in northwestern North Dakota (fig. 1). A subsidiary fold, the Sanish anticline, branches from its east limb and trends S. 30° E., parallel to the Cedar Creek anticline. The Sanish anticline follows the trend of the ancestral Nesson anticline of Devonian time (fig. 11).

The Poplar dome is an elliptical feature, 25 miles long from east to west and 15 miles wide in northeastern Montana (fig. 1). Its west end lies at the projected trend of the Cedar Creek anticline.

The Bowdoin dome is a large subcircular feature, about 65 miles long from east to west and about 50 miles wide in north-central Montana (fig. 1). It is bordered on the southwest by the Coburg syncline, whose axis trends N. 30° W. The Western limit of the Williston basin is drawn around the east and south flanks of the Bowdoin dome by some geologists. The dome is here included within the Williston basin, however, as dips on any of its flanks rarely exceed 1°. The only steep dips that logically limit the Williston basin in north-central Montana are west of the Coburg syncline on the flanks of the Little Rocky and Bearpaw Mountains.

The Freedom dome is a small elliptical feature, whose longer dimension is less than 10 miles. It lies north of the large Porcupine dome at the east end of the Central Montana uplift (fig. 1). Freedom dome is included in the Central Montana uplift by many geologists, although it is much lower than the other structural features on the north side of the uplift (figs. 23 and 25).

The Blood Creek syncline lies between Freedom dome on the south and the Bowdoin dome and Little Rocky Mountains on the north. The syncline terminates abruptly, possibly because of a subsurface fault, at the north limb of the Cat Creek anticline of the Central Montana uplift (fig. 1).

Faults

The latest deformation of the Williston basin area resulted only in gentle folding, and faults are rare in the surface rocks. The only two known major surface faults are the Brockton-Froid fault zone and the Weldon fault, which parallel one of the secondary structural grains. Several large faults have been recognized in the subsurface, however. These are associated with ancestral anticlines and parallel the primary grain.

The Brockton-Froid fault zone is half a mile wide and extends eastward for 35 miles from the east end of the Poplar dome (Colton and Bateman, 1956). Its trend is about N. 55° E. Rocks are apparently downdropped 75 to 200 feet on the north side of the fault zone.

The Weldon fault extends about N. 58° E. for 8 miles in east-central Montana (Dobbin and Erdmann, 1955; Sandberg, D., 1959), about midway between the Freedom and Poplar domes (fig. 1). Evidence for minor subsurface faults related to the Weldon fault has been found in several wells drilled about 3 miles south and about 10 miles east of the Weldon fault. A Pennsylvanian fault, downdropped on the south side, has been inferred by Blair (1960) to pass through the Richey oilfield (fig. 3). An earliest Mississippian monoclinal fold or fault, downdropped on the north, has been postulated by Sandberg (1961a) to pass through the Southwest Richey oilfield. Considered together with the Weldon fault, these subsurface faults suggest the presence in east-central Montana of a long fault zone parallel to the Brockton-Froid fault zone.

The largest fault in the Williston basin area is the subsurface fault that offsets the steep west limb of the Cedar Creek anticline. The Cedar Creek fault trends N. 30° W. for at least 55 miles in east-central Montana (figs. 4 and 11). It may be as long as 125 miles and extend into northwestern South Dakota (fig. 18). This fault actually is a zone along which several types of fault movement have occurred at least four times between the Precambrian and Tertiary. A small normal fault of undetermined trend cuts out about 250 feet of Mississippian rocks in the Cabin Creek oilfield (fig. 3) on the crest of the Cedar Creek anticline. It may be a transverse fault related to the longitudinal Cedar Creek fault, because several small transverse surface faults have been mapped in the same area (Erdmann and Larsen, 1934). Another normal fault of undetermined trend is present in a well drilled near the crest of the Plevna anticline.

A large subsurface fault, which may be as much as 20 miles in length, has been inferred along the Sanish anticline by Bateman (1957). The inferred Sanish fault trends about N. 30° W., and offsets Mississippian rocks, which are apparently downthrown on its east side.

Age of deformation

The Williston basin and its surficial structural features were shaped by Laramide orogeny during latest Cretaceous and early Tertiary time. The youngest widely folded strata appear to be in the Fort Union Formation of Paleocene age, although the conformably overlying Golden

Valley Formation of Eocene age has been reduced in areal extent by Recent erosion and is absent adjacent to the major folds. Because the White River Formation of Oligocene age overlies a widespread unconformity developed on older Tertiary and Upper Cretaceous rocks, the final movements of Laramide orogeny can be dated as probably late Eocene or possibly earliest Oligocene. Shallow northeast-trending folds in Oligocene and Miocene rocks of southwestern North Dakota and northwestern South Dakota suggest a local post-Laramide episode of folding (N. M. Denson and J. R. Gill, oral communication, Jan. 31, 1962).

Most major structural features of the Williston basin area did not originate during the Laramide orogeny but had already formed in Precambrian time. These ancestral structural features were reactivated during several subsequent orogenies, of which the latest was the Laramide. The major orogenies occurred largely between Middle Devonian and Early Jurassic time, however, and a long period of relative quiescence preceded the Laramide orogeny.

The long history of structural features of the Williston basin area is exemplified by the Cedar Creek anticline, whose complex structural movements are interpreted from extensive subsurface data. The ancestral Cedar Creek anticline of Precambrian time probably was similar in size and shape to the present anticline and was bounded on the west by a normal fault, whose west side was downthrown (fig. 4). The anticline was relatively inactive during Cambrian, Ordovician, and Silurian time, as shown by the uniform thickness of the formations in the area (figs. 7-10). Intermittent movement of the ancestral anticline during Middle and Late Devonian time reduced the amount of sedimentation in the area. This movement culminated during earliest Mississippian time in folding accompanied by high-angle reverse faulting, which offsets only Devonian and older strata on the west limb. Erosion largely beveled the ancestral anticline before Lower Mississippian rocks were laid down. Slight movement recurred during Late Mississippian time, however, and controlled sedimentation in the Central Williston basin area. During the Permian a monocline, higher on the west, developed in the vicinity of the Cedar Creek anticline. Continued movement of the monocline culminated during post-Permian, pre-Middle Jurassic time in high-angle reverse faulting along the ancestral fault zone (fig. 18). During this deformation the west side of the fault was upthrown, whereas the east side of the earliest Mississippian fault had been upthrown. Erosion beveled the faulted monocline prior to deposition of Middle Jurassic sediments. Normal faulting of the west limb accompanied Laramide folding of the Cedar Creek anticline, and the west side of the fault was deeply downdropped.

ECONOMIC GEOLOGY

Oil is the most important natural resource of the Williston basin area. Lignite is another major resource, but it is at present not as important commercially as the oil. Gas, uranium, gravel, sand, clay, and other resources are relatively unimportant.

Oil and gas

Almost 40 million barrels of oil were produced in the Williston basin during 1960 from about 30 oilfields in Montana, about 70 oilfields in North Dakota, and 1 oilfield in South Dakota (fig. 3). About three-quarters of the oil production came from pools in the Red River Formation of Ordovician age on the Cedar Creek anticline and pools in the Madison Group of Mississippian age on the Nesson and Sanish anticlines and on the Poplar dome (fig. 1). Other major production was from the Madison Group in scattered oilfields in northern North Dakota, east of the Nesson anticline (fig. 3). Important but relatively minor production came from the Stony Mountain Formation of Ordovician age, the Interlake Formation of Silurian age, the Winnipegosis, Dawson Bay, Souris River, Duperow, Birdbear, and Three Forks Formations of Devonian age, the Bakken Formation of Devonian(?) and Mississippian age, and the Tyler Formation of Pennsylvanian age in these and other parts of the basin. The thick carbonate sequence of Ordovician through Pennsylvanian age (fig. 5) yielded 96 percent of the oil produced in the Williston basin during 1960; the other 4 percent came from pools that produced jointly from the Madison Group and the overlying Saude Formation of Jurassic age in northern North Dakota.

Several nonproductive formations either have yielded near-commercial oil shows in the Williston basin area or have produced oil in adjacent areas. These potentially productive formations are the

Winnipeg Formation of Ordovician age, the Kibbey Formation of Mississippian age, the Amsden Formation of Pennsylvanian age, the Minnelusa Formation of Pennyslvanian and Permian age, the Piper, Swift, and Sundance Formations of Jurassic age, and the Dakota Group, Kootenai Formation, and Newcastle Sandstone of Cretaceous age. Significant oil shows have not been found in rocks below the Winnipeg Formation or above the Newcastle Sandstone or in the redbed sequence of Permian and Triassic age (fig. 5). These strata, therefore, are not at present regarded as potentially oil-bearing in the Williston basin area.

Natural gas production is insignificant in the Williston basin area. Most of the natural gas is a byproduct of producing oil wells, and a large part of this gas is flared. Bowdoin and Cedar Creek are the only important gasfields (fig. 3). The Bowdoin field produces gas from two local beds of sandstone in the upper part of the Colorado Group of Cretaceous age and the Cedar Creek field produces gas from silty and sandy shale and shaly and sandy siltstone at two horizons, equivalent to the Eagle Sandstone and Judith River Formation, in the Pierre Shale of Cretaceous age (Billings Geological Society, 1958). Plevna gasfield, just west of the Cedar Creek gasfield (fig. 3), has minor gas production from the Judith River equivalent.

Only a limited market exists at present for natural gas produced in the Williston basin area, and hence there is little active exploration.

Lignite

The area of outcropping Tertiary rocks in the Williston basin (fig. 2) constitutes most of the Fort Union region of the Great Plains coal province (Trumbull, 1960). The Williston basin probably contains the largest lignite reserves of any area in the United States. North Dakota leads the United States in annual lignite production with about three million tons (Hainer, 1956).

Commercial deposits of lignite, in beds as much as 40 feet thick, are abundant and widely distributed in the Fort Union Formation of Paleocene age. Most of the lignite reserves are contained in the Tongue River Member. Thin, largely noncommercial beds of lignite are locally present at or near the surface in the Eagle Sandstone, Judith River Formation, and lower part of the Hell Creek Formation of Cretaceous age and in the Golden Valley Formation of Eocene age (Combo and others, 1949; Hainer, 1956; Rothrock, 1944). Thin local beds of bituminous coal may be present at depth in the Morrison Formation of Jurassic age.

Lignite is mined in the Williston basin area largely by stripping, and this will probably continue to be the major method of mining. Underground mining, except at very shallow depths, appears unlikely, at least for some time to come.

Uranium

Uranium is present in carbonaceous shale and lignite beds of the Hell Creek Formation of Late Cretaceous age and the Fort Union Formation of Paleocene age along the southwestern margin of the Williston basin in southwestern North Dakota, northwestern South Dakota, and southeastern Montana (Denson and others, 1959). Reserves of rock containing greater than 0.1 percent uranium are estimated to be in excess of one million tons (N. M. Denson and J. R. Gill, oral communication, Jan. 31, 1962). Lignite is not being commercially mined solely for its uranium content at present. Any future mining of uranium-bearing carbonaceous shale and lignite probably would be largely by stripping.

Ground water

Upper Cretaceous and Tertiary rocks as well as glacial drift and unconsolidated deposits yield potable water by pumping from shallow wells for farm and ranch consumption in many parts of the Williston basin. Sandstone beds in Upper Jurassic and Lower Cretaceous rocks are important aquifers, which flow potable water in the western part of the Williston basin near their intake areas in the Black Hills (Rothrock, 1944). In the vicinity of the Black Hills, the Deadwood, Winnipeg, and Minnelusa Formations and the Pahasapa Limestone locally serve as aquifers (Rothrock, 1944). Along the eastern margin of the basin, the most important aquifers are the Dakota Group and Newcastle

Sandstone of Early Cretaceous age. The thick Paleozoic carbonate sequence and the Winnipeg Formation probably contain many deep aquifers throughout the Williston basin.

Hydrodynamic studies suggest that formation waters in the thick Paleozoic carbonate sequence flow northeastward through the Williston basin under considerable hydrostatic head from intake areas in the Big Snowy and Little Rocky Mountains and Black Hills along the western margin. A similar direction of flow is postulated for waters in the Winnipeg Formation. Salinity studies indicate that waters in Devonian and Mississippian rocks become highly saline in the Central Williston basin probably in part through solution of salt beds and in part through addition of connate waters. Salinity studies of waters in Cambrian to Silurian rocks indicate a similar increase in salinity in the Central Williston basin (Porter and Fuller, 1959). A northeast movement of water accompanied by salt solution is taking place in Devonian rocks in the Saskatchewan part of the Williston basin (Milner, 1956). A number of brine springs, high in sodium chloride content, flow from Devonian rocks at the eastern margin of the Williston basin in Manitoba (Baillie, 1953). Along the eastern margin of the Williston basin in North Dakota, however, aquifers in the Paleozoic carbonate sequence are truncated by Cretaceous aquifers, which probably absorb most of the flow. There the saline water may be freshened by the addition of upward-flowing water from vertical fractures in the underlying Precambrian rocks.

Other resources

The salt member of the Prairie Formation of Middle Devonian age probably contains sizable but unestimated reserves of sylvite at great depth in the Central Williston basin. Potash production from this formation at somewhat shallower depths has been under investigation since 1953 in the Saskatchewan part of the basin (Cheesman, 1958).

Undrained saline lakes in the glacial drift area of northwestern North Dakota contain high concentrations of sodium sulfate (Hainer, 1956). Although some Glauber's salt was produced and marketed in 1951, this resource is not at present being exploited.

The surficial strata of the Williston basin area contain large deposits of clay, shale, sand, and gravel, some of which are being used in road construction and by local industries (Hainer, 1956; Rothrock, 1944). Deposits of bentonite, however, are generally too thin for commercial exploitation by present methods (Rothrock, 1944).

WASTE DISPOSAL POSSIBILITIES

Many formations in the Williston basin may be considered fair to good possibilities for the subsurface disposal of radioactive wastes. The only strata that probably do not contain potential storage reservoirs are the Big Snowy Group, rocks between the top of the Minnelusa Formation and base of the Swift Formation except for interbeds of salt, and rocks between the top of the Pierre Shale and the surface (fig. 5). Rocks of the first two sequences are believed to be unfavorable because of their lithologies. They comprise heterogeneous assemblages of shale, siltstone, sandstone, and limestone, in which fluid movement would be largely unpredictable. Rocks between the top of the Pierre Shale and the surface are believed to be less favorable because of economic, lithologic, and safety considerations. These rocks contain all the important lignite reserves of the area and many aquifers that are widely used for potable water. The post-Pierre rocks comprise a heterogeneous assemblage of discontinuous beds and lenses of sandstone, claystone, shale, siltstone, and lignite, in which fluid movement would be unpredictable. Furthermore, in some areas west and south of the Missouri River they are being deeply dissected by Recent headward erosion and in areas of glacial drift they are cut by buried pre-Pleistocene valleys. Wastes injected into these rocks, therefore, might leak into springs, lakes, streams and aquifers.

The remaining formations of the Williston basin afford a large variety of possible reservoirs at a wide range of depths. Four categories of possible reservoir formations are considered: (a) permeable sandstone and carbonate beds at moderate to great depths, (b) salt beds at moderate to great depths, (c) thick shale beds at shallow depths, and (d) permeable sandstone beds at shallow depths. (Shallow is here used arbitrarily for depths less than 5,000 feet; moderate, for depths between 5,000 and 10,000 feet; and great, for depths more than 10,000 feet.) The formations recommended for consideration in each category are: (a) the Deadwood, Winnipeg, Bakken, and Minnelusa Formations as deep sandstone and carbonate reservoirs; (b) the Pine and Dunham Salts and the unnamed salt bed in the Opeche Formation as salt-solution caverns; (c) the Belle Fourche, Carlile, and Pierre Shales and the Greenhorn and Niobrara Formations as shallow sand-fractured shale reservoirs; and (d) the Swift Formation and Newcastle Sandstone as shallow sandstone reservoirs (fig. 5). Other formations may afford fair to good possibilities for the storage of radioactive wastes, but they are disqualified from consideration for various reasons given in the discussion of each category.

Deep sandstone and carbonate reservoirs

The two sandstones of the Winnipeg Formation (fig. 8) deserve primary consideration, if deep-well disposal of low- to intermediate-activity radioactive wastes were attempted in the Williston basin. The Winnipeg lies about 13,000 to 15,000 feet below the surface in the Central Williston basin, where its salinity exceeds 150,000 ppm chloride (Porter and Fuller, 1959). Wastes could be injected into either sandstone at depths of 8,000 to 9,000 feet in eastern Montana and into the upper sandstone at depths of about 5,000 feet in western South Dakota with the expectation that they would flow northeastward into the Central Williston basin. Tighter cementation and increased clay content of the lower sandstone in the central part of the basin and gradation of the upper sandstone to shale northward in North Dakota might provide porosity traps in the deepest part of the basin and attenuate the continued flow of injected wastes toward the eastern margin. In any event, the radioactivity of low-activity wastes probably would be greatly decreased as they migrate the approximately 250-mile distance from the injection site to the eastern margin.

Additional factors favoring consideration of the Winnipeg are its higher permeability relative to underlying and overlying strata and its stratigraphic position below all oil-producing reservoirs. Some features of the Winnipeg, however, are less favorable: (a) it is potentially oil-productive in areas such as the Nesson anticline, and (b) it probably is a fresh-water aquifer usable for potable water along the eastern margin of the basin, so the maximum possible rate of fluid movement would have to be determined and considered in relation to sorptive properties and rate of radioactive decay. Nevertheless, the Winnipeg probably presents fewer obstacles to the safe and predictable flow of radioactive wastes than any other deep salaquifer in the Williston basin.

The Deadwood Formation (fig. 7) merits attention if deep disposal of radioactive waster in sandstone or limestone bodies intertonguing with shale is considered. Several favorable factors, which have been noted in regard to the Winnipeg Formation, such as depth, stratigraphic position, and salinity and flow of formation waters, apply also to the Deadwood. Another factor favoring the

Deadwood is its apparent lack of oil-producing potential. Furthermore, possible downward migration of wastes into the directly underlying granite wash or Precambrian rocks would be permissible, and the possibility of upward movement of wastes into the overlying porous Winnipeg is lessened by basinward thickening of the Deadwood north of the Black Hills. Some factors, however, weigh against disposal in the Deadwood without more detailed study: the thickness, size, shape, porosity, and permeability of its potential reservoirs are not available because of (a) lack of data, and (b) leakage into stratigraphically higher formations might occur on the flanks of undiscovered Precambrian monadnocks, similar to the one near Pierre, S. Dak. Although an approximate location for a disposal site in the Deadwood cannot be suggested without more detailed studies of its facies changes, the Deadwood merits careful consideration as a possible reservoir formation because of its favorable stratigraphic position.

The Bakken Formation (figs. 13, 14) deserves qualified consideration for the disposal of low- to intermediate-level radioactive wastes at moderate to great depths in the Central Williston basin. There its middle unit constitutes a potential carbonate reservoir, consisting of about 30 to 50 feet of silty dolomite and dolomitic siltstone and sandstone. This silty dolomite reservoir is capped and bottomed by the largely impermeable black carbonaceous shales of the Bakken (fig. 5), and the only likelihood of leakage of wastes would be through fractures in these shales. Two factors detract from consideration of the Bakken: (a) it has recently been found to be oil-productive along with the underlying Three Forks Formation in west-central North Dakota, and (b) an underlying quartzitic sandstone at the top of the Three Forks produces oil from vertical fractures on parts of the Sanish and Nesson anticlines. Nevertheless, in areas of slight structural closure, where its oil-producing potential has already been disproven and where vertical fractures are absent, the Bakken might provide a suitable reservoir.

Permeable lenticular sandstones of the Minnelusa Formation at moderate to great depths might be used for waste disposal in the southern part of the Williston basin. Although the Minnelusa produces oil in a field south of the Black Hills in South Dakota, it is not being actively explored in the Williston basin. Sufficient well data are available, however, for a moderately detailed study of the size, shape, thickness, and reservoir characteristics of the sandstones in the upper part of its lower member and in its upper member.

Most strata between the top of the Winnipeg Formation and the base of the Big Snowy Group should not at present be considered for the deep disposal of radioactive wastes in the Williston basin. These predominantly carbonate rocks, which account for nearly all of the present oil production and most of the future oil-producing capacity of the Williston basin, are the Red River, Stony Mountain, Stonewall, Interlake, Winnipegosis, Dawson Bay, Souris River, Duperow, Birdbear, and Three Forks Formations and the Lodgepole and Mission Canyon Limestones and Charles Formation of the Madison Group (fig. 5). Apart from economic considerations, these formations consist of many minor facies, whose varied porosity and permeability could not be safely predicted, and contain few barriers to the upward or downward migration of fluids. Interconnection of oil reservoirs in adjacent formations has been demonstrated in several producing oilfields. Other oil-productive or potentially oil-productive formations that should not be considered for deep waste disposal are the Tyler and Amsden Formations.

Reservoirs in salt beds

The Pine and Dunham Salts and the unnamed salt bed in the Opeche Formation (figs. 18, 20, and 22) of the Williston basin might be utilized for disposal of radioactive wastes in artificial solution caverns (National Academy of Sciences, 1957, p. 136). These three salt beds lie within an interval of about 500 to 800 feet at depths of 4,000 to 7,700 feet below the surface. The salt beds are thin, somewhat discontinuous, and enclosed largely by redbeds. Their thinness and discontinuity probably would be advantageous in controlling the size and shape of solution caverns. Furthermore, any slight leakage from these caverns into surrounding strata would not be economically harmful as the redbeds are not considered to be potentially productive of oil.

The thick salt member of the Prairie Formation (fig. 12) and the seven salt beds within the Madison Group (fig. 16) probably should be disregarded as reservoirs for radioactive wastes. The salt member of the Prairie may contain large potash reserves and it is directly underlain and overlain by oil-producing formations, which might be contaminated if leakage of wastes occurred. Because of the great thickness and depth of the salt, solution caverns in the Prairie probably would be subjected to salt flowage. The thinner salt beds in the Madison are closely interbedded with oil-producing carbonate beds, which might be contaminated by the slightest leakage. Another deterrent to storage in the Prairie and Madison salt beds is the likelihood that they are being partly dissolved at present by the flow of formation waters in some areas.

Shallow shale reservoirs

The Belle Fourche Shale, Greenhorn Formation, and Carlile Shale (fig. 27), and the Niobrara Formation and Pierre Shale (fig. 28) offer possibilities for the disposal of small volumes of radioactive wastes in shallow shale reservoirs in North Dakota which could be hydraulically fractured. They constitute a sequence of marine shale, as much as 3,600 feet thick, and extend from the surface at the basin margins to a depth of about 5,000 feet below the surface in the Central Williston basin. They contain no significant beds of sandstone in North Dakota, where the shale sequence is interrupted only by thin silty, calcareous, and bentonitic zones. Although this sequence produces gas in three fields along the western margin of the Williston basin, it is not regarded as potentially productive of oil or gas in North Dakota.

The Skull Creek and Mowry Shales are less favorable shale reservoirs because of their proximity to the Newcastle Sandstone and Dakota Group (fig. 5), two major sandstone aquifers, which yield potable water in some areas.

Shallow sandstone reservoirs

The Newcastle Sandstone (fig. 26) offers reservoir possibilities for the shallow disposal of radioactive wastes where it lies about 1,500 to 5,000 feet below the surface in eastern Montana and western North Dakota. In this area it forms lenses and pods of sandstone, as much as 120 feet thick, entirely enclosed by shale. The sandstone commonly is silty or shaly but probably has sufficient porosity and permeability for the injection of wastes. Although the contacts of the sand bodies with the enclosing shale apparently are gradational, little leakage of wastes into the shale is anticipated. The Newcastle produces oil in the nearby Powder River Basin but has yielded only minor oil shows in the Williston basin. Although it has an oil-producing potential, the Newcastle has proved to be unproductive in many areas, which could be studied in detail for possible disposal sites. The Newcastle Sandstone should not be regarded as a potential waste disposal reservoir in South Dakota and southern North Dakota, for in that area it serves as a major fresh-water aquifer.

Sandstone beds in the upper part of the Swift Formation of Montana and North Dakota merit secondary consideration as possible shallow sandstone reservoirs for waste disposal. These beds of sandstone are interbedded with and gradational to calcareous shale and siltstone, which probably would serve as fairly impermeable barriers to migration of injected wastes. The base of the Swift lies about 200 to 600 feet above the middle member of the Piper Formation (fig. 23). The secondary rating of the Swift results from a lack of data on the thickness, distribution, and reservoir characteristics of its sandstones and on the exact location of the unconformity between the Swift and the underlying Rierdon Formation. Furthermore, the Swift produces oil from several fields in northwestern and central Montana and hence has a higher oil-producing potential than the Newcastle in the Williston basin. Nevertheless, the Swift has many unproductive areas, which could be studied in detail as possible disposal sites. Correlative beds in the upper part of the Sundance Formation of South Dakota should not be considered as waste disposal reservoirs because they serve as important fresh-water aquifers adjacent to the Black Hills.

The Morrison Formation (fig. 24) is not highly regarded as a possible reservoir formation because of its proximity to the Dakota Group and because it comprises a heterogeneous assemblage of discontinuous beds of claystone, shale, siltstone, and sandstone. However, in local areas, where the shape, thickness, and reservoir characteristics of individual sandstone bodies could be studied in detail, suitable sandstone reservoirs might be located.

The Dakota Group (figs. 24, 25) should not be considered as a reservoir for radioactive wastes because it is an important fresh-water aquifer in some parts of the Williston basin and has a high oil-producing potential elsewhere.

CONCLUSIONS

The Williston basin offers geographically and geologically feasible possibilities for the subsurface disposal of radioactive wastes. The thick and varied stratigraphic sequence contains almost all types of subsurface reservoirs now under consideration. Geographic factors such as low population density, relatively level land surface, and large road network, are favorable features of the Williston basin. The size of the basin, moreover, is so great that many possible sites are available where large quantities of wastes probably could be injected with minimal danger of contamination of fresh-water aquifers and oil-producing strata.

The strata and types of reservoirs that deserve primary consideration for waste disposal are the Winnipeg Formation as a deep salaquifer, the Permian, Triassic, and Jurassic salt beds as moderately deep solution caverns, the thick Upper Cretaceous shale beds as shallow hydraulically fractured shale reservoirs, and the Newcastle Sandstone as a shallow shale-enclosed sandstone reservoir.

Detailed studies of the pressure gradient and salinity of formation waters, based on drill stem tests, and of the porosity, permeability, and detailed stratigraphy of possible reservoir formations, based on well cuttings and cores, should precede even the tentative location of disposal sites. Before final site selections are made, further complex studies and tests at tentative locations will be required to determine the flow of injected wastes as well as chemical compatibility to insure adequate and safe containment.

It is difficult to escape the conclusion, however, that for maximum safety of population, preference in the selection of disposal sites should be given to unpopulated or to least populated areas.

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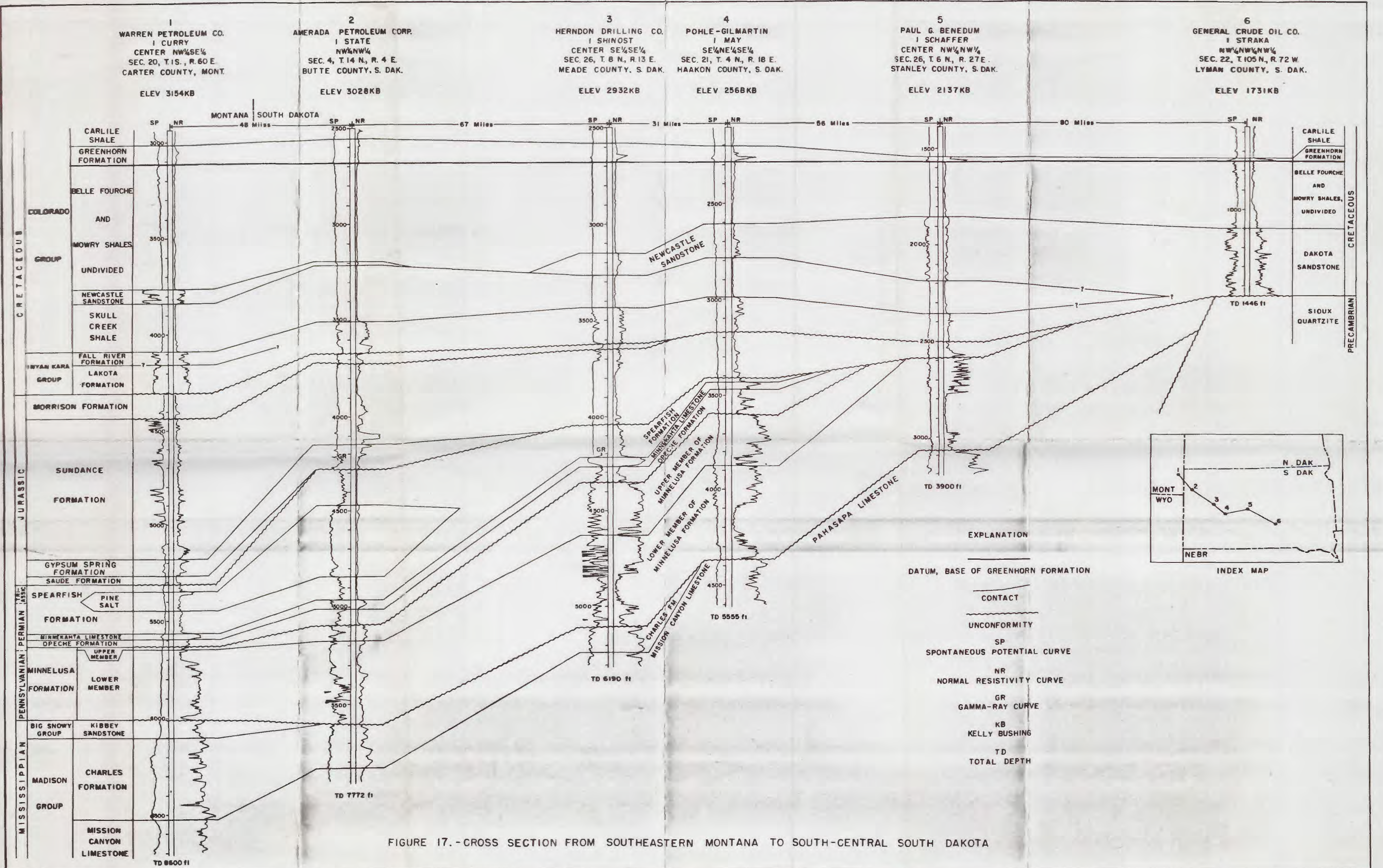
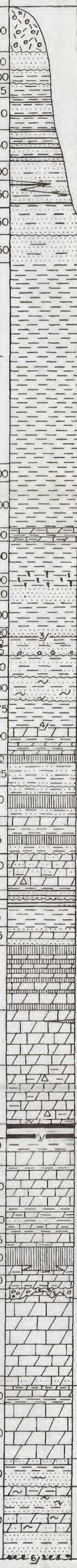


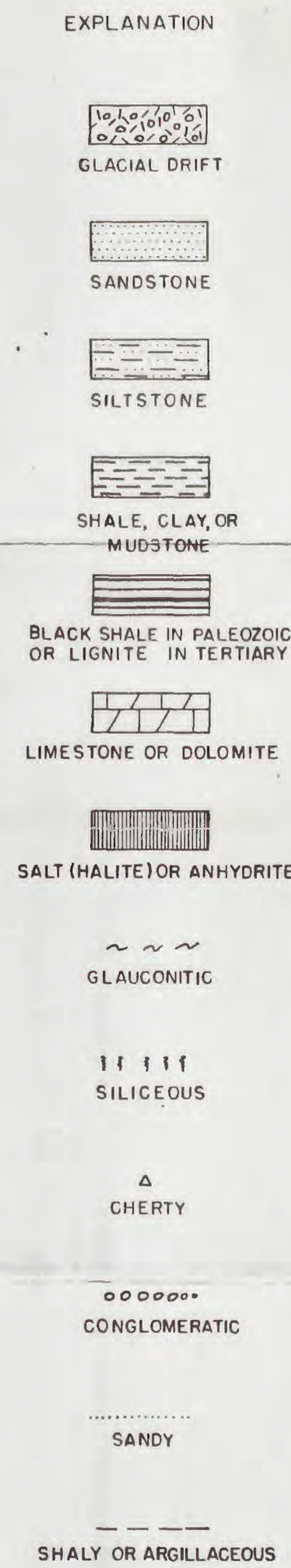
FIGURE 17.-CROSS SECTION FROM SOUTHEASTERN MONTANA TO SOUTH-CENTRAL SOUTH DAKOTA

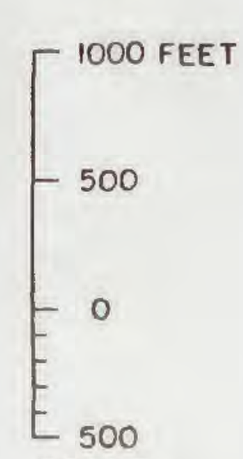
62-115

Era	System	Series	Group / Formation / Member	Thickness in feet 1/	Stratigraphic subdivision discussed in this report	Thickness in feet 1/	Isopach map shown in this report
CENOZOIC	QUATERNARY	PLEISTOCENE	GLACIAL DRIFT	0 - 500	ROCKS BETWEEN TOP OF PIERRE SHALE AND SURFACE	500-2800	NOT MAPPED
	TERTIARY	MIOCENE	ARIKAREE FORMATION	0 - 300			
		OLIGOCENE	WHITE RIVER FORMATION	0 - 400			
		EOCENE	GOLDEN VALLY FORMATION	0 - 175			
		PALEOCENE	FORT UNION FORMATION: SENTINEL BUTTE MEMBER	0 - 950			
			FORT UNION FORMATION: TONGUE RIVER MEMBER	0 - 650			
			FORT UNION FORMATION: CANNONBALL MEMBER	0 - 300			
			FORT UNION FORMATION: LUDLOW MEMBER	0 - 350			
MESOZOIC	CRETACEOUS	UPPER	HELL CREEK FORMATION	100-550			
			MONTANA GROUP: FOX HILLS SANDSTONE	150-350			
			MONTANA GROUP: PIERRE SHALE	1500-2300	NIOBRARA FORMATION AND PIERRE SHALE	1650-2500	FIG. 28
			COLORADO GROUP: NIOBRARA FM	100-200			
			COLORADO GROUP: CARLILE SHALE	200-500	BELLE FOURCHE SHALE, GREENHORN FORMATION, AND CARLILE SHALE	400-1100	FIG. 27
			COLORADO GROUP: GREENHORN FM	50-200			
			COLORADO GROUP: BELLE FOURCHE SHALE	150-450			
		LOWER	COLORADO GROUP: MOWRY SHALE	50-200	LOWER PART OF COLORADO GROUP	250-400	NOT MAPPED
			COLORADO GROUP: NEWCASTLE SS	0 - 120			FIG. 26
			COLORADO GROUP: SKULL CREEK SHALE	200-300			NOT MAPPED
			DAKOTA GROUP: FALL RIVER FM	50-200	DAKOTA GROUP AND RELATED ROCKS	150-400	FIG. 24
			DAKOTA GROUP: FUSON FM	20-125			
			DAKOTA GROUP: LAKOTA FM	50-125			
	JURASSIC	UPPER	MORRISON FORMATION	0 - 250	POST - SAUDE JURASSIC ROCKS	800-1300	FIG. 21
			SWIFT FORMATION	350-400			
			RIERDON FORMATION	125 - 475			
		MIDDLE	PIPER FORMATION	150-400			
			DUNHAM SALT 2/	0 - 140			FIG. 22
			SAUDE FORMATION 2/	50-325	SPEARFISH AND SAUDE FORMATIONS	100-700	FIG. 19
	TRIASSIC		SPEARFISH FORMATION: PINE SALT 2/	0 - 500			FIG. 20
PALEOZOIC	PERMIAN		MINNEKAHTA LIMESTONE	0 - 50	OPECHE FORMATION AND MINNEKAHTA LIMESTONE	0 - 475	FIG. 18
			OPECHE FORMATION: UNNAMED SALT	0 - 425			
	PENNSYLVANIAN		MINNELUSA FORMATION	0 - 500	MINNELUSA FORMATION AND RELATED ROCKS	0 - 750	NOT MAPPED
			AMSDEN FORMATION	0 - 150			
			TYLER FORMATION 2/	0 - 100			
	MISSISSIPPIAN	UPPER	BIG SNOWY GROUP: HEATH FM	0 - 100	BIG SNOWY GROUP	0-600	NOT MAPPED
			BIG SNOWY GROUP: OTTER FM	0-225			
			BIG SNOWY GROUP: KIBBEY SS	0-275			
			MADISON GROUP: CHARLES FORMATION	525-725	MADISON GROUP	1400-2300	FIG. 15; FIG. 16 7/
		LOWER	MADISON GROUP: MISSION CANYON LIMESTONE	350-775			
			MADISON GROUP: LODGEPOLE LIMESTONE	525-850			
			BAKKEN FORMATION	0 - 140	BAKKEN FORMATION	0 - 140	FIG. 13
	DEVONIAN	UPPER	THREE FORKS FORMATION	0 - 240	DEVONIAN ROCKS	300-2000	FIG. 11
			JEFFERSON GROUP: BIRDBEAR FM	0 - 120			
			JEFFERSON GROUP: DUPEROW FM	125-450			
			SOURIS RIVER FORMATION	100-340			
		MIDDLE	DAWSON BAY FORMATION	25 - 155			
			ELK POINT GROUP: PRAIRIE FM, SALT MBR	0- 400			FIG. 12
			ELK POINT GROUP: PRAIRIE FM, LOWER MBR	0 - 125			
			ELK POINT GROUP: WINNIPEGOSIS FM	50-300			
		LOWER	BEARTOOTH BUTTE (?) FM	0 - 50			
	SILURIAN	MIDDLE / LOWER	INTERLAKE FORMATION 2/	300-1100	STONEWALL AND INTERLAKE FORMATIONS	350-1200	FIG. 10
			STONEWALL FORMATION 2/	50-100			
	ORDOVICIAN	UPPER	STONY MOUNTAIN FM	140-200	RED RIVER AND STONY MOUNTAIN FORMATIONS	550-900	FIG. 9
			RED RIVER FORMATION	410-700			
		MIDDLE	WINNIPEG FORMATION	130-350	WINNIPEG FORMATION	130-350	FIG. 8
		LOWER					
	CAMBRIAN	UPPER / MIDDLE	DEADWOOD FORMATION	70-1020	DEADWOOD FORMATION AND RELATED ROCKS	70-1020	FIG. 7

GENERALIZED LITHOLOGY







1/ IN CENTRAL WILLISTON BASIN
2/ OF INFORMAL SUBSURFACE USAGE
3/-6/ STRUCTURE CONTOUR MAPS AT THESE HORIZONS SHOWN ON FIGS. 25, 23, 14, AND 4, RESPECTIVELY
7/ AGGREGATE THICKNESS MAP OF 7 SALT BEDS

FIGURE 5. GENERALIZED STRATIGRAPHIC SECTION OF SEDIMENTARY ROCKS IN CENTRAL WILLISTON BASIN

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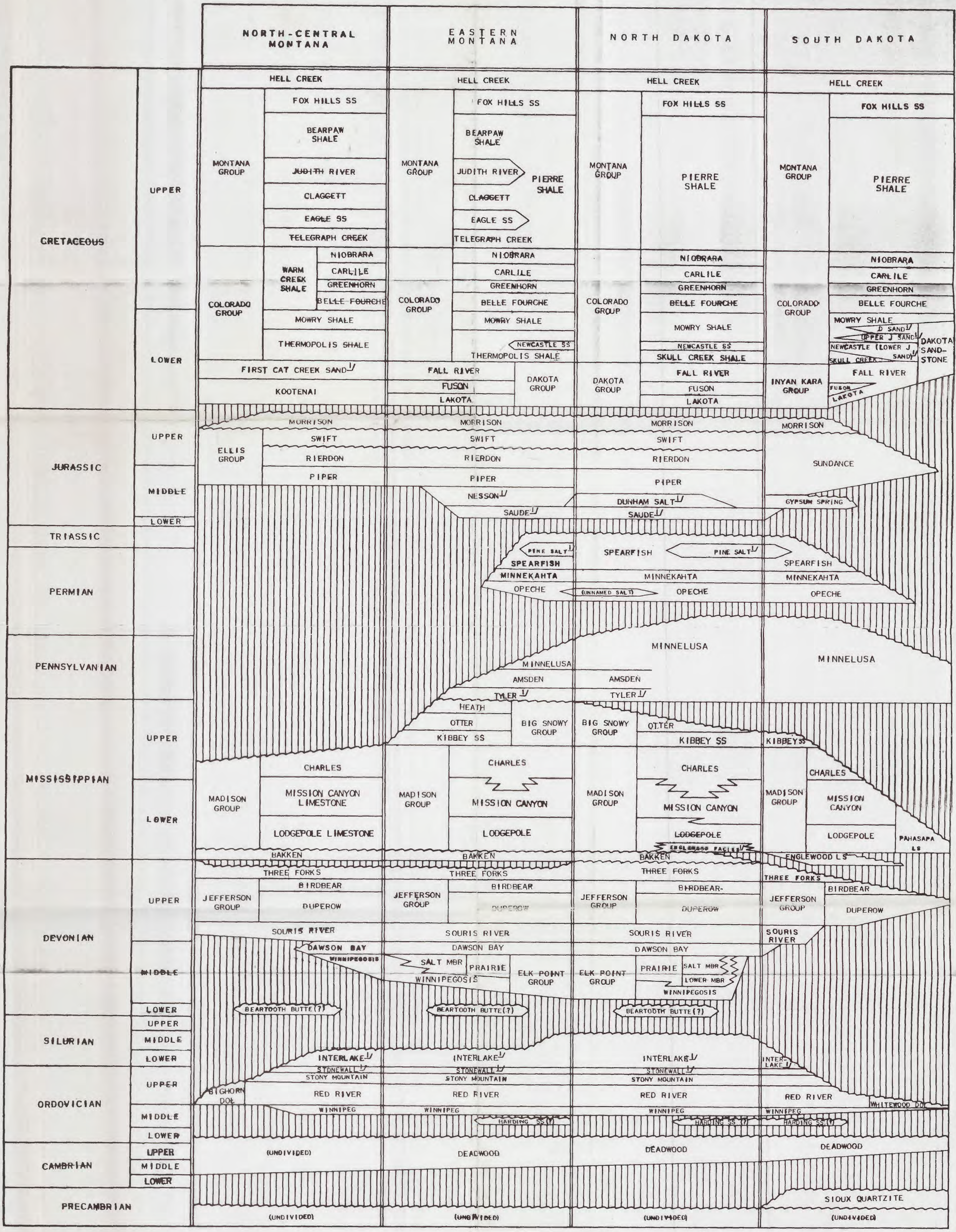

1/ OF SUBSURFACE USAGE

FIGURE 6.- CORRELATION CHART OF PRE-TERTIARY FORMATIONS IN WILLISTON BASIN