THE CARRINGTON SHALE FACIES (MISSISSIPPIAN) AND ITS RELATIONSHIP TO THE SCALLION SUBINTERVAL IN CENTRAL NORTH DAKOTA

by

Peter F. Bjorlie

REPORT OF INVESTIGATION NO. 67

NORTH DAKOTA GEOLOGICAL SURVEY

Lee C. Gerhard, State Geologist

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ABSTRACT

The Carrington shale facies is a radioactive illitic lagoonal shale, apparently deposited behind lime mudstone banks (Waulsortian bioherms), along the eastern margin of the Williston basin during Early Mississippian time.

The Scallion subinterval, which is the basal subunit of the Bottineau interval of the Madison Formation in North Dakota, is divisible into six lithologic facies, one of which is the Carrington shale facies. West of the shale facies, on the basin-shelf hinge line, is the lime mudstone facies. Basinward of this facies is the interbedded shale-limestone facies. Stratigraphically above the latter two facies is the sand-silt-shale facies. Overlying a portion of this facies and the Carrington shale facies is the crinoid packstone-grainstone facies. Overlying the remaining portion of the sand-silt-shale facies is the wacke-packstone facies.

Following a period of erosion during the latest Devonian-earliest Mississippian time, Waulsortian mounds formed along the basin-shelf hinge line. These mounds and associated sediments (lime mudstone facies) created a barrier which allowed the deposition of the Carrington shale facies in a restricted environment. The source of the shale was the weathered Precambrian shield to the east. The sand-silt-shale facies was deposited on the basin slope during the deposition of the Carrington shale facies. After the deposition of these two clastic facies, carbonate deposition occurred on the basin shelf and slope in the form of the crinoid packstone-grainstone and wacke-packstone facies, respectively.

Possible petroleum traps exist where the Carrington shale facies overlies erosionally truncated Devonian strata, abrupt facies changes occur whithin the Scallion subinterval, and along the pre-Mesozoic subcrop of the Scallion. Conditions necessary for the concentration of uranium beneath or within the Carrington shale facies may have occurred after the deposition of the shale facies.

ACKNOWLEDGMENTS

Many people provided assistance towards the completion of this report. Sidney Anderson of the North Dakota Geological Survey is gratefully acknowledged for exposing me to this problem and assisting me throughout the study. Dr. Walter Moore, committee chairman, is acknowledged for his helpful criticism during the writing of the Master's thesis. The other committee members, Drs. Odin Christensen and Frank Karner, also assisted in editing of the thesis.

Hugh McCabe of the Manitoba Department of Mineral Resources is acknowledged for his assistance to the author in obtaining samples of the Routledge Shale and copies of mechanical logs from Manitoba. Robert Schoon of the South Dakota Geological Survey is acknowledged for his assistance while the author examined mechanical logs and sample logs from South Dakota.

Financial assistance for this study was provided by the United States Department of Health, Education and Welfare in the form of a graduate research fellowship and from the North Dakota Geological Survey. Material assistance was provided by the Department of Geology, University of North Dakota, the North Dakota Geological Survey, and the United States Department of Energy.

INTRODUCTION

General Statement

The basal shale facies of the Bottineau interval of the Madison Formation have been described and named in Manitoba, North Dakota, and South Dakota, as the Routledge Shale, Carrington shale facies and the Englewood Formation, respectively. The relationships between these units and the limestone units which surround them have not been studied in detail nor are their origins fully understood. It is the purpose of this study to provide a regional picture of the history of sedimentation, during the deposition of the basal shale units of the Bottineau interval, along the eastern margin of the Williston basin and to assess the economic potential of these units.

Area of Study

The area of study includes approximately 40,000 square miles in southwestern Manitoba and east-central North Dakota (fig. 1). This area includes the eastern limit of Mississippian strata in the Williston basin.

All of the units studied in this report are known only in the subsurface and were studied by the use of well cuttings, cores, and mechanical logs from wells drilled in Manitoba and North Dakota. A list of wells used and log tops of the Scallion subinterval, Carrington shale facies, and underlying formation appear in the appendices of this report. Lithologic descriptions of the samples studied are in an appendix in a master's thesis (Bjorlie, 1978, p. 89-108).

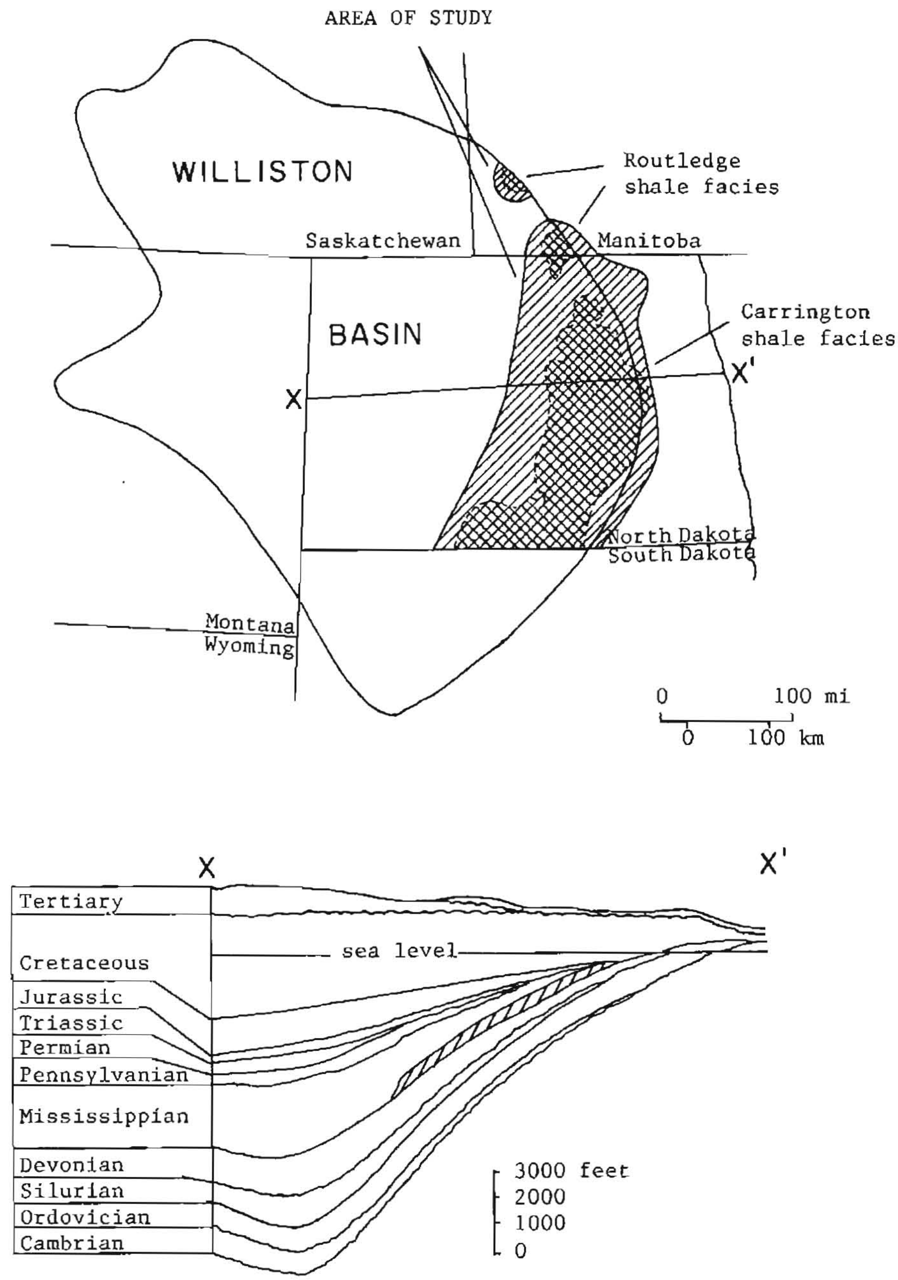


Figure 1. Location of study area in map view and cross section. Modified from Carlson and Anderson (1970).

Regional Setting

The Williston basin is an intracratonic basin with a depocenter southeast of Williston, North Dakota. During the latest Devonian and earliest Mississippian time, uplift occurred along the basin margins exposing Devonian strata. The resulting erosion created an angular unconformity around the eastern margin of the basin. At this same time deposition continued in the deeper or more central portions of the basin.

Minor structural features within the eastern margin of the basin, in North Dakota, have been described by Ballard (1963). These minor features include the Burleigh, Cavalier, Foster, and Stutsman Highs (fig. 2). These highs were identified on the basis of structure contour and isopachous maps. They are most prominent in the lower parts of the Paleozoic and their prominence decreases upward in the section. The causes of these structural highs were related to topographic highs on the Precambrian surface.

Structural features evident on the Pre-Mississippian surface (fig. 2) are quite subtle. The basin hinge line, located at approximately 100 west longitude, is shown by a slight compression of the contour lines. Widened contour lines to the east reflect the gentler sloping surface of the basin margin area. Irregularities in this area are numerous.

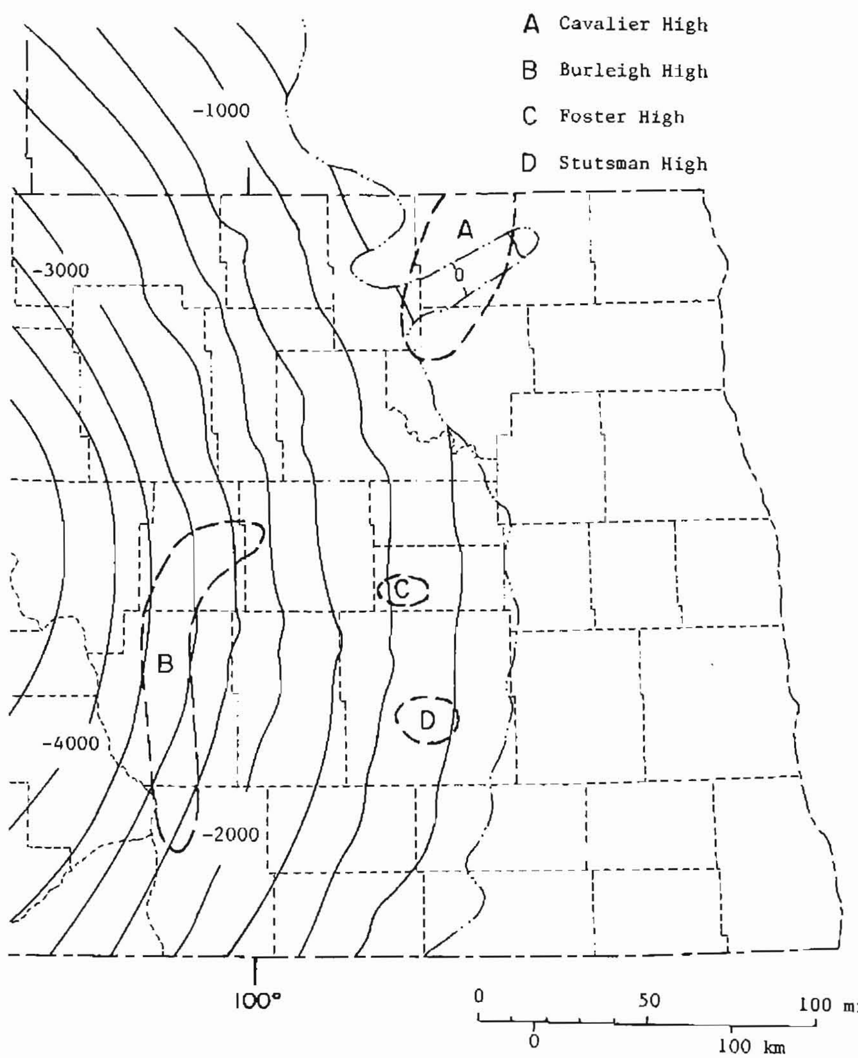


Figure 2. Structure contour map of the base of Mississippian strata. Location of structural highs after Ballard (1963).

Stratigraphy

The subdivisions of the Lodgepole Formation were first proposed by Stanton (1956). He described and named the Routledge Shale, Scallion, Virden, and Whitewater Lake Members, as subdivisions of the Lodgepole in southwestern Manitoba. McCabe (1963) added one member to the top of the Lodgepole by naming the Flossie Lake Member. This terminology is accepted by the Geological Branch of the Manitoba Department of Mines and Natural Resources.

Smith (1960) proposed that the Madison Group be subdivided into intervals. From base to top these intervals are the Bottineau, Tilston, Frobisher-Alida, Ratcliffe, and Poplar intervals. Carlson and Anderson (1970) demoted the Madison to formation status within the confines of the North Dakota portion of the Williston basin.

The stratigraphic column (fig. 3) shows the shale units of this study and the underlying and overlying units.

In order to remain consistent with accepted North Dakota terminology and also to use the subdivisions of the Lodgepole Formation, the author proposes to refer to the subdivisions as subintervals of the Bottineau interval.

Methods of Study

During the summer of 1977 the author examined well cuttings from North Dakota and cores from Manitoba and North Dakota. These samples are the property of the respective Geologic Surveys, having been obtained from companies and individuals that drilled oil or stratigraphic tests in the area of this study. Cores were available from only a few wells and from limited intervals within these wells. Cores were examined by means of hand lens, acetate peels, and thin sections. Cuttings were available from most of the wells in the area at five- to ten-foot intervals. Cuttings were examined by laying out approximately 200-foot intervals of the samples in sample trays. Samples were then examined for color or lithologic breaks; samples were next examined using a binocular microscope under reflected light. In the case of carbonate rock chips, transmitted light was used. This was done by wetting the rock chip on a clear plastic tray. Alizarin red was used to differentiate calcite from dolomite. Particular attention was given to the fabric and fauna of the carbonate rocks. Dunham's (1962) classification of carbonate rocks was used.

Determination of Shale Mineralogy

To determine the mineralogy of the clay and silt in core samples, X-ray diffraction was used. Clay, silt, and sand fractions were separated from the shale using the procedure outlined by Brekke (1978). The clay-size fraction was then placed on porous ceramic tiles and suction used to produce a durable oriented sample. Silt-size fractions were prepared for X-ray analysis by backfilling an aluminum sample holder and exerting pressure to obtain an unoriented backloaded sample. The sand-sized fraction was examined using a binocular microscope.

Size analysis of the shale unit was attempted but abandoned for the following reasons: (1) difficulty in disaggregating the shale, (2) flocculation of clay,' (3) small number of cores available, making it difficult to extend results beyond control points. Estimates of grain size were made during examination of well cuttings; however, the reliability of well cuttings in size analysis is very questionable.

No attempt was made to systematically study the fauna of the units in this study. Many fossils were noted during the lithologic study. Identifications of these fossils were attempted in most cases and the results utilized in the environmental analysis of the units.

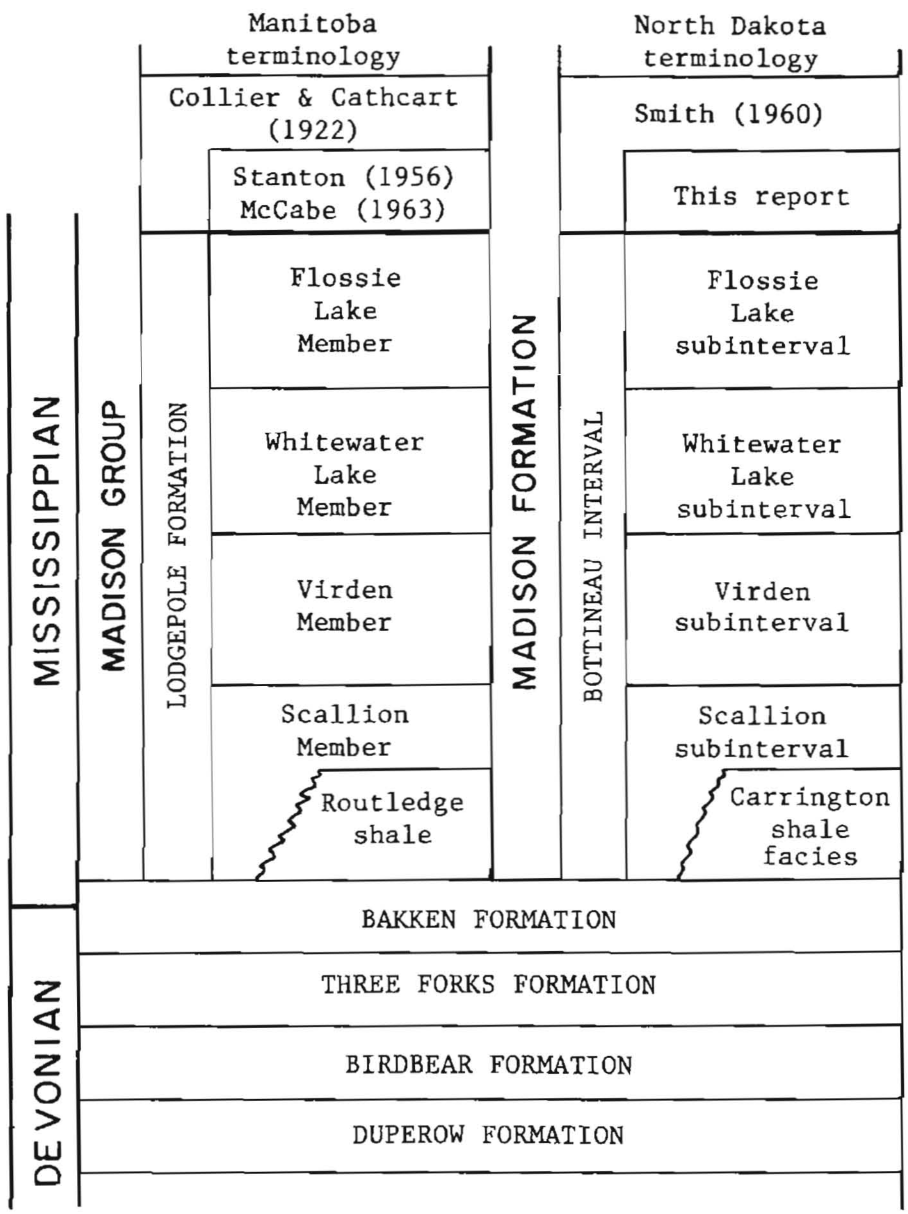


Figure 3. Stratigraphic column of interval studied.

Mapping

The North Dakota Geological Survey well file number (well 23) was used for North Dakota wells and an arbitrary number (M-1 to M-15) was assigned to the Manitoba wells. A computer program (SYMAP, Dougenik and Sheehan, 1975) was used in all structure contour and isopachous mapping. After the computer-constructed maps were completed, the author revised the maps before drafting them. In several cases the computer program interpolated beyond reasonable limits. In these cases the author contributed to the final product in an attempt to provide a more realistic map.

Previous Work

The first published mention of a basal Mississippian Shale (in the eastern portion of the Williston basin), separate from the Bakken Formation, was by Stanton (1955, 1956, 1958) in reports on the stratigraphy of the Lodgepole Formation in Manitoba. He named the Routledge Shale as a basal member of the Lodgepole Formation, reporting it to be comformable on the Bakken Formation and probably a continuation of Bakken deposition. Stanton (1956) considered it to be equivalent to the lower portion of the Scallion Member. The shale in the type section (Calstan Routledge Prov. 13-29, 13-29-9-25 WPM, 2230 to 2307 feet) was black and dark brown to gray.

McCabe (1959) mapped the occurrence of the Routledge Shale in Manitoba and north-central North Dakota. He presented two hypotheses for its formation: (1) deposition behind a barrier of some type, (2) local thickening of the Bakken Formation caused by collapse of salt formations in the underlying strata.

Sandberg and Hammond (1958) mentioned the occurrence of discontinuous shales located stratigraphically above the Bakken Formation on the south and east margins of the Williston basin. These shales were considered to be a facies of the Englewood Formation (Darton, 1901) which was believed to be of Early Mississippian age.

Work by Klapper and Furnish (1962), based on conodont studies, gave the Englewood Formation a Late Devonian-Early Mississippian age, making it more closely related to the Bakken Formation which had been recognized by Christopher (1961) to be a transitional Devonian-Mississippian formation.

Based on this time correlation of the Englewood Formation with the Bakken Formation, Sandberg (1962) questioned the correlation of the Englewood (shale) facies with the Englewood Formation. He considered the Englewood facies to be a portion of the Lodgepole Formation and described the shale facies as a dark-gray shale interbedded with highly argillaceous limestone and calcareous shale or siltstone or a gray-red or greenish-gray shale speckled with grayish red. He noted that laterally it graded abruptly into a less argillaceous limestone. This fact had also been noted by investigators of the Routledge Shale (Stanton, 1958; McCabe, 1959).

Ballard (1963) isopached the basal shale facies of the Bottineau interval in North Dakota and named it the Carrington shale facies. He recognized it as distinct from the Bakken Formation, describing it as a bentonitic, red-brown calcareous shale. He recognized the similarity in the stratigraphic positions of the Carrington shale facies and the Routledge Shale. However, he interpreted the Carrington shale facies to be an isolated occurrence due to the formation of a basin behind the Burleigh High, a north-south low relief structural feature discovered in his study of the Paleozoic rocks of eastern North Dakota (fig. 2).

STRATIGRAPHY

Mechanical Log Characteristics

Spontaneous potential and gamma ray logs were used in the determination of thicknesses and correlation of units in the study area. Figure 4 is a reproduction of a typical log pattern and the log characteristics of the units shown on this figure are similar to that of the other wells in the study area.

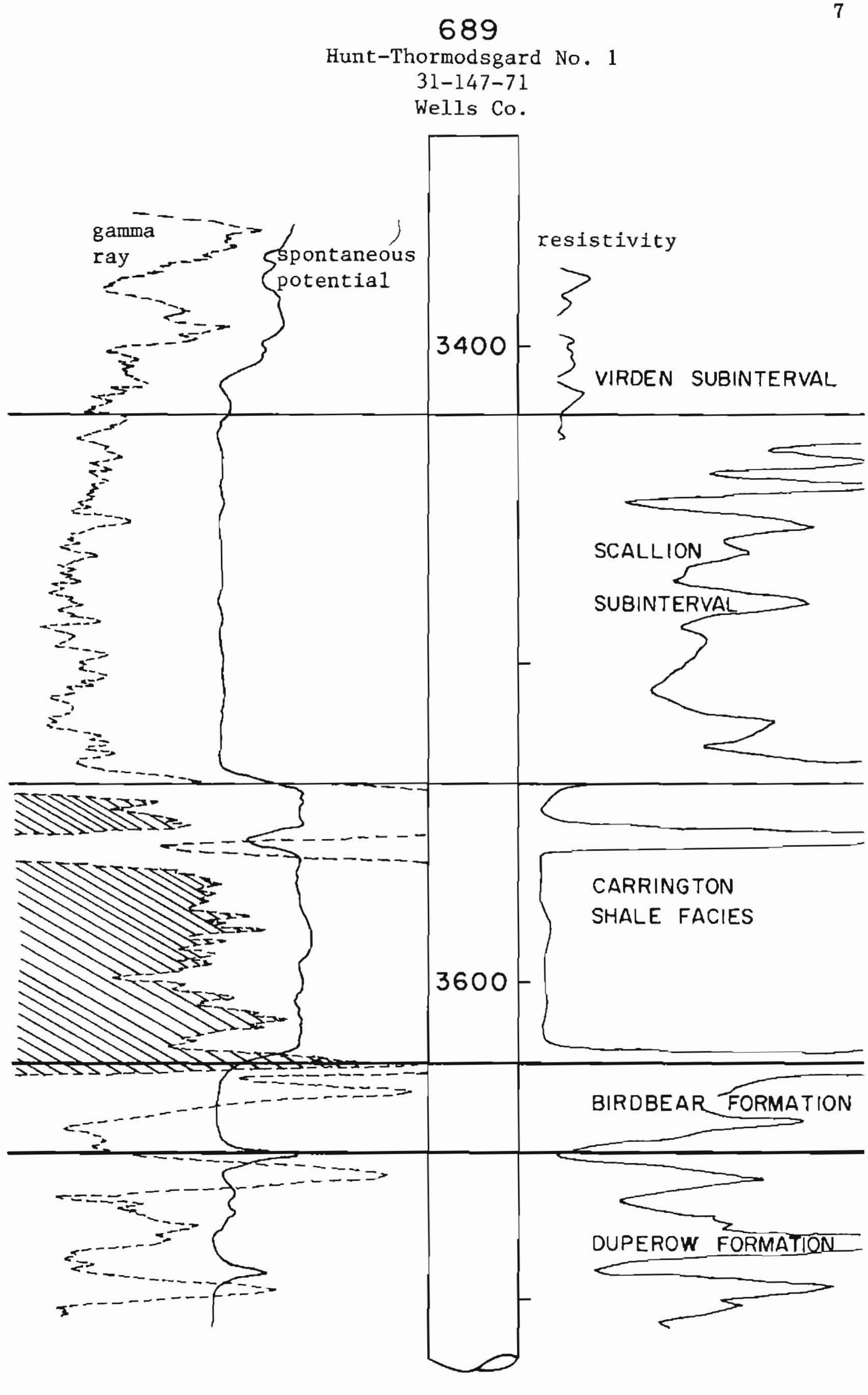


Figure 4. Typical mechanical log from the area of study.

The Duperow and Birdbear Formations typically show intermediate resistivity and negative deflecting spontaneous potential. This pattern is interrupted by thin streaks of lower resistivity and increased gamma ray counts. The former represent limestone and dolomite and the latter thin shale beds.

The Carrington shale facies exhibits very low resistivity, positive deflecting spontaneous potential, and high to very high gamma ray counts. It is usually consistent vertically, giving a smooth log appearance. In some cases a thin zone of high resistivity, a negative deflecting spontaneous potential, and lower gamma ray counts occur in the upper one-third of the shale section. This is probably the result of a thin limestone bed.

The Scallion subinterval has a fairly smooth negative deflecting spontaneous potential, low gamma ray intensity, and high resistivity. Some logs do show a zone of increased radioactivity and positive deflecting spontaneous potential near the center of the subinterval. This log pattern occurs only to the west of the Carrington shale facies. It represents a shaly bed that appears to form a boundary between two distinct carbonate units in the Scallion subinterval. The mechanical log patterns of these two units are very similar (see well 207, cross-section B-B', pl. 6). The top of the Scallion subinterval was usually picked at the first consistent increase in radioactivity and increasingly positive spontaneous potential.

The Virden subinterval has an irregular spontaneous potential and a higher radioactivity than the underlying Scallion subinterval.

In some cases the Scallion subinterval or the units stratigraphically beneath it to the east are directly overlain by rocks of Mesozoic age. These rocks exhibited a high positive deflecting spontaneous potential, high radioactivity, and very low resistivity. The beds also appeared to be more massive and lacked the many thin shale beds common to the Mississippian and Devonian rocks.

Underlying Units

The Scallion subinterval is underlain by formations ranging in age from Ordovician to Mississippian. This is the result of erosion that occurred in latest Devonian-earliest Mississippian time. Figure 5 is a diagrammatic east-west cross section showing the relationship between these units and the overlying Scallion subinterval.

Of the units shown on the cross section, the Duperow, Birdbear, Three Forks and Bakken Formations will be discussed briefly. The older units were not examined during the sample study and will not be discussed further in this section. Isopachous maps and a discussion of the Paleozoic section of eastern North Dakota can be found in Ballard (1963).

Duperow Formation

The Duperow Formation (Devonian) is composed of limestone, dolomite, and interbedded shales and siltstones. It conformably overlies the Souris River Formation throughout the Williston basin except on the eastern margin where it rests unconformably on rocks of Silurian and Ordovician age. It is conformably overlain by the Birdbear Formation except where this unit has been removed by Early Mississippian erosion. In these areas the Duperow is unconformably overlain by the Bottineau interval or, in areas further to the east, by Mesozoic-age rocks. These relationships are illustrated on cross-section B-B' (pl. 6).

In the area of study the Duperow ranged in thickness from 0 feet along the erosional edge to 400 feet in Bottineau and Rolette Counties, North Dakota.

Birdbear Formation

The Birdbear Formation is composed of porous limestone and dolomite. It conformably overlies the Duperow Formation and is conformably overlain by the Three Forks Formation in the central basin area. On the basin margin it is unconformably overlain by the Bottineau interval of Mississippian age or by Mesozoic-age rocks. In the area of study the Birdbear Formation ranges in thickness from 0 feet at its erosional edge to 100 feet in Bottineau County.

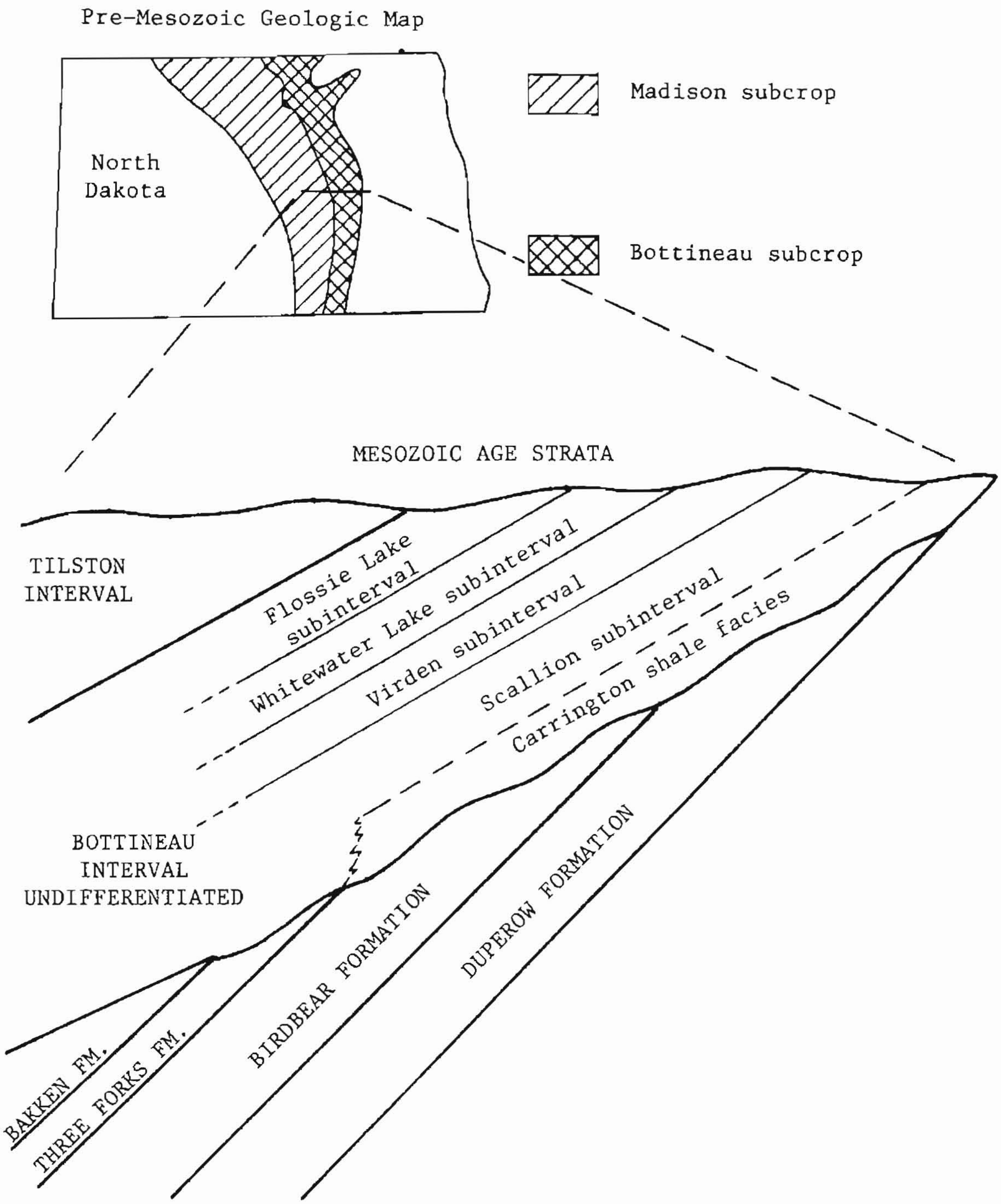


Figure 5. Diagrammatic cross section through the area of study.

Three Forks Formation

The Three Forks Formation is composed of red dolomitic shales and siltstones. It conformably overlies the Birdbear Formation. The Bakken Formation overlies the Three Forks in the central basin area. In some cases the Three Forks extends beyond the limit of the Bakken and is unconformably overlain by the Bottineau interval. This case is illustrated on cross-section C-C' (pl. 6). Thickness of the Three Forks Formation ranges from 0 to 100 feet in the study area.

Bakken Formation

The Bakken Formation is composed of three separate units. The lower is a fissile organic black shale. The middle unit is composed of dolomitic siltstone and sandstone. The upper member is composed of a black shale similar to the lower member but not as dark in color. The Bakken unconformably overlies the Three Forks Formation and is conformably overlain by the Bottineau interval. In the area of study the Bakken ranges in thickness from 0 to 60 feet.

Bottineau Interval

The Bottineau interval is composed of several different shale and limestone units. The limestone units may be separated based on fabrics and faunal constituents. Four separate members have been proposed by Stanton (1958) and McCabe (1963) for this formation (fig. 3). These units are easily identifiable based on electric log characteristics; however, they do not necessarily represent a single lithologic facies. The Scallion subinterval has been divided into six lithologic facies in this report.

Scallion Subinterval

The Scallion subinterval as described by Stanton (1958) is a crinoidal, cherty limestone to argillaceous limestone, fine- to coarse-grained, compact to chalky, becoming oolitic in the upper portions. It varies from 0 to 245 feet in thickness in the area of study. On the east it is bounded by the erosional limit of Mississippian rocks. On the west the unit loses its typical electric log character and becomes indistinguishable from the overlying units. This problem was also mentioned by Stanton (1958).

Plate 2 is an isopachous map of the Scallion subinterval in North Dakota. The Scallion is also shown on the stratigraphic cross section (pl. 6). The subinterval has been divided into six separate lithologic facies on the basis of sample and log studies. These facies will each be discussed separately in the section on facies analysis. The stratigraphy of the Carrington shale facies and Routledge Shale will be discussed in more detail in this section.

Carrington Shale Facies

The type section of the Carrington shale facies is the Pure--J.M. Carr 1 (NDGS 403), sec 15, T146N, R66W, Foster County, near the town of Carrington, North Dakota. Core from this section and samples from other wells in eastern North Dakota reveal the shale to be a distinct lithologic unit within the Scallion subinterval. Its log character also separates it from the adjoining carbonate units.

As a separate stratigraphic unit the Carrington shale facies is traceable over an area equal to approximately 10,000 square miles in eastern North Dakota. Its western limit extends to the basin hinge line. Its eastern limit is bounded by the erosional limit of Mississippian strata. To the north, the unit is bounded by the Scallion subinterval. To the south, the unit probably extends into South Dakota, following the outline of the Williston basin, but the extent of the Carrington shale facies in South Dakota is not known. Correlation of the Carrington shale facies into South Dakota is greatly hampered by lack of well control in north-central South Dakota. For the above reason South Dakota has been excluded from this study.

The four cross sections (pl. 6), all of which show portions of the Carrington shale facies, illustrate the facies relationship of the shale unit. The east-west cross sections show the abrupt change from the limestone unit to the Carrington shale and that the shale unit is a lateral equivalent of the basinward limestone. Isopachous maps of the Scallion subinterval also illustrate this relationship. Plate 2 shows the total thickness of the Scallion including the shale unit, while Plate 3 shows the thickness of the Scallion minus the shale units. It is apparent from this comparison that the Carrington shale facies is an integral part of the Scallion, a lithologic facies of it, not a separate stratigraphic unit of equal status.

Thickness of the Carrington shale facies varies from 0-90 feet. The thickest portion is along the western margin of the shale body. It can be seen (pl. 1) that the thickness decreases more rapidly to the west and less rapidly to the east.

Variations in thickness occur in several locations. Most notable are two indentations along the western margin of the shale, located in Burleigh and Benson Counties. The thickness of the shale decreases rapidly in these areas.

Correlation of the unit was relatively easy, with a few notable exceptions. The shale section in well 631 in Sioux County displayed a slightly different log pattern as seen on cross-section A-A' (pl. 6). Lack of well control in that area also makes the correlation difficult. If it is not part of the Carrington shale facies, the possibility exists that the Three Forks Formation extends that far to the south and east. However, the shale interval does occupy the proper place in the section. Also the thickness of the limestone portion of the Scallion subinterval is normal in well 631 for wells which penetrate the Carrington shale facies. For these reasons the author has continued to extend the Carrington shale facies into Sioux County, following Ballard (1963).

The Carrington shale facies has been extended further to the north than it had been previously (Ballard, 1963). This was done on the basis of sample and mechanical log characteristics and stratigraphic position. On cross-section A-A' wells 435 and 683 were not included in the Carrington shale facies by Ballard. Although well 683 has an abundance of sand and rock fragments, which is atypical of a Carrington shale section, it is bounded to the north by a typical shale section (well 435) and does display a fairly typical mechanical log character. For these reasons and its stratigraphic position it has been included within the Carrington shale facies.

Routledge Shale Facies

This shale unit is located in southwestern Manitoba and extends into north-central North Dakota. Two separate bodies of shale exist (fig. 1). The Routledge shale can also be considered a facies of the Scallion subinterval, for the same reasons given for the Carrington shale facies.

Only the south unit of this shale, because of its location near the international border, has been mapped in this study. McCabe (1959) discussed the similar lithology and stratigraphic position of the two shale bodies and considered them to be correlative units. The Routledge Shale, like the Carrington, is bounded to the west by the basin hinge line and to the east by the erosional limit of the Mississippian strata. Erosion has probably removed more of the Routledge, evidenced by its rapid thinning eastward. The Routledge (0 to 100 feet) is slightly thicker than the Carrington shale facies (0 to 90 feet). This difference may be the result of the author's picking of the Routledge Shale-Bakken Formation contact slightly lower than it had been picked by McCabe (1959). However, it is not unusual for formations to thicken in this area of Rolette County, North Dakota. Ballard (1963) illustrated that the Bakken and Three Forks Formations are slightly thicker in this area.

From the preceding discussion it seems reasonable that these two shale units were deposited at the same time and most likely under similar environmental conditions. This is evidenced by their stratigraphic positions and lithologies (to be discussed in more detail in the next section). For this reason they could be considered correlative units and assume the same name; however, their physical separation makes this difficult. The author will continue to recognize them as distinct units. For the purpose of facies analysis they will be discussed as one unit and so be called the Carrington-Routledge shale facies.

Overlying Units

Normally the Virden subinterval overlies the Scallion subinterval in the area of study. This unit is typically composed of a lower shaly oolitic and/or bioclastic limestone and an upper crinoidal limestone member. It ranges in thickness from 0 to 40 feet (Stanton, 1958).

Where the Virden subinterval has been removed by pre-Mesozoic erosion, the Scallion is covered by the Triassic Spearfish or the Jurassic Piper Formation. The Piper extends further to the east than the Spearfish. Many irregularities occur on the upper surface of the Mississippian section due to pre-Mesozoic and Mesozoic erosion. This relationship is illustrated on the log of well 316 on stratigraphic cross-section A-A'. Discussion of these erosional features is beyond the scope of this report.

FACIES ANALYSIS

The Scallion subinterval has been subdivided into six facies by the author of this report. This subdivision was based on sample and mechanical log characteristics of the subinterval. It is the intention of the author for these to be lithologic facies without any generic implication in their names. Environmental interpretations have been made of the facies and these are included in the discussion of each facies.

The facies are best documented through the center of the study area along the cross-section B-B' on plate 6. The author has extended the facies throughout the study area by the use of mechanical log characteristics and the sample studies.

The naming of the carbonate units was based primarily on the dominant fabrics present, using Dunham's (1962) classification of carbonate rocks. Clastic units are named by the components of the units. Variations are common within units due to lateral and vertical variations in lithology. The fact that well cuttings were used to describe the facies necessitated that the facies be described in general terms. Minor variations in the samples could not be automatically attributed to lithologic variations within the facies.

Carrington-Routledge Shale Facies

Lithology and Fauna

The Carrington-Routledge shale facies is typically a dark-gray or a red-brown shale with green mottles. It contains approximately 60 to 70 percent clay, 30 to 40 percent silt, and trace amounts of sand. The red-brown colored shale could be called a mudstone, due to its massive blocky character at times. However, the presence of faint laminations on the cored surface and its tendency to break horizontally more often than not, suggest that it is slightly fissile and therefore should be referred to as a shale. The darker shales are considerably more fissile. Some fragments of the red-brown shale showed irregular small-scale disturbed bedding (well 689).

No fauna was noted within the shale itself, with the exception of a brachiopod reported by Sidney Anderson (personal communication). Lack of fauna noted is probably due to small sample size and to conditions within the shale which may not have been conducive to life at the time of deposition or to the preservation of fossils following deposition. The author made no attempt to pick samples for microfossils. The possibility exists that a conodont fauna is present in the shale facies. More core of this interval would be necessary before a study of that nature could be undertaken.

Variations in Lithology

A thin limestone bed is located in the upper one-third of the shale bed in several wells within the area of the Carrington shale facies. It is shown in cross-section A-A'. This limestone bed may be present throughout the occurrence of the Carrington shale facies; however, it was not found in the sample study of wells in the area. Increasing resistivity, decreasing spontaneous potential and lower gamma ray intensity on the mechanical logs is the only evidence for it. Variations noted in the sample study were anomalously large amounts of siltstone, sand, and rock fragments found in wells 683 and 644. These clastic sediments reflect environments of increased energy over the surrounding areas. It is possible that a channel passed through these portions of the shale facies. However, lack of control prevents extending the data from these wells. Variations in the color of the shale will be discussed in the section on chemical environment.

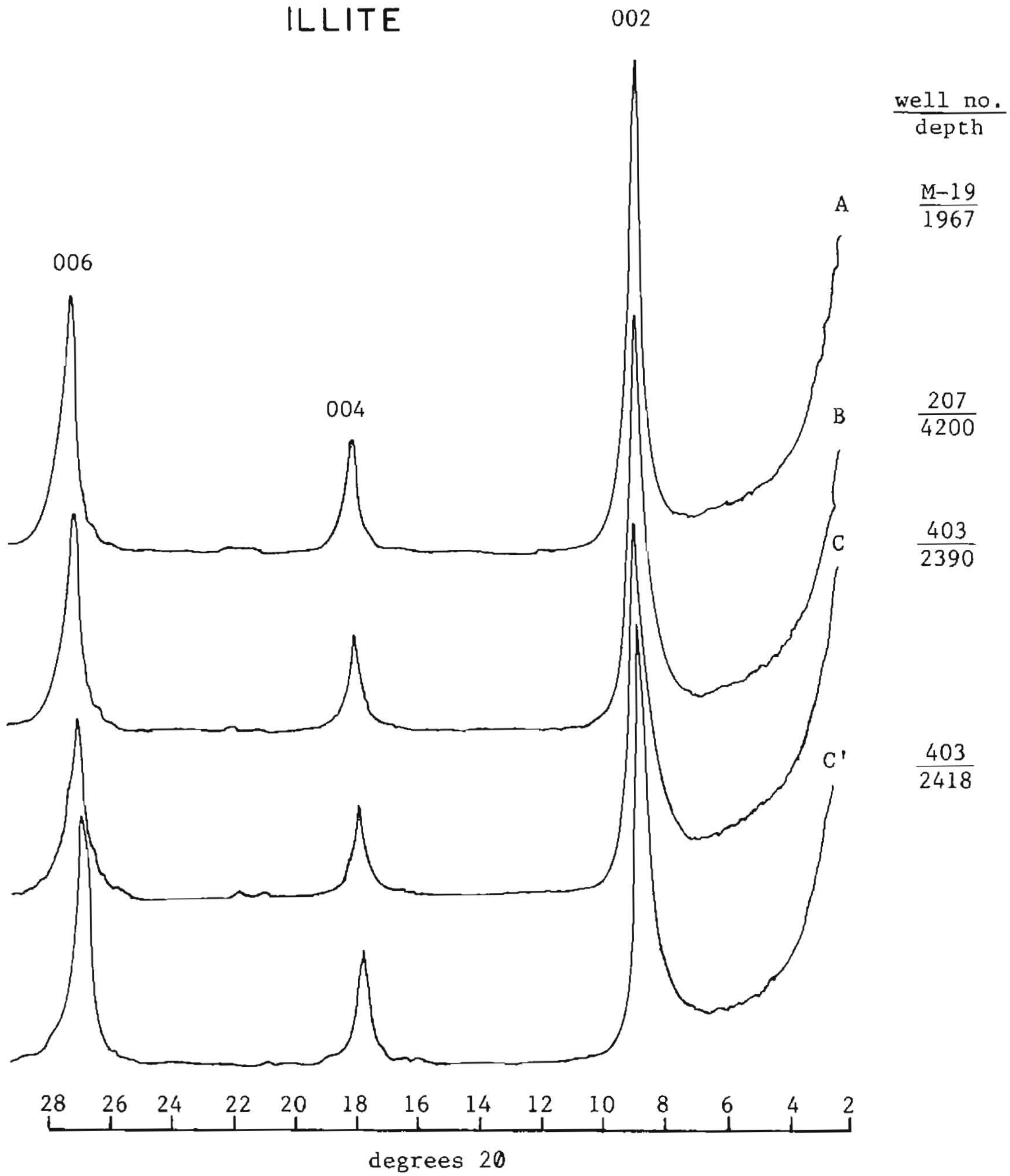


Figure 6. **X-ray diffraction tracings of the clay size fraction. (A) Routledge shale facies, Manitoba; (B) Carrington shale facies, Wells County, North Dakota; (C) and (C') Carrington shale facies, Foster County, North Dakota.**

Mineralogy of the Carrington-Routledge Shale Facies

Results of X-ray diffraction analysis of core samples of the Carrington shale facies show that illite is the dominant mineral in the shale. The clay-size fraction is essentially 100 percent illite with trace amounts of quartz present. Samples of the Routledge Shale gave similar X-ray diffraction patterns. Figure 6 illustrates the degree of similarity between the two. Glycolation and intense heating of samples did not alter the X-ray tracings or give evidence of other clay minerals.

Slaking of the Carrington Shale Facies

Ballard (1963) referred to the Carrington shale facies as bentonitic. However, X-ray data has shown that the shale is devoid of bentonite and instead composed of illite. The discrepancy was probably caused by Ballard's observance of the shales reaction with water. When a fragment of the red-brown Carrington shale is placed in water it breaks apart giving off small gas bubbles. This reaction could easily be mistaken for a swelling reaction. The shale does not become sticky and hold or absorb water as montmorillonites (bentonite) do. The Carrington shale falls apart in the bottom of the beaker. This process has been referred to as slaking, as in a slaking coal. This process was noted in the red-brown shales and in a few cases in some of the darker brown shales, although these shales did not slake as readily.

Cause of the Slaking

The slaking of the shale appears to be related to the chemical environment of the shale. This is evidenced by the fact that the shales which slake most readily are those which have been oxidized. It is also evident that the presence of water initiates the slaking action. Knowing the mode of interaction between the shale and the water would undoubtedly reveal much of the cause of the slaking. What can be said, concerning this interaction, is that the water is not moving into the interlayer spaces of the clay particles. This conclusion is based on the invariance of the interlayer spacing during glycol saturation and heating. Instead, the water is apparently interacting with whole particles of the shale. Clay particles are known to be bound together by a delicate balance of attractive and repulsive forces (Olphen, 1963). It appears that the water is strongly attracted to the clay particle surfaces, readily overcoming the interparticle attractive forces.

Variations in Thickness

As noted earlier in the section on stratigraphy of the Carrington shale facies, there are two areas in which the shale facies is abnormally thin. These areas occur in Benson and Emmons Counties and can be seen on the isopachous map of the Carrington and Routledge shale facies (pl. 1). They are also visible on the isopachous map of the Scallion subinterval (pl. 2).

It is the interpretation of the author that these thin areas formed as the result of channels (submarine or subaerial) which formed across the Carrington shale facies during and/or after its deposition. This interpretation is based on: (1) the narrow and elongate geometry of the thin areas, and (2) the presence of sand in wells 663 and 742 directly basinward of the proposed channels. Accumulation of sand in the areas of these proposed channels is also possible. However, it is not the intention of the author to depict these areas as elongate bodies of sand. It is conceivable that the winnowing of the shale from these areas resulted in the formation of these thin areas. It is not necessary for the deposition of sand to have occurred. Well control in these areas is not sufficient for further discussion of this problem.

Origin of the Shale Facies

McCabe (1959) discussed two theories on the accumulation of the Routledge Shale: The first, formation of a barrier (reef or shoal) which caused a local restriction of circulation and deposition of the shale. The second, the Routledge is a continuation of Bakken deposition. The second explanation necessitates the solution of underlying salt beds. Although this theory could explain the occurrence of the Routledge Shale, salt beds are lacking in the area of the Carrington shale facies; so it cannot explain the occurrence of the stratigraphically equivalent Carrington shale facies.

Ballard (1963) proposed that the Carrington shale facies formed behind the Burleigh High (fig. 2). A comparison of the location of this high with the location of the Carrington shale facies (pl. 1) shows that this high is located 10 to 20 miles basinward of the shale facies. It is the interpretation of the author that this high is located too far basinward to have affected the deposition of the shale itself. The depositional slope would probably have rendered ineffective any structural relief. Also this structural high does not extend far enough to the north to account for the northern portion of the

Carrington shale facies or for the stratigraphically equivalent Routledge shale facies.

It is the intention of the author to, in this and the following sections, develop a theory that will be applicable to both the Carrington and Routledge shale facies.

Environmental Analysis

Factors which should be considered when interpreting the environment of deposition of the shale facies are:

1. Location of the shale on the basin margin or shelf.
2. Separation of the shale from typical basinal shale deposits, i.e., the older Bakken Formation, which was deposited in the central basin.
3. Thickness and areal extent of the shale.
4. Extremely abrupt lateral facies change into the limestone unit of the Scallion subinterval basinward of the shale. This has been documented as occurring within three miles (McCabe, 1959).
5. Color variations within the shale units.
6. The presence of abundant illite associated with quartz, mica, K-feldspar and rock fragments.

From these statements the following conclusions can be made:

1. The source of the shale was likely a weathered igneous-metamorphic terrain, based on the composition of the shale and associated clasts, as discussed earlier.
2. The shale was deposited in an area of restricted circulation, based on the need for reducing conditions to account for the darker shales.
3. The shale was separated from the central basin by some type of barrier.

It is the author's interpretation that the Carrington-Routledge shale facies were deposited in restricted lagoonal environments. The areas were protected from the open sea by barriers located along the basin hinge line. The sediment was derived from the weathered land surface to the east.

Lime Mudstone Facies

Location

This facies is located westward and directly basinward of the previously discussed shale facies. Its precise location is difficult to map due to the lack of adequate control in the area. Plate 4 is an isopachous map which approximates the location of the facies. Thickness may be exaggerated in places as this map was constructed from mechanical log data only. On the stratigraphic cross sections this facies is represented by the crinoidal wackestone and micrite lithologic pattern. It is located directly west of the Carrington shale facies and below a thin, silty shale bed. This facies onlaps the Carrington shale facies (fig. 8).

Lithology and Fauna

This facies is typically composed of crinoidal wackestones and micrites along with occasional packstones. Bryozoans and brachiopods are also present. This description is based on sample studies by the author. McCabe (1959) mentions "12 feet of very coarsely fossiliferous, porous limestone with a reefoid appearance," that was located five feet from the base of the Scallion subinterval, which directly overlies 10 to 20 feet of Routledge Shale (well M-7). The fossils noted in this rock were bryozoa, brachiopods, and spines from brachiopods and/or echinoids. He described these fossils as appearing to be in growth position, including branching bryozoa. The limestone above and below this bed were described as fine grained, tight and with few to abundant scattered crinoid fragments. It is probable that this section is a part of the mudstone facies, as it is located above the Routledge Shale along its northwestern margin.

Environmental Analysis

Factors to consider in the environmental interpretation of this facies are:

1. This facies is the basinward lateral equivalent of the shale facies.
2. It is located on the basin-shelf margin or hinge line.
3. It has an abundance of micrite.
4. It has a sparse fauna, dominated by crinoids, with the exception of the "reef-like" bed described by McCabe (1959).

From these known facts the following conclusions can be made:

1. This unit occupies the position of the barrier which allowed the formation of the Carrington-Routledge shale facies.
2. The fabric and fauna of the facies is similar to that of the bioherm facies described by Smith (1972).

Smith's work in the Lodgepole Formation of central Montana revealed the presence of Waulsortian mounds. These mounds are composed of an inner core of micrite and flanking beds of crinoid and bryozoan wackestones. (The lime mudstone facies is also composed of micrite and crinoid wackestones, with some evidence of bryozoan.) These mounds are relatively common in the lower Mississippian (Wilson, 1975). Figure 10 shows a typical Waulsortian mound as described by Wilson. Examples of Waulsortian mounds are located in the Lodgepole Formation of Montana (Smith, 1972; Stone, 1972) and the Alamogordo Formation of New Mexico (Laudon and Bowsher, 1941). They are also found in England, France, Belgium (the name Waulsortian being taken from a village in the Dinant basin, south of Namur, Belgium), and Ireland (Wilson, 1975).

These mounds are believed by some (Wilson, 1975) to have formed below wave base by the entrapment of lime mud by the baffling action of the crinoids and bryozoans. Figure 10 shows the stages involved in the formation of a Waulsortian mound.

Characteristics that are common to most Waulsortian bioherm facies of Europe were listed by Wilson (1975). Some of the most important are:

1. They formed in clear, open water near the shelf margin.
2. Basinal facies consisted of shale, sandstone, and calcareous mudstone.
3. Shelf facies are highly varied, including lagoonal carbonates, cross-bedded grainstones, and deltaic clastics.

Stone (1972) described the distribution of these mounds in the Bridger Range of Montana. The mounds were located in an elongate trend with a surrounding facies composed of crinoid wacke-packstones. The individual mounds were dome shaped and up to 60 feet in height and up to 500 feet in length. The surrounding facies are continuous with original dips of up to 25° where it overlaps the bioherm cores. Stone states that up to 60 feet of depositional relief was present in places during the formation of these bioherms. Smith (1972) stated that these flank facies were deposited after the bioherm growth. He interpreted the bioherms to be located on the open shelf or slope in deeper water than later units within the Lodgepole Formation. Figure 11 illustrates the location of these bioherms in relation to Early Mississippian basin tectonics of the area.

The lime mudstone facies was probably deposited as a Waulsortian bioherm complex, as described by Wilson (1975). Evidence for this conclusion is:

1. Similarity of fabric and fauna to that reported in other Waulsortian bioherms.
2. Location on a shelf margin away from the shoreline, as other bioherms have been reported to have formed.
3. Presence of mounds in the Lower Mississippian of central Montana on the western margin of the Williston basin, places these deposits in the proper time-stratigraphic framework.

Figure 12 illustrates the possible mode of formation of the lime mudstone facies as a Waulsortian bioherm complex.

Interbedded Shale-Limestone Facies

Location

This facies is west (basinward) of the lime mudstone facies. It has an elongate north-south trend. The precise limits of this facies are not known. It can be seen on stratigraphic cross-sections B-B' and C-C', in wells 693 and 61, respectively. It is a rock-stratigraphic equivalent to the lime mudstone and Carrington shale facies. Figure 8 shows its areal distribution and its location on an east-west diagrammatic cross section. The facies ranges in thickness from 0 to 80 feet. Along its eastern margin it onlaps the lime mudstone facies.

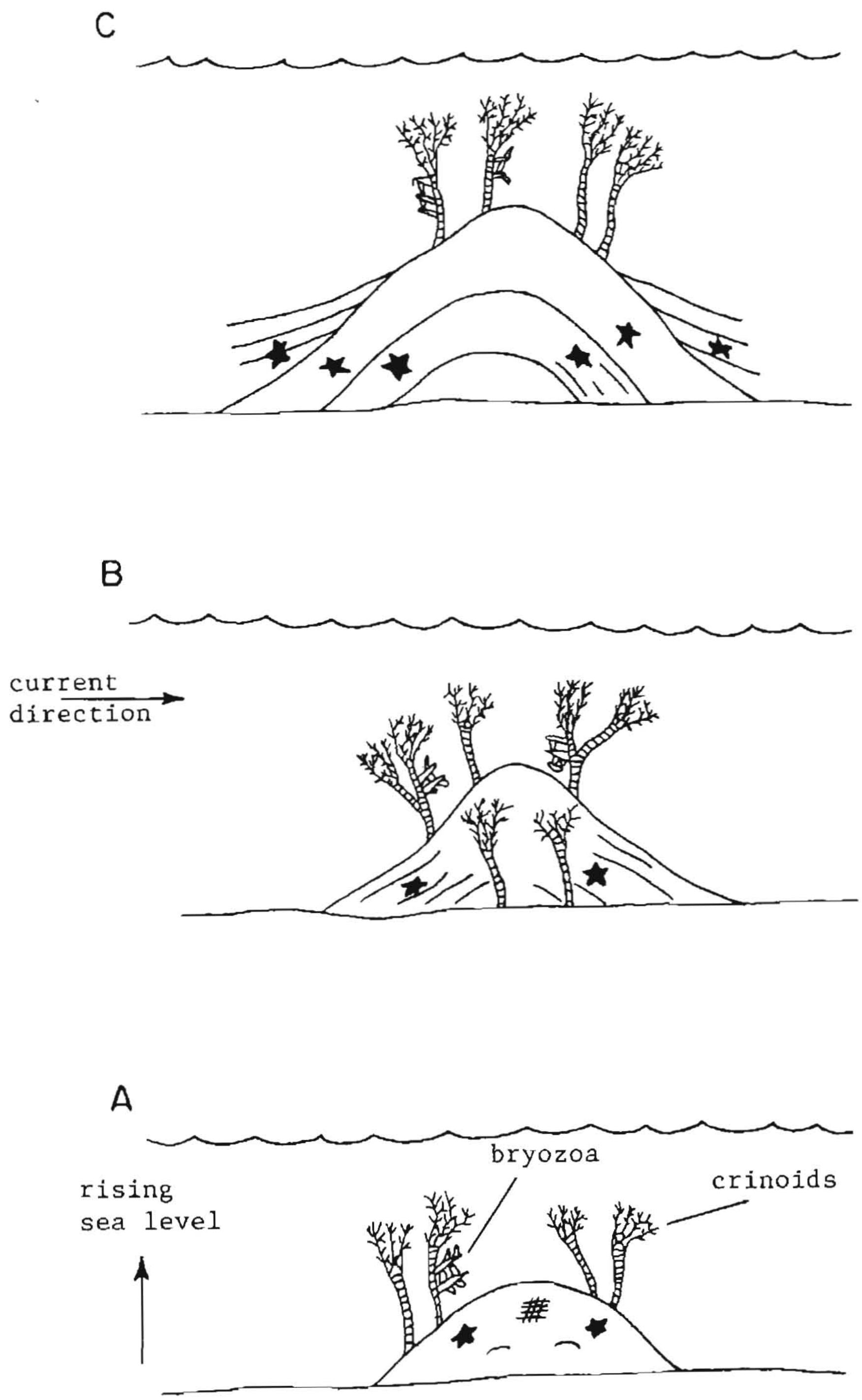


Figure 10. Possible mode of formation of Waulsortian bioherms, after Wilson (1975).

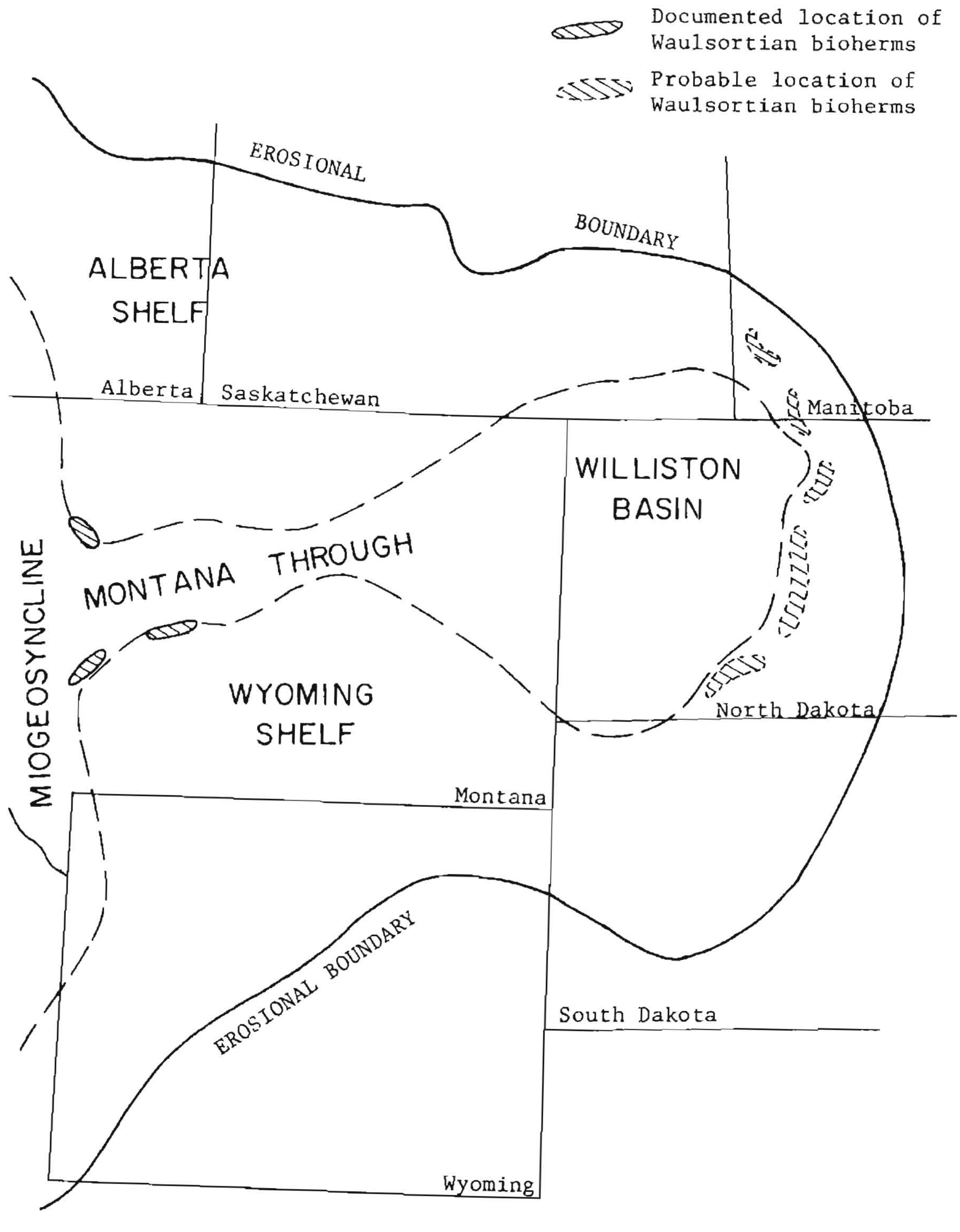


Figure 11. **Relationship between known and probable Waulsortian bioherms and the basin-shelf configuration at the time of the bioherms formation (early Mississippian). After, Craig (1972), Macauley et al (1964), Stone (1972), and Carlson and Anderson (1970).**

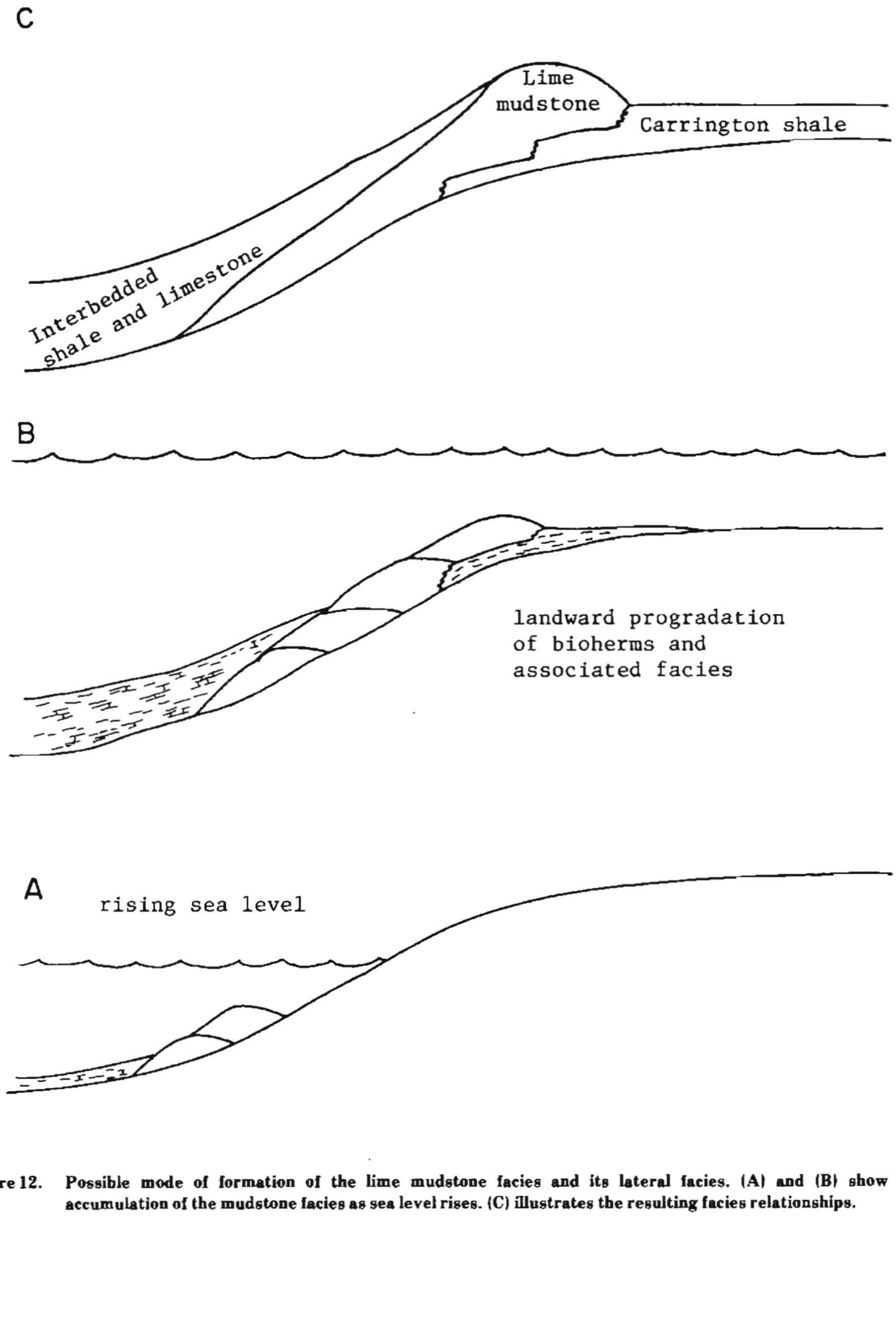


Figure 12. Possible mode of formation of the lime mudstone facies and its lateral facies. (A) and (B) show accumulation of the mudstone facies as sea level rises. (C) illustrates the resulting facies relationships.

Lithology and Fauna

Well 693 (cross-section B-B') has 75 feet of interbedded shale and crinoidal lime wackestones and packstones. Since this interval has not been cored it is difficult to describe the lithology in detail from the well cuttings alone. The above interpretation was based on the irregular nature of the spontaneous potential log, which suggests a varied lithology, and the presence of shale and carbonate in the samples, which leads to the conclusion of an interbedded nature.

Environmental Analysis

The interbedded nature of this facies necessitates an environment in which some factor was cyclic. Building upon the conclusions from the previous sections, this facies was probably deposited on the basin slope during and/or after the lime mudstone facies was deposited on the shelf margin. Periodic influxes of fine clastics washing off the shelf were interspersed with periods of reduced influx which allowed carbonate deposition to occur.

Sand-Silt-Shale Facies

Location

This facies is located directly above the mudstone and interbedded shale limestone facies, in approximately the middle of the Scallion subinterval. It is represented on the mechanical logs by an increase in spontaneous potential and gamma ray intensity. It ranges in thickness from 0 to 50 feet. Figure 13 shows the approximate areal distribution of this facies.

Lithology and Fauna

This facies is composed of fine to medium, well-sorted sand, silt, and gray shale, the grain size increasing basinward. Well 693 (cross-section B-B') has an abundance of sand in this interval, while well 207 is dominantly shale. No fauna was noted from this interval in the sample descriptions. No core was available from this interval.

Environmental Analysis

The coarse clastic nature of parts of this facies are an aid in the interpretation of this facies. The medium sand that is moderately well rounded and sorted, such as the sand in well 693, can have but a few origins when the surrounding deposits are considered. The surrounding limestone units are definitely marine in origin with a typical marine fauna (crinoids, brachiopods, bryozoans). Within the marine environment the possible processes that could result in the formation of this deposit are:

1. Deposition in a shallow near-shore environment. This would necessitate a fall in sea level following the deposition of the Carrington shale facies and a subsequent rise following the deposition of the sand beds as near-shore sediments. A continued rise in sea level would then be necessary for the deposition of the shale beds to the east. This regression of the shoreline could explain the oxidation of the Carrington shale facies. Assuming that the sands were deposited as beach sands it is possible that the lower sand in well 693 was the regressive sand while the upper sand represents the transgressive phase. Following the period of sand deposition, the sea level continued to rise allowing the deposition of the shales and siltstones.
2. Deposition of the shale and the silt on the shelf margin, possibly during the final phases of the deposition of the Carrington shale facies. At this same time and possibly during much of the time of the shale facies deposition, the sand was being deposited basinward of the shelf margin. Offshore submarine currents may have transported the sand from its point of entry into the basin and deposited it into elongate bodies which parallel the shoreline.

Support for the above hypotheses are scant. The partial oxidation of the Carrington shale facies seems to indicate that it was exposed to the surface at some time in the past. This conclusion supports the first hypothesis. Indirect evidence for the second hypothesis is related to the problem of source of the sand. Possible sources are:

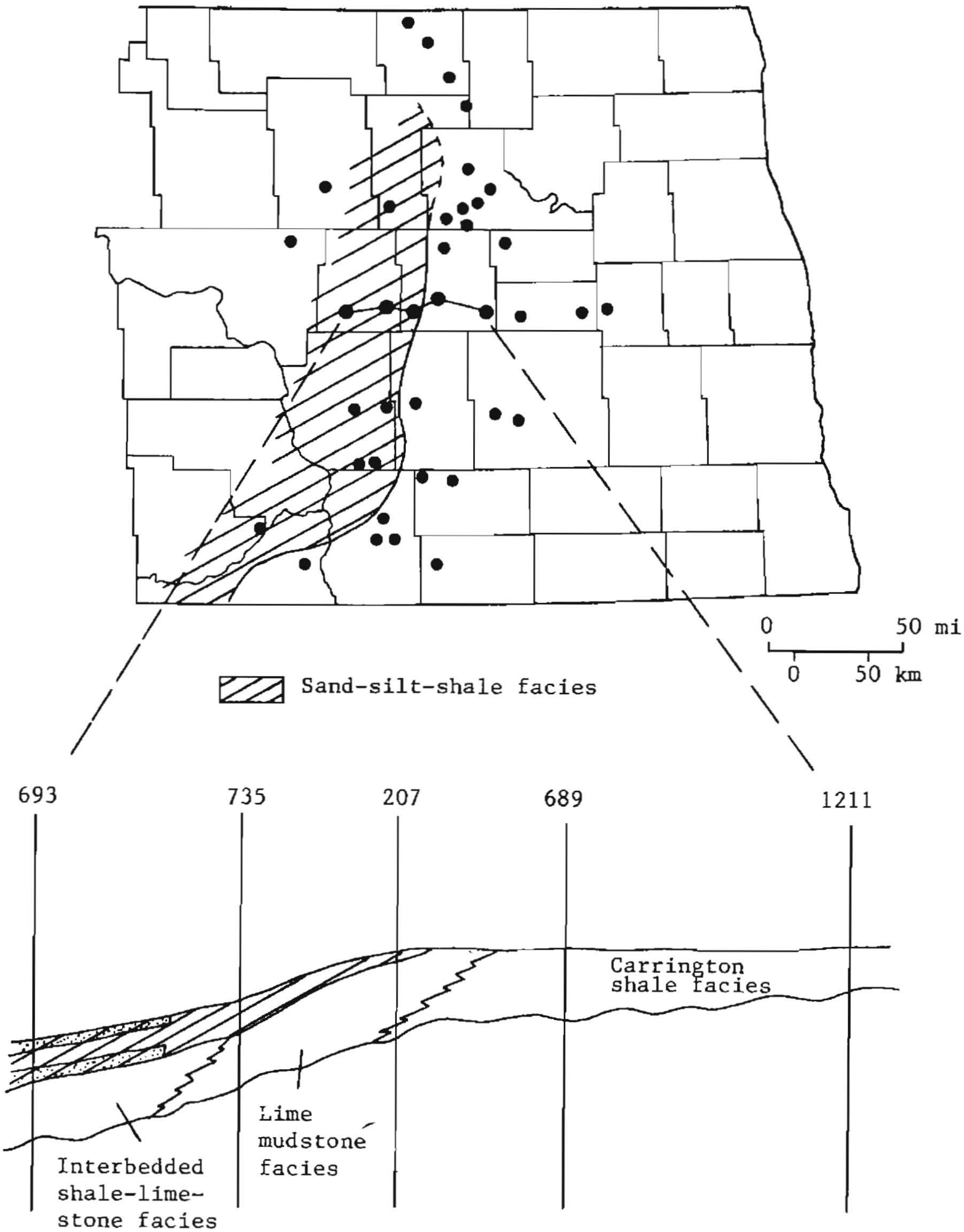


Figure 13. Lithofacies map and cross section illustrating the sand-silt-shale facies.

1. The open area between the Routledge Shale and the Carrington shale facies in Rolette County (see plate 1). The absence of the shale in this area may have been related to increased currents through this area.
2. The possible occurrence of channels on the surface of the Carrington shale facies in Benson and Emmons Counties.

These source areas, though not supported by a great deal of evidence, are possible feeder channels for the transport of the sand from the land surface, to the east, across the shelf platform and into the basin. This second hypothesis has one very favorable aspect in that it does not necessitate a major regression and transgression of the shoreline, and simplifies the overall depositional model. The author prefers the latter hypothesis.

Crinoid Packstone-Grainstone Facies

Location

This facies directly overlies the Carrington shale facies and is the lateral equivalent of the wacke-packstone facies just described. It is bounded to the east by the erosional limit of the Mississippian strata. Figure 14 shows the location of this facies in map view and cross section. It ranges in thickness from 0 to 160 feet.

Lithology and Fauna

A large amount of loose, rounded crinoid grains were noted in the samples from this interval. Based on this observation it is the author's interpretation that crinoidal grainstones compose a large portion of this rock. Actual rock chips in the samples were mostly packstones with abundant white chalky micrite and sand and shale. No core was available from this interval.

Environmental Analysis

The presence of abundant crinoidal grainstones from this facies indicates that the facies was deposited under relatively high-energy conditions. This, along with the landward location of this facies on the shelf itself, indicates that the limestones were deposited as shallow subtidal shoal-like crinoid sands. Formed above wave base these sediments would have been continually reworked and redeposited by wave action. In outcrop (if one existed) it is likely that these sediments would be seen to be cross bedded.

Wacke-Packstone Facies

Location

This facies is located above the sand-silt-shale facies (fig. 14) and extends to the upper surface of the Scallion subinterval. It is approximately 0 to 90 feet in thickness. It is the lateral equivalent of the crinoid packstone-grainstone facies which will be discussed in the next section. The exact relationship between these two facies is difficult to determine due to lack of adequate well control. However, it is likely that the wacke-packstone facies overlaps the crinoid packstone-grainstone facies. This assumption is based on the relationships of the underlying facies.

Lithology and Fauna

Crinoidal lime wackestones, packstones, and micrites along with scattered brachiopods make up this facies. Samples from this interval also showed moderate to abundant amounts of shale and siltstone. However, the mechanical log character does not indicate the presence of these materials. The log normally has a low spontaneous potential and low gamma ray intensity. The presence of shale and siltstone should normally cause an increase in the intensity of these two log patterns. It is likely that most of the clastic material in.the samples is caving from above units. As with the facies discussed previously, no core was available from this interval. The above description was based solely on sample studies and mechanical log character.

Environmental Analysis

Based on location of this facies with relation to the probable shoreline and the interpretation of the environment of the landward facies it is reasonable to assume that this carbonate was deposited on the shelf margin and basin slope. The assumption that the shoreline was as much

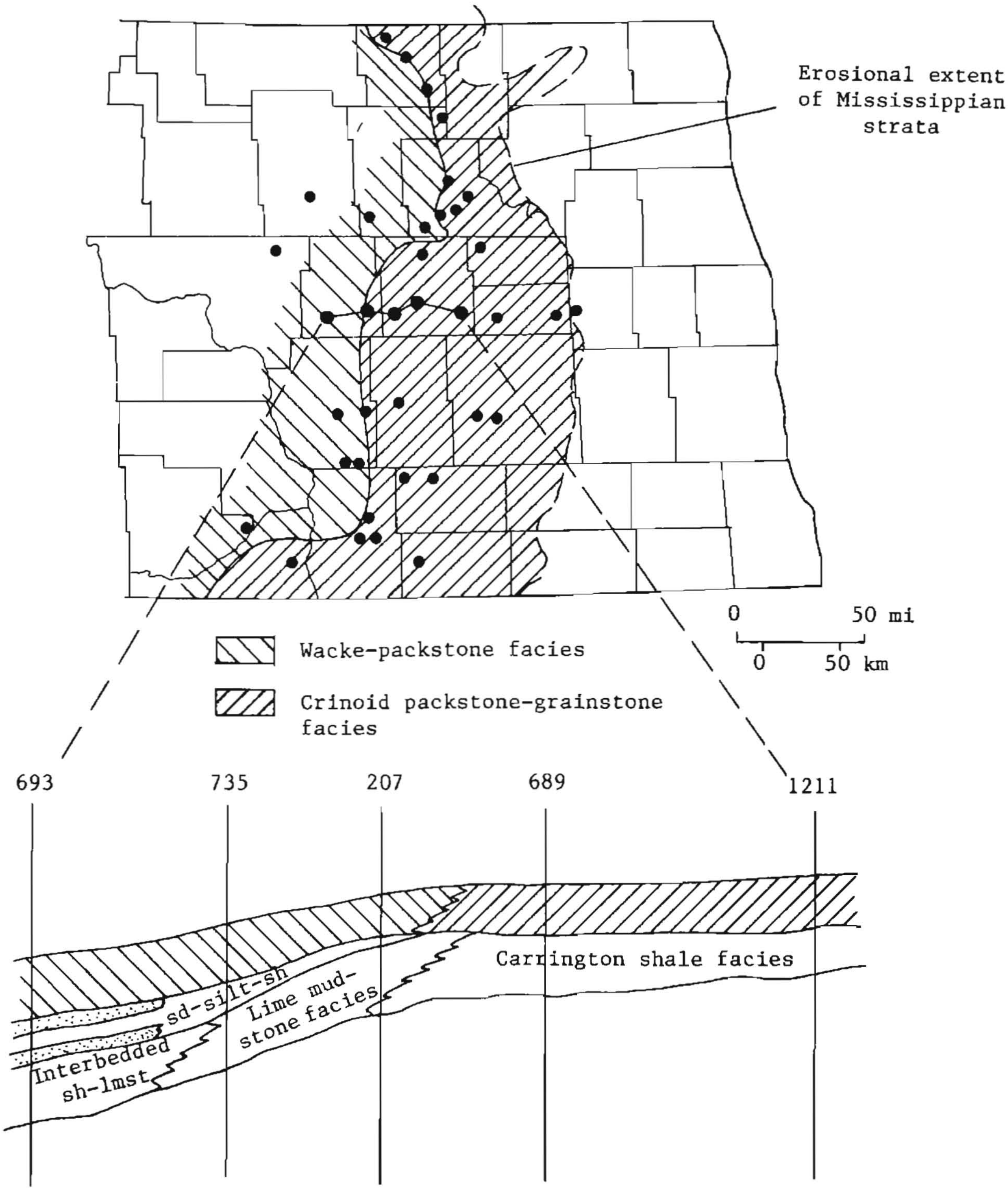


Figure 14. Lithofacies map and cross section illustrating the wacke-packstone and crinoid packstone-grainstone facies.

as 65 miles eastward is based on the presence of the crinoidal packstone-grainstone facies which was deposited on a shallow shelf type environment landward of the wacke-packstone facies. The apparent lack of clastic sediments also indicates that the shoreline was somewhat distant. This relatively fine-grained carbonate was probably deposited below normal wave base, possibly being affected by storms. Evidence for this is the dominance of mud-supported limestones with the exception of the occasional packstones.

PALEOGEOGRAPHY

From the conclusions made about the environments of deposition of the facies in the previous section, the following statements of the paleogeography at the time of the deposition of the Scallion subinterval can be made.

Prior to the start of Scallion deposition the Bakken Formation was being deposited in the central basin area. During this time the Devonian Birdbear and Duperow Formations, as well as the Stony Mountain, Red River, and Winnipeg Formations, were exposed to the east. To the east of these sedimentary rocks, Precambrian igneous and metamorphic rocks were exposed. Figure 15 is a paleogeologic map of the eastern half of North Dakota before the deposition of the Scallion subinterval. The weathering of this exposed surface provided the sediment necessary for the formation of the Bakken shales. Figure 16 is a paleogeographic map depicting the possible geography at this time. The location of streams on this map is arbitrary. The basal Mississippian structure contour map (fig. 2) shows that some contour lines are deflected eastward. This may be the result of channels on the pre-Mississippian erosional surface. The lack of sufficient well control in the area prevents further analysis.

Following deposition of the Bakken Formation sea level rose throughout the Williston basin (Carlson and Anderson, 1970). The shoreline extended farther eastward than the present erosional limit of the Scallion subinterval. During this time the mudstone facies was deposited as a Waulsortian bioherm complex.

Figure 17 illustrates the possible geography at the time of the deposition of the Carrington shale facies. The location of streams is purely hypothetical. The topography of the land surface was most likely subdued as the result of the numerous periods of erosion that had taken place in earlier geologic time. The map also shows the location of the Waulsortian bioherms. These bioherms may have formed prior to the deposition of the majority of the shale facies. The breaks in the continuity of the bioherms correspond to areas of thinning of the Carrington shale facies. Increased currents in these areas, possibly associated with landward fluvial systems, may have prevented the formation of the bioherms and resulted in thinning of the shale facies (most notably in Benson and Emmons Counties).

These possible channels may have been related to the deposition of the sand beds in the sand-silt-shale facies as discussed in the section on this facies. Sand carried into the basin may have been deposited along the basin slope parallel to the shoreline. The remaining portions of this facies may have been deposited as a late stage of the Carrington shale facies deposition, if the shale extended over the top of the mudstone facies.

A regression of the shoreline at this time would be an aid in explaining the partial oxidation of the Carrington shale facies. The channels on the Carrington shale could also have occurred at this time and the deposition of the sand-silt-shale facies occurred as outlined in the earlier section on this facies. However, the author of this report does not feel that a regression of the sea is essential to the explanation of these deposits.

Following the period of clastic deposition of the Carrington shale facies and the sand-silt-shale facies, a return to carbonate deposition occurred. This most likely happened as the result of decreased erosion and transport of clastics into the shelf area or the more efficient removal of these clastics by currents.

The two uppermost facies of the Scallion subinterval were then deposited on the shelf margin and basin slope. The packstone-grainstone facies was deposited

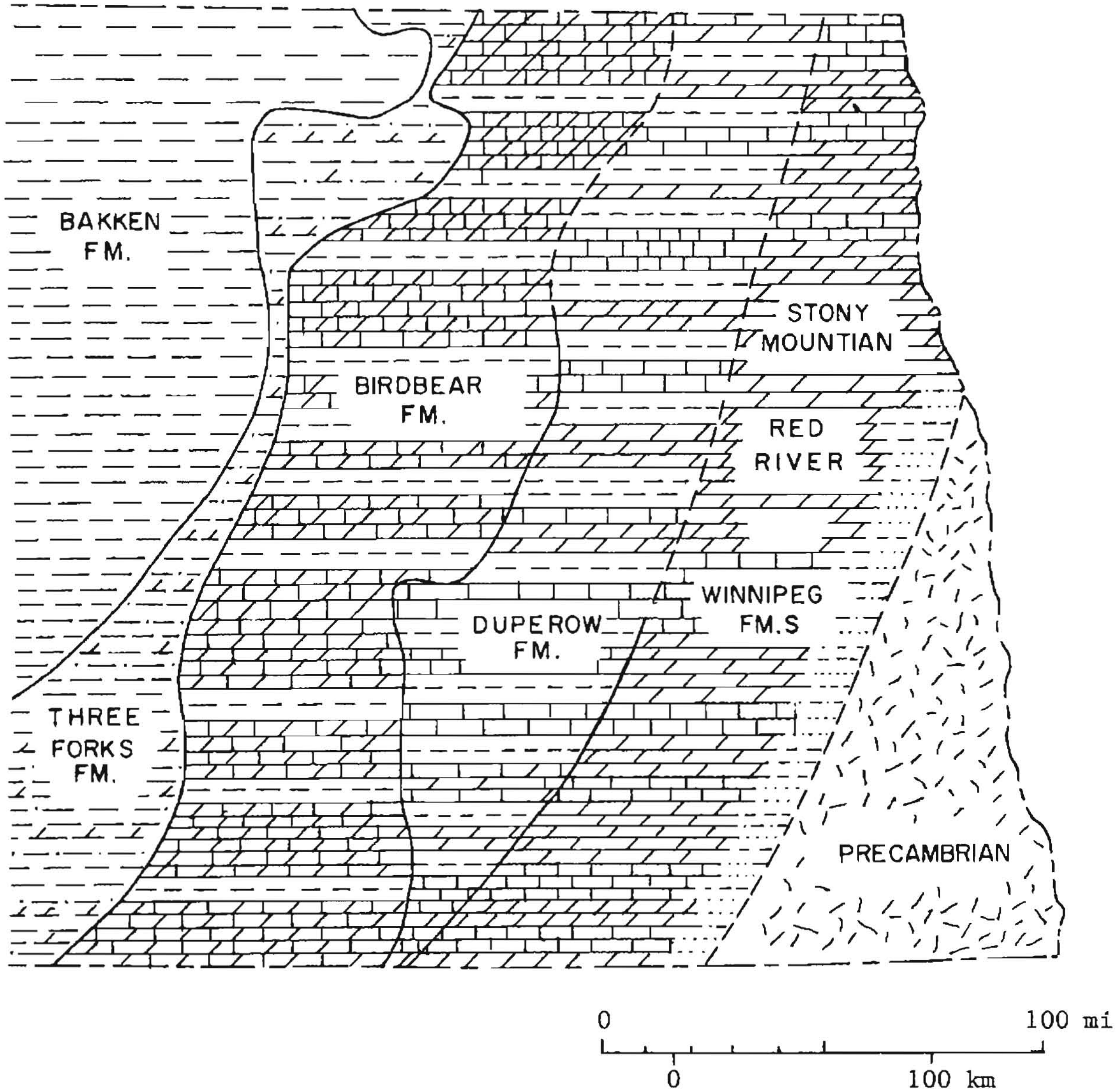


Figure 15. Paleogeologic map of eastern North Dakota during the deposition of the Bakken Formation and prior to the start of Madison deposition.

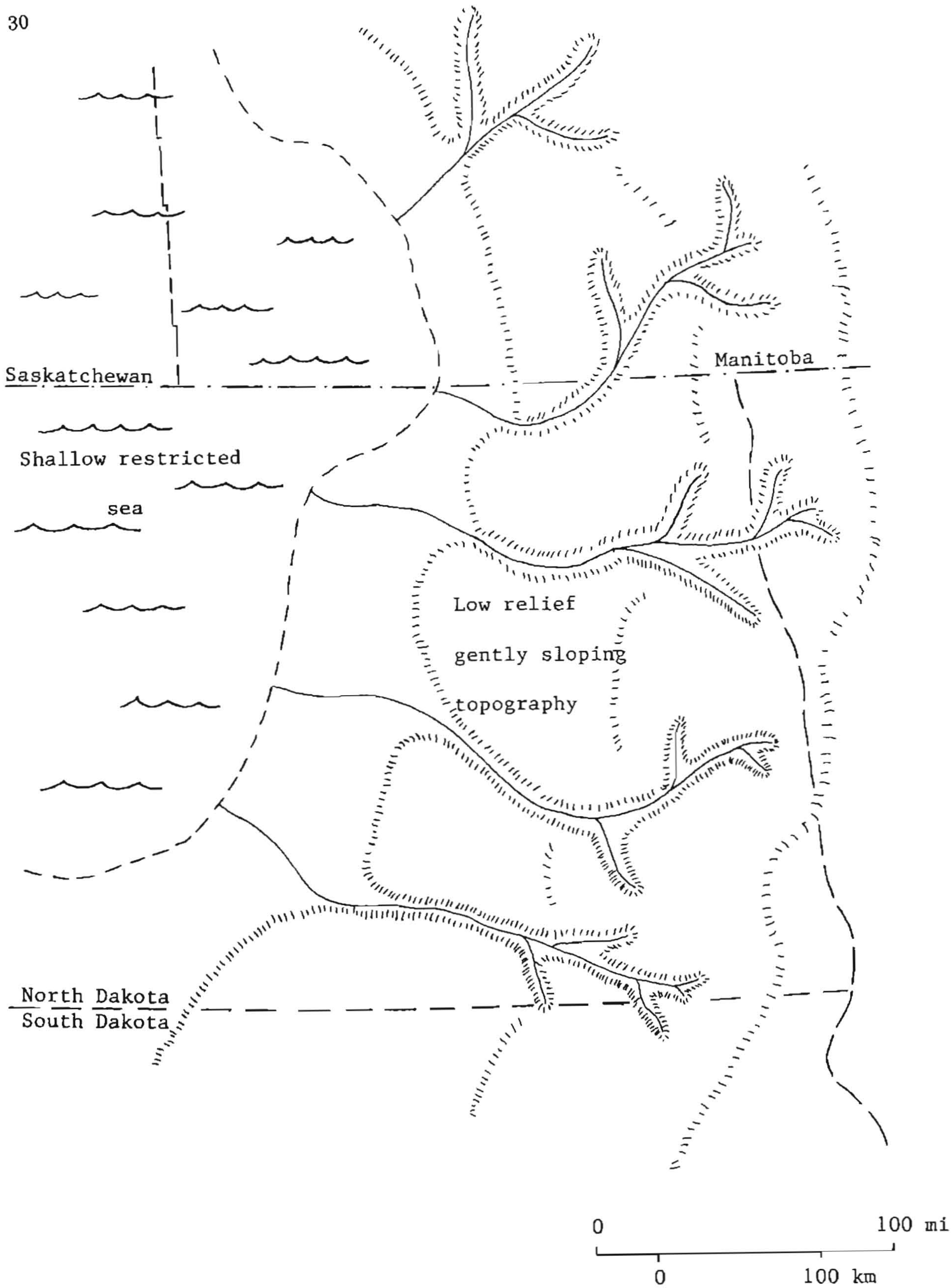


Figure 16. Diagrammatic paleogeographic map of the eastern margin of the Williston basin during deposition of the Bakken Formation.

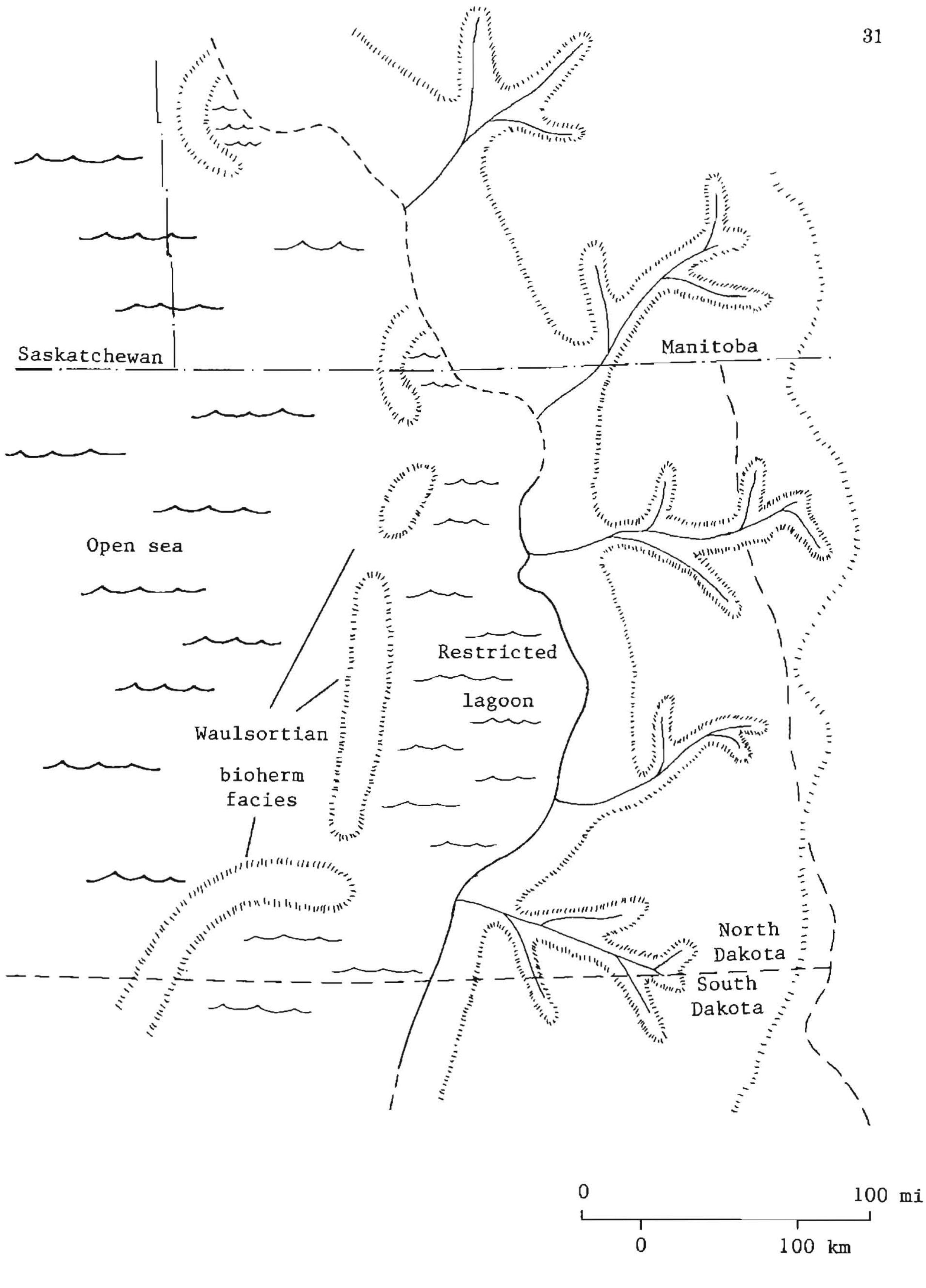


Figure 17. Diagrammatic paleogeographic map of the eastern margin of the Williston basin during the deposition of the Carrington shale facies.

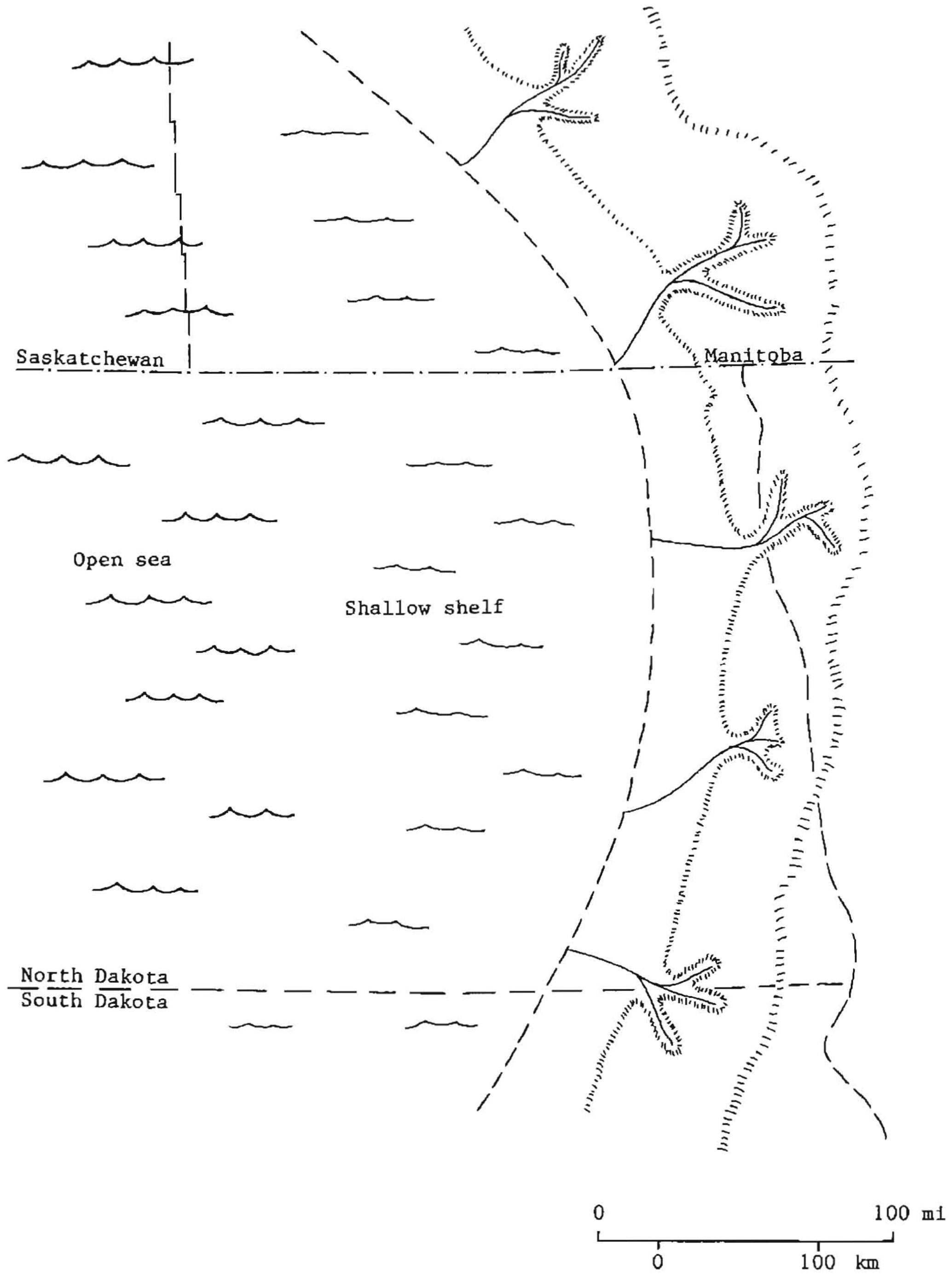


Figure 18. Diagrammatic paleogeographic map of the eastern margin of the Williston basin during the time of the deposition of the wacke-packstone and crinoid packstone-grainstone facies.

in shallow water near the shoreline and the wacke-packstone facies was deposited basinward on the deeper shelf and basin slope. Figure 18 illustrates the possible paleogeography at the time of deposition of these two facies. The shoreline is highly speculative and possibly farther to the east.

Pre-Mesozoic erosion has removed the easternmost sediments of the Scallion subinterval. The presence of 40 feet of Scallion sediments in well 36 in Cavalier County (see plate 5 for precise location) supports the extending of the shoreline eastward.

ECONOMIC POTENTIAL
Oil

The number of oil tests drilled in the North Dakota portion of the study area which penetrate the Scallion subinterval are 194 to January 1, 1976. This portion of the study area covers approximately 31,500 square miles. This works out to a density of 1 well for every 162 square miles. This portion of the Williston basin can therefore be considered to be relatively untested.

Scallion Production in Manitoba

The Scallion subinterval produces oil in the North Virden Scallion Field and from other fields in the area. Oil production in Manitoba is associated with the truncation of porous reservoir rocks by the Mississippian erosional surface. The regional dip of the formations in this portion of the Williston basin is to the southwest. Therefore older strata are more productive to the northeast. According to McCabe (1963) this is not entirely due to the truncation of progressively older strata, but also is a function of the drop in the stratigraphic depth of dolomitization along the surface of the Mississippian strata. This dolomitized zone provides the seal necessary for the entrapment of the updip-migrating oil. Variations in the permeability of reservoir rocks and dolomitization cause local variations in oil production. Berg (1956) reported that extensive leaching (pre-Jurassic) of the Scallion has resulted in porosities of up to 40 percent and permeabilities of up to 500 millidarcies in the North Virden Scallion Field.

Relationship of the Routledge Shale to Manitoba Oil Production

According to McCabe (1963) the Routledge Shale is not associated with any oil production in the province. He does mention the possibility of the shale being a source rock. This will be discussed in a later section along with the Carrington shale facies. Since at the present time no production of oil from the pre-Mississippian strata in this area has been reported, it is difficult to discuss the possibility of the Routledge Shale being a seal for oil traps below it. Also complicating this discussion is the fact that at present the Routledge appears to be underlain by the Bakken Formation throughout its area of occurrence. The possibility does exist that the middle siltstone bed of the Bakken Formation could serve as a reservoir rock as it does produce oil in both North Dakota and Saskatchewan. However, the siltstone bed would have to extend beyond the upper shale of the Bakken in order for the Routledge to seal it.

Facies changes along the western margin of the Routledge Shale have been recognized by McCabe (1963) as possible areas in which accumulation of oil could possibly take place. He notes that, in one case, by moving downdip a distance of 2 miles, 70 feet of shale section is lost to carbonate. Normally this carbonate is rather tight but in one locality McCabe noted that rocks of a porous "reefy" nature were found near the base of the Scallion subinterval. This is unusual since the lower portion of the Scallion is normally finer grained and tight. The possibility exists that this material of a "reefy" nature is only the edge of a much larger carbonate buildup. Should this be the case it could make an excellent stratigraphic trap for the accumulation of oil.

The Scallion Subinterval in North Dakota and Possible Oil Accumulations

As stated earlier the Scallion subinterval has not been adequately tested for oil and gas in North Dakota. The lack of obvious structural features has probably been the greatest hindrance to exploration along the eastern margin of the Williston basin. Ballard (1963) mapped several structural features in the area (fig. 2). However, due to the very low relief of these features it is likely that little or no closure is possible because of the basinward dip of the stratigraphic units. Any traps that are present in this area are probably of the same nature as those in southwestern Manitoba. **All of the elements necessary for these traps exist in North Dakota. They are:**

1. **Truncation of porous units by the Mississippian erosional surface. The Scallion in the eastern portion of the study area is erosionally truncated**

(see plate 2 for area of Scallion subcrop).

2. The presence of what should be an effective cap rock above the subcropping Scallion. The Mesozoic-age rocks in this area are typically shaly and impermeable.
3. The presence of known oil production is downdip from this area in the center of the basin.
4. Lateral closure, though not documented, is likely to be present just as it is present in Manitoba.

Traps other than those of the type found in Manitoba are possible in North Dakota. Facies changes within the Scallion subinterval have been documented in this study. The presence of these rapid changes in lithology could result in the formation of a suitable stratigraphic trap.

The Lime Mudstone Facies and Possible Stratigraphic Traps

This facies appears to be overlain by a thin shale bed (see well 207, plate 6). It is also bounded updip by the Carrington shale facies. This combination of relationships could result in the formation of a stratigraphic trap. If the lime mudstone facies has the porosity and permeability necessary it could be a reservoir rock. At present there is no evidence of this with the exception of "reefy" limestone mentioned by McCabe (1963). If the lime mudstone was exposed to the surface or near surface soon after its formation, as disucssed earlier, the possibility exists that the upper portions of the facies were altered by groundwater solution. This could have resulted in the formation of porosity and permeability needed for this to become a reservoir rock.

Choquette and Pray (1970) term this stage in porosity development as the Eogenetic stage, this term applying to the time interval after final deposition and before burial of the sediments. Processes noted by Choquette and Pray are burrowing, root penetration, sediment shrinkage, boring, solution of selected minerals such as aragonite, and decomposition of organic matter. They also note that porosity reduction in this environment is also very prevalent. Solution in later times at deeper depths is not considered to be as extensive by these authors.

The Carrington Shale Facies as a Reservoir Seal

Anderson (1963) discusses the oil potential of the Devonian Birdbear and Duperow Formations. These formations were both truncated by erosion during the Early Mississippian, prior to the deposition of the Carrington shale facies which forms a cap over the two formations. Concerning the migration of the oil, Anderson notes that this locality is updip from the Nesson anticline and it is not unreasonable to assume that oil could migrate into this area.

The Devonian rocks would be adequate reservoir rocks. Core of the Duperow Formation (well 403), immediately below the Carrington shale facies, exhibited excellent porosity. Vugs up to 2 inches in diameter were present. It is likely that this type of porosity is present in other areas also, assuming that the rocks underwent similar diagenetic and erosional processes during the period of time when these rocks were exposed. Figure 16 illustrates the paleogeography at that time. It is also very likely that some type of erosional relief developed during this time. Topographic highs on this surface would make excellent reservoirs.

To date the Devonian-age rocks in eastern North Dakota have been tested even less than the Mississippian age strata. Most of the wells drilled in the area bottom in the Mississippian.

Source Rocks

The most obvious source for petroleum in the area of study would be the Bakken Formation. Dow (1974) illustrated that the Bakken Formation probably provided the oil that migrated updip to the northeast and resulted in the pinchout accumulations in north-central North Dakota and southwestern Manitoba. This was done by a comparison of chemical analysis of the Bakken shale with chemical analysis of oil produced from these areas. Dow was of the opinion that this oil would not have accumulated in eastern North Dakota due to the reduced thickness and the shallow depth

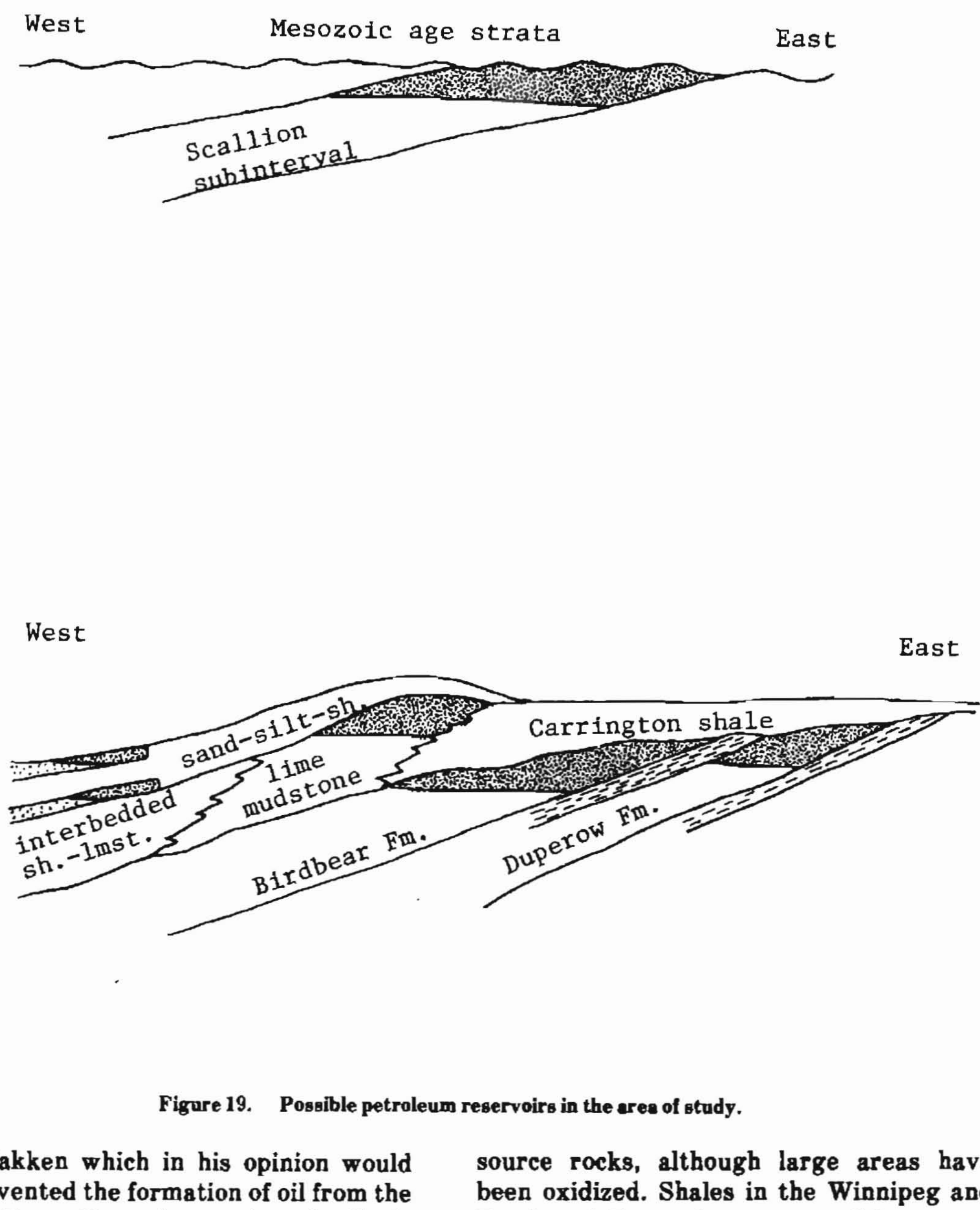


Figure 19. Possible petroleum reservoirs in the area of study.

of the Bakken which in his opinion would have prevented the formation of oil from the Bakken Formation. A greater depth is required for the oil-forming reactions to proceed.

However, other shale in the Paleozoic section could have contributed to oil formation in this area. The Carrington and Routledge shales have some potential as source rocks, although large areas have been oxidized. Shales in the Winnipeg and Deadwood Formations are possible sources stratigraphically lower than the potential reservoir rocks and are also at a greater depth, thus more favorable for the oil-forming processes to proceed.

Figure 19 illustrates the possible petroleum reservoirs that could be present in the interval of this study.

Uranium

The Carrington and Routledge shale facies are both highly radioactive (pl.6). The gamma ray curves often go off scale for the shale sections. It was thought that the source of this radioactivity might be uranium within the shale. If this had been the case, there existed the possibility of concentration of uranium in other portions of the shale body. However, analyses of the shale (see appendix C) gave no indication that uranium was the cause of the radioactivity. Thorium and potassium are the probable sources of the radioactivity.

However, the possibility does exist that concentrations of uranium are present within portions of the shale itself or possibly immediately beneath it. Conditions necessary for these accumulations are:

1. Source area: The Precambrian shield to the east would be a likely source for uranium-bearing sediments. Uranium is presently being produced from portions of the shield in the Blind River area of Ontario, Canada (Lamey, 1966).
2. Method of transport: The shield is topographically higher than the Carrington shale facies. Normal erosional and fluvial processes which resulted in the transportation of the clay, silt, and sand off the shield would also transport any uranium-bearing minerals that were exposed at the surface.
3. Concentration of the uranium: This is probably the most difficult problem to resolve and will be discussed in greater detail.

Possible Modes of Uranium Concentration

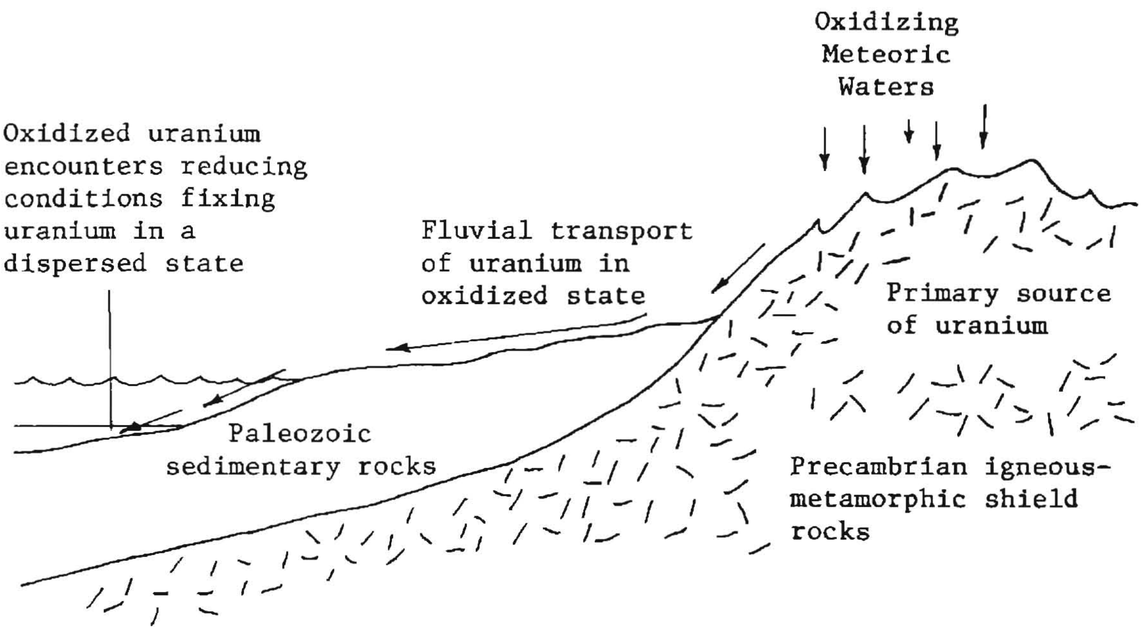
Assuming that more than trace amounts of uranium existed in the Carrington shale facies at one time, concentration of this uranium could have resulted in significant deposits. In order to concentrate the uranium it must become mobile. The best way for this to happen would be for the uranium to be in solution and carried by groundwater. The condition which would allow this to happen is the oxidation of the sediments. According to Park and MacDiarmid (1974) uranium is relatively soluble under oxidizing conditions. The presence of oxidizing conditions during and/or after the deposition of the Carrington shale facies has already been established in this report.

Following the oxidation of the uranium and subsequent transport by groundwater, the uranium may have been concentrated in underlying units. This could occur if the solutions encountered reducing conditions (Fischer, 1974). This is the accepted mode of formation of many sedimentary uranium deposits in the western United States (Finch, 1967). Gruner (1956) proposed that uranium leached directly from Precambrian plutonic rocks could be transported into drainage basins and deposited under locally reducing conditions. This is a possibility in the case of the Carrington shale due to its proximity to the Precambrian shield. Reducing conditions probably existed during the deposition of the shale followed by oxidizing conditions that may have further concentrated the uranium as previously stated.

The host rock should preferably be a sandstone. The possibility of sandstone deposits directly below the Carrington shale has already been alluded to. If stream channels did cross over the Early Mississippian-Devonian erosional surface, stream channel deposits are likely to have formed. Evidence for the presence of sand does exist in the samples studied. In a few instances minor to moderate amounts of sand were noted in the samples directly below the Carrington shale facies. Wells in which sand grains were noted are 23, 24, 89, 660, and 672.

Uranium could also be concentrated within the Carrington shale facies. Sand and coarser clastics were also noted in several wells in the Carrington shale facies. These are 287, 590, 644, 645, 654, 683, 689, and 1346. Figure 20 illustrates the possible method of accumulation of uranium in the study area. Figure 21 shows the relationship between the wells noted above and the Carrington shale facies and the pre-Mississippian structure contour surface.

Stage 1. Initial transport of uranium



Stage 2. Concentration of uranium

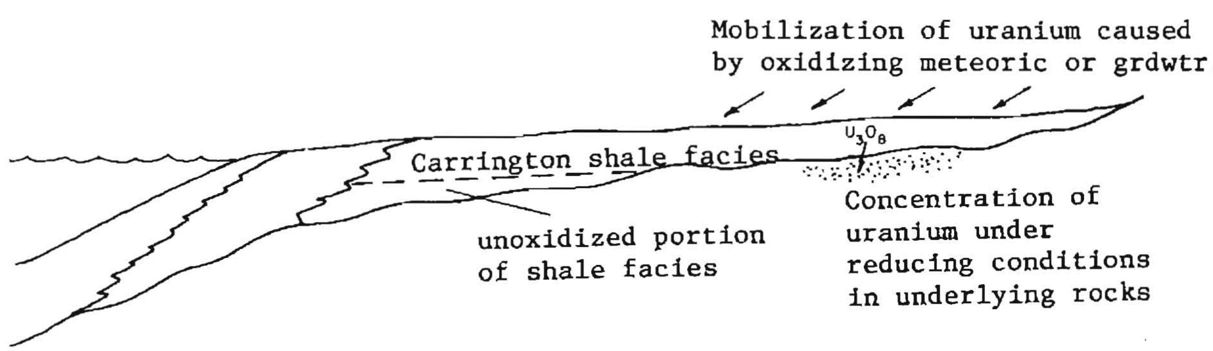


Figure 20. Possible method of transportation and accumulation of uranium in the study area.

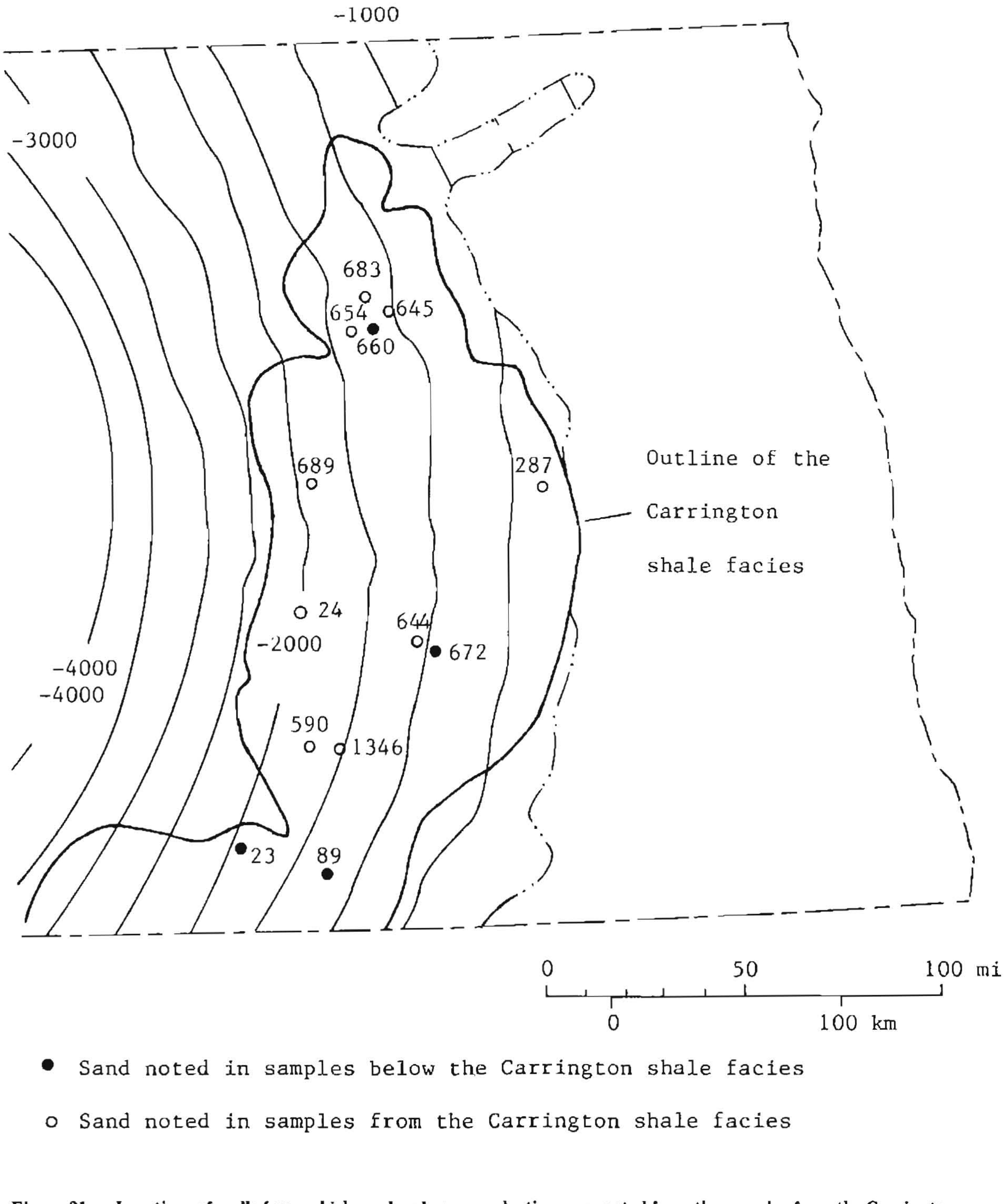


Figure 21. Locations of wells from which sand and coarser clastics were noted from the samples from the Carrington shale facies or below it.

CONCLUSIONS

As a result of this study the following conclusions can be made concerning the stratigraphy and depositional setting of the units studied:

1. The Scallion subinterval can be subdivided into six lithologic facies, each of which is described in the text.
2. The Carrington and Routledge shale facies, based on stratigraphic and mineralogic evidence, can be considered equivalent units.
3. The source of these shale units was the weathered Precambrian igneous and metamorphic surface to the east.
4. These shale units were deposited in protected lagoonal environments under reducing conditions.
5. The lagoonal environments were protected from the open sea by a barrier.
6. This barrier was composed of lime mudstone and can be considered a Waulsortian bioherm facies.
7. The bioherms formed on the Williston basin's shelf margin in Early Mississippian time during a period of rising sea level, much in the same manner as Waulsortian bioherms formed on the Alberta and Wyoming shelf margins during this same time period.
8. During and after deposition of the Carrington shale facies a clastic facies (sand-silt-shale facies) was deposited above the bioherm facies (lime mudstone facies) and its associated facies (interbedded shale and limestone facies).
9. These clastics may have been transported into the area of deposition by submarine currents which formed channels across the Carrington shale facies and between the Carrington and Routledge shale facies.
10. It is also possible, though not as probable, that following the deposition of the Carrington shale facies sea level dropped resulting in the deposition of the sand-silt-shale facies. Partial oxidation of the Carrington shale facies may have occurred at this time.
11. A return to normal carbonate deposition occurred following the deposition of the sand-silt-shale facies. This was possible due to a reduced influx of clastics into the area of deposition, resulting from either a reduction in erosion of the neighboring landmass or changing current patterns which removed the clastics from the shelf area. At this time the wacke-packstone and crinoid packstone-grainstone facies were deposited on the basin slope and shelf, respectively.

Some miscellaneous conclusions are:

1. The Carrington and Routledge shale facies are composed dominantly of the clay mineral illite. No other clay minerals were noted.
2. The cause of the slaking of the Carrington shale facies is related to water, upsetting the interparticle attractive forces of the clay particles.
3. Abrupt facies changes, basinward dipping beds, and unconformities all suggest potential petroleum traps.
4. The conditions necessary for the accumulation of uranium may have been present in the past.

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APPENDICES

659 Sun Oil Co. — Arthur Espe No. 1, NWSW S5, T165N, R72W, Rolette Co.

660 Shell Oil Co. — John K. Myre No. 1, SENE S16, T152N, R68W, Benson Co.

661 S. D. Johnson — C. W. Burnham No. 1, SESE S17, T145N, R66W, Foster Co.

663 Shell Oil Co. — Rudolph Gigstad No. 1, NENW S10, T151N, R70W, Benson Co.

665 Caroline Hunt Trust Estate — John Waltz, Jr. No. 1, NENE S15, T148N, R76W, Sheridan Co.

668 Calvert Expl. Co. — Margaret Meyers No. 1, SESW S25, T137N, R67W, Stutsman Co.

669 Calvert Expl. Co. — Christ. Rau No. 1, SESW S35, T139N, R68W, Stutsman Co.

670 Calvert Expl. Co. — D. C. Wood No. 1, SESW S24, T139N, R67W, Stutsman Co.

671 Calvert Expl. Co. — George Ganser No. 1, NWSW S12, T140N, R67W, Stutsman Co.

672 Calvert Expl. Co. — Vincent Wanzek No. 1, NWNW S12, T139N, R67W, Stutsman Co.

673 Calvert Expl. Co. — F. L. Robertson No. 1, NENE S26, T138N, R67W, Stutsman Co.

678 Shell Oil Co. — Lars A. Togstad No. 1, NWNE S22, T153N, R69W, Benson Co.

683 Shell Oil Co. — H. R. Hofstrand No. 1, NENE S22, T154N, R69W, Benson Co.

684 Caroline Hunt Trust Estate — J. R. Mates No. 1, NENE S1, T147N, R75W, Sheridan Co.

685 British American Oil Producing Co. — P. Wenstad No. 1, SWSW S32, T163N, R73W, Rolette Co.

689 Caroline Hunt Trust Estate — N. Thormodsgard No. 1, NENE S31, T147N, R71W, Wells Co.

692 Shell Oil Co. — Oscar Sinness No. 1, NESW S2, T156N, R67W, Benson Co.

693 Caroline Hunt Trust Estate — Walter E. Bauer No. 1, SWSW S19, T146N, R76W, Sheridan Co.

695 Shell Oil Co. — Joseph O. Belgen No. 1, SWSE S14, T155N, R67W, Benson Co.

701 Caroline Hunt Trust Estate — Board of Univ. & School Lands No. 1, NENE S36, T144N, R75W, Burleigh Co.

702 Shell Oil Co. — Ella M. Amble No. 1, SESW S10, T159N, R71W, Rolette Co.

706 Shell Oil Co. — Gifford Marchus No. 1, SESE S23, T157N, R70W, Pierce Co.

716 Shell Oil Co. — Joseph D. Bacher No. 1, NWNE S3, T158N, R70W, Pierce Co.

723 Caroline Hunt Trust Estate — R. P. Schlabach No. 1, NENE S36, T139N, R76W, Burleigh Co.

735 Caroline Hunt Trust Estate — C. A. Pfieffer No. 1, SWSW S16, T146N, R74W, Sheridan Co.

742 Socony-Vacuum Oil Co. — Kruse F 22-30-P, SENW S30, T134N, R75W, Emmons Co.

748 Caroline Hunt Trust Estate — E. B. Sauter No. 1, NWNE S23, T142N, R74W, Kidder Co.

754 British American Oil Co. — S. Grenier No. 1, SWSW S18, T161N, R70W, Rolette Co.

756 Caroline Hunt Trust Estate — R. A. Nicholson No. 1, SESE S32, T137N, R77W, Burleigh Co.

763 Caroline Hunt Trust Estate — Anton Novy No. 1, SESE S14, T144N, R77W, Burleigh Co.

765 Caroline Hunt Trust Estate — Soder Investment Co. No. 1, SWSW S31, T142N, R76W, Burleigh Co.

768 Calvert Expl. Co. — No. 1 State No. 1, NENE S8, T150N, R65W, Eddy Co.

772 Caroline Hunt Trust Estate — Paul Ryberg No. 1, NWNW S23, T140N, R79W, Burleigh Co.

780 Earl F. Wakefield — Christenson No. 1, NWSW S3, T157N, R73W, Pierce Co.

806 British American Oil Prod. Co. — Henry Dietrich No. 1, NESE S14, T163N, R73W, Rolette Co.

917 Lion Oil Co. — Peter P. Nelson et ux No. 1, NESE S22, T160N, R72W, Rolette Co.

927 Lion Oil Co. — State of North Dakota No. 1, NESW S36, T163N, R73W, Rolette Co.

955 Lion Oil Co. — Roy Larson No. 1, SWNW S7, T163N, R74W, Bottineau Co.

981 Lion Oil Co. — Peter Danielson No. 1, SENE S26, T163N, R72W, Rolette Co.

1102 Cardinal Drilling Co. et al. — J. Andrieux No. 1, SWNE S2, T161N, R74W, Bottineau Co.

1105 Cardinal Drilling Co. et al. — J. S. Smith No. 1, SESW S8, T146N, R65W, Foster Co.

1112 Cardinal Drilling Co. et al. — N. A. Graves & Federal Land Bank No. 1, NENE S23, T146N, R66W, Foster Co.

1126 Cardinal Drilling Co. et al. — J. M. Anderson No. 1, NWNW S10, T146N, R67W, Foster Co.

1208 Calvert Drilling, Inc. — Woodrow Topp No. 1, SWNE S2, T147N, R64W, Foster Co.

1211 Calvert Drilling, Inc. — Francis Zwinger No. 1, NENE S8, T146N, R68W, Wells Co.

1227 Mike Wetch — H. F. Spickler No. 1-A, NENE S25, T147N, R64W, Foster Co.

1274 Wetch, Zachmeier & Disney Drilling Co. — C. E. Blasky No. 1, SESE S9, T148N, R62W, Eddy Co.

1314 Wetch, Zachmeier & Disney Drilling Co. — C. E. Blasky No. 1, SESE S9, T148N, R62W, Eddy Co.

1346 Calvert Drilling, Inc. — C. A. Zimmerman No. 1, NWSW S8, T136N, R71W, Logan Co.

1347 Calvert Drilling, Inc. — Ray Craig No. 1, NWNW S25, T136N, R71W, Logan Co.

1394 Calvert Drilling, Inc. — Marvin Kamm No. 1, NWNW S22, T129N, R66W, Dickey Co.

1409 Leach Oil Corp. — Calvert Drilling, Inc. — Patterson Land Co. No. 1, NWSE S11, T140N, R77W, Burleigh Co.

1517 Cities Service Oil Co. — Chippewa No. 1, NWNW S16, T162N, R71W, Rolette Co.

1630 General-Crude Oil Co. — Aida Higgins No. 1, NWSE S19, T161N, R72W, Rolette Co.

1666 General Crude Oil Co. — Kenneth Tooke No. 1, SWNE S2, T161N, R73W, Rolette Co.

1673 General Crude Oil Co. — Martin Rude No. 1, NESW S23, T163N, R74W, Bottineau Co.

1682 Amerada Petr. Corp. — A. Kvalheim "A" No. 1, SENE S9, T161N, R79W, Bottineau Co.

2521 Amerada Petr. Corp. — Abe Loewen T-1 No. 1, NESE S35, T161N, R62W, Cavalier Co.

2523 Amerada Petr. Corp. — Myklebust No. 1, SESE S5, T157N, R63W, Ramsey Co.

2608 Amerada Petr. Corp. — Ruby Parker No. 1, SESE S21, T159N, R62W, Cavalier Co.

2612 Amerada Petr. Corp. — F. Skaar No. 1, NENE S11, T158N, R62W, Ramsey Co.

3859 Amerada Petr. Corp. — James Meyer No. 1, SENE S34, T135N, R83W, Morton Co.

3920 A. J. Hodges Industries, Inc. — Alex Martin No. 1, SESE S23, T152N, R74W, Pierce Co.

3978 Austral Oil Co., Inc. — John J. Leingang No. 1, SENW S34, T137N, R83W, Morton Co.

3980 LaHabana Corp. & Nat'l. Assoc. Petr. Co. — Keith R. Dunlop No. 1, SWSE S7, T162N, R68W, Towner Co.

3999 Vaughn Petr., Inc. — H. Smith No. 1, NWNW S18, T133N, R64W, LaMoure Co.

4309 I. J. Wilhite, Simcox Oil Co. — Lauritz & Gordon Amoth No. 1, SESE S2, T161N, R62W, Cavalier Co.

4626 J. M. Johnston et al. — Leo Nichols No. 1, SENW S24, T138N, R62W, Stutsman Co.

4664 Jack M. Johnston et al. — Sydney L. Haas No. 1, NWSW S32, T151N, R61W, Nelson Co.

4678 Jack M. Johnston Drilling Corp. et al. — Clarence Johnson No. 1, NWSE S3, T141N, R61W, Barnes Co.

4689 Jack M. Johnston Drilling Corp. et al. — Mathilda Weiland No. 1, SWNE S29, T143N, R58W, Barnes Co.

4719 J. M. Johnston Drilling Corp. et al. — William M. Rahlf No. 1, NWSE S5, T164N, R61W, Griggs Co.

4750 Jack M. Johnston Drilling Corp. — Arvid Flaaggen No. 1, SWNE S23, T149N, R61W, Nelson Co.

4755 Jack M. Johnston Drilling Corp. — Morris Peters No. 1, SESE S17, T152N, R62W, Ramsey Co.

4771 Jack M. Johnston Drilling Corp. — William Overbo No. 1, NWNW S2, T155N, R64W, Ramsey Co.

4976 Eagle Oil Co. — Elmer Cole, State of North Dakota No. 1, SWNE S22, T163N, R65W, Towner Co.

5117 Don Bills — Juvelus Bjur No. 1, SWSW S9, T133N, R66W, LaMoure Co.

5279 McMoran Exploration Co. — State No. 1, NESW S34, T157N, R76W, McHenry Co.

5281 McMoran Exploration Co. — State No. 2, SWSW S16, T158N, R75W, McHenry Co.

5379 Campbell Partners, Ltd. — Picha No. 1, NWNE S5, T138N, R83W, Morton Co.

5523 Wise Oil Co. No. 2 et al. — Baltzer A. Weigel No. 1, NWNW S29, T135N, R73W, Logan Co.

APPENDIX B

Formation Tops

EXPLANATION

Numbers are those of the North Dakota Geological Survey. Tops are given as feet below Kelly Bushing (K.B., approximately 10 feet above ground level). Letters in parentheses refer to specific shale facies: (C) Carrington, (R) Routledge, or underlying Formations, (Bk) Bakken, (Tf) Three Forks, (Bd) Birdbear, and (Dp) Duperow. Dashes indicate that the particular unit was absent. In the case of the absence of the Scallion subinterval the K.B. and underlying formation was not recorded.

WELL NO.	K.B.	SCALLION SUBINTERVAL	SHALE FACIES	UNDERLYING FORMATION
15	2033	6220	-	(Bk)6350
16	2026	3723	-	(Bd)3935
19	1909	4810	-	(Bd)4992
22	1994	6330	-	(Bk)6450
23	2012	3858	(C)4010	(Bd)4060
24	1968	3779	(C)3933	(Bd)3998
26	2005	5420	-	(Bk)5580
27	1562	1476	-	(Dp)1600
31	-	-	-	-
36	1646	1050	-	(Dp)1090
37	-	-	-	-
40	1863	2710	(C)2856	(Dp)2906
43	1820	4080	-	(Bd)4275
49	2100	6330	-	(Bk)6450
61	1570	4653	-	(Bk)4320
83	1627	3020	-	(Bk)3260
89	2176	3421	(C)3590	(Bd)3612
95	1924	6000	-	(Tf)6350
100	-	-	-	-
120	1493	1774	(C)1890	(Dp)1932
134	1552	2090	(C)2233	(Dp)2270
145	1869	4244	-	(Bd)4437
151	1922	5645	-	(Dp)5812
155	1912	4210	-	(Dp)4400
171	1597	1700	-	(Bd)1742
174	1981	4750	-	(Dp)4952
194	-	-	-	-
196	1487	2120	-	(Dp)2152
207	1933	4004	(C)4195	(Bd)4206
227	1465	2026	-	(Bd)2151

WELL NO.	K.B.	SCALLION SUBINTERVAL	SHALE FACIES	UNDERLYING FORMATION
230	1889	3462	(C)3620	(Dp)3683
232	1997	5635	-	(Tf)5580
287	1518	1723	(C)1877	(Dp)1933
295	1496	1713	(C)1750	(Dp)1790
316	1691	2587	-	(Tf)2756
328	1895	3462	-	(Bk)3680
334	1547	1940	(C)2067	(Bd)2118
348	1603	3380	-	(Bk)1603
358	1502	4020	-	(Bk)4186
359	2256	3506	-	(Bk)3720
370	1573	2114	(C)2246	(Dp)2270
383	-	-	-	-
390	-	-	-	-
401	-	-	-	-
403	1547	2233	(C)2363	(Dp)2424
406	1576	2125	(C)2254	(Dp)2281
407	-	-	-	-
411	-	-	-	-
434	1729	2124	-	(Tf)2277
435	1589	2385		(Bd)
437	1478	2398	(C)2555	(Bd)2564
538	1566	3300	-	(Bd)3510
549	-	-	-	-
553	1868	2432	-	(Bk)2572
568	1677	2936	(R)3150	(Bk)3178
569	1919	2733	(R)2867	(Tf)2905
579	1902	2567	(R)2726	(Tf)2752
590	1893	3700	(C)3857	(Bd)3904
602	1946	3216	(C)3380	(Dp)3450
609	1612	3186	(C)3298	(Bd)3390
615	1809	2463	-	(Bk)2637
616	1584	2446	(C)2605	(Bd)2627
619	2024	2495	-	(?)2590
620	2042	2440	-	(?)2540
621	2056	2630	-	(?)2733
622	2143	2670	-	-
631	1730	4307	(C)4416	(Dp)4506
632	1637	3023	(C)3193	(Bd)3204
635	1785	2930	(C)3070	(Bd)3150
636	1644	2660	(C)2815	(Bd)2831
642	1599	3098	(C)3200	(Bd)3278
644	1943	2830	(C)3059	(Dp)3100
645	1492	2273	(C)2414	(Bd)2437
651	1510	2735	(C)2895	(Bd)2900
652	1659	2675	(C)2788	(Dp)2852
654	1589	2747	(C)2827	(Bd)2922
659	2288	3330	(R)2462	(Bk)3540
660	1609	2580	(C)2682	(Bd)2756
661	1596	2382	(C)2511	(Dp)2578
663	1560	2959	-	(Bd)3120
665	1793	4554	-	(Tf)4790

WELL NO.	K.B.	SCALLION SUBINTERVAL	SHALE FACIES	UNDERLYING FORMATION
668	1907	2563	(C)2683	(Dp)2709
669	1880	2758	(C)2913	(Dp)2948
670	1874	2625	(C)2743	(Dp)2763
671	1900	2654	(C)2790	(Dp)2836
672	1867	2655	(C)2775	(Dp)2798
673	2919	2580	(C)2725	(Dp)2747
673	1919	2655	(C)2725	(Dp)2747
678	1673	2834	(C)2966	(Dp)3010
683	1767	2796	(C)2933	(Dp)2989
684	1849	4322	-	(Tf)4517
685	2042	3360	-	(Bk)3582
689	1702	3427	(C)3537	(Bd)3623
692	1490	2118	(C)2238	(Dp)2247
693	1984	4954	-	(Tf)5177
695	1469	2173	(C)2312	(Dp)2322
701	2023	4382	-	(Bd)4583
702	1599	273	-	(Tf)2960
706	1652	2760	-	(Tf)2957
716	1608	2577	-	(Tf)2787
723	1880	4210	-	(Bd)4400
735	1994	4372	-	(Tf)4567
742	2044	3918	-	(Bd)4156
748	1848	4100	-	(Bd)4288
754	1734	2720	-	(Bk)2917
756	1891	4472	-	(Tf)4674
763	1947	4860	-	(Bd)5086
765	2027	4818	-	(Bd)5040
768	1561	2107	(C)2289	(Bd)2299
772	2007	5227	-	(Tf)5432
780	1486	3183	-	(Tf)3373
806	2180	3334	-	(Bk)3540
917	1602	2817	-	(Tf)3060
927	2198	3384	-	(Bk)3602
955	2236	3680	-	(Bk)3900
981	2218	3224	(R)3403	(Bk)3434
1102	1653	3187	-	(Bk)3410
1105	1533	2185	(C)2293	(Dp)2353
1112	1535	2260	(C)2388	(Dp)2453
1126	1589	2520	(C)2646	(Bd)2716
1208	1503	1900	(C)1985	(Dp)2048
1211	1608	2727	(C)2840	(Bd)2916
1227	1463	1820	(C)1943	(Dp)2003
1274	1584	1734	-	(Dp)1854
1314	-	-	-	-
1346	2022	3311	(C)3480	(Dp)3525
1347	1917	3127	(C)3285	(Dp)3315
1409	2019	4715	-	(Dp)4935
1517	2158	3138	-	(Bk)3348
1630	1633	2962	-	(Bk)3199
1666	1675	3011	-	(Bk)3256
1673	2160	3523	-	(Bk)3748

WELL NO.	K.B.	SCALLION SUBINTERVAL	SHALE FACIES	UNDERLYING FORMATION
2521	-	-	-	-
2523	-	-	-	-
2608	-	-	-	-
2612	-	-	-	-
3859	2125	5810	-	(Tf)5980
3920	1605	3738	-	(Bd)3935
3978	2281	6295	-	(Tf)6455
3980	1761	2320	-	(Bk)2445
3999	-	-	-	-
4309	-	-	-	-
4626	-	-	-	-
4664	-	-	-	-
4678	-	-	-	-
4689	-	-	-	-
4719	-	-	-	-
4750	-	-	-	-
4755	-	-	-	-
4771	-	-	-	-
4976	-	-	-	-
5117	1970	2400	-	-
5279	1476	4047	-	(Bk)4200
5281	1469	3708	-	(Bk)3860
5379	1979	6285	-	(Tf)6450
5523	2117	3700	(C)3840	(Bd)3885

APPENDIX C

Results of Chemical Analyses of Shale Samples

EXPLANATION

Samples from wells no. 207 and 403 were sent to Merle Crew, Casper Field Office of the Energy Research and Development Administration (presently the Department of Energy), for assaying. Results obtained are shown below. Emission spectrograph and gamma-ray spectroscopy were used. Lower detection limits are given in parentheses at the base of the elements column. N- indicates the element was not detected. L- indicates the element was detected but its amount was below the limit of determination. Values are in parts per million unless indicated to be in percentages. Elements Au, Zn, Mo, W, Cd, As, Sb, Bi, Sn, were not detected in the samples.

Sample No.	Well No.	Depth	Color	K%	U	Th	Ag
1	207	4197	Dk. gray	6.27	4.8	10.1	L
2	207	4200	Dk. gray	6.50	3.9	12.0	N
3	403	2391	Red-brn.	5.53	1.8	11.3	L
4	403	2395	Red-brn.	5.67	1.5	13.0	L
5	403	2401	Red-brn.	5.54	1.4	13.0	N
6	403	2405	Red-brn.	5.59	1.2	12.3	N
7	403	2412	Red-brn.	5.54	1.0	13.0	L
8	403	2418	Red-brn.	6.04	1.6	13.0	L
							(.5)

Sample No.	Cu	Pb	Fe%	Ni	Co	Cr	Mn	V	Zr	B	Ba	Be
1	10	70	2.0	70	L	150	200	300	300	200	700	15
2	7	50	2.0	70	L	150	200	200	200	200	500	15
3	15	150	2.0	70	10	150	200	200	100	200	500	10
4	15	70	2.0	70	10	150	200	200	200	200	500	15
5	15	50	3.0	70	20	150	200	200	200	200	500	20
6	15	70	3.0	70	20	150	200	150	300	200	500	15
7	20	70	3.0	70	20	150	200	200	200	200	700	20
8	7	50	5.0	70	20	150	200	300	200	200	700	15
	(5)	(10)	(.05%)	(5)	(10)	(20)	(10)	(10)	(10)	(10)	(10)	(2)

Sample No.	La	Nb	Sc	Sr	Y	Ca%	Mg%	Ti%	Na%
1	50	20	15	100	10	5.0	3.0	0.5	1.0
2	50	L	10	100	10	5.0	3.0	0.3	1.0
3	50	L	N	100	10	1.5	1.0	0.3	0.7
4	L	L	N	100	10	1.5	2.0	0.3	0.7
5	50	L	10	100	20	1.5	2.0	0.5	0.7
6	50	L	10	200	20	5.0	2.0	0.5	0.7
7	50	L	15	200	10	1.5	2.0	0.5	0.7
8	50	20	15	200	10	1.5	2.0	0.5	0.7
	(20)	(10)	(5)	(100)	(10)	(.05%)	(.02%)	(.001%)	(0.2%)

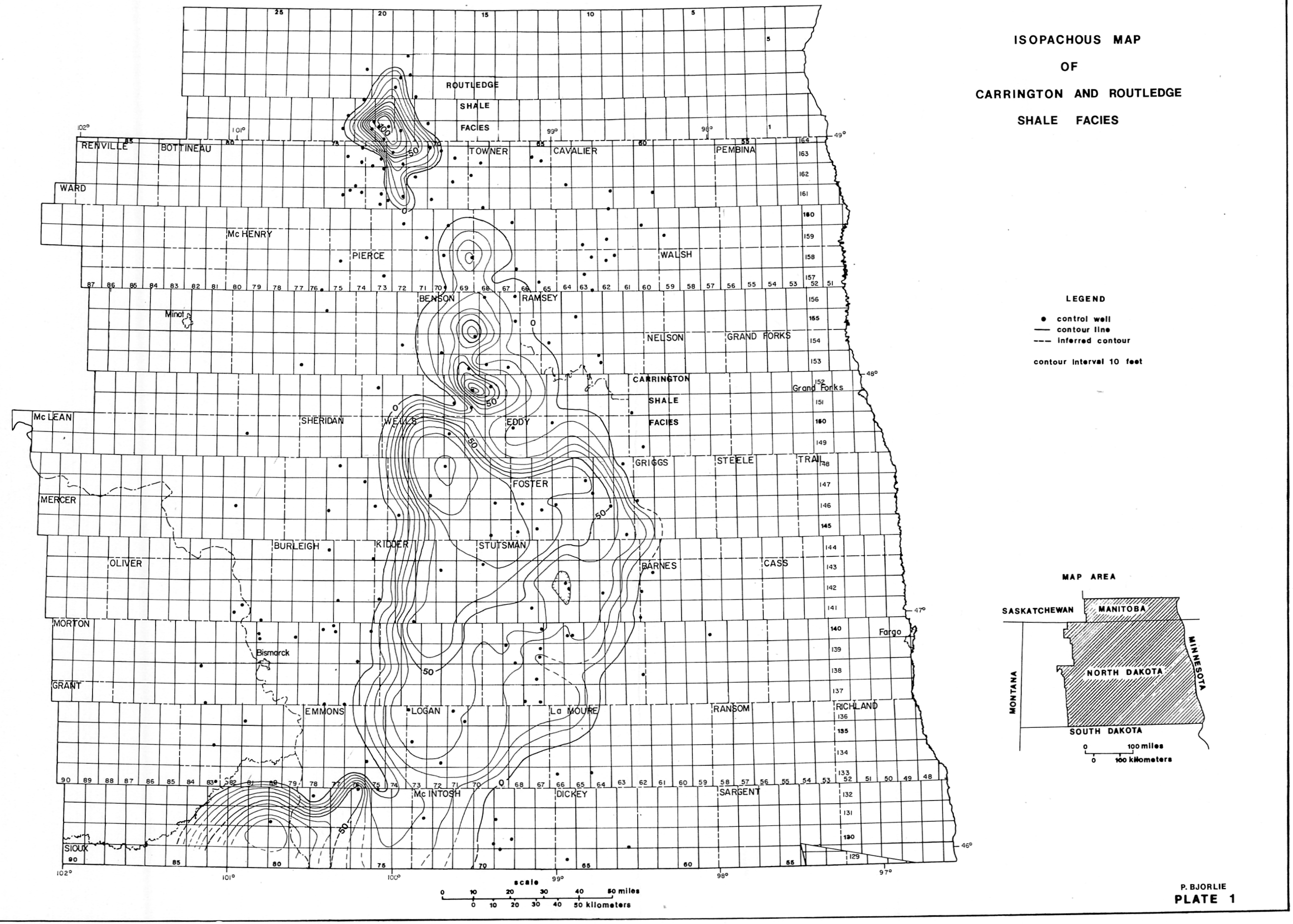

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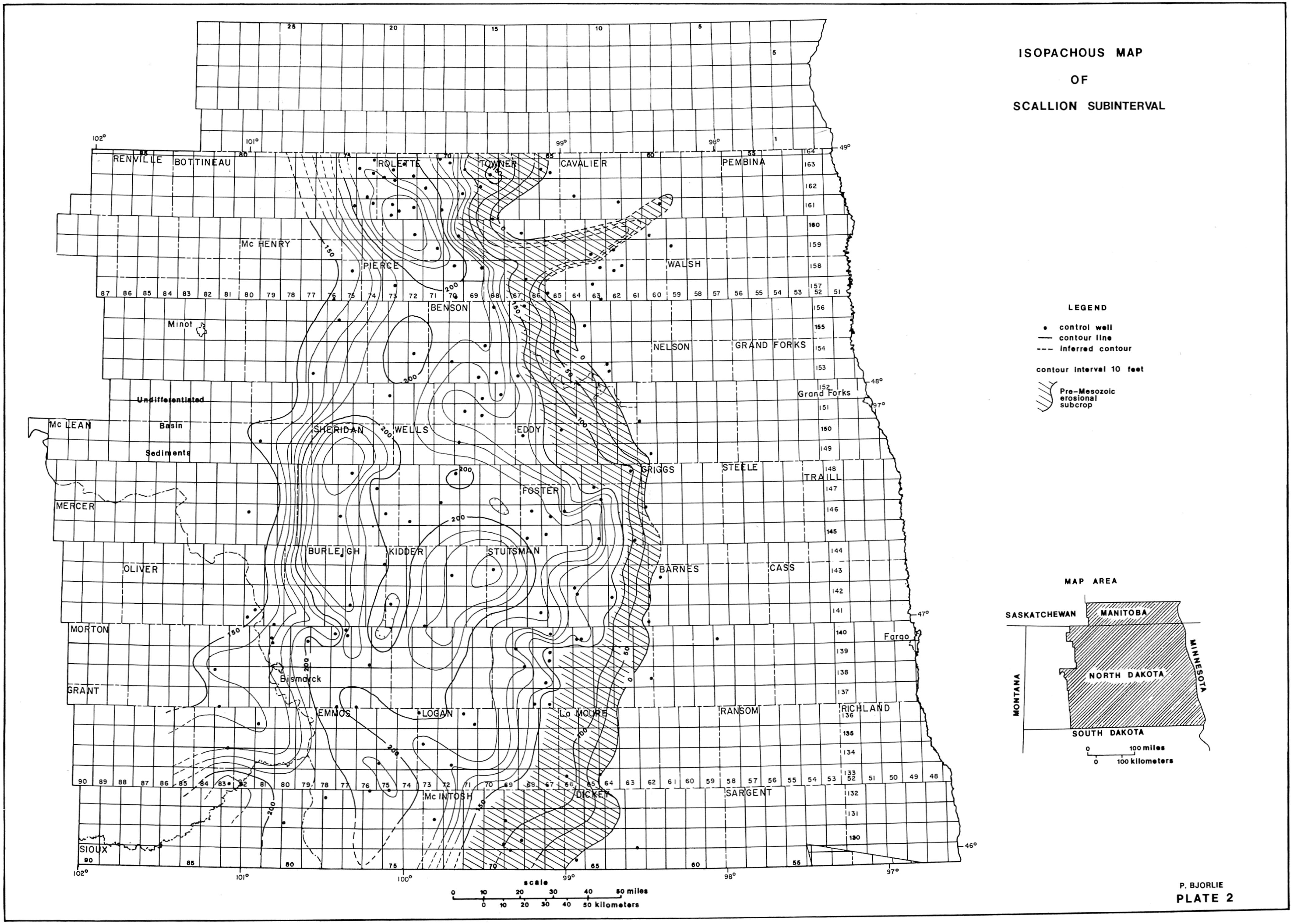
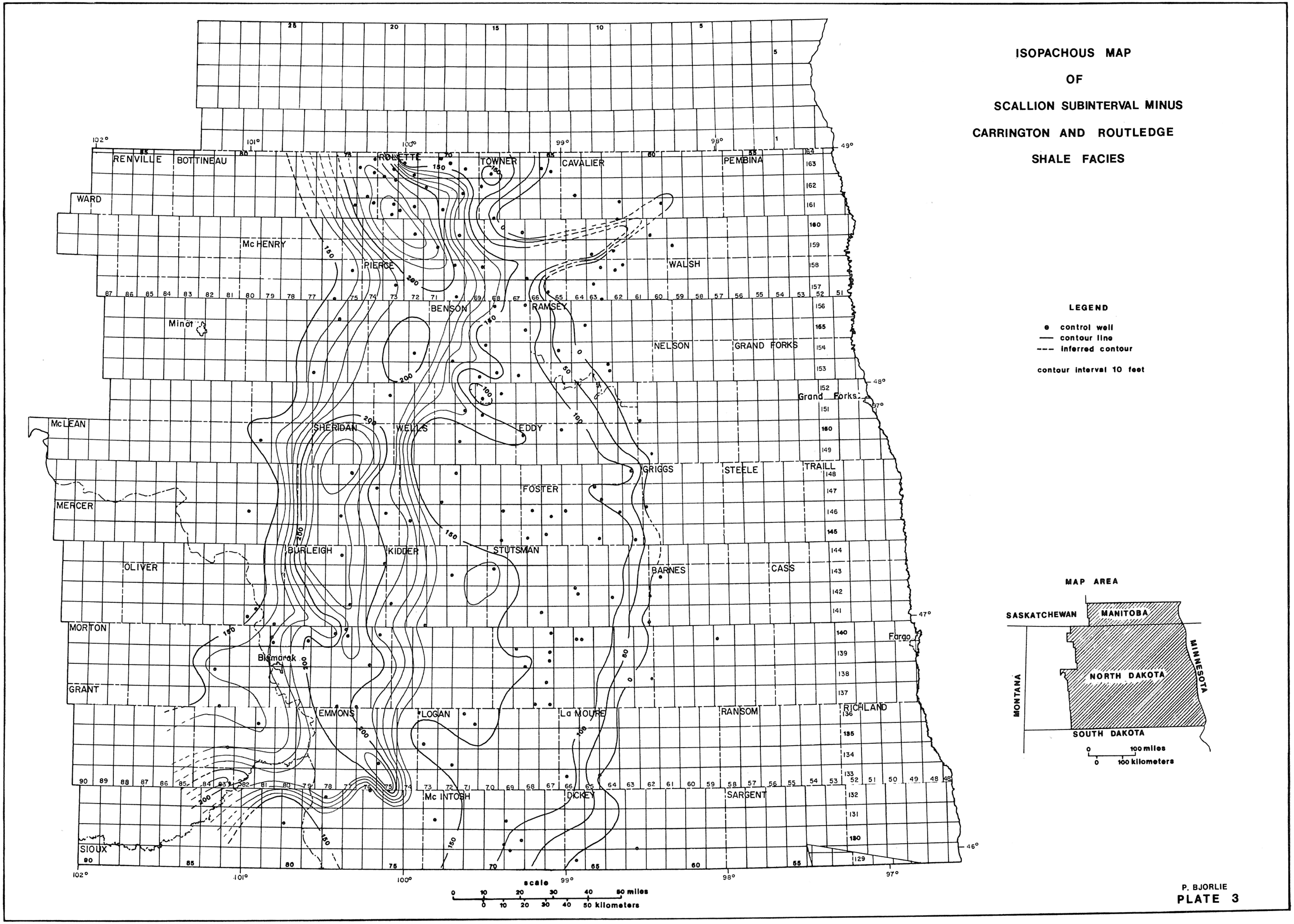
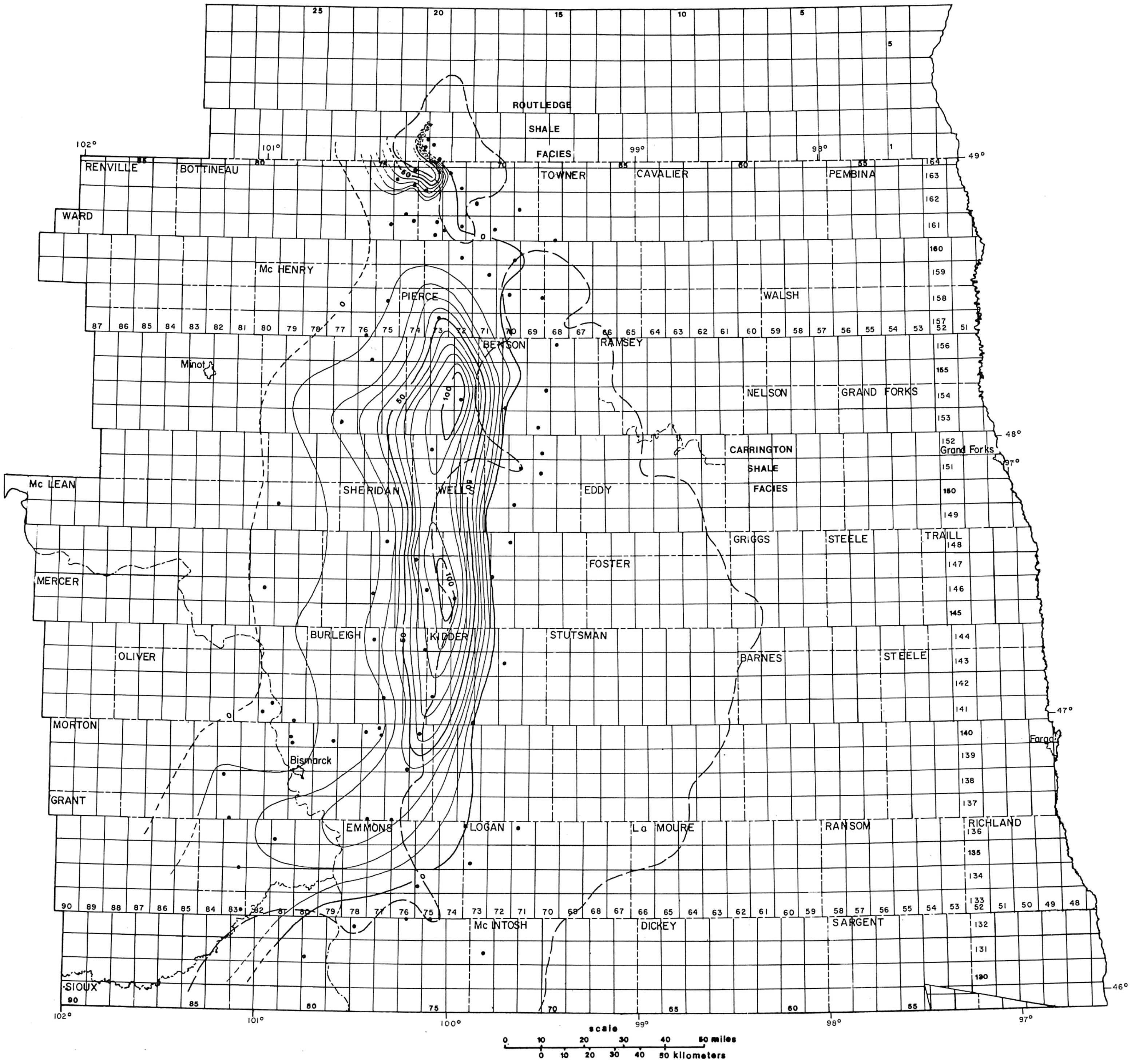
PLATE 1



ISOPACHOUS MAP
OF
SCALLION SUBINTERVAL
LEGEND
control well
contour line
inferred contour
contour interval 10 feet
Pre-Mesozoic erosional subcrop
RENVILLE
BOTTINEAU
ROLETTE
TOWNER
CAVALIER
PEMBINA
Mc HENRY
PIERCE
WALSH
BENSON
Minot
NELSON
GRAND FORKS
Grand Forks
Undifferentiated
Basin
Sediments
Mc LEAN
SHERIDAN
WELLS
EDDY
GRIGGS
STEELE
TRAILL
MERCER
FOSTER
BURLEIGH
KIDDER
STUTSMAN
OLIVER
BARNES
CASS
MORTON
Fargo
Bismarck
GRANT
EMMONS
LOGAN
La MOURE
RANSOM
RICHLAND
McINTOSH
DICKEY
SARGENT
SIOUX
MAP AREA
SASKATCHEWAN
MANITOBA
MINNESOTA
MONTANA
NORTH DAKOTA
SOUTH DAKOTA
100 miles
100 kilometers
scale
50 miles
50 kilometers
P. BJORLIE
PLATE 2


ISOPACHOUS MAP
OF
SCALLION SUBINTERVAL MINUS
CARRINGTON AND ROUTLEDGE
SHALE FACIES
LEGEND
control well
contour line
inferred contour
contour interval 10 feet
MAP AREA
SASKATCHEWAN
MANITOBA
MINNESOTA
NORTH DAKOTA
MONTANA
SOUTH DAKOTA
100 miles
100 kilometers
RENVILLE
BOTTINEAU
ROLETTE
TOWNER
CAVALIER
PEMBINA
WARD
McHENRY
PIERCE
WALSH
BENSON
RAMSEY
Minot
NELSON
GRAND FORKS
Grand Forks
McLEAN
SHERIDAN
WELLS
EDDY
GRIGGS
STEELE
TRAILL
MERCER
FOSTER
BURLEIGH
KIDDER
STUTSMAN
OLIVER
BARNES
CASS
MORTON
Fargo
Bismarck
GRANT
EMMONS
LOGAN
La MOURE
RANSOM
RICHLAND
Mc INTOSH
DICKEY
SARGENT
SIOUX
102°
101°
100°
99°
98°
97°
49°
48°
47°
46°
scale
50 miles
50 kilometers
P. BJORLIE
PLATE 3

ISOPACHOUS MAP OF SCALLION SUBINTERVAL'S BASAL CARBONATE



LEGEND

- • control well
- — contour line
- --- inferred contour

contour interval 10 feet

MAP AREA

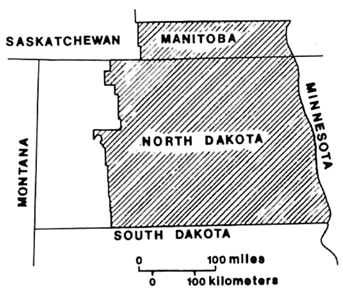


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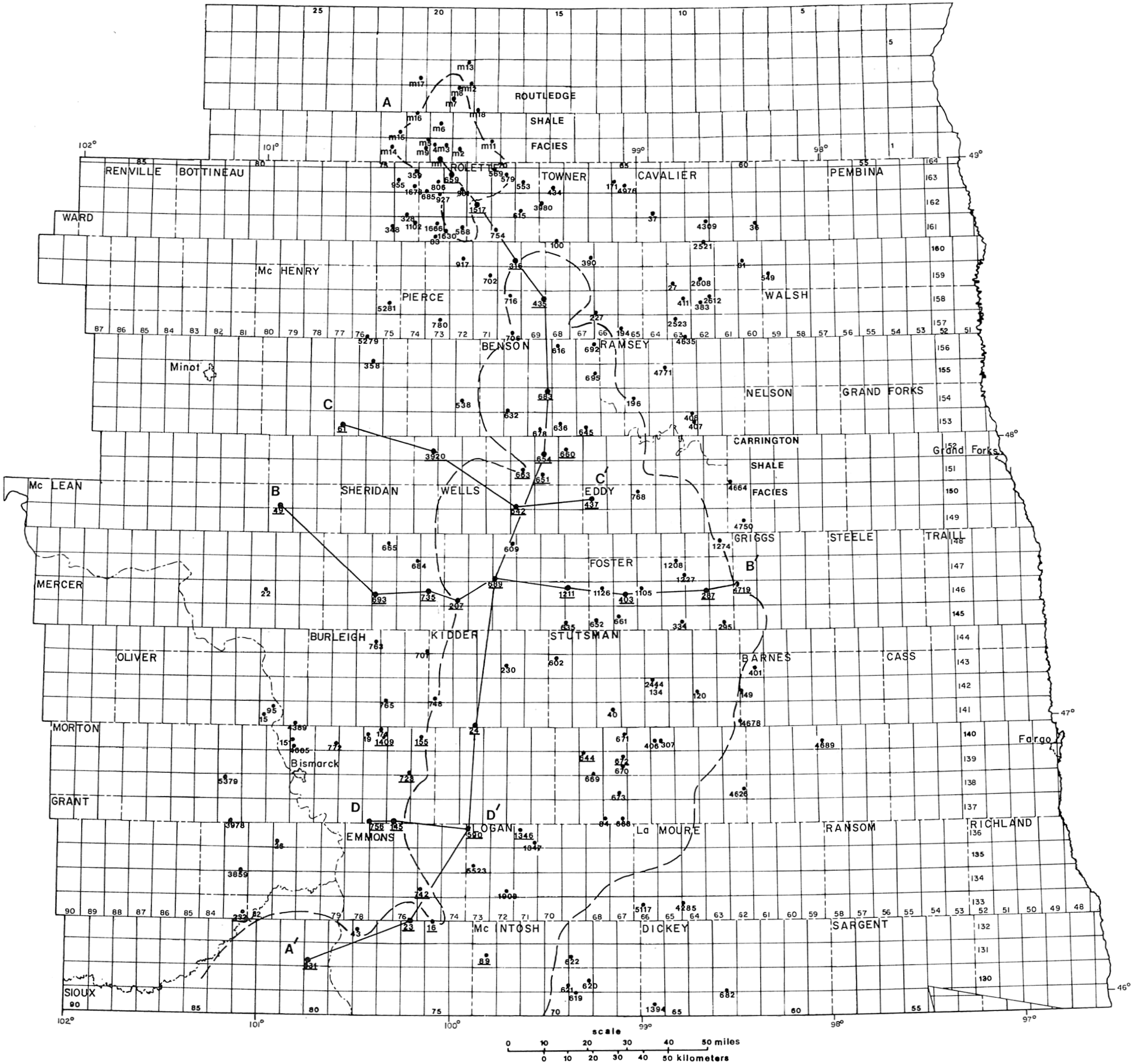
PLATE 4

INDEX MAP OF CONTROL WELLS



LEGEND

• control well
wells used for lithology study are underlined

MAP AREA

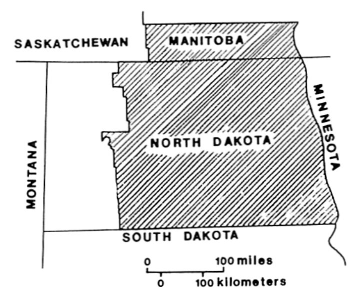


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PLATE 5


STRATIGRAPHIC CROSS SECTIONS
A
A′
SCALLION SUBINTERVAL
ROUTLEDGE SHALE FACIES
BAKKEN Fm.
THREE FORKS Fm.
MESOZOIC AGE
"VALLEY FILL"
VIRDEN SUBINTERVAL
CARRINGTON SHALE FACIES
DEVONIAN AGE ROCKS
B
B′
Wacke packstone facies
Sand-silt-shale facies
Interbedded shale and limestone facies
Lime mudstone facies
Crinoid packstone grainstone facies
MESOZOIC AGE ROCKS
BIRDBEAR Fm.
DUPEROW Fm.
SILURIAN-ORDOVICIAN AGE ROCKS
C
C′
D
D′
THREE FORKS FORMATION
SCALLION SUBINTERVAL
NORTH DAKOTA
ROUTLEDGE SHALE FACIES
CARRINGTON SHALE FACIES
0 50 100 miles
STRATIGRAPHIC COLUMN
MISSISSIPPIAN
Madison Formation
BOTTINEAU INTERVAL
Flossie Lake subinterval
Whitewater Lake subinterval
Virden subinterval
Scallion subinterval
Carrington and Routledge shale facies
DEVONIAN
BAKKEN FM.
THREE FORKS FM.
BIRDBEAR FM.
DUPEROW FM.
Spontaneous Potential
Gamma Ray
Resistivity
LEGEND
Shale
Siltstone
Sandstone
Sandstone with pebbles
Crinoid lime wackestone & micrite
Crinoid lime wacke-packstone
Crinoid lime packstone & grainstone
Dolomite
Brachiopods
Bryozoans
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