THE MIDDLE DEVONIAN
WINNIPEGOSIS FORMATION OF
WEST-CENTRAL SASKATCHEWAN

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree of
Master of Arts
in Geology
Department of Geological Sciences
University of Saskatchewan

by

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May 1971

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ABSTRACT

The Winnipegosis Formation of west-central Saskatchewan consists of three members which are, in ascending order, the Lower Winnipegosis Member (Lower Member), the Upper Winnipegosis Member (Upper Member), and the Ratner Member.

The Lower Member is regionally developed, 20 to 50 feet in thickness, and consists of oncolitic packstone, with less common interlaminated argillaceous-carbonaceous mudstones, dolomite laminites, and intraformational conglomerates at its top. These sediments were deposited in a shallow-water, marine environment, with energy levels ranging from high to low. Low energy conditions prevailed late in lower Winnipegosis time, although scattered shoals had developed and were eroded.

Frame-building organisms, such as corals and stromatoporoids comprise less than 2 percent by volume of core from the Upper Member. They are not in growth position, are heavily abraded, and are less common than sediment-baffling and -binding organisms, such as crinoids, algae, and dendroid stromatoporoids, especially *Amphipora* sp.

The Upper Member consists of extensive but discrete carbonate banks, up to 345 feet thick, which are bounded by low-angle average marginal slopes. Both lateral and vertical variations in lithology and faunal content occur within the banks, however, a lack of time-control makes definition of facies relationships unreliable. The
dominant rock types are laminated, unfossiliferous mudstones and pelleted, biofragmental grainstones, with a fringing cap unit formed during subaerial exposure of some portions of the banks. Laminated mudstones overlie pelleted grainstones in the centers of banks, and also grade vertically into the Shell Lake Member of the lower Prairie Evaporite Formation, indicating that there was increasing restriction in the centers of banks as they developed. The gradational relationship at the top of Upper Winnipegosis banks is evidence to suggest that not all portions of the banks were subaerially exposed, as has been postulated by other workers.

The off-bank Ratner Member consists of up to 77 feet of interlaminated carbonate mudstone and enterolithic anhydrite. These sediments probably were deposited in a quiet-water marine environment after most of the Winnipegosis banks had formed.
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INTRODUCTION

General Remarks

Location. - This report is the result of a study of the Middle Devonian Winnipegosis and lower Prairie Evaporite Formations of west-central Saskatchewan. The area of study extends from township 30 to township 64 inclusive, and includes all ranges west of the Third Meridian to the Alberta border, an area of approximately 900 townships (Fig. 1).

The area was chosen for study because carbonate banks are well-developed in the Winnipegosis Formation, and a major objective of the study was to define the geometry and composition of these banks with a view to inferring their origin. At least 50 boreholes drilled in this area since the end of 1965 penetrated the Winnipegosis Formation. Thus, new borehole data and several hundred feet of core were available for examination. A further attractive feature of the area is that, within it, the formations contain limestone as well as dolomite (Jones, 1965). It was thought that the original textures and fossil components could be studied more effectively in limestone, and thus, a more valid interpretation of the petrology and petrography of the Winnipegosis Formation might be attained.

Methods of study. - There are no Winnipegosis outcrops in the area of study, hence the author made use of available borehole information and core. Approximately 2,700 feet of core from 50 boreholes was examined
Figure 1: Location Map
and sampled at the Department of Mineral Resources Core Laboratory in Regina. A binocular microscope was used to examine polished surfaces, and approximately 150 thin sections were prepared. These thin sections were studied with the aid of a polarizing microscope.

Some minor use was made of different etching and staining solutions to illustrate the distribution of different mineral constituents and to accentuate structures and textures. The organic dye, alizerine red S, was used to differentiate between calcite and dolomite. Polished and etched surfaces of samples and thin sections were treated with acidic and basic solutions containing the dye in the manner described by Friedman (1959), Evamy (1963, 1969), and Streeton (1969).

Classification of carbonate rocks. - Dunham's classification of carbonate rocks was used (Table 1).

<table>
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<tr>
<th>DEPOSITIONAL TEXTURE</th>
<th>RECOGNIZABLE</th>
<th>DEPOSITIONAL TEXTURE</th>
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<tr>
<td>Original Components</td>
<td>Not Bound</td>
<td>Together During</td>
</tr>
<tr>
<td></td>
<td>Deposition</td>
<td></td>
</tr>
<tr>
<td>Contains Mud</td>
<td></td>
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<td>Mud - supported</td>
<td></td>
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<td>Less than 10 percent</td>
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<tr>
<td>grains</td>
<td>More than</td>
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<td>MUDSTONE</td>
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Table 1: Classification of Carbonate Rocks (From Dunham, 1962)
According to Dunham (1962, p. 108), three textural features are useful in classifying those carbonate rocks which retain their depositional textures. These include: (1) presence or absence of lime-mud, which distinguishes mudstone from grainstone; (2) abundance of grains, which allows muddy carbonate rocks to be divided into mudstone, wackestone, and packstone; and (3) presence of signs of binding, which characterizes boundstone. Rocks which retain too little of their recognizable depositional texture are called crystalline carbonates.

<table>
<thead>
<tr>
<th>Grain Size Classification</th>
<th>Grain size between</th>
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<tr>
<td>Coarse-grained</td>
<td>0.50 mm and 2.0 mm</td>
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<tr>
<td>Coarsely crystalline</td>
<td></td>
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<tr>
<td>Medium-grained</td>
<td>0.0625 mm and 0.50 mm</td>
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<tr>
<td>Medium crystalline</td>
<td></td>
</tr>
<tr>
<td>Fine-grained</td>
<td>0.02 mm and 0.0625 mm</td>
</tr>
<tr>
<td>Finely crystalline</td>
<td></td>
</tr>
<tr>
<td>Cryptocrystalline</td>
<td>Grain size less than 0.02 mm</td>
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</table>

Table 2: Particle Size Classification
Borehole logs. - Several different types of borehole logs were used to differentiate between shales, anhydrite, halite, and carbonate rocks. Density, sonic, gamma-ray, and neutron logs were used when possible. These proved most reliable in detecting lithologic boundaries. Electrical logs were used only when others were not available, and proved less reliable, especially in detecting beds only a few feet thick.

Objectives. - The Winnipegosis Formation was examined in the area of study with the following objectives:

1) to study the form and geometry of Upper Winnipegosis carbonate banks;

2) to determine if Upper Winnipegosis banks are influenced by structural control;

3) to determine any lateral or vertical variations in lithology or fauna within Upper Winnipegosis banks;

4) to study the relationship between Upper Winnipegosis banks and the Ratner Member of the Winnipegosis Formation (Reinson, 1970; Wardlaw and Reinson, 1971, in press).

5) to study the distribution of calcite and dolomite in the Winnipegosis Formation and document any observed textural features; and

6) to determine the environment of deposition of the Winnipegosis Formation.
Acknowledgements

I would like to thank Dr. N. C. Wardlaw for his interest and encouragement in the supervision of this study.

Financial assistance was obtained from a National Research Council of Canada Bursary and a University of Saskatchewan Graduate Unit Scholarship. These are gratefully acknowledged. Additional financial assistance was obtained in the form of a grant-in-aid of research to Dr. Wardlaw.

Mr. D. R. Francis, Director of the Geological Sciences Branch of the Department of Mineral Resources, and Mr. G. Runtz and staff of the Government Core Laboratory in Regina were most co-operative in making borehole data and core available for study. Their help is greatly appreciated.

The author would like to thank Dr. E. Jamieson, now of Union Oil Company, Calgary, who identified some species of algae from the Winnipegosis Formation.

The author is also grateful for the opportunity to accompany Dr. W. K. Braun and Dr. D. M. Kent on a brief excursion to study and sample Winnipegosis outcrops in Manitoba. This trip gave the author a chance to compare Winnipegosis outcrop sections with subsurface sections in the area of study.
Dr. W. G. E. Caldwell critically read the manuscript in the absence of Dr. Wardlaw and made some helpful editorial comments. His suggestions and help are greatly appreciated.

Special thanks go to Mr. E. Hawkins, who prepared approximately 150 thin sections for study and to Mrs. Phyllis Smith, who typed the manuscript.
Regional Setting

Elk Point basin. - The regional setting of the Elk Point basin has been described by Govett (1961), Grayston et al. (1964), and Bassett and Stout (1967). The regional framework of the basin and a cross-section through the Elk Point and Williston basins are illustrated (Figs. 2 and 3).

In earliest Elk Point time (Fig. 2), there were two separate basins which acted as sites for deposition of cyclical sequences of variegated shales, carbonate rocks, anhydrite, and halite. These were the Hay River basin and the Elk Point basin proper.

The Precambrian Shield bounded the Elk Point basin to the east and northeast, whereas a combined Peace River-Athabasca Arch, Western Alberta Ridge, and Swift Current Platform acted as a boundary to the west. The southern boundary of the earliest Elk Point basin was the Meadow Lake Escarpment (Figs. 2 and 3). Van Hees (1958, p. 70) referred to the escarpment as an erosional lineament. It originated during the pre-Devonian depositional hiatus. To the south of the escarpment, much of what is present-day Saskatchewan was an elevated area-- the Prairie Plateau of Van Hees (1958).

In later Elk Point time, the Meadow Lake Escarpment was inundated as the upper Elk Point seaway transgressed to the southeast. The
Figure 2: Regional Framework of the Elk Point and Williston basins
(From Bassett and Stout, 1967)
Figure 3: Generalized cross-section through the Elk Point and Williston basins
(From Bassett and Stout, 1967)
Upper Elk Point Subgroup, again a cyclical sequence of variegated shales, carbonate rocks, anhydrite, and halite, was deposited. These sediments are grouped as the Ashern, Winnipegosis, and Prairie Evaporite Formations. The Upper Elk Point Subgroup is bounded to the south by the Transcontinental Arch, a positive Devonian element extending from the Precambrian Shield to the Cordilleran Geosyncline (Kent, 1964, p. 61). This arch had a northeast-southwest trending axis running through present-day South Dakota.

**Nomenclature**

**Elk Point nomenclature.** - Table 3 summarizes nomenclature of the Elk Point Group in Alberta, Saskatchewan, and Manitoba. McGehee (1949) first used the term Elk Point Formation in defining a sequence of red shales, anhydritic dolomites, a thin, slightly fossiliferous, argillaceous limestone, and one to three salt members which are to be found in east-central Alberta. Belyea (1952) assigned group status to McGehee's Elk Point Formation. Crickmay (1954) divided Belyea's Elk Point Group into nine members and named the Anglo Canadian Elk Point No. 1 borehole (Lsd. 2-21-57-5 W 4) as the type location. Law (1955) formally divided the Elk Point Group of northwestern Alberta into the Watt Mountain, Muskeg, Keg River, and Chinchaga Formations (Table 3).

Baillie (1953) similarly divided the Elk Point Group of the Williston basin into the Ashern, Winnipegosis, and Prairie Evaporite Formations. He excluded the overlying strata, which he named Dawson
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<tr>
<th></th>
<th>TYRRELL (1892)</th>
<th>KINDLE (1914)</th>
<th>McGEHRE (1946)</th>
<th>BAILLIE (1950)</th>
<th>BELYEA (1952)</th>
<th>BAILLIE (1953)</th>
<th>LAW (1955)</th>
<th>NORTIS (1963)</th>
<th>GRAYSTON et al. (1964)</th>
<th>JONES (1965)</th>
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<tr>
<td>Manitoban</td>
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<td>Winnipegosan</td>
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<td>Elm Point</td>
<td>Elm Point Formation</td>
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<td>Ashern Formation</td>
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Table 3: History of Nomenclature of the Elk Point Group
Bay Formation. Van Hees (1956) and Grayston et al. (1964) included the Dawson Bay Formation and overlying "First Red Bed" within the Elk Point Group in order to make definition of the group consistent throughout Alberta, Saskatchewan, and Manitoba.

Grayston et al. (1964) also divided the Elk Point Group into lower and upper subgroups. The base of the Keg River-Methy-Winnipegosis Formations is taken as the boundary between the divisions. This separated the widespread Upper Elk Point Subgroup from its more areally-restricted lower counterpart.

Nomenclature of Winnipegosis and lower Prairie Evaporite Formations.

Table 4 illustrates nomenclature of the Winnipegosis and Prairie Evaporite Formations in Saskatchewan. Several authors have modified the nomenclature prior to Jones (1965). Powley (1951) traced the Ashern, Elm Point, and Winnipegosan Formations of Baillie (1950) into central Saskatchewan. Baillie (1953) combined the Elm Point and Winnipegosan Formations into the Winnipegosis Formation. MacLennan and Kamens-Kaye (1954) and Walker (1956, 1957) used the term Winnipegosis Formation. Sandberg and Hammond (1958) placed the red and grey beds of the Ashern Formation within the Winnipegosis Formation, however, this usage was not generally accepted.

Both Yont (1960) and Jones (1965) divided the Winnipegosis Formation into lower and upper members. A laterally-persistent, radioactive shale marker bed is used as a boundary between the divisions. Jones (1965) differentiated between the mechanically
Table 4: History of Nomenclature of Winnipegosis and Lower Prairie Evaporite Formations
accumulated, bank strata and off-bank, laminated dolostones and limestones.

Jordan (1967, 1968) informally used the names "Shell Lake Gypsum" and "Whitkow Salt" in reference to the evaporite sequence immediately overlying the Winnipegosis Formation. Reinson (1970) proposed that the lower Prairie Evaporite Formation be divided into the Shell Lake, Whitkow, and Ratner Members (Table 4). The Ratner Member includes the off-bank laminated dolostones and limestones of Jones (1965) and the interlaminated carbonate mudstones and enterolithic anhydrite which were discussed by Shearman and Fuller (1969A, B).

The author has included the Ratner Member within the Winnipegosis Formation, as did Wardlaw and Reinson (1971, in press). It is not known whether the Ratner laminites formed during late stages of Winnipegosis bank development or after cessation of bank growth.
PRE-WINNIPEGOSIS SEDIMENTATION

Ashern Formation

General remarks. - The Ashern Formation is the basal unit of the Elk Point Group throughout most of Saskatchewan. Baillie (1953) originally defined the Ashern Formation as a brick-red to greyish-orange, argillaceous dolostone and noted that it is readily discernible in borehole logs.

Walker (1957) divided the Ashern Formation into two informal units, a lower dark-red to chocolate-colored, calcareous silty shale and an upper red and green to grey-green, calcareous shale. Both units have been observed within the area of study, however, there is insufficient core to verify the presence of both units throughout the entire area.

Walker (1957) attributed the color variation within the Ashern Formation to reworking and deposition of red beds in an oxidizing environment, and subsequent deposition of grey shales in the bottom of the deepening Elk Point seaway. Jones (1965, p. 9) considered the color variation as a result of differential reduction in depth after marine inundation, with surficial reworking and redistribution caused by that inundation. Because of the paucity of core, it is not known if this vertical variation in color and lithology is a local or a regional feature. Presumably, a vertical gradation of red beds into grey-green, calcareous mudstones reflects a change from
oxidizing to slightly reducing conditions of deposition.

**Distribution, thickness, and macroscopic description.** - An examination of cores of the Ashern Formation from two boreholes, Banff et al. Asquith (Lsd. 13-1-38-8 W 3) and Britalta Brightholme no. 1 (Lsd. 5-29-47-3 W 3), reveals that the formation consists of a grey-green, calcareous or dolomitic mudstone or shale, with a lower reddish, calcareous silty shale.

Figure 4 is an isopach map of the Ashern Formation in the area of study. The formation is usually between 20 and 50 feet thick, but there are local exceptions. For example, thickness exceeds 100 feet in the Imperial Goodsoil no. 8-11 borehole (Lsd. 8-11-62-22 W 3) and in several boreholes in the northwestern corner of the area of study.

A structural contour map of the top of the Ashern Formation (Fig. 5) illustrates that the formation dips gradually to the south-southwest at a rate of approximately 20 feet per mile. The northeast-southwest trending outline of the Meadow Lake Escarpment is readily observable in the northern one-third of the area of study.

It is interesting to compare the isopach map of the Ashern Formation (Fig. 4) with the structural contour map of the top of the formation (Fig. 5). The Ashern Formation is usually thicker on the northwestern side of the Meadow Lake Escarpment. This indicates that the escarpment was a positive structural element during the time of deposition of the Ashern Formation.
LEGEND:

- Boreholes in which the Ashern Formation is not completely penetrated
- Boreholes in which the Ashern Formation is completely penetrated
- Isopach interval 10 feet
- Approximate isopach
- Meadow Lake Escarpment

Figure 4 ISOPACH MAP OF ASHERN FORMATION
LEGEND:

- BOREHOLES IN WHICH THE TOP OF THE ASHERN FORMATION IS NOT PENETRATED
- BOREHOLES IN WHICH THE TOP OF THE ASHERN FORMATION IS PENETRATED
- CONTour INTERVAL 100 FEET
- MEADOW LAKE ESCARPMENT
- APPROXIMATE CONTOUR

DATUM IS SEA LEVEL

Figure 5 STRUCTURAL CONTOUR OF THE TOP OF THE ASHERN FORMATION
Lower and upper boundaries. - Walker (1957) observed that the Lower Paleozoic surface below the Ashern Formation has been reddened, oxidized, anhydritized, and possibly exposed to subaerial solution weathering. The author did not observe the lower contact of the Ashern Formation; however, if Walker's observations are correct, then it is unconformable.

The upper contact of the Ashern Formation with the overlying Winnipegosis Formation is gradational. There is a color change from the mottled, blue-grey to green-grey mudstone of the Ashern Formation upwards to the mottled grey-brown to olive-grey packstone of the Lower Winnipegosis Member. This contact is readily observable in the Tidewater Allan Crown no. 16-11 borehole (Lsd. 16-11-33-1 W 3) at 4,189 feet below K.B. and has been illustrated by Jones (1965, Pl. Ia, p. 63).
WINNIPEGOSIS SEDIMENTATION

General Remarks

Previous investigations. - Because of the close association between carbonate rocks and the occurrence of hydrocarbons, the Winnipegosis Formation has received some attention from the oil industry, especially in the last two decades. Powley (1951), MacLennan and Kamen-Kaye (1954), Walker (1956, 1957), Edie (1959), Yont (1960), Jones (1965), and Wardlaw and Reinson (1971, in press) have all reported on the geology of the Winnipegosis Formation.

Both Yont (1960) and Jones (1965) divided the Winnipegosis Formation into lower and upper members. The boundary between the members is a widespread, radioactive, argillaceous marker. According to Jones (1965, p. 9), this argillaceous marker ranges from bituminous, dolomitic or calcareous mudstone to bituminous, argillaceous dolomite or limestone. This argillaceous marker deserves special attention and will be discussed later.

Reinson (1970) and Wardlaw and Reinson (1971, in press) described off-bank interlaminated carbonate mudstone and enterolithic anhydrite, which they refer to as the Ratner Member of the Winnipegosis Formation (Table 4, Figs. 7, 8, 9, 10, and 17). They traced eight laterally persistent units within this member into the east-central part of the area of study and also observed that the Ratner is thinner in the southern part of their area of study. The overlying
Shell Lake and Whitkow Members are preferentially thicker on the southeast flanks of Upper Winnipegosis carbonate banks. This observation led them to postulate that the open seaway probably lay to the northwest during deposition of the lower Prairie Evaporite Formation.

**Macroscopic description.** - The Winnipegosis Formation in the area of study is of variable lithology, ranging from light- to dark-brown, fine- to medium-grained, extensively dolomitized, variably fossiliferous and argillaceous, carbonate rock, to interlaminated calcite or dolomite laminite and enterolithic anhydrite. Thickness of the formation varies from a known minimum of 31 feet to a known maximum of 379 feet (Fig. 5).

The Lower Winnipegosis Member is a mottled extensively dolomitized, light- to dark-brown, fossiliferous packstone, with less common argillaceous-carbonaceous mudstone, dolomite laminite, and intraformational conglomerate (Pl. 1, Fig. 1).

Pelleted wackestone and grainstone and vaguely laminated mudstone are by far the dominant rock types of the Upper Winnipegosis Member. Where both pelleted and laminated rocks occur in carbonate banks, laminated ones overlie pelleted ones (Pl. 4).

Frame-building and encrusting organisms, which characterize boundstone, are common in only 12 of the 50 boreholes from which core
LEGEND:

- BOREHOLES IN WHICH THE WINNIPEGOSIS FORMATION IS NOT COMPLETELY PENETRATED
- BOREHOLES IN WHICH THE WINNIPEGOSIS FORMATION IS COMPLETELY PENETRATED
- BOREHOLES IN WHICH CORALS AND STROMATOPIDS ARE ABUNDANT IN WINNIPEGOSIS CORE
- ISOPACH INTERVAL 50 FEET
- APPROXIMATE ISOPACH

Figure 6 ISOPACH MAP OF THE WINNIPEGOSIS FORMATION
was examined. Tabulate corals and stromatoporoids are the dominant frame-builders. As can be seen in Figure 6, most of the 12 boreholes are near the perimeter of Winnipegosis banks. Although the amount of data is extremely limited, the possibility that frame-building organisms grew preferentially around the margins of Winnipegosis banks cannot be excluded.

The relative scarcity and high degree of abrasion of frame-building organisms in the total available core from the Upper Winnipegosis Member indicate that almost certainly Upper Winnipegosis carbonate mounds lacked the rigidity of frame which characterize reefs. These mounds are best regarded and referred to as banks. Corals and stromatoporoids probably comprise less than 1 or 2 percent by volume of all available core from the Upper Winnipegosis Member, although locally they may comprise 20 to 30 percent by volume of a single core. These organisms are heavily abraded and do not show evidence for in situ growth.

A cap rock unit, which is partly pisolitic, partly oncolitic, and partly stomatolitic, is present at the top of some Winnipegosis banks. Wardlaw and Reinson (1971, in press) observed that this unit, which forms the upper 30 feet of Upper Winnipegosis banks, consists of pisolite beds interbedded with pelleted grainstones and wackestones containing calcispheres, crinoids, and ostracods. Although Wardlaw and Reinson (1971, in press) implied that the unit covers the top of all the banks, it has been observed that the cap rock unit forms only a partial cover on some banks. Where it is absent,
vaguely laminated carbonate mudstones within the banks pass upward transitionally into Shell Lake anhydrites. It is concluded, therefore, that the cap rock unit may be merely a marginal development.

Fore-bank strata consist of argillaceous, fossiliferous wackestone and packstone (Pl. 4) with a highly varied fauna (Fig. 15).

The Ratner Member in the area of study consists of interlaminated calcite or dolomite laminite and enterolithic anhydrite. A lack of core from the Ratner Member in the area of study makes lateral correlation of the eight units described by Wardlaw and Reinson (1971, in press) difficult. However, these units have been traced into the south-central part of the study area. The Ratner Member is present in four basins (Fig. 17) which are bounded by Upper Winnipegosis banks. Maximum known thickness of the member in the area of study is 77 feet.

Stratigraphic relationships. - Figures 7, 8, 9, and 10 are cross-sections through the Elk Point Group in the area of study. Figure 6 shows the locations of these various cross-sections.

As can be seen, the Lower Winnipegosis Member is of fairly consistent thickness. Some of the thicker accumulations of the member underlie Upper Winnipegosis banks, but this relationship is inconsistent. Ratner laminites overlie the Lower Winnipegosis Member in an off-bank position and also overlie Upper Winnipegosis strata in a fore-bank position.
Figure 7 NORTHEAST - SOUTHWEST STRATIGRAPHIC CROSS-SECTION A-A' SHOWING RELATIONSHIP OF LOWER PRAIRIE EVAPORITE AND WINNIPEGOSIS FORMATIONS IN SOUTHEAST CORNER OF AREA OF STUDY.
Figure 8: NORTH-SOUTH STRATIGRAPHIC CROSS-SECTION B'-B' SHOWING RELATIONSHIP OF LOWER PRAIRIE EVAPORITE AND WINNIPEGOSIS FORMATIONS IN THE SOUTH-CENTRAL PART OF AREA OF STY
One problem encountered in the present study is that of defining the northern limits of the Ratner, Whitkow, and Shell Lake Members. Solution of the Prairie Evaporite Formation across the northern half of the area of study has caused thinning or complete removal of the evaporite sequence. Thus, delineation of the boundaries of the Shell Lake and Whitkow Members is difficult, especially in view of the poor well control in some areas. The Ratner Member is also affected by solution of the evaporite sequence, and replacement of the original enterolithic anhydrite by calcite (Pl. 9) makes any attempt to define the boundaries of the member difficult, if not impossible.

In the southern part of the area of study, the Shell Lake and Whitkow Members are thicker on the southeast flanks of Upper Winnipegosis banks (Fig. 7). Thickness of the combined Shell Lake-Whitkow Members exceeds 230 feet in two boreholes, Fina Conquest (Lsd. 16-9-31-8 W 3) and Gridoil Kenaston (Lsd. 9-29-30-1 W 3), both of which are on the southeast flank of a Winnipegosis bank. This observation agrees with that of Wardlaw and Reinson (1971, in press).

In the central part of the area of study, deposition of the Shell Lake and Whitkow Members does not appear to have followed the same pattern as closely. For example, in the Pheasant Banff Red Pheasant Borehole (Lsd. 13-19-40-15 W 3), the combined Shell Lake-Whitkow Member exceeds 230 feet in thickness, but the nearest and thickest Upper Winnipegosis bank is present to the south and east of this location (Fig. 6).
LOWER WINNIPEGOSIS MEMBER

General Remarks

Distribution, thickness, and macroscopic description. - Four different rock types have been observed within the Lower Winnipegosis Member (Pl. 1, Fig. 1). These include the following:

1) oncolitic packstone;
2) black, argillaceous-carbonaceous mudstone with cricoconarids and tasmanitids;
3) dense, cryptocrystalline dolomite laminithe, and
4) mottled brown, fine- to medium-grained, intraformational conglomerate.

Only one of these rock types, namely, the oncolitic packstone, is present throughout the study area, and it is the thickest and most laterally persistent lithological unit in the Lower Winnipegosis Member. The other three rock types—dolomite laminite, argillaceous-carbonaceous mudstone, and intraformational conglomerate—are interlaminated at the top of the Lower Winnipegosis Member in some places and are only a few centimeters thick. Thickness of the Lower Winnipegosis Member ranges from 10 to 50 feet, although thicker accumulations occur (Fig. 11).

Algal oncoliths of the oncolitic packstone unit are up to 3 cm in diameter and are subspherical to elongate in the plane of bedding. They are composed of closely-spaced, vaguely concentric laminations of dark-brown, cryptocrystalline dolomite (Pl. 1, Fig. 2). Algal
LEGEND:

* BOREHOLES IN WHICH THE LOWER MEMBER IS NOT COMPLETELY PENETRATED
○ BOREHOLES IN WHICH THE LOWER MEMBER IS COMPLETELY PENETRATED
---- ISOPACH INTERVAL 10 FEET
----- APPROXIMATE ISOPACH

Figure II ISOPACH MAP OF THE LOWER WINNIPEGOSIS MEMBER
filaments are usually lacking, however rare tubules of (?)Girvanella sp. have been observed in thin section (Wardlaw and Reinson, 1971, in press).

Oncoliths commonly form about a nucleus of skeletal debris, especially crinoid ossicles, bryozoan fragments, and immature gastropods. These oncoliths are usually smaller than those without skeletal nuclei.

The matrix for the oncoliths is a light- to dark-brown, fossiliferous packstone, with crinoid ossicles, fragmented and articulated punctate and impunctate brachiopods, bryozoans, corals, and gastropods in a lime-mud. The spiral angle of the gastropods varies from high to low. Small amber spore cases are also present in the packstone unit, as are tasmanitids, cricoconarids, and ostracods.

Some of the skeletal debris in the oncolitic packstone appears to have been replaced by micrite (Pl. 1, Figs. 3 and 4). Crinoid ossicles and brachiopod fragments are particularly susceptible to this replacement and commonly have "nibbled" edges now occupied by lime-mud. Bathurst (1966) has described a process in which boring algae penetrate the skeletons of organisms, creating small tubular cavities which become filled with micrite. The end result of this process is a complete alteration of skeletal debris to micrite.

Bathurst (1966) observed that the micritic envelope is able to form a mold. The original skeletal debris, usually aragonite, is
dissolved away, and the mold subsequently filled by a granular calcite. However, one question which Bathurst could not answer was why the aragonite in skeletal material dissolved completely but the aragonite needles which he found in the micritic envelope did not.

Buchbinder and Friedman (1970) inferred that the original micritic envelope was composed of high-magnesium calcite and not aragonite. If high-magnesium calcite were subsequently dolomitized, a solubility contrast would be established between the dolomitized micritic envelope and the aragonite skeletal material. Selective solution of aragonite would leave a mold which later could be filled by the clear calcite cement or drusy calcite mosaics described by Orme and Brown (1963). Some of the skeletal debris found in the Lower Winnipegosis Member probably has been preserved in this manner.

The micritic coatings found around skeletal debris in the Lower Winnipegosis Member probably formed in the manner described by Bathurst. Small tubular cavities have been found in some of the unaltered skeletal material (Pl. 1, Fig. 4). These were probably caused by boring algae.

Both pyrite and anhydrite are present in the oncolitic packstone unit. Anhydrite is present in three distinct forms:

1) as crystallotopic laths which are formed preferentially in the oncoliths;

2) as a mosaic of submillimeter-size needles which plugs voids; and
3) as a replacement of the original calcite or aragonite of skeletal material. Pyrite occurs as a thin rind composed of cryptocrystalline grains which lines cavities plugged by anhydrite.

Dense, black-argillaceous-carbonaceous mudstone beds are present near the top of the Lower Winnipegosis Member (Pl. 1, Fig. 1). This unit compares to the argillaceous beds which Jones (1965, p. 9) used to define the top of that member. Although Jones did not specify that the argillaceous beds pass below Upper Winnipegosis banks, this conclusion can be drawn from his figures.

Densely-spaced, argillaceous-carbonaceous mudstone stringers, with cricoconarids and tasmanitids, show the effects of differential compaction where they overlie oncoliths, and appear to "flow" about rounded to ellipsoidal clasts of siliceous cryptocrystalline clasts with the form of boudins (Pl. 1, Fig. 5).

The clasts or boudins in the argillaceous-carbonaceous mudstone unit commonly contain nuclei of dark-brown cryptocrystalline dolomite and a thin rind of white chalcedony, encased in an envelope of brown cryptocrystalline dolomite (Pl. 1, Figs. 1 and 5). Other clasts consist of a pelleted lime-mud, with cricoconarids and tasmanitids, and still others contain pelleted bank material.

The boudinage structures closely resemble the "sedimentary boudinage" described by McCrossan (1958, p. 316-320) from the Upper
Devonian Ireton Shale of central Alberta. McCrossan interpreted sedimentary boudinage as a pull-apart structure which is formed during compaction of lime-rich beds sandwiched between layers of clayey material moved laterally, whereas the more competent limy beds pinched and swelled and finally broke into nodules, lenses or boudins.

These nodular forms, aside from clasts, might also be the result of localized cementation within limy blebs or nodules, followed by differential compaction, the uncemented material being preferentially compacted. Siliceous dolomite nodules may be concretions which were penecontemporaneous with the matrix, however they do not show concretionary structure.

Both pyrite and anhydrite are present in the argillaceous-carbonaceous mudstone. Pyrite occurs as blebs (up to 5 mm in diameter) of cryptocrystalline grains and also as a mosaic which is disseminated throughout the unit. Anhydrite occurs as crystallotopic laths which are not penetrated by argillaceous-carbonaceous stringers.

Organic content of the argillaceous-carbonaceous mudstones is relatively high. Wardlaw and Reinson (1971, in press) reported a total organic content of as much as 3.21 percent by weight from this unit.

Argillaceous-carbonaceous mudstones contain cricoconarids, tasmanitids, ostracods, and immature brachiopods. The conical forms
of dacryocaridns and tentaculitids are orientated parallel to the plane of bedding, whereas spherical tasmanitids and ostracods are flattened and crushed. This crushing probably is the result of greater compaction of the argillaceous-carbonaceous matrix.

Two different types of calcite are associated with cricoconarids and tasmanitids (Pl. 2, Figs. 3 and 4). These types display similar characteristics to those described by Orme and Brown (1963). One type is a replacement of pre-existing material and the other is a cement.

A syntaxial fibrous calcite halo surrounds skeletal debris and replaces the original argillaceous-carbonaceous mudstone matrix. It also occurs within skeletal debris and again is of a replacement and not a drusy character. In most examples studied, the syntaxial fibrous calcite within shells is an optical continuity with that which surrounds shells (Pl. 2, Fig. 3).

A drusy fibrous calcite mosaic partly or completely fills the interior of some shells (Pl. 2, Fig. 4). According to Orme and Brown (1963), mosaics of this type are cements which were deposited in pre-existing voids.

Occasional small clasts (less than 3 cm in diameter) of pelleted grainstone, containing calcspheres and rounded sac-like forms attributed to dasycladaceous algae, have been observed in argillaceous-carbonaceous mudstones (Pl. 2, Fig. 5). These clasts are of the same
lithology and fauna as the pelleted grainstone unit of Upper
Winnipegosis banks (Pl. 4), but pelleted grainstones have not been
observed in the Lower Winnipegosis Member. These clasts likely
were derived by erosion of Upper Winnipegosis banks -- portions of
which must have been in existence and relatively consolidated at the
time the upper argillaceous-carbonaceous mudstones were being
deposited in off-bank positions.

Evidence for the existence of Upper Winnipegosis banks at the
time argillaceous-carbonaceous mudstone sediments were being deposit-
ed in an off-bank position gains support from other observations. In
the Imperial Barnes no. 1-33 borehole (Lsd. 1-33-61-17 W 3), there are
two similar argillaceous-carbonaceous mudstone beds containing
cricoconarids and tasmanitids (Pl. 2, Figs. 1 and 2). The lower one
is at the top of the Lower Winnipegosis Member; the upper one overlies
approximately 55 feet of Upper Winnipegosis strata and underlies
Ratner laminites.

A study of gamma-ray logs from three other boreholes indicates
that there may be radioactive argillaceous-carbonaceous mudstone beds
within Upper Winnipegosis banks, but there is no core available to
test this inference. These boreholes are B.A. Gillespie (Lsd. 16-2-
51-18 W 3), Husky D.H. Turtleford (Lsd. 6-5-51-20 W 3), and Husky
D.H. Englishman Lake (Lsd. 1-25-51-22 W 3).

Argillaceous-carbonaceous mudstone beds have not been found in
the off-bank Ratner Member, although they are present at the top of
the Lower Winnipegosis Member in both bank and off-bank positions and are also present near the top of Upper Winnipegosis fore-bank strata. However, in both fore-bank and off-bank position, Ratner laminites are found to overlie argillaceous-carbonaceous mudstone beds where the latter are present. It is very unlikely that argillaceous-carbonaceous mudstone beds in Upper Winnipegosis fore-bank strata are facies equivalents of the Ratner Member. It is almost certain, in fact, that all argillaceous-carbonaceous mudstone beds in both the Lower and Upper Winnipegosis Members coalesce below the Ratner laminites in off-bank positions. (Pl. 2, Figs. 1 and 2).

If the interpretations regarding the argillaceous-carbonaceous mudstone beds are valid, a few conclusions can be drawn. These are as follows:

1) some portion, if not all, of the Upper Winnipegosis banks was in existence prior to deposition of the uppermost argillaceous-carbonaceous mudstone beds at the top of the Lower Winnipegosis Member in off-bank positions;

2) because Ratner laminites overlie argillaceous-carbonaceous mudstone beds in both fore-bank and off-bank positions, deposition of the Ratner Member must post-date deposition of both argillaceous-carbonaceous mudstones and some portion, if not all, of the Upper Winnipegosis banks;

3) approximately the same conditions of deposition must have prevailed at least twice during Winnipegosis time -- during late stages of deposition of the Lower Member and during late stages of deposition of the Upper Member, or at least prior to deposition of the Ratner Member;
4) some idea of relative rates of deposition of Winnipegosis strata at different locations can be inferred. For example, as much as 55 feet of Upper Winnipegosis strata may have accumulated in a fore-bank position at the same time as only a few inches or feet of argillaceous-carbonaceous mudstones were deposited in an off-bank position; and

5) the Lower and Upper Winnipegosis Members cannot be differentiated from each other on the basis of a widespread radioactive argillaceous unit, as Jones (1965) suggested, because of the presence of similar argillaceous-carbonaceous mudstone beds within or on top of Upper Winnipegosis fore-bank strata.

It is herein recommended that the boundary between the Lower and Upper Winnipegosis Members be taken as the lowermost occurrence of radioactive argillaceous-carbonaceous mudstone beds in a bank position.

Dense, cryptocrystalline, light-brown dolomite laminite is present at the top of the Lower Winnipegosis Member in some boreholes (Pl. 1, Fig. 1). Laminae are less than 5 mm thick, of uneven thickness, and are separated by argillaceous-carbonaceous partings. Laminae are fractured and brecciated in some places. In the Britalta Brightholme no. 1 borehole (Lsd. 5-29-47-3 W 3), the overlying intraformational conglomerate and dolomite clasts have sunk into vertical fractures in the laminite and underlying argillaceous-carbonaceous mudstone has been squeezed up into fractures to form small diapirs (Pl. 1, Fig. 1).
Intraformational conglomerate contains lath-shaped clasts of dark-brown, finely-crystalline dolomite and angular fragments of argillaceous-carbonaceous mudstone with cricoconarids and tasmanitids. The matrix is a poorly sorted, fossiliferous packstone with a varied coral, crinoid, and brachiopod fauna. Some of the lath-shaped clasts are bent, indicating either incomplete lithification or dessication of a subaerially exposed carbonate laminite prior to transportation.

At some locations, dolomite laminite, argillaceous-carbonaceous mudstone, and intraformational conglomerate are interlaminated in a vertical sequence through a few centimeters or inches at the top of the Lower Winnipegosis Member (Pl. 1, Fig. 1). However, at other locations where the contact between the Lower and Upper Members is cored, two different relationships exist. At some locations, the contact between the two members is unconformable, whereas at other locations, the contact is gradational.

In the UOIL Parkside no. 8-3 borehole (Lsd. 8-3-48-5 W 3), the contact between the Lower and Upper Winnipegosis Members is abrupt and unconformable. The oncolitic packstone of the Lower Member is separated from pelleted grainstones of the Upper Member by a conglomerate bed which is less than one-half inch in thickness and is wavy and uneven. The conglomerate consists of angular fragments of carbonate rock in a black, argillaceous-carbonaceous matrix. The contact with the underlying Lower Member is abrupt and irregular, suggesting that the top of the Lower Member was eroded. The contact with the overlying Upper Member is even and gradational. It is
interesting that this borehole is only 10 miles from the Brightholme no. 1 borehole, where all four units of the Lower Member are preserved.

Figure 12 illustrates the different rock types which are present on both sides of the contact between the Lower and Upper Members at the two locations in question. The dolomite laminitie, intraformational conglomerate, and argillaceous-carbonaceous mudstone are missing in the Parkside no. 8-3 borehole because of either erosion, non-deposition or facies change.

There are no fossils present which could be used to prove or disprove a facies change from pelleted grainstones to dolomite laminitie and intraformational conglomerate. However, the presence of an unconformable contact between the Upper and Lower Member under an Upper Winnipegosis bank, as well as the presence of an intraformational conglomerate in an off-bank position, is evidence that supports the idea that scattered shoals or "highs" had formed late in early Winnipegosis time. These shoals were eroded and the detritus was swept into nearby depressions. At least some of these shoals became sites for deposition of Upper Winnipegosis bank strata, as, for example, in the UOHL Parkside no. 8-3 borehole (Lsd. 8-3-48-5 W 3).

The second type of contact between the Lower and Upper Winnipegosis Members is a transitional one. In the Home Cigal Meadow Lake borehole (Lsd. 9-15-61-20 W 3), the oncolitic packstone of the Lower Member is overlain by a dark-brown, fine- to medium-crystalline, well-laminated dolomite. Dolomite laminae are wavy, of uneven
Figure 12: Different rock types encountered across the contact between the Lower Member and Upper Member and the Lower Member and Ratner Member. The two boreholes are 10 miles apart. The contact between the Lower and Upper Members in the Parkside borehole is unconformable.
thickness (up to 20 mm), and dip at approximately 15 degrees. Rare crinoids and vague clasts or oncolites are also present. There are no argillaceous-carbonaceous mudstone beds or intraformational conglomerate. The presence of this laminated unit indicates that there was no hiatus between deposition of the Lower and Upper Members in this area.

The rocks of the Lower Winnipegosis Member have been extensively dolomitized. Dolomite appears in thin section as a mosaic of fine crystals, rhombic in outline, and with mutually-interfering intercrystalline boundaries where dolomitization is complete. In several sections, however, the Lower Member is only partially dolomitized. Dolomite rhombs appear to have formed preferentially in some positions, which include

1) the matrix, where patches, which are mosaics of fine crystals, are present;

2) oncoliths, which contain brown cryptocrystalline mosaics;

3) vugs, especially those plugged by gypsum, within and around which fine crystals are common; and

4) sites of partly recrystallized skeletal debris accumulation, around which fine crystals are present.

The distribution of dolomite accounts, in part, for the color-mottling so characteristic of the Lower Winnipegosis Member.

A detailed discussion of the chemistry of the formation of dolomite is not presented in this report. A few points, however, are worthy of note. Several variables influence the formation
of dolomite. Some of these include (1) a supply of magnesium ions; (2) a transporting medium for these ions; (3) adequate porosity and permeability of the rock to be dolomitized; and (4) chemical instability.

With regard to a supply of magnesium ions, Fairbridge (1957, p. 132) stated that magnesium enrichment in a marine environment can take place in three different ways:

1) clastic or mechanical means, by which magnesium-rich rocks may be derived, at least in part, by erosion of pre-existing dolomites;

2) organic means, by which magnesium is trapped within crystal lattices of the skeletons of lime-secreting organisms; and

3) chemical or metasomatic means, implying processes of inorganic magnesium enrichment and metasomatism in a sediment by magnesium-bearing sea water at or below the sediment-water interface.

Magnesium ions may have been present in the form of high-magnesium calcite as the carbonate rocks of the Lower Winnipegosis Member was being deposited. According to Buchbinder and Friedman (1970), micritic envelopes and skeletons of algae, especially coralline algae, are rich in high-magnesium calcite. As previously discussed, both algal oncoliths and micritic envelopes are present in the Lower Member. These probably were a source for at least some of the magnesium ions.

Another source for magnesium ions may have been in the matrix itself. Shinn (1969) and Taylor and Illing (1969) confirmed the
presence of high-magnesium calcite cement in carbonate sediments of the Persian Gulf. According to Shinn (1969, p. 129), the type of cement present seems to depend on grain size. Aragonite cement is deposited in sands, whereas high-magnesium calcite cement occurs in lime muds. It is possible that the lime-mud matrix of the Lower Member may have been cemented by high-magnesium calcite and thus provided a second source for magnesium.

As previously mentioned, the fine-grained matrix of the Lower Member has been preferentially dolomitized. For a given composition, dolomitization will proceed more rapidly in a fine-grained sediment because it has a greater chemical instability than a coarse-grained sediment. Other controls influence selective dolomitization, however, because not all of the lime-mud matrix has been dolomitized.

If there were magnesium enrichment in the Lower Member, factors such as porosity and permeability of the rocks of that member are important. Assuming the presence of magnesium-bearing formation water, the degree to which dolomite will form in a carbonate rock depends on the pore space and permeability of that rock. The elimination of pore space during cementation reduces the possibility of extensive dolomitization. Although no porosity and permeability study was made of the rocks of the Lower Member, these factors may have a bearing on its incomplete dolomitization.

The principal factors conducive to submarine cementation of carbonate sediments are relatively low rates of sedimentation,
sediment stability, and a high initial permeability (Shinn, 1969, p. 109). A slow rate of sedimentation favors cementation of the sediment until the volume of cement produced is sufficient to impede downward migration of water. Hence, there is an inherent control on the depth to which submarine cementation can take place in a sediment. On the other hand, a rapid rate of sedimentation reduces cementation and can prevent it completely.

The Lower Winnipegosis Member is well-cemented. Perhaps the volume of cement was sufficient to impede the flow of magnesium-bearing water and cause selective dolomitization.

Two characteristic features of the Lower Winnipegosis Member are the uneven and nodular bedding and the color-mottling of the rocks. The uneven and nodular bedding is the result of organic reworking of the strata and differential compaction of a carbonate rock of varying argillaceous-carbonaceous content. The color-mottling is the result of preferential or selective dolomitization of the matrix and partial recrystallization and dolomitization of skeletal material.

The nodular appearance of the rocks is largely due to sedimentary "boudinage" structures which are common (Pl. 1, Fig. 5). These boudins closely resemble those described by McCrossan (1958, p. 316-320) and are thought to have formed in much the same manner. However, some of the blebs or boudins are actually intraclasts. Compaction has caused a slight shifting of the argillaceous-carbonaceous matrix and has accentuated the nodular forms (Pl. 1, Figs. 1 and 5; Pl. 3, Fig. 1).
Aside from the nodular bedding, some parts of the Lower Member appears to have been disturbed and reworked. The oncolitic packstone unit appears to have been most susceptible to reworking, which is probably the result of the action of burrowing and sediment-ingesting organisms on the unconsolidated sediment. Irregular, sediment-filled worm burrows have been observed in the oncolitic packstone unit (Pl. 3, Figs. 2 and 3). It is thought that bioturbation of the sediment accounts for its uneven nature.

Apart from the color variation within the Lower Member, there is an apparent color-mottling largely due to selective or preferential dolomitization of the matrix, algal oncoliths, micritic envelopes, and skeletal debris, as well as partial recrystallization of patches of skeletal debris such as crinoid ossicles (Pl. 3, Figs. 4, 5, and 6). Skeletal debris shows different degrees of recrystallization, ranging from that of a few scattered grains around and within the skeletal material to a total change resulting in a mosaic of equi-dimensional grains with mutually interfering grain boundaries (Pl. 3, Fig. 5).

Fossils and paleoecology. - The distribution of organic remains in the Winnipegosis Formation can be compared to the distribution of similar remains in other carbonate complexes (Figs. 14 and 15).

The Lower Winnipegosis Member contains an abundant and varied fauna, and two different associations can be recognized. One association is present within the oncolitic packstone and intraformational
conglomerate units and consists of fragments of corals, crinoids, bryozoans, algae, fragmented and articulated punctate and impunctate brachiopods, trilobites, cricoconarids, and tasminitids. The other association occurs within argillaceous-carbonaceous mudstones and consists of cricoconarids, tasminitids, ostracods, and immature articulated brachiopods.

Algal oncoliths dominate the oncolitic packstone unit of the Lower Winnipegosis Member. Ginsburg (1960, Table 1, p. 29) found that oncoliths form in a marine environment at water depths of less than 8 feet. Thin section studies of the oncoliths of the Lower Member reveal the presence of minute tubules of (?)Girvanella sp. (Wardlaw and Reinson, 1971, in press). Johnson (1961, p. 37) stated that the Schizophyceae, which includes Girvanella, inhabit marine, brackish- and fresh-water environments, but most of the marine forms grow in the inter-tidal zone.

Algal oncoliths are associated with a mixed and varied faunal assemblage. This assemblage probably inhabited an open marine environment.

Small, translucent, amber-colored spherical forms have been found in the Lower Winnipegosis Member. Yont (1960) suggested that they were spore cases. Their diameter varies from 0.02 to 1 mm, they are hollow, and generally flattened and crushed. Because of their fragile nature, these spore cases are difficult to extract from rocks and have not been studied.
Fisher (in Moore, 1962, p. 103-105) discussed the morphology and paleoecology of cricoconarids. His observations are summarized as follows:

1) the two divisions of cricoconarids are the dacryoconarids and the tentaculitids;
2) cricoconarids are tolerant of many different environments but are especially prolific in shallow-water lagoonal sediments;
3) cricoconarids occur in rocks in two different ways, indicating two different environments of deposition. The include:
   i) extreme proliferation on the bedding planes and with a common direction of elongation, indicative of deposition in a quiet-water environment, with unidirectional currents, and
   ii) isolate specimens, commonly incomplete apically and/or aperturally, indicative of deposition in an agitated marine environment;
4) dacryoconarids probably had a pelagic existence and were distributed by ocean currents. They achieved relatively rapid world-wide dispersal. Their thin, non-septate shells suggest that they could not live in bathyal depths or in turbulent waters;
5) tentaculitids were probably nektobenthonic scavengers. In contrast to the dacryoconarids, their multiseptate shells suggest that they could live in agitated water; and
6) the characteristic faunal association of cricoconarids includes ostracods, conodonts, small brachiopods, and small peneopods. This lack of diversity of fauna suggests that the environment of deposition was one of abnormal salinity, very muddy bottoms, or else
was a "boreal environment" (by which Fisher probably implied cold water).

Cricoconarids of the argillaceous–carbonaceous mudstone unit occur in extreme proliferation, are flat-lying, but do not have a common direction of elongation. The associated fauna is neither abundant nor varied. If Fisher's observations are valid, then these were probably deposited in a quiet-water environment with weak, multidirectional currents.

The relatively high organic content and the presence of pyrite within argillaceous–carbonaceous mudstones indicate that reducing conditions prevailed at the time of deposition. Reducing conditions generally are not conducive to organic life but are conducive to the preservation of organic matter.

The dolomite laminite unit contains no fossils. The presence of laminations and the fine-grained nature of the matrix suggests that conditions of deposition were quiet and not conducive to organic life. On the other hand, the laminites show the effects of in place brecciation and must have been lithified penecontemporaneously. It is probable that this unit was deposited in quiet water, with episodes of agitation, emergence and erosion.

The presence of an intraformational conglomerate near the top of the Lower Winnipegosis Member is evidence for a shallow-water depositional environment. Periodic emergence and erosion of at least local
areas of positive relief must have occurred in order to produce such a sediment.

The fauna and lithology of the lower Winnipegosis Member permit several different environmental interpretations to be made. Schmalz (1969, p. 800), in his model of deep-water evaporite deposition, considered argillaceous-carbonaceous mudstones to be a basal sapropel unit formed under strongly reducing conditions. He could not reconcile this unit to a shallow-water model for evaporite deposition and, instead, postulated that units such as these, formed in a deep-water, euxinic environment.

On the other hand, argillaceous-carbonaceous mudstones are interlaminated with oncolitic packstones, intraformational conglomerates and dolomite laminites which show effects of in-place brecciation. These formed in a shallow-water environment, with periodic turbulence and erosion. This suggests that the argillaceous-carbonaceous mudstones could not have formed in deep water, unless there were abrupt fluctuations of sea level.

The rocks of the lower Winnipegosis Member probably were deposited in a shallow-water environment, with fluctuations from agitated marine conditions to quiet lagoonal or euxinic conditions and corresponding fluctuation from an oxidizing to a reducing environment.
Structure. - A structural contour of the top of the Lower Winnipegosis Member (Fig. 13) illustrates the gradual dip of that member to the south-southwest. The Meadow Lake Escarpment can be traced across the northern one-third of the study area. However, the Lower Winnipegosis Member is not thicker (Fig. 11) to the northwest of the escarpment. The Meadow Lake Escarpment does not appear to have influenced Lower Winnipegosis sedimentation.
LEGEND:

- BOREHOLES IN WHICH THE TOP OF THE LOWER MEMBER IS NOT PENETRATED
- BOREHOLES IN WHICH THE TOP OF THE LOWER MEMBER IS PENETRATED

- CONTOUR INTERVAL 100 FEET
- MEADOW LAKE ESCRAPMENT
- APPROXIMATE CONTOUR

DATUM IS SEA LEVEL

Figure 13 STRUCTURAL CONTOUR OF THE TOP OF THE LOWER WINNIPEGOSIS MEMBER
UPPER WINNIPEGOSIS MEMBER

General Remarks

Previous investigations. - Some controversy persists as to whether or not the Upper Winnipegosis carbonate mounds are reefs or banks. MacLennan and Kamen-Kaye (1954), Edie (1958), and Yont (1960) have described Winnipegosis reef development in Saskatchewan. Walker (1956, p. 134-136), on the other hand, argued that marine conditions sufficiently saline for evaporite precipitation would not be conducive to prolific organic activity. He suggested, therefore, that Winnipegosis carbonate mounds are not organic reefs, but formed either as calcareous sand banks, somewhat akin to those on the Bahama Banks today, or else by metasomatic replacement of porous dolomite by halite and anhydrite, leaving relict mounds of unaltered carbonate. Evidence for this massive replacement of carbonate rock by evaporite rocks is entirely lacking.

Jones (1965, p. 9) observed that the Upper Winnipegosis carbonate mounds consist of mechanically accumulated, biofragmental, lump, and pellet material, forming carbonate banks which probably were not wave-resistant. He thought that the volume of frame-building organisms was insufficient to qualify these mounds as reefs.

Comparison of reefs and banks. - Table 5 summarizes several criteria which have been used to differentiate between reefs and banks. Several workers, such as Lowenstam (1950), Nelson et al. (1962),
<table>
<thead>
<tr>
<th><strong>REEFS</strong></th>
<th><strong>BANKS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure originally was <strong>built</strong> on the sea floor.</td>
<td>Structure originally was <strong>formed</strong> on the sea floor.</td>
</tr>
<tr>
<td>The organic part of the structure was built by those organisms generally known to have had the ecologic potential to cement themselves to the substrate and construct a three-dimensional frame-work. These include stromatoporoids, colonial hexacorals, calcareous sponges, bryozoans, tabulate corals, and coralline algae. The organic reef and associated sediments form a reef complex.</td>
<td>Structure is formed by the mechanical accumulation of chemically precipitated carbonate sediments and bioclastic detritus, if present. Sediments may be held in place by the binding and baffling activity of those organisms not generally known to have been frame-builders. These include dendroid tabulate corals, dendroid stromatoporoids, crinoids, algae, gastropods, brachiopods, and others.</td>
</tr>
<tr>
<td>The vertical component of development is as important as, if not more important than, the lateral component.</td>
<td>Chemically precipitated carbonate sediment and bioclastic detritus, if present, is transported laterally. Lateral component of growth is very important.</td>
</tr>
<tr>
<td>There must be evidence to show that frame-building organisms grew in place.</td>
<td>Frame-building organisms may be present but are not in growth position.</td>
</tr>
<tr>
<td>Reef structures are wave-resistant. Reef-building organisms are capable of maintaining their structures in a high-energy environment.</td>
<td>Banks may or may not be wave-resistant. They may form in or below the zone of wave action, and may also be a result of current action.</td>
</tr>
<tr>
<td>Reefs are bounded by relatively steep marginal slopes.</td>
<td>Banks are bounded by low-angle marginal slopes because sediments are winnowed and transported laterally to their margins.</td>
</tr>
<tr>
<td>There is almost always evidence for biologic and sedimentary zonation across a reef.</td>
<td>There may or may not be evidence for biologic and sedimentary zonation across a bank.</td>
</tr>
</tbody>
</table>
Klovan (1964), and Klement (1967) have dealt with these different criteria. As can be seen from Table 5, there is no single feature which can be used to distinguish reefs from banks. A combination of several criteria may be used more effectively. These include the following: (1) differences in faunal content of reefs and banks; (2) evidence that frame-building organisms grew in place; (3) wave-resistance of a carbonate complex; and (4) marginal slopes of a carbonate complex.

Both Lowenstam (1950, p. 433-435) and Klement (1967, p. 168) maintained that reefs and banks differ in faunal content. Whereas reefs are characterized by the presence of those organisms generally known to be frame-builders, banks may or may not contain sediment-baffling and -binding organisms (Table 5).

The presence of frame-building organisms is not conclusive evidence for reef growth for two reasons. In the first place, frame-building organisms can live in environments which are not conducive to their prolific growth. Secondly, the growth form of frame-building organisms, especially stromatoporoids, is controlled by environmental conditions. In other words, reefs develop only where conditions are favorable for prolific growth of frame-builders, but frame-builders can inhabit other environments as well.

The same argument applies to bank-forming organisms as well. The presence of bank-forming organisms is not conclusive evidence for calling a carbonate mound a bank. Banks can form purely as a
result of current action. Other features besides faunal content must be used to differentiate between reefs and banks.

The Upper Winnipegosis Member contains both reef- and bank-forming organisms. Frame-building organisms, such as corals and stromatoporoids, are present in only 12 of the 50 boreholes from which core was examined. These organisms probably comprise less than 2 percent by volume of core from the Upper Winnipegosis Member, although they comprise up to 20 or 30 percent of the volume of some cores. Frame-building organisms are not in growth position and usually are heavily abraded. They are not as abundant as sediment-baffling and -binding organisms, such as dendroid stromatoporoids, crinoids, and algae. Therefore, even if frame-building organisms are present in the Upper Winnipegosis Member, the carbonate mounds in that member probably are banks.

The concept of relative wave-resistance of a reef as opposed to a lack of wave-resistance of a bank is not valid. As Kornicker and Boyd (1962, p. 670) pointed out: "Wave-resistance is a relative thing, and a community (of organisms) in relatively protected waters may build a wave-resistant structure which lacks the rigidity of frame which would characterize a reef maintained in open marine conditions." Banks may be as wave-resistant as reefs are, depending on the intensity of turbulence and current-interplay which is present as they form.
The angle of slope along the margins of a carbonate complex is important in determining whether it is a reef or bank. According to Lowenstam (1950, p. 433-435), the skeletal and mechanical debris of bank-forming organisms is subject to winnowing and transport by wave and current action, so that banks grow, in part, by lateral accumulation and are bounded by low-angle marginal slopes. On the other hand, Klovan (1964, p. 13) stated that "Steeply inclined, stratified detrital sediments are one of the best criteria for recognition of a reef."

Upper Winnipegosis carbonate mounds are bounded by low-angle average marginal slopes and, therefore, are considered to be banks. Figure 16 is an isopach map of the Upper Winnipegosis Member. Although there is insufficient well control to gain any idea of local marginal slopes around Winnipegosis banks, steep marginal slopes may exist at some locations. However, measurements made on the existing data indicate that the margins of Winnipegosis banks are bounded by average slopes of less than 2 degrees.

There is some evidence to suggest that steeper marginal slopes do exist around Winnipegosis banks. In the Copee Kepkel Forest no. 8-3 borehole (Lsd. 8-3-40-14 W 3), individual laminae in core from the Upper Member dip as much as 30 degrees. Laminae are fractured and over-ride each other along fractures (Pl. 5, Fig. 1), so that the primary dip likely has been modified by slumping. Therefore, such a steep marginal dip is not typical of Winnipegosis banks.
Form and geometry. - Table 6 illustrates a comparison of Upper Winnipegosis banks with several other carbonate complexes on the basis of areal extent, thickness, and marginal slope. The data shown is approximate because of the varying scales from the different sources which were used. It must also be pointed out that all the calculated marginal slopes are average slopes, based on large scale drawings, and local, steeper marginal slopes have not been recorded.

The data serves to show that Winnipegosis banks are most similar to individual Swan Hills Reef Complexes in the Swan Hills area of Alberta in thickness, but have more gentle average marginal slopes. Winnipegosis banks are most dissimilar to Keg River Reef Complexes in all dimensions. In areal extent, the smallest Winnipegosis bank is comparable to the Redwater Reef Complex, the largest in Alberta. Most Winnipegosis banks have a far greater areal extent than any carbonate complex in Alberta.

A cursory review of literature on the modern carbonate complexes of the Bahama Banks suggests that even they are bounded by steeper marginal slopes than are the Winnipegosis banks. An example of such a marginal slope would be the outer platform of Andros Island (Newell and Rigby, 1957, p. 41).

Winnipegosis banks do not have specific orientations and probably were not structurally controlled. Larger banks are relatively flat-topped and show numerous prominent re-entrants (Fig. 16). In their study of the Goose River Reef Complex of Alberta, Jenik and Lerbekmo
<table>
<thead>
<tr>
<th>NAME OF CARBONATE COMPLEX</th>
<th>AREAL EXTENT OF CARBONATE COMPLEX</th>
<th>THICKNESS OF COMPLEX</th>
<th>AVERAGE MARGINAL SLOPES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keg River Reef Complex, Rainbow Member (Langton and Chin, 1969)</td>
<td>Less than 20 square miles</td>
<td>800 feet</td>
<td>Approximately 15 degrees</td>
</tr>
<tr>
<td>Carson Creek North Reef Complex (Leavitt, 1968)</td>
<td>Approximately 24 square miles</td>
<td>350 feet</td>
<td>Approximately 5 degrees</td>
</tr>
<tr>
<td>Swan Hills Member, Judy Creek (Murray, 1966)</td>
<td>Approximately 50 square miles</td>
<td>400 feet</td>
<td>Approximately 5 degrees</td>
</tr>
<tr>
<td>Redwater Reef Complex (Klovan, 1964)</td>
<td>230 square miles</td>
<td>1035-1190 feet</td>
<td>Approximately 4.5 degrees</td>
</tr>
<tr>
<td>Goose River Reef Complex (Jenik and Lerbekmo, 1968)</td>
<td>Approximately 35 square miles</td>
<td>180 feet</td>
<td>Approximately 2 degrees</td>
</tr>
<tr>
<td>Swan Hills Member, Swan Hills Reef Complexes (Fischbuch, 1968)</td>
<td>Approximately 40 square miles</td>
<td>400 feet</td>
<td>Approximately 2 degrees</td>
</tr>
<tr>
<td>Winnipegosis Banks</td>
<td>Smallest is approximately 150 square miles. Largest is over 1000 square miles</td>
<td>345 feet</td>
<td>Less than 2 degrees</td>
</tr>
<tr>
<td>Andros Island, Bahama Banks (Newell and Rigby, 1957)</td>
<td>Estimated at 60,000 square miles</td>
<td>over 14,000 feet</td>
<td>Varies from 90 degrees at marginal escarpment to 3-4 degrees on outer platform, Andros Island</td>
</tr>
</tbody>
</table>

Table 6: Comparison of Winnipegosis Banks with other Carbonate Complexes
(1968, p. 25) observed similar re-entrants and suggested that they represent channels between the lagoonal part of the reef complex and deeper, open water. It is unlikely that the re-entrants in Winnipegosis banks have a similar origin, and they may be simply a result of current action.

Organisms as Environmental Indicators

General remarks. - Figure 14 is a generalized diagram illustrating the distribution of different organisms throughout the various members and lithologic units of the Winnipegosis Formation in the area of study. It was thought that a study of the distribution of these organisms might provide an interpretation of the environments of deposition, particularly of the Upper Winnipegosis Member. The different rock types observed in the Upper Winnipegosis Member are also illustrated (Pl. 4 and Fig. 15).

Figure 15 illustrates the distribution of many of the same organisms in carbonate complexes which have been studied by other workers. Table 7 acknowledges the various other carbonate complexes which were used as a comparison with the Winnipegosis Formation. It must be made clear at this time that studies of Devonian carbonate complexes of western Canada were used as the main sources for information because these complexes occupy much the same general frame-work as the Winnipegosis Formation.

The following organisms are thought to be particularly useful as environmental indicators.
Figure 15: Distribution of different organisms throughout several carbonate complexes
Figure 14: Distribution of various organisms, rock types, and lithologic features throughout the Winnipegosis Formation
<table>
<thead>
<tr>
<th>AUTHOR</th>
<th>AREA OF STUDY</th>
<th>EPOCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newell et al. (1953)</td>
<td>Permian Reef Complex, Guadalupe Mountains region, Texas and New Mexico</td>
<td>Permian</td>
</tr>
<tr>
<td>Lowenstein et al. (1956)</td>
<td>Niagaran reefs of the Great Lakes area</td>
<td>Middle Silurian</td>
</tr>
<tr>
<td>Klovian (1964)</td>
<td>Redwater Reef Complex, Alberta</td>
<td>Upper Devonian</td>
</tr>
<tr>
<td>Murray (1966)</td>
<td>Reef-fringed bank, Swan Hills Member, Judy Creek, Alberta</td>
<td>Upper Devonian</td>
</tr>
<tr>
<td>Leavitt (1968)</td>
<td>Carson Creek North Reef Complex, Alberta</td>
<td>Upper Devonian</td>
</tr>
<tr>
<td>Fischbuch (1968 A, B)</td>
<td>Swan Hills Reef Complex, Alberta</td>
<td>Upper Devonian</td>
</tr>
<tr>
<td>Jenik and Lerbekmo (1968)</td>
<td>Swan Hills Reef Member, Goose River field, Alberta</td>
<td>Upper Devonian</td>
</tr>
</tbody>
</table>

Table 7: Studies of Organisms as Environmental Indicators
LEGEND:

- • Boreholes in which the upper member is not present
- ○ Boreholes in which the upper member is not completely penetrated
- • Boreholes in which the upper member is completely penetrated
- — Contour interval 50 feet
- —— Approximate contour
- ——— Approximate zero edge of the upper member

Figure 16 ISOPACH MAP OF THE UPPER WINNIPEGOSIS MEMBER
Stromatoporoids. Various growth forms of stromatoporoids -- massive, tabular, bulbous, and dendroid -- have been recognized. It generally is believed that the various growth forms are environmentally controlled.

Massive stromatoporoids have been found in the peripheral organic and fore-bank units of the Upper Winnipegosis Member (Fig. 14). These organisms range up to 12 cm in thickness, are heavily abraded, and are randomly orientated. No evidence for growth of massive stromatoporoids in situ could be found. These observations suggest that massive stromatoporoids probably inhabited a turbulent-water, marine environment.

Klovan (1964, p. 35) made several observations pertaining to the ecology of massive stromatoporoids in the Redwater Reef Complex and concluded that they inhabited a shallow, turbulent-water, marine environment. Fischbuch (1968A, B) and Leavitt (1968), in their respective studies, both agreed with this conclusion, as did Jenik and Lerbekmo (1968, p. 35), who reported massive stromatoporoids in a reef-rim position, i.e. a high-energy environment, in the Goose River Reef Complex.

Tabular stromatoporoids have been found in the peripheral organic and fore-bank units of the Upper Winnipegosis Member (Fig. 14). These organisms usually are less than 3 cm thick and are flat-lying. In the peripheral organic unit, tabular stromatoporoids are fragmented and generally less than 1 cm in thickness. In the fore-bank unit, they are flat-lying and less fragmented.
Klovan (1964, p. 36), in his study of the Redwater Reef Complex, made several observations about tabular stromatoporoids and concluded that these organisms inhabited both turbulent and quiet-water environments, but were more abundant in a quiet-water environment. In the Winnipegosis Formation, tabular stromatoporoids were found in both pelleted grainstones and argillaceous lime-muds, and probably inhabited both turbulent and quiet-water environments.

Fischbuch (1968B, p. 500) stated that most of the tabular stromatoporoids of the Swan Hills Reef Complexes are found in the reef platform, and encrust previously deposited sediment. It appears that algae, and not tabular stromatoporoids, are the dominant sediment-binders in the Upper Winnipegosis Member.

Bulbous stromatoporoids are spherical to oblate in shape and are up to 5 cm in diameter. They have been found in the peripheral organic unit of the Upper Member, but are not in growth position and usually are abraded. The matrix consists of a pelleted, biofragmental grainstone, with common crinoid ossicles, calcispheres, ostracods, algae, and Amphipora sp. (Fig. 14). These observations suggest that the organism probably inhabited turbulent waters.

In their respective studies, Murray (1966, p. 17) and Leavitt (1968, p. 325) had different opinions in regards to bulbous stromatoporoids. Murray made several points pertaining to their ecology and concluded that they probably inhabited quiet, restricted waters such as may have existed in a broad shelf lagoon. On the other hand, Leavitt observed that specimens of bulbous stromatoporoids were well-
rounded, showed no means of attachment, and commonly were coated with a thin layer of micritic or algal material. He suggested, therefore, that bulbous stromatoporoids probably lived in turbulent waters and, after death, became eroded and transported by rolling into quieter waters.

*Amphipora sp.* is the most common dendroid stromatoporoid found in the Upper Winnipegosis Member. It is characterized by a rod-like shape and generally is less than 5 mm in diameter. *Amphipora sp.* is to be differentiated from *Stachyodes sp.*, which may be up to 1 cm in diameter and lacks the marginal vesicles of *Amphipora sp.*

*Amphipora sp.* is common in the pelleted grainstone unit and in fore-bank strata. In the grainstone unit, colonies usually are flat-lying and very fragmented, but rarely are orientated perpendicular to bedding and may be in growth position. *Amphipora sp.* is more common, however, in fore-bank strata, where specimens are flat-lying in a lime-mud matrix.

According to Klovan (1964, p. 38), *Amphipora sp.* occurs in almost all of the limestones of the Redwater Reef Complex, although it is most abundant in the back-reef deposits of the Upper Leduc unit of the Leduc Formation. Klovan (1964, p. 38) indicated that *Amphipora sp.* is most abundant in limestones regarded as quiet-water deposits, but not those of a fore-reef position. This indicates that it may have preferred the less-oxygenated, possibly more saline waters in back-reef areas. Fischbuch (1968A, p. 66) agreed with this conclusion and
suggested that the marked salinity and temperature variation in lagoonal areas could be tolerated only by *Amphipora* sp. In their respective studies, Murray (1966, p. 18-19), Leavitt (1968, p. 326), and Jenik and Lerbelmo (1968, p. 37) all agreed that *Amphipora* sp. was more common in sediments deposited in a back-reef position.

The occurrence of *Amphipora* sp. in association with calcispheres, foraminifers, ostracods, and algae in the pelleted grainstone unit suggests that the organism may have favored shallow, slightly restricted, marine waters. This is in general agreement with the findings of other workers.

The presence of *Amphipora* sp. in extensively dolomitized and argillaceous lime-mud in a fore-bank position is more difficult to explain. For example, *Amphipora* sp. is the dominant organism in the fore-bank unit cored in two boreholes -- Pheasant Sinclair Valley Center (Lsd. 9-21-33-15 W 3) and Pheasant Husky D.H. Livelong (Lsd. 1-35-51-21 W 3) -- in which the Upper Winnipegosis Member is less than 150 feet thick.

No other organism is present in the core from these boreholes. It seems unlikely that *Amphipora* sp. was transported to these locations in preference to any other organism, therefore, it is concluded that *Amphipora* sp. must have been tolerant of marine environments other than those found in a back-reef position.
Corals. - Odd solitary and compound rugose corals and many colonial tabulate corals have been recognized in the Winnipegosis Formation. Corals are most common in the Upper Winnipegosis Member and include *Hexagonaria* sp., *Alveolites* sp., *Favosites* sp., and *Thamnopora* sp. The distribution of corals has been illustrated (Fig. 14).

Corals probably are more common than stromatoporoids in the Winnipegosis Formation. They are particularly common in the peripheral organic unit and in the fore-bank unit of the Upper Member. *Alveolites* sp. is the most abundant genus. At least two growth forms have been recognized: subspherical colonies, up to 5 cm in diameter, and thinner encrusting layers, less than 2 cm in thickness (Pl. 5, Fig. 2). In the Canadian Seaboard Divide no. 1 core (Lsd. 10-16-56-14 W 3), *Alveolites* sp. may have been preserved in growth position. The matrix in this core ranges from pelleted grainstone to argillaceous lime-mud.

According to Klovan (1964, p. 39), *Alveolites* sp. is the most common coral genus in the Redwater Reef Complex. The growth form of the organism is variable, as is the matrix in which it is found. Klovan concluded, therefore, that *Alveolites* sp. was tolerant of a wide range of marine environments.

Jamieson (1967, p. 160-161) reported *Alveolites* sp. as being the most common coral genus in the Alexander Reef Complex. The organism is most common in sediments interpreted by Jamieson to be fore-reef and proto-reef deposits.
In the Winnipegosis Formation, *Alveolites* sp. have been found in pelleted grainstones and in argillaceous lime-muds, indicating that it probably was tolerant of both turbulent and quiet-water marine waters.

*Favosites* sp. and *Hexagonaria* sp. are present, but not common, in the peripheral organic and fore-bank units. *Favosites* sp. has been found in both a pelleted grainstone and an argillaceous lime-mud matrix, whereas *Hexagonaria* sp. usually is found in an argillaceous lime-mud matrix. Most corallites appear to have been flattened to some extent.

Fragments of *Thamnopora* sp. have been found in almost all units of the Upper Winnipegosis Member except the laminated mudstone and fringing cap units.

According to Fischbuch (1968B, p. 531), tabulate and rugose corals did not form wave-resistant structures in the Swan Hills Reef Complexes, although rare tabulates (*Thamnopora* sp. and *Coenites* sp.) are intergrown with frame-building stomatoporoids. Locally, tabulate corals comprise 30 percent of the rock volume of the lowermost Swan Hills division (Fischbuch, 1968B, p. 476). The matrix for this division consists of fine-grained fossil debris, micrite, and dark-colored, bituminous or argillaceous material in stylolites. Fischbuch suggested that this unit probably was deposited on a broad shoal, where organisms were not subjected to severe, near-surface wave action, but thrived below the wave base, where currents traversed the sea bottom.
The colonial rugose and tabulate corals of the Winnipegosis Formation are present in sediments interpreted to have been deposited in marine environments ranging from turbulent to quiet-waters. However, they are not present in sediments which were deposited in restricted marine environments.

**Brachiopods.** - Brachiopods are very persistent fossils throughout the Winnipegosis Formation. Articulated and fragmented, punctate and impunctate brachiopods are present within the oncolitic packstone and intraformational conglomerate units of the Lower Member. Articulated, impunctate brachiopods are present in most units of the Upper Member (Fig. 14), and are most common in pelleted grainstones and in forebank units. They are not present in the laminated mudstones or in the fringing cap unit. Within pelleted grainstones, the interiors of brachiopods have been plugged by gypsum in some places.

Newell *et al.* (1953) reported brachiopods in the reef and fore-reef facies, but not in back-reef facies, of the Permian reef complex of the Guadalupe Mountains of Texas and New Mexico. In their respective studies, both Murray (1966, p. 20) and Leavitt (1968, p. 327) noted that brachiopods appear to have been able to adapt themselves to a wide variety of environments, however, they are rare in those sediments which were deposited in back-reef areas.

The widespread distribution of brachiopods throughout the Winnipegosis Formation is evidence to suggest that they were adaptable. In the pelleted grainstone unit, brachiopods are associated with calcispheres, algae, ostracods, and *Amphipora* sp. These generally
are considered to have been most common in sediments which were deposited in back-reef areas (Fig. 15). In a fore-bank position, however, brachiopods are associated with corals and stromatoporoids. These organisms are more common in those sediments which were deposited in a turbulent-water, marine environment.

**Crinoids.** Crinoid debris is common throughout much of the Lower and Upper Winnipegosis Members, and probably is the most abundant type of organic remains. In rocks with a fine-grained matrix, crinoid ossicles remain articulated and are not fragmented. In contrast, they commonly are fragmented in rocks with a pelleted grainstone matrix.

Klovan (1964, p. 41) suggested that crinoids grew in the deep, quiet-water environment of the lower fore-reef slope and basin of the Redwater Reef Complex, as well as in sheltered areas of the reef. In their study of the Goose River Reef Complex, Jenik and Lerbekmo (1968, p. 39) found that crinoid ossicles were most abundant and remained articulated in the dark, argillaceous sediments of the fore-reef slope, indicating that these organisms preferred a quiet-water environment. Jamieson (1967, p. 171) maintained that crinoids flourished best in a deeper, quiet marine environment in the Alexandra Reef Complex.

On the other hand, Leavitt (1968, p. 328) observed that crinoids probably grew in the more sheltered parts of the Carson Creek North Reef Complex and in the relatively shallow, agitated waters of the fore-reef slope. He inferred that the fragmented nature of crinoid ossicles in the fore-reef position implied that crinoid ossicles were
transported to a quiet-water environment.

The persistence of crinoid ossicles throughout much of the Winnipegosis Formation, irrespective of differences in lithology, is taken as evidence that these organisms inhabited both turbulent and quiet-water environments. Crinoid debris occasionally remains articulated in sediments with a fine-grained matrix, however, for the most part, individual crinoid ossicles are present in different rock types, and crinoids probably inhabited a wide range of marine environments.

**Gastropods.** Both high- and low-spired gastropods have been found within the Winnipegosis Formation. Usually fragmented, they are most common in the oncolitic packstones of the Lower Member and in Upper Winnipegosis fore-bank rocks, in which they form nuclei for oncoliths (Pl. 5, Fig. 3). They are also present in pelleted grainstones of the Upper Member. Such a distribution suggests that these organisms inhabited a wide variety of marine environments, ranging from restricted to normal marine and characterized by quiet to turbulent waters.

**Newell et al.** (1953) pointed out that gastropods were adaptable animals, and are especially abundant in back-reef sediments of the Permian reef complex of the Guadalupe Mountains of Texas and New Mexico. In their respective studies, Klovan (1964), Murray (1966), and Leavitt (1968) all agreed that both high- and low-spired gastropods were tolerant of marine environments ranging from turbulent to quiet-waters.
Ostracods. - Ostracods are rare but persistent fossils throughout most of the Winnipegosis Formation. They are most common in argillaceous-carbonaceous mudstones of the Lower Member and usually flattened. They are associated with cricoconarids, tasmanitids, and immature brachiopods in these rocks. They probably lived in a quiet-water environment which was not conducive to an abundant and varied fauna. Ostracods are also common in pelleted grainstones in fore-bank rocks of the Upper Member. This suggests that they inhabited slightly restricted, agitated-water environments as well.

In their respective studies, Klovan (1964, p. 41), Murray (1966, p. 21), Leavitt (1968, p. 328), and Jenik and Lerbekmo (1968, p. 40) all reported that ostracods were more common in muddy-textured sediments of a back-reef to lagoonal environment, where salinities probably were above normal.

Bryozoans. - Bryozoans are rare fossils in the Winnipegosis Formation and have been found in the oncolitic packstones of the Lower Member and in the fore-bank unit of the Upper Member, where they rarely are present in oncoliths. Bryozoans always are fragmented and are found in rocks with an argillaceous lime-mud matrix, indicating that they preferred turbulent to quiet-water environments, with normal salinities. Newell et al. (1953) and Leavitt (1968, p. 328) found bryozoans dominantly in the reef and fore-reef positions of reef complexes.

Calcispheres. - Spherical spinose calcareous organisms, known as calcispheres, are common in the Upper Winnipegosis Member. They are most
common in pelleted grainstones and wackestones, and are rare in the argillaceous, fossiliferous packstones of the fore-bank unit (Pl. 4).

There are at least two types of calcispheres present: although of comparable size, one bears only a few large spines and the other numerous small spines (Pl. 5, Figs. 4 and 5).

Calcispheres are most commonly associated with Amphipora sp., ostracods, crinoids, foraminifera, and algae. Individual specimens usually are abraded and some of the spines broken, probably as a result of abrasion during transportation.

Calcispheres are most common in rocks thought to have been deposited under shallow, turbulent, slightly restricted, marine conditions.

Calcispheres have been found in several carbonate complexes in Alberta. Johnson and Konishi (1958, p. 104) suggested that the extensive and widespread distribution of calcispheres is a result of their marine pelagic habit. On the other hand, Klovan (1964, p. 43) noted that calcispheres are most common in the deposits of a quiet back-reef environment. Jenik and Lerbekmo (1968, p. 40) found calcispheres to be dominantly lagoonal organisms.

Foraminifera. - Foraminifers are persistent but never common in the Winnipegosis Formation, and usually are found in pelleted grainstones and fore-bank rocks in the Upper Member. The foraminifers were tentatively assigned to two different genera -- Parathurammina sp. and
Wetheredella sp. Recognition of these organisms is based on the illustrations of Johnson (1964), Toomey (1965), and Toomey et al. (1970).

Parathurammina sp. closely resembles calcispheres in that it has spiny protuberances. However, calcispheres are spherical in shape, whereas Parathurammina sp. has an oblate shape (Pl. 5, Figs. 6 and 7). It appears to have occupied the same ecologic niche as calcispheres; i.e., that of relatively shallow and quiet-water conditions (Toomey, 1965; Toomey et al., 1970).

Johnson (1964, Pl. 29, Figs. 3 and 4) illustrated a tiny, bean-shaped organism, which he named Wetheredella sp. Clusters of similar, bean-shaped organisms have been found in the fore-bank rocks cored in the Imperial Barnes no. 1-33 borehole (Lsd. 1-33-61-17 W 3). They are less than 0.25 mm in diameter and have a radial internal structure (Pl. 5, Figs. 8 and 9). Isolated specimens are surrounded by a lime-mud matrix, and clusters of them are found in algal(? ) oncoliths. These organisms probably were tolerant of a wide range of marine conditions, including quiet- to agitated-waters.

Algae. - Algal material has been found throughout the Winnipegosis Formation and, next to crinoids, is probably the most common kind of fossil remains.

The environment of deposition of the algal oncoliths of the Lower Member has been discussed previously. Ginsburg (1960, Table 1, p. 29)
reported oncoliths forming in a marine environment in less than 8 feet of water. Johnson (1961, p. 37) stated that the Schizophyceae, which includes (?)Girvanella sp., inhabit marine, brackish, and freshwater environments, and that most of the marine forms grow in the inter-tidal zone.

Several different species of algae have been found in the Upper Winnipegosis Member. They are present in all units but are most abundant in pelleted grainstones and in the argillaceous lime-mud matrix of fore-bank rocks.

In the fore-bank rocks, clasts of filamentous blue-green algae have been observed (Pl. 6, Fig. 1), as have two-walled, sac-like forms (Pl. 6, Fig. 2) similar to dasycladacean algal sacs described by Jamieson (1967). Other forms, tentatively identified as Lanciaia cf. alta Maslov and Litanaia sp. or possibly Protoslavina sp. (Pl. 6, Figs. 3 to 8) have been found. These closely resemble the specimens illustrated by Johnson and Konishi (1958, Pl. 12, p. 44 and Pl. 24, p. 74) and Johnson (1961, Pl. 111-113, p. 239-241).

Individual specimens of Litanaia sp. or Protoslavina sp. are severely abraded. In longitudinal section (Pl. 6, Figs. 3, 4, and 5), a central canal, up to 0.3 mm in diameter, can be seen. Smaller canals, up to 0.15 mm in diameter, appear to branch from the main canal. In transverse section, there is either one or four central canals, surrounded by as many as 13 smaller ones (Pl. 6, Figs. 6, 7, and 8).
In the pelleted grainstone unit (Pl. 4), dasycladacean algal sacs, filamentous algal clasts, Lancicula cf. alta, and Vermiporella sp. have been recognized. In longitudinal section (Pl. 6, Figs. 8 and 9), Lancicula cf. alta shows a regular branching of smaller canals about a central canal. In transverse section (Pl. 6, Fig. 10), a central canal, 0.4 mm at maximum diameter, can be seen, surrounded by as many as 13 smaller canals.

Vermiporella sp. colonies are up to 1 mm in diameter and consist of a mosaic of small polygonal canals which, in transverse section (Pl. 6, Fig. 11), are about 0.05 mm in diameter.

Algae are associated with a varied fauna in the Winnipegos Formation carbonate banks. They are most common in the pelleted grainstone unit, associated with calcispheres, crinoids, ostracods, Amphipora sp., and foraminifers. The sediments in this unit probably were deposited in a shallow, slightly restricted, turbulent-water, marine environment.

In a fore-bank position, algae are commonly present in an argillaceous lime-mud matrix, indicating that they may have preferred a quiet-water marine environment.

In her study of the Alexandra Reef Complex, Jamieson (1967, p. 153) stated that dasycladacean algae were important sediment producers in restricted muddy lagoons, whereas blue-green algae were important sediment stabilizers in very shallow water on the reef-flat and around the margins of restricted lagoons. Algae present in the Winnipegos Formation appear to have been tolerant of a wide range of marine environments.
LITHOLOGY AND PETROLOGY OF THE UPPER WINNIPEGOSIS MEMBER

General Remarks

Discussion of units. - Several problems arise in any attempt to establish definite facies relationships within Upper Winnipegosis banks. These include the following:

1) insufficient well control and core from any one bank;

2) extensive dolomitization and recrystallization, which destroys original textures;

3) a lack of any persistent lithological marker, which might have time-stratigraphic significance; and

4) a lack of diagnostic fossil assemblages which could be used to establish zones.

The most serious problem is that there is a limited amount of core from any one bank. An entire Upper Winnipegosis bank is cored in only two boreholes in the area of study and generally only small portions of the banks are cored.

Nevertheless, evidence from the cores is sufficient to suggest that both lateral and vertical variations of lithology and fauna occur in Upper Winnipegosis banks. Six different lithologic units can be recognized:

1) Laminated mudstone unit;

2) Pelleted grainstone unit;

3) Peripheral organic unit;

4) Fore-bank unit;
Laminal Mudstone Unit

Distribution, thickness, and macroscopic descriptions. - Dense, fine-grained, light-to-medium brown, extensively dolomitized carbonate mudstones form the bulk of the interior of the two largest banks in the study area. These mudstones are indistinctly laminated throughout. The vague laminations are caused by numerous, regularly-spaced, argillaceous-carbonaceous partings and stylolites. Laminations are most pronounced in the upper 40 feet of the unit.

Thickness of the unit ranges up to a known maximum of 125 feet (measured from core) in the Banff et al. Asquith borehole (Lsd. 13-1-38-8 W3). The mudstone unit overlies the pelleted grainstone unit and in places underlies the fringing cap unit (Pl. 4).

At least three different rock types are present within the upper 40 feet of the laminated mudstone unit. In ascending order, these are dolomite laminitie, dolomite and anhydrite with algal nodules, and laminated dolomite mudstone with enterolithic anhydrite. The same lithologic sequence can be traced in two boreholes, which are 60 miles apart and in two different banks. These boreholes are UOHL Parkside
no. 8-5 (Lsd. 8-5-47-4 W 3) and Banff et al. Asquith (Lsd. 13-1-38-8 W 3).

The lowermost rock type is a dark-brown, cryptocrystalline, dolomite laminité. Laminae are of uneven thickness, up to 7 mm thick, and bounded by thin, argillaceous-carbonaceous partings and stylolites. Locally, these laminae appear to be brecciated and reworked, giving an intensely mottled white-to-brown-colored rock. In this mottled rock, regular laminae are broken by small, anhydrite-plugged, vertical fractures. Regularly laminated beds are interspersed with disturbed and reworked beds in a vertical direction, indicating that brecciation or reworking took place during or shortly after deposition of the sediments. In thin sections, vague pseudo-pelleted forms, less than 1 mm in diameter, produce a "clotted grumeleuse" texture, which perhaps is the result of recrystallization. Mosaics of submillimeter-sized anhydrite needles commonly occur in the lime-mud matrix.

The middle rock type consists of a mottled, intermixed dolomite and anhydrite, with rod-shaped and spherical bodies probably of algal origin (Pl. 7, Figs. 1 and 2). Spherical forms are less than 1 cm in diameter, and consist of vaguely concentric laminations of cryptocrystalline dolomite. The rod-shaped bodies, up to 1 mm in diameter and 5 mm in length, are encased in a micritic coating. In thin section (Pl. 7, Fig. 2), a vague internal structure suggests a probable algal origin. A "clotted grumeleuse" matrix, probably the result of recrystallization, is common in this rock type.
The uppermost rock type is a brown dolomite laminit with rounded blebs of white to grey anhydrite. Laminae are disrupted locally by blebs of anhydrite and thin layers of enterolithic anhydrite. The contrast with the overlying Shell Lake Member of the lower Prairie Evaporite Formation is transitional, with an increase in anhydrite in a vertical direction. At some locations, however, laminated mudstones are overlain by the fringing cap unit (Pl. 4).

Fossils and paleoecology. - Questionable algal forms constitute the only fossil remains in this unit. The environment of deposition of the sediments in this unit must not have been conducive to organic life. The fine-grained nature of the matrix and the presence of laminations is taken as evidence that these sediments were deposited in a quiet-water environment. In a vertical direction, the interbedding of well-laminated beds with fractured and reworked beds is evidence to suggest a shallow-water environment of deposition, with episodes of emergence and erosion.

The position of the laminated mudstone unit within central areas of Upper Winnipegosis banks is significant because it indicates that the sediments of this unit were deposited during late stages of Winnipegosis bank development. The uppermost sediments of this unit probably were deposited under conditions of increasing restriction and above normal salinities very late in Winnipegosis time.

One important observation which should be stressed at this point is that a gradational relationship usually exists between the laminated
mudstones and the overlying Shell Lake Member of the lower Prairie Evaporite Formation. This is some evidence to suggest that Winnipegosis banks were not completely exposed as a result of a profound drop in relative water-level after the formation of the Winnipegosis banks. Other workers, especially Fuller and Porter (1969) and Shearman and Fuller (1969B), have suggested that a profound drop in sea-level did take place after the cessation of Winnipegosis bank development.

**Pelleted Grainstone Unit**

**Distribution, thickness, and macroscopic description.** - Pelleted grainstones and packstones are the most laterally extensive lithology encountered in the study area and form the bulk of the Upper Winnipegosis banks. This unit attains a maximum known thickness of 109 feet in the core of the UOHL Parkside no. 8-3 borehole (Lsd. 8-3-48-5 W 3). In a central bank position, this unit is overlain by the laminated mudstone unit, as in the Banff et al. Asquith borehole (Lsd. 13-1-38-8 W 3). However, towards the perimeter of banks, pelleted grainstones are overlain by the fringing cap unit.

The pelleted grainstone unit was encountered in three banks in the area of study, but is most widespread in the southernmost bank (Fig. 16), where it can be traced horizontally for 60 miles.

The unit consists of light- to medium-brown, fine- to medium-grained, pelleted grainstones and packstones. It may be limestone, as in core from the Seaboard Meadow Lake Crown no. 1 borehole (Lsd. 13-21-61-15 W 3), or it may be altered completely to dolomite. Jones (1965,
p. 19) referred to the pelletal/lump/biofragmental lithology of Upper Winnipegosis banks -- this unit compares in lithology to the rocks described by him.

Constituent fragments include pellets, skeletal debris, intraclasts, grapestone clumps, and clasts of filamentous algae. The matrix consists of a lime-mud, which is extensively recrystallized in some places. Where there is little lime-mud, a sparry granular cement dominates and, in places, forms a syntaxial rim around crinoid ossicles.

Pellets and intraclasts have a variety of shapes. Some pellets are well-rounded and have no internal structure; others are rod-like and appear to intertwine. These rod-like pellets are approximately 0.1 mm in diameter and 0.4 mm long. Commonly, the pellets and skeletal debris are clumped together and are coated by a fine micrite so as to resemble a "grapestone", "botryoidal lumps" and "encrusted lumps" of Illing (1954). This feature has been illustrated (Pl. 7, Fig. 3).

The packstones differ from grainstones in that the skeletal debris of packstones commonly is deformed and elongate in the plane of bedding, possibly as a result of compaction. Packstones are also characterized by the presence of a fine-grained, grey sparry calcite, which may be either a fine granular cement or a product of recrystallization.

One characteristic feature of this pelleted unit is the presence of what has been called "birdseye structure" by Shinn (1968) or
"radiaxial fibrous mosaic" by Bathurst (1959, p. 506). This consists of a white- to brown-colored rind lining vugs and cavities and coating clasts (Pl. 7, Figs. 4 and 5). This rind generally is less than 5 mm thick and shows concentric banding (Pl. 7, Fig. 5). Gypsum or anhydrite is usually present within cavities coated by birdseye structure.

This birdseye coating is fragmented in some places and fragments appear to be enclosed in the anhydrite or gypsum. This indicates that the cavities were formed and lined by birdseye structure prior to fracturing and plugging by anhydrite. The rind, however, does not floor cavities preferentially and is not an internal sediment.

Illing (1954, p. 36-37) suggested six possible causes for birdseye structure:

1) Water droplets in a lime-mud gel;
2) Algae;
3) Gas bubbles;
4) Anhydrite;
5) Shrinkage; and
6) Diagenetic recrystallization.

Shinn (1968, p. 215) also suggested that the structure formed as a result of gas bubbles and shrinkage and dessication. He considered the structure to be important in that he believed it to be restricted to deposits of supratidal to intertidal environments.

Studies of thin sections reveal that the structure is composed of grey- to brown-colored, drusy, fibrous mosaics, which are orientated
normal to the original surface of growth, and commonly, mosaics are cut by concentric bands (Pl. 7, Fig. 5), indicating that the formation of birdseye structure probably was a discontinuous process. The banding may also indicate that drusy mosaics were precipitated from solutions of varying composition. Dolomite rhombs are present along these concentric bands (Pl. 7, Fig. 5). Individual grains in the drusy mosaic have undulose extinction but do not have planer boundaries. Bathurst (1959) concluded that drusy mosaics, similar to those described, formed by chemical precipitation on the walls of post-depositional cavities in the primary sediment.

Another feature worthy of note is the concentric banding found in subspherical, grapestone-like bodies, which recalls the "colloform" texture described by Roedder (1958) in sphalerite ores. This banding probably formed in the same manner as the "radial fibrous mosaics" of Bathurst (1959) (Pl. 7, Fig. 6).

The pelleted grainstone unit has no apparent bedding and appears to have been brecciated and reworked. Most of the cavities and voids are angular or lens-shaped, and some appear to be roofed-over (Pl. 8, Fig. 1). These probably were formed during deposition of the sediments and are not a result of leaching. Some of the cavities appear to have been caused by a loose packing of partially cemented fragments and clasts. It appears as though any early binding or cementation process was disrupted repeatedly, probably by wave and current action or else by borrowing organisms.
A simplified sequence of events can be reconstructed, as follows: (1) deposition of pelleted, fossiliferous grainstones; (2) partial binding and cementation of these sediments; and (3) repeated disruption of the binding and cementation processes by erosion and reworking.

Gypsum and anhydrite both are present within cavities. Whereas gypsum usually exists as a single crystal completely filling a vug, anhydrite is more common as a mosaic of fine, needle-like crystals. Anhydrite usually has been replaced by gypsum.

A notable proportion of dolomite is present in the pelleted grainstone unit. Quite apart from that which is a product of the widespread dolomitization of the unit, dolomite is also present as finely crystalline rhombs concentrated along concentric bands in the birdseye structure and also as a finely disseminated mosaic of rhombs in gypsum and anhydrite (Pl. 8, Figs. 1, 2, and 3). In some cases, dolomite rhombs are formed in the lower portions of a roofed-over cavity (Pl. 8, Fig. 1), whereas gypsum plugs the upper portion. This occurrence of dolomite in the lower part of a cavity may indicate that at least some dolomitization pre-dates the plugging of vugs by gypsum and anhydrite.

Dendroid stromatoporoids are especially susceptible to recrystallization. Much of their internal structure has been destroyed and replaced by sparry calcite.

Purple fluorite, plugging a void of about 1 cm in diameter, has been observed in the pelleted grainstones of the Mobil Oil Von Mehren
Lake X-8-15 core (Lsd. 8-15-52-2 W 3). The origin of this fluorite is not known.

**Fossils and paleoecology.** - Figure 14 illustrates the fauna of the pelleted grainstone unit. As can be seen, calcispheres, *Amphipora* sp. foraminifers, crinoids, articulate brachiopods, ostracods, and algae are the dominant organisms. Tabulate corals and gastropods are less common. Most of the skeletal debris is severely abraded and fragmented or disarticulated. In other carbonate complexes (Fig. 15), most of these organisms have been found in sediments which were deposited in quiet- to turbulent-waters of above normal salinity. The fragmented and abraded nature of these organisms is evidence that they have been transported in a turbulent-water environment.

On the other hand, the presence of rare tabulate corals and articulated brachiopods in these sediments suggests that the environment of deposition was of normal marine salinity.

The relative absence of lime-mud in the sediments of the pelleted grainstone unit, as well as the fragmented and reworked nature of the grainstones, is evidence that these sediments were deposited in a turbulent-water environment.

The environment of deposition of the sediments of this unit is, therefore, taken to have been a shallow, turbulent-water environment, with slightly above normal salinities.
Peripheral Organic Unit

**Distribution, thickness, and macroscopic description.** - The peripheral organic unit is characterized by the presence of organisms, which, under suitable conditions, have the ability to build reefal frameworks. These organisms include tabulate corals and stromatoporoids. Only 12 of the 50 boreholes from which core was examined contained frame-building organisms. As can be seen from Figure 6, most of these boreholes occupy positions along the margins of Winnipegosis banks. Frame-building organisms locally comprise 20 to 30 percent of the volume of some cores. Very little evidence for growth of these organisms in situ could be found.

Two rock types can be recognized in the peripheral organic unit (Pl. 8, Figs. 4 and 5). In the southern and central part of the area of study, the unit consists of a pelleted, biofragmental grainstone, whereas, in the northern part of the area (and particularly northwest of the Meadow Lake Escarpment), argillaceous-carbonaceous, fossiliferous wackestone and packstone are dominant.

Thickness of the pelleted biofragmental grainstones in the peripheral organic unit is variable, ranging up to 57 feet in the core of the Pheasant Sun Birch Lake borehole (Lsd. 16-10-51-15 W 3). The matrix is a light-brown, medium-grained, pelleted grainstone.

Both lithology and fauna of the pelleted biofragmental grainstones are similar to the pelleted grainstone unit. However, massive,
tabular, and bulbous stromatoporoids and tabulate corals are the dominant skeletal remains. Massive stromatoporoids, up to 12 cm thick, and bulbous stromatoporoids, up to 5 cm in diameter, usually are abraded and have no preferred orientation. Sparry calcite within the structure of these organisms has been recrystallized, whereas, much of the original skeletal structure has been altered to a mosaic of dolomite rhombs. Tabulate corals are as abundant as stromatoporoids in the pelleted biofragmental grainstones. Alveolites sp. and Favosites sp. have been recognized. Colonies of Favosites sp. are up to 6 cm in diameter. They have been extensively dolomitized. Abraded fragments of Alveolites sp. are up to 3 cm in diameter and are not in growth position.

In the northern part of the area of study the organic unit consists of dark-brown, argillaceous-carbonaceous, fossiliferous packstone and wackestones. These rocks attain a known maximum thickness of 51 feet in the core of the Pheasant Placid Tenn Mornery River borehole (Lsd. 12-36-54-25 W 3). Frame-building organisms consist of massive and tabular stromatoporoids and tabulate corals, including those tentatively recognized as Alveolites sp. and Favosites sp. The compound rugose coral, Hexagonaria sp., also is present. Other organisms include crinoids, small brachiopods, algal debris, gastropods, foraminifers, rare algal(?) oncoliths, and calcispheres and algal debris in rounded clasts of pelleted grainstone. The matrix is an argillaceous-carbonaceous lime-mud. This rock type generally is not dolomitized, however, some recrystallization of the fossil debris has taken place.
Rounded clasts of pelleted lime-mud are present in the peripheral organic unit in the northern part of the study area. These clasts contain the same fauna as the pelleted grainstone unit within banks.

Sulphur has been found within the peripheral organic unit. It exists as a mosaic of euhedral, yellow grains, up to 4 mm across, which lines vugs in association with gypsum or anhydrite. It probably has been formed from sulphates by bacterial action. Sulphur is most common in core from the Pheasant San Birch Lake borehole (Lsd. 16-10-51-15 W 3).

**Fossils and paleoecology.** - In general, the presence of frame-building organisms, such as massive stromatoporoids, can be taken as evidence for a turbulent-water, normal marine environment (Fig. 15).

The tabulate coral, *Alveolites* sp., dominant in the peripheral organic unit of the northern part of the area of study, is present as either massive subspherical colonies, 2 to 5 cm in diameter, or irregular subrounded fragments. It usually is abraded and not in growth position. Most workers, including Klovan (1964), reported *Alveolites* sp. to have been common in a reef to fore-reef position.

In the southern part of the area of study, frame-building organisms are imbedded in a pelleted grainstone matrix, probably deposited in a shallow, agitated-water, slightly restricted, marine environment.

In the northern part of the area of study, the matrix for the
frame-building organisms consists of an argillaceous-carbonaceous, fossiliferous wackestone and packstone. Algal fragments, described as either *Litanaia* sp. or *Protoslavina* sp., are common.

Algal oncoliths consist of vaguely concentric, micritic coatings, which surround nuclei of corals, gastropods, or bryozoans (Pl. 8, Fig. 6). No algal filaments have been found in these oncoliths, but the rounded shape and encrusting habit are suggestive of an algal origin.

In the northern part of the area of study, the argillaceous-carbonaceous, fossiliferous packstones and wackestones probably were deposited in a quiet-water, normal marine environment. Presence of a fine-grained and argillaceous-carbonaceous matrix is evidence for deposition of the sediments in quiet-water, and the abundance and diversity of fauna indicates that normal marine conditions prevailed.

**Fore-bank Unit**

*Distribution, thickness, and macroscopic description.* - The fore-bank unit is most common in the western third of the area of study where Upper Winnipegosis banks are not as extensive (Fig. 16). There are again two major rock types in this unit -- a dolomitized *Amphipora* mudstone in the southern and central part of the area of study, and an argillaceous-carbonaceous packstone and wackestone in the northern part (Pl. 4).
In the southern and central part of the area, fore-bank strata consists of dense, fine- to medium-grained, extensively dolomitized Amphipora mudstones. The thickness of the rocks is at least 25 feet in the core of the Pheasant Sinclair Valley Center borehole (Lsd. 9-21-33-15 W 3) and at least 41 feet in the core of the Pheasant Husky DH Livelong borehole (Lsd. 1-35-61-21 W 3). The only recognizable fossil is Amphipora sp. which is not in growth position and is extensively dolomitized and recrystallized. The matrix is a dolomitized lime-mud, with numerous densely-spaced, black, argillaceous-carbonaceous partings and stringers.

These mudstones are present in the core of the Ceepee Keppel Forest no. 8-3 borehole (Lsd. 8-3-40-14 W 3), in which there are no visible fossils except for rare crinoid ossicles. In this core, however, rounded blebs, up to 5 cm in diameter and composed of mosaics of fine gypsum needles, appear to displace and replace the dolomitized lime-mud (Pl. 8, Fig. 7). Small needles of gypsum penetrate and appear to replace the original lime-mud matrix (Pl. 8, Fig. 8). Pyrite is common along the boundary between the gypsum and the lime-mud.

In the northern part of the area of study, fore-bank rocks attain a known maximum thickness of 57 feet in the core of the Imperial Barnes no. 1-33 borehole (Lsd. 1-33-61-17 W 3).

Three lithologic types can be recognized in the Imperial Barnes no. 1-33 borehole but these do not extend any great distance. The lowermost is a dark-brown, argillaceous and fossiliferous wackestone
which is in part conglomeratic. Articulated brachiopods, gastropods, tabulate corals, Litanaia sp. or Protslavina sp., Wetheredella sp., and crinoids are the dominant skeletal materials. Ostracods are also present. The matrix is a dark-brown, argillaceous lime-mud. Well-rounded clasts, up to 3.5 cm in diameter, and oncoliths are present in the lowest rock type. Many of the clasts are composed of a pelleted lime-mud and probably were derived from a nearby bank. The oncoliths consist of concentric micritic coatings about a nucleus of skeletal material. No algal filaments have been found, but the spherical shape and encrusting habit suggest an algal origin.

The middle rock type is a medium-brown, mottled packstone, with occasional black mudstone stringers. Lenses or thin bands of light-brown, pelleted grainstone are present, as are rounded clasts of the same material. These clasts are in a matrix of dark-brown micrite. Argillaceous-carbonaceous mudstringers appear to "flow" about the intra-clasts, giving the appearance of boudinage structure.

The upper rock type consists of olive-grey to dark-brown wackestone with numerous laminae or beds of argillaceous-carbonaceous mudstone containing tasmanitids and cricoconarids. The mudstone laminae are of the same lithology and have the same faunal content as those at the top of the Lower Winnipegosis Member (Pl. 2, Figs. 1 and 2). Rounded clasts of pelleted grainstone, as much as 3 cm in diameter, are common in the upper rock type. Clasts of filamentous algae and articulated brachiopods, filled with pelleted grainstone, are also common. Most of the clasts probably were derived from nearby Upper Winnipegosis
banks. Sparry calcite fills fractures and vugs and replaces the original shelly material. Replacement of the shells by silica and anhydrite also is common.

**Fossils and paleoecology.** - *Amphipora* sp. and rare crinoid ossicles are the only recognizable fossils in the fore-bank unit of the central and southern part of the area of study. As can be seen in Figure 15, *Amphipora* sp. is thought to have inhabited back-reef and lagoonal environments, yet in this area, it is common in the fore-bank unit (Pl. 4). Some fragments of *Amphipora* sp. may have been derived from another source, however, this is unlikely because no other organisms were transported with *Amphipora* sp. The dominance of *Amphipora* sp. and the presence of an argillaceous lime-mud matrix indicates that the environment of deposition was one of quiet waters and possibly was restricted.

Articulated brachiopods, gastropods, tabulate corals, bryozoans, foraminifers, crinoid ossicles, algal oncoliths, and algal debris are found in fore-bank rocks in the northern part of the area of study. The matrix is an argillaceous-carbonaceous lime-mud.

The presence of clasts and lenses of pelleted grainstone is important. The clasts are of the same lithology and contain the same fossils as the pelleted grainstones of Upper Winnipegosis banks. The clasts probably were derived from nearby banks and deposited under quiet-water conditions.
The presence of cricoconarids and tasmanitids at the top of the Upper Member in a fore-bank position already has been discussed (Pl. 2, Figs. 1 and 2). These organisms probably were deposited in a quiet-water environment.

**Basinal Unit**

**Distribution, thickness, and macroscopic description.** The basinal unit has been found only in the southern and southwestern part of the area of study. The unit consists of a fine-grained, olive-grey to brown, dolomitized mudstone and is similar to the "Elbow-Weyburn Basin Facies" of Jones (1965, p. 16). Maximum known thickness of the unit is 45 feet in the core of the Imperial Fortune borehole (Lsd. 13-20-30-14 W 3).

Rare crinoid ossicles, brachiopods, ostracods, and tasmanitids were found in this unit. The matrix is a dolomitized, argillaceous lime-mud. Closely spaced, argillaceous-carbonaceous stringers account, in part, for the nodular bedding of the unit -- bedding that in places is similar to sedimentary boudinage structure.

Finely crystalline dolomite rhombs form a mosaic throughout the matrix and are present within and around crinoid ossicles, which are also recrystallized. The dolomite within the crinoid ossicles has replaced the original calcite.

Anhydrite and pyrite are present in the basinal unit. Anhydrite fills vugs and the interiors of articulate brachiopods. Pyrite usually is present as a thin rind or film which lines cavities plugged with anhydrite.
Fossils and paleoecology. - Crinoids, brachiopods, ostracods, and tasmanitids are the dominant fossils of the basinal unit. These organisms may inhabit a variety of marine environments (Fig. 15).

The fine-grained nature of the matrix and the presence of argillaceous-carbonaceous stringers with pyrite is taken as evidence for deposition of these mudstones in a low-energy environment, perhaps as a result of local restriction of circulation of the Winnipegosis sea by the development of very large Upper Winnipegosis banks.

Fringing Cap Unit

Distribution, thickness, and macroscopic description. - Reinson (1970) and Wardlaw and Reinson (1971, in press) described a distinctive cap unit present on top of Upper Winnipegosis banks. According to Reinson (1970), this is an algal cap, which consists of highly dolomitized, interbedded algae boundstones, grainstones, and packstones. On the other hand, Wardlaw and Reinson (1971, in press) maintained that the unit consists of distinctive pisolite beds which exhibit structures similar to caliche structures formed during a subaerial weathering in the vadose zone. Some of the pisoliths may have had an algal origin, but this could not be confirmed by the presence of filaments or other typical algal structures.

The fringing cap unit does not entirely cover the tops of Upper Winnipegosis banks in the area of study, but is more a marginal development (Pl. 4).
The unit consists of extensively dolomitized, light- to dark-brown, boundstones, grainstones, and wackestones, which are, in part, oncolitic or pisolitic and also stromatolitic (Pl. 9, Fig. 1).

Boundstone generally takes the form of fine-grained, dark-brown laminae, which mark the top of the unit and also encrust previously formed oncoliths, pisoliths, and coarse grapestone-like fragments. Laminae are up to 3 mm thick and probably formed as stromatolitic encrustations. Algal structures, however, could not be found in thin sections.

Some oncoliths have fine micritic coatings which occur preferentially on their upper sides, indicating that growth was predominantly upward (Pl. 9, Fig. 2). The upward direction of growth of these oncoliths is suggestive of an algal origin, however, algal filaments have not been found in thin sections. Other subspherical forms consist of micritic coatings preferentially on the lower sides of previously formed pisoliths or clasts of dolomite laminites and pelleted grainstones, and appear to have fitted polygonal structures (Pl. 9, Fig. 3). The requirement for sunlight makes it unlikely that algal colonies developed preferentially on their lower sides, and thus these are probably not algal structures.

In situ brecciation of pisoliths and concretionary coatings is common. The fitted polygonal structures which are present suggests that fragments must have moved into positions of maximum stability, thus producing a reduction in total volume. The presence of continuous outer coatings on fractured pisoliths indicates that growth of
the pisoliths was interrupted by episodes of non-tectonic fracturing.

Large voids and fractures are elongated perpendicular and parallel to bedding and truncate laminae and pisoliths. Vugs and fractures are lined by a rind of dolomite rhombohedra, coarse-grained at their rims. Gypsum and anhydrite plug vugs and fractures.

Some highly brecciated layers are interbedded with others that are more evenly laminated. The breccias are thought to have formed during episodes of emergence and subaerial exposure, erosion, dessication, and shrinkage. The more regular laminae probably formed under shallow, quiet-water, marine conditions.

Fossils and paleoecology. - Calcispheres, ostracods, and foraminifers have been found in the fringing cap unit. These commonly have been found in sediments which were deposited in a quiet-water restricted environment (Fig. 15).

The presence of oncoliths and encrusting stromatolitic layers, probably of algal origin, is indicative of a shallow-water marine environment (Fig. 15).

On the other hand, the presence of pisoliths with fitted polygonal structures similar to those described by Dunham (1969) as having formed in the vadose zone during emergence of an island, as well as the fragmentary nature of the rocks, interlaminated with unfragmented laminae, suggests that episodes of emergence and subaerial weathering must have taken place.
Both Reinson (1970) and Wardlaw and Reinson (1971, in press) correlated this vadose pisolitic cap rock on lithologic grounds to the Quill Lake Marker Beds of the Shell Lake Member in the lower Prairie Evaporite Formation. If this is so, then some portion of the lower Prairie Evaporite Formation was deposited before the fringing vadose cap rock unit was formed.

It is to be stressed that the vadose cap rock unit does not completely cover the Winnipegosis banks. This means that not all portions of the banks were subaerially exposed and that there may have been brine ponds and restricted lagoons within the banks during, and probably after, late stages of bank development. The fact that this cap rock unit may be only a marginal development is some evidence to suggest that probably there was no profound drop in relative water-level after the formation of the Winnipegosis banks, as has been postulated by Fuller and Porter (1969).
General Remarks

Previous investigations. - The off-bank interlaminated carbonate mudstones and nodular or "enterolithic" anhydrites of the Ratner Member have been studied by Jones (1965), Shearman and Fuller (1969 A, B), Reinson (1970), and Wardlaw and Reinson (1971, in press). Reinson (1970) assigned member status to the unit and adopted the California Standard Ratner no. 1-15 borehole (Lsd. 1-15-48-17 W 2) as the type location.

Wardlaw and Reinson (1971, in press) divided the Ratner Member, on the basis of lithology and structure into eight laterally-persistant units, which are, in ascending order:

1) Finely laminated, tan carbonate mudstone;

2) Distorted, interlaminated tan carbonate mudstone and grey, nodular-mosaic to mosaic anhydrite;

3) Fine, irregularly-laminated, grey, mosaic anhydrite with bituminous partings;

4) Regular, dark-brown carbonate laminite;

5) Fine, irregularly-laminated, grey, mosaic anhydrite with bituminous partings and carbonate mudstone laminae;

6) Irregularly laminated, tan carbonate mudstone;

7) Interlaminated tan carbonate mudstone and grey mosaic and nodular mosaic anhydrite; and

8) Laminated carbonate.
These units have been traced into the east-central part of the area of study and are present in the cores of several boreholes, such as White Rose et al. St. Denis no. 7-2 (Lsd. 7-2-38-1 W 3), White Rose et al. St. Denis no. 6-16 (Lsd. 6-16-38-1 W 3), and White Rose et al. St. Denis 1-22 (Lsd. 1-22-37-1 W 3).

**Distribution, thickness, and macroscopic description.** - Figure 17 is an isopach map of the Ratner Member in the area of study. As can be seen, the sediments of the member are present in four isolated basins bounded by Upper Winnipegosis banks. Maximum recorded thickness of the Ratner Member in the area of study is 77 feet in the Pheasant Triad BP Fielding borehole (Lsd. 4-2-41-11 W 3).

In the southern part of the area of study (Fig. 17) maximum known thickness of the Ratner Member is 38 feet in the Tidewater Swanson Crown no. 2 borehole (Lsd. 16-9-32-8 W 3). The member is only about half as thick as in the central part. The overlying Shell Lake and Whitkow Members of the lower Prairie Evaporite Formation, however, are correspondingly thicker, attaining a combined thickness of over 230 feet in the Gridoil Kenaston borehole (Lsd. 1-29-30-1 W 3) and in the Fina Conquest borehole (Lsd. 16-19-31-8 W 3). Both of these boreholes are on the extreme southeast flank of an Upper Winnipegosis bank (Figs. 6 and 7). It is apparent that, in this southern area, the Shell Lake and Whitkow Members are thicker preferentially on the southeast flanks of Winnipegosis banks. This observation agrees with that of Reinson (1970) and Wardlaw and Reinson (1971, in press).
Figure 17 ISOPACH MAP OF THE RATNER MEMBER
There is insufficient core from the Ratner Member in the area of study to continue the lateral correlation of Wardlaw and Reinson's divisions, however, they have been traced as far west as the Pheasant Triad BP Fielding borehole (Lsd. 4-2-41-11 W 3). Most of the information about the areal extent of the Ratner Member was obtained from borehole logs.

In the central part of the area of study, the Shell Lake and Whitkow Members are not preferentially thicker on the southeast flanks of Upper Winnipegosis banks. For example, in the Pheasant Banff Red Pheasant borehole (Lsd. 13-19-40-15 W 3), the combined Shell Lake and Whitkow Members exceed 230 feet in thickness, however, the nearest and thickest Winnipegosis carbonate bank is present to the south and east of this location.

In the north-central and northeastern part of the area of study, solution and removal of the Prairie Evaporite Formation, a lack of core, and extensive recrystallization and replacement of anhydrite by calcite, make delineation of the boundaries of the Ratner Member difficult. Within the member in this area, carbonate laminites containing what are believed to be enterolithic structures are found in the core of two boreholes -- Seaboard Meadow Lake Crown no. 2 (Lsd. 9-21-63-8 W 3) and Hudson's Bay Green Lake no. 2 (Lsd. 16-21-61-10 W 3). In both cores, the entire section of laminites is composed of calcite, with relict textures of what probably was anhydrite. Thus, delineation of the boundaries of the Ratner Member in this area is not possible without use of core, because of the absence of anhydrite.
For this reason, a detailed study of the Ratner Member in the northeastern part of the area of study has been undertaken.

In this area, the Ratner laminites are white to brown in color and medium- to coarse-crystalline. Calcite laminae are 3 to 5 mm thick and even in some places. In others, they are discontinuous and are cut by densely-spaced stylolites and disrupted by blebs and nodules of clear to light-grey calcite which has replaced the original nodular or enterolithic anhydrite.

Studies of thin sections of Ratner laminites indicate that both recrystallization of lime-mud and replacement of nodular or enterolithic anhydrite by calcite has taken place (Pl. 9, Figs. 4, 5, 6, and 7). Several different forms of calcite are present in thin sections of Ratner laminites. A description of these different types of calcite permits a reconstruction of the sequence of events which must have taken place during the replacement of anhydrite by calcite. The different forms of calcite are as follows:

1) Lime-mud, which has a vague, pseudo-pelletoidal or "clotted-grumeleuse" texture, probably a result of recrystallization. Laminae of lime-mud are bounded by bituminous partings and stylolites.

2) Yellow-brown, pseudo-pleochroic calcite crystals, up to 0.5 mm in diameter, which are usually present within recrystallized mudstone laminae. The brown coloration appears to pass through several crystals and is not bounded by crystal boundaries. Within any one crystal, a brown-colored center may be encased by a clear rim, which may have formed as a syntaxial rim. Fuller and Porter (1969) and Shearman and
Fuller (1969 B, p. 525) described similar crystals and suggested that the brown coloration was due to organic matter pervading each crystal of calcite which grew in an organic substrate thought to have been of gelatinous consistency.

3) Drusy mosaic of sparry calcite which fill vugs and fractures. Calcite crystals are of variable size and are larger in the centers of vugs. They have planer boundaries and rarely are twinned. They were formed as a result of cementation and cavity filling (Pl. 9, Fig. 6). Cavities often are lined brown bituminous material.

4) Rounded blebs and nodules composed of a mosaic of interlocking, approximately equidimensional, crystals with stippled centers (Pl. 9, Fig. 7). The stippling is due to inclusions. The outer rims of some of these crystals are clear. Most grains have undulose extinction when viewed under crossed nicols. Grain boundaries are very jagged and irregular.

Vague needles of calcite, random in orientation, are common in the blebs and nodules. Some are actually crystals (Pl. 9, Figs. 6 and 7), however, most are relicts, which are not stippled and are locked in larger crystals. The needles are thought to be relicts of pre-existing anhydrite needles, replaced completely by calcite, and probably recrystallized at a later time.

5) Mosaics of fine calcite, confined to mudstone laminae bounded by bituminous partings, individual grains, with irregular boundaries, are up to 0.5 mm in diameter. They usually display high interference colors. These mosaics formed as a result of recrystallization of lime-mud.
Studies of thin sections of all the various forms of calcite reveal that the following sequence of events probably took place:

1) Deposition of mudstone laminite, with either displacive, nodular and enterolithic anhydrite or anhydrite replacement of the carbonate mudstones;
2) Replacement of blebs and nodules of anhydrite; and
3) Recrystallization, with cementation and cavity filling.

The petrology of the Ratner Member has been described by Shearman and Fuller (1969 A, B), Reinson (1970), and Wardlaw and Reinson (1971, in press). Thus, a detailed discussion of such features as formation of enterolithic anhydrites and calcitization and dolomitization of organic matter and anhydrite need not be repeated.

Fossils and paleoecology. - No fossils were observed in the Ratner Member. This suggests that the environment of formation was not conducive to organic life.

There are two opposing ideas regarding the environment of deposition of the Ratner Member. Shearman and Fuller (1969 A, B) concluded that the laminated carbonate mudstone units were probably intertidal algal mats and that the presence of nodular or enterolithic anhydrite is evidence that the Ratner Member was formed in a supratidal sabkha environment, such as occurs in the Persian Gulf. According to Shearman and Fuller (1969 B, p. 514):
"To postulate a supratidal origin for the anhydrite of the Winnipegosis laminites requires, as does the presence of 'intertidal' algal mat on the basin-floor, that there was a profound fall in relative-water level after the formation of the Winnipegosis reefs. Independent evidence that this did in fact happen is provided by borehole cores through the reefs, which show weathering features and solution cavities with sediment infill within the reefs.... The fall in water-level, which left the reefs exposed, would have rendered the former sea-floor a vast area of low relief shoals and emergent brine logged flats. The emergent areas would in effect be island sabkhas, and as such would have been as equally susceptible to the formation of anhydrite as the present day coastal sabkhas that are tied to the land along the Trucial Coast."

On the other hand, Wardlaw and Reinson (1971, in press) could not find any direct means, such as the presence of algal filaments, within Ratner laminites to support Shearman and Fuller's hypothesis. They also showed that regularly laminated beds, only a few centimeters thick, can be traced in cores over a distance of 100 miles. These two features suggested to Wardlaw and Reinson that the Ratner laminites were deposited in a quiet-water marine environment.

Several authors, such as Shearman (1966) and Kinsman (1966), have described diagenetic nodular anhydrites, which are forming in supratidal sabkha flats of the Trucial Coast today. The textures of the anhydrite within the Ratner Member do bear a close resemblance to those of the Persian Gulf. However, similar displacive anhydrites are known to form in a marine environment. Anhydrite is present in the Atlantis II core from the Red Sea (Ross and Degens, 1969, p. 364). It occurs below the sediment-water interface, in water over 2000
meters deep. It is not known whether the anhydrite was deposited directly or whether it has displaced pre-existing sediments. There is a superficial similarity of structure and texture in the anhydrites from the Trucial Coast and Red Sea which obviously formed in different environments.

Ratner laminites overlie the Upper Winnipegosis banks in a fore-bank position. It is thus apparent that deposition of at least some portion, if not all, of the Winnipegosis banks, pre-dates deposition of the sediments of the Ratner Member.

As mentioned before, there is a vadose pisolitic cap rock unit which is present on top of Winnipegosis banks at some locations. The presence of this unit, which probably formed during emergence and subaerial exposure, is evidence that some parts of the Upper Winnipegosis banks were subaerially exposed. Deposition of the Ratner laminites may have taken place after this episode of subaerial exposure of Winnipegosis banks.

At other locations, however, there is no cap rock, and the laminated mudstones in the centers of Winnipegosis banks appear to have a gradational relationship with the overlying Shell Lake Member of the Lower Prairie Evaporite Formation. These mudstones may have been deposited in restricted lagoons within the banks while the banks themselves were subaerially exposed, giving rise to atoll-like structures. But the lagoons would not persist for any great length of time if the climate were arid, as it is in the Persian Gulf. The
lagoons would probably persist in a wet climate, but the Winnipegosis banks themselves would be more susceptible to solution and erosion if they were subaerially exposed to a wet climate. It is thus apparent that the gradational relationship which exists between the laminated mudstone unit in Upper Winnipegosis banks and the Shell Lake Member of the Lower Prairie Evaporite Formation is difficult to explain, especially if the entire Winnipegosis banks were subaerially exposed. It is more likely that the Ratner laminites were not formed in a sabkha environment after Winnipegosis banks were subaerially exposed, but were deposited in a quiet-water, marine environment.
SUMMARY AND CONCLUSIONS

1) The Winnipegosis Formation in the area of study consists of three distinct members: a Lower Member, which is regionally developed and of relatively uniform thickness (20 to 50 feet); an Upper Member, which consists of a series of extensive but disconnected banks of up to 345 feet in thickness; and a series of carbonate mudstones and enterolithic anhydrites in inter-bank positions (Ratner Member). Maximum thickness of the Ratner Member is 77 feet.

2) Four rock types are recognized in the Lower Member: (i) oncolitic packstone; (ii) argillaceous-carbonaceous mudstones; (iii) dolomite laminite; and (iv) intraformational conglomerate.

3) In early Winnipegosis time, the Elk Point and Williston basins were occupied by a shallow inland sea. The abundant and varied remains of shallow-water, marine organisms in the Lower Member indicate that the sea was shallow and of normal salinity. The presence of argillaceous-carbonaceous mudstones, interlaminated with dolomite laminites and intraformational conglomerates, at the top of the Lower Member indicates that energy conditions in the sea fluctuated from low to high. Locally, shoals had been developed and were eroded. Some of these shoals became sites for the development of extensive Upper Winnipegosis carbonate banks.

4) Upper Winnipegosis carbonate mounds are called banks for the following reasons: (i) they are bounded by low-angle average
marginal slopes (less than two degrees); (ii) frame-building organisms, such as corals and stromatoporoids, comprise less than 2 percent of the core from the Upper Winnipegosis Member; (iii) very little evidence for growth of these organisms in situ was found; and (iv) sediment-baffling and -binding organisms, such as crinoids, dendroid stromatoporoids, and algae, as well as bachiopods and gastropods, are the dominant organisms. Algae may have been of particular importance in sediment-binding.

5) Amphipora sp. and brachiopods occupied a wider range of environments in the Winnipegosis sea than was previously thought. They are found in fore-bank sediments, which were deposited in quiet-water, and in pelleted grainstones, which formed under slightly restricted conditions with shallow, agitated waters.

6) Lateral and vertical variations in lithology and fauna occur within Upper Winnipegosis banks (Pl. 4 and Fig. 14), although a lack of time control makes definition of facies relationships unreliable.

7) In Upper Winnipegosis carbonate banks, three rock types dominate: laminated, unfossiliferous mudstone; pelleted, fossiliferous grainstone; and pisolitic-oncolitic-stromatolitic rocks, the last of which is found in a fringing cap unit interpreted as having formed in the vadose zone. Where both laminated mudstones and pelleted grainstones are present, the mudstones overlie grainstones. In the centers of Winnipegosis banks, laminated mudstones were deposited in shallow, quiet waters where organisms did not thrive. There probably
was increasing restriction of marine circulation within banks during their development.

8) The fringing cap unit was deposited in a shallow-water environment, with episodes of subaerial exposure and dessication of the sediments. If this unit can be correlated with the Quill Lake Marker Beds, as Wardlaw and Reinson (1971, in press) suggested, then deposition of the sediments of the Ratner Member and Lower Prairie Evaporite Formation probably was a response to increasing salinities caused by restricted circulation subsequent to bank development.

9) Ratner laminites were deposited either during late stages or after cessation of Winnipegosis bank development. The Ratner Member overlies Upper Winnipegosis strata in a fore-bank position. It also overlies argillaceous-carbonaceous, cricoconarid- and tasmanitid-bearing mudstones, some of which have been traced to the top of Upper Winnipegosis strata in a fore-bank position (Pl. 2). These mudstones were deposited in a quiet-water environment, indicating that there may have been episodes of restricted circulation during latest stages of Winnipegosis bank development.

10) In Winnipegosis banks, the laminated mudstone unit appears to have a gradational relationship with the overlying Shell Lake Member. The mudstones do not appear to have been subaerially exposed, whereas the fringing cap rock does. Lagoonal conditions could not have prevailed for any great length of time in the centers of Winnipegosis banks if, as has been postulated, there was a profound
drop in sea-level such that Winnipegosis banks were subaerially exposed. This supports the idea that Ratner laminites are a product of deposition under quiet-water marine conditions.

11) Limestone is more prevalent in the northern part of the area of study, whereas dolomite is more common in the southern part. Some of the limestone in the northern part is the result of extensive replacement of anhydrite by calcite (Pl. 9).

12) Argillaceous lime-mud dominates fore-bank strata, especially in the northwestern corner of the area of study (and also northwest of the Meadow Lake Escarpment). This feature may have been a response to more open marine conditions to the northwest, or may indicate that quieter, and probably deeper-water marine conditions prevailed to the northwest of the Meadow Lake Escarpment. This interpretation, however, requires a great deal of further study.
REFERENCES CITED


———, 1953, Devonian system of the Williston basin area: Publication 52-5, Province of Manitoba, Mines Branch, 105 p.


APPENDIX

Borehole Data

1. Formation and member limits were determined from cores, samples, and mechanical logs.

2. "K.B." means kelly bushing or the datum on the drilling rig from which depths of formation and member limits are referred.

3. "N.P." represents a formation or member which is not present. "?" represents a formation or member limit which is not known or cannot be determined. A number with a "?" following it represents an uncertain limit. "N.Pen." represents a member or formation which was not penetrated in that borehole.
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PLATE 1

Figure 1. Polished core slab: Interbedding of four rock types at the top of the Lower Winnipegosis Member: The four rock types are: (A) oncotic packstone; (B) argillaceous-carbonaceous mudstone; (C) dolomite laminit; and (D) intraformational conglomerate. Britalta Brightholmes no. 1 (Lsd. 5-29-47-3 W 3), depth 2447 feet.

Figure 2. Polished core slab: Algal oncoliths consist of concentric coatings of brown cryptocrystalline dolomite about a nucleus, usually of skeletal debris. Oncolitic packstone unit. UCHL Parkside no. 8-3 (Lsd. 8-3-48-5 W 3), depth 2483.5 feet.

Figure 3. Photomicrograph: Micritization of a crinoid ossicle, plane polarized light. Note the concentric coatings of micrite, which has replaced much of the ossicle (light-colored). Oncolitic packstone unit. White Rose et al. St. Denis no. 6-16 (Lsd. 6-16-38-1 W 3), depth 3875.5 feet.

Figure 4. Photomicrograph: Micritization of a crinoid ossicle, crossed-nics. Note the presence of tiny, sediment-filled algal borings (A) within the ossicle. Oncolitic packstone unit. White Rose et al. St. Denis no. 6-16 (Lsd. 6-16-38-1 W 3), depth 3875.5 feet.

Figure 5. Polished core slab: Sedimentary boudinage structure in the argillaceous-carbonaceous mudstone unit. Note the presence of a thin white rind of chalcedony in the larger, dark-colored boudins in the upper half of the sample. Smaller, light-colored boudins are present in the lower half of the sample. White Rose et al. St. Denis no. 7-2 (Lsd. 7-2-38-1 W 3), depth 3886 feet.
Figure 1. Polished core slab: Argillaceous-carbonaceous mudstone beds, with cricoconarids and tasmanitids (light-colored), near the top of the Upper Winnipegosis Member in a forebank position. Imperial Barnes no. 1-33 (Lsd. 1-33-61-17 W 3), depth 1895.5 feet.

Figure 2. Polished core slab: Argillaceous-carbonaceous mudstone beds, with cricoconarids and tasmanitids (white specks), near the top of the Lower Winnipegosis Member in a forebank position. Note the similarity with Figure 1. These two mudstone beds are separated by approximately 55 feet of Upper Winnipegosis strata. Imperial Barnes no. 1-33 (Lsd. 1-33-61-17 W 3), depth 1944.2 feet.

Figure 3. Photomicrograph: Drusy calcite replacing lime-mud around tasmanitids, plane polarized light. Calcite crystals develop normal to their surface of attachment and replace lime-mud (black). Argillaceous-carbonaceous mudstone unit. White Rose et al. St. Denis No. 7-2 (Lsd. 7-2-38-1 W 3), depth 3891 feet.

Figure 4. Photomicrograph: As in Figure 3, but with crossed-nicols. There is optical continuity between calcite within tasmanitids and outside them.

Figure 5. Photomicrograph: Clast of pelleted grainstone, with calcispheres (C) and dasycladacean algal sacs (D), in the argillaceous-carbonaceous mudstone unit, plane polarized light. White Rose et al. St. Denis no. 6-16 (Lsd. 6-16-38-1 W 3), depth 3856.75 feet.
Figure 1. Polished core slab: Rounded intraclasts or boudins of pelleted lime-mud in an argillaceous-carbonaceous mudstone matrix. Note how argillaceous-carbonaceous stringers tend to "flow" around clasts, which are usually elongate parallel to bedding. Imperial Barnes No. 1-33 (Lsd. 1-33-61-17 W 3), depth 1943.3 feet.

Figures 2. and 3. Polished core slab: Cylindrical, sediment-filled, worm burrows (B) account, in part, for the uneven bedding of the Lower Winnipegosis Member. Sediment (S) has filled burrows on the left side of Figure 3. Oncolitic packstone unit. Imperial Barnes no. 1-33 (Lsd. 1-33-61-17 W 3), depth 1950 feet.

Figure 4. Polished core slab: Selective dolomitization of the fine-grained matrix (lighter-colored). Clasts and skeletal debris are not dolomitized. Oncolitic packstone unit. Imperial Barnes no. 1-33 (Lsd. 1-33-61-17 W 3), depth 1959 feet.

Figure 5. Photomicrograph: Selective dolomitization around a crinoid ossicle, crossed-nicols. Note that most of the original ossicle was replaced by micrite, which subsequently was dolomitized. This gives the ossicle a halo composed of a mosaic of dolomite rhombs. White Rose et al. St. Denis no. 6-16 (Lsd. 6-16-38-1 W 3), depth 3862 feet.

Figure 6. Photomicrograph: Selective dolomitization of a crinoid ossicle, crossed-nicols. Note presence of a mosaic of white rhombs of dolomite (D) within the ossicle. White Rose et al. St. Denis no. 6-16 (Lsd. 6-16-38-1 W 3), depth 3864.75 feet.
Polished core slabs: Generalized cross-section illustrating the distribution of different lithologic units throughout an Upper Winnipegosis carbonate bank. There are six different lithologic units within Upper Winnipegosis banks. These include:

(A) Laminated mudstone unit;
(B) Pelleted grainstone unit;
(C) Peripheral organic unit;
(D) Fore-bank unit;
(E) Basinal unit; and
(F) Fringing cap unit.

A) UOHL Parkside no. 8-3 (Lsd. 8-3-48-5 W 3), depth 2398 feet.
B.1) UOHL Parkside no. 8-5 (Lsd. 8-5-47-4 W 3), depth 2373 feet.
B.2) UOHL Parkside no. 8-5 (Lsd. 8-5-47-4 W 3), depth 2440 feet.
C) Pheasant Sun Birch Lake 16-10-51-15 (Lsd. 16-10-51-15 W 3), depth 3025 feet.
D.2) Pheasant Placid Tenn Monnery River 12-36-54-25 (Lsd. 12-36-54-25 W 3), depth 3094 feet.
D.3) Pheasant Placid Tenn Monnery River 12-36-54-25 (Lsd. 12-36-54-25 W 3), depth 3123 feet.
Figure 1. Polished core slab: Steeply-dipping fore-bank strata along the margins of an Upper Winnipegosis bank. Note how laminae are contorted in the upper half of the sample and appear to over-ride each other along fractures in the lower part. Fore-bank unit. Ceepee Keppell Forest no. 8-3 (Lsd. 8-3-40-14 W 3), depth 4435.5 feet.

Figures 2. and 3. Polished core slab: Different growth forms of the tabulate coral Alveolites sp. Figure 2 illustrates subspherical growth forms; Figure 3 illustrates irregular encrusting laminae. Peripheral organic unit. Canadian Seaboard Divide no. 1 (Lsd. 10-16-56-14 W 3), depths 2019.5 and 2013 feet, respectively.

Figure 4. Polished core slab: Gastropod is a nucleus for growth of an algal oncolith. Fore-bank unit. Imperial Barnes no. 1-33 (Lsd. 1-33-61-17 W 3), depth 1937.5 feet.

Figure 5. Photomicrograph: Calcispheres, plane polarized light. Note the presence of a few large spines extending from the organism. Fore-bank unit. Ceepee Keppell Forest no. 8-3 (Lsd. 8-3-40-14 W 3), depth 4453 feet.

Figure 6. Photomicrograph: Calcisphere, plane polarized light. Note the presence of numerous thin spines extending from the organism. Pelleted grainstone unit. Pheasant Noel et al., Dundurn 14-8-32-4 (Lsd. 14-8-32-4 W 3), depth 4333.5 feet.

Figures 7. and 8. Photomicrograph: Parathurammina sp., a foraminifera, plane polarized light. Note the presence of a few large spines in Figure 7. Fore-bank unit. Imperial Barnes no. 1-33 (Lsd. 1-33-61-17 W 3), depth 1906 feet.

Figure 1. Photomicrograph: Filaments of blue-green algae, plane polarized light. Fore-bank unit. Imperial Barnes no. 1-33 (Lsd. 1-33-61-17 W 3), depth 1891.5 feet.


Figures 3, 4, and 5. Photomicrographs: Litanaia sp. or Protoslavina sp., longitudinal section, plane polarized light. Note branching of smaller canals from a larger central canal. Fore-bank unit. Imperial Barnes no. 1-33 (Lsd. 1-33-61-17 W 3), depths 1937.5, 1931.5, and 1931.5 feet, respectively.

Figures 6, 7, and 9. Photomicrographs: Litanaia sp. or Protoslavina sp., transverse section, plane polarized light. Note how smaller canals surround the larger ones in the center. Fore-bank unit. Imperial Barnes no. 1-33 (Lsd. 1-33-61-17 W 3), depth 1931.5 feet.


Figure 11. Photomicrograph: Vermiporella sp., a dasycladacean algae, transverse section plane polarized light. Colony is composed of several individual canals. Pelleted grainstone unit. Seaboard Meadow Lake Crown no. 1 (Lsd. 13-21-61-15 W 3), depth 1643 feet.
Figure 1. Polished core slab: Vague, subspherical forms probably are of algal origin, but show no internal structure in thin section. Laminated mudstone unit. UOHL Parkside no. 8-5 (Lsd. 8-5-47-4 W 3), depth 2380.5 feet.

Figure 2. Photomicrograph: Cylindrical-shaped organism with an internal structure probably of an algal origin, plane polarized light. Laminated mudstone unit. Banff et al. Asquith 13-1-38-8 (Lsd. 13-1-38-8 W 3), depth 3633 feet.


Figures 4. and 5. Photomicrographs: "Radial fibrous mosaics" of calcite (Bathurst, 1959) which form birdseye structure, crossed-nicols and plane polarized light, respectively. Note the presence of concentric bands which pass through the mosaics, indicating either that the depositional process was discontinuous or that there was deposition from solutions of varying composition. Pelleted grainstone unit. UOHL Parkside no. 8-3 (Lsd. 8-3-48-5 W 3), depth 2457.5 feet.

Figure 6. Photomicrograph: Vaguely concentric bands in large grapestone-like fragments. Note the similarity to "colloform" textures as described by Roedder (1958) in sphalerite ores. The origin of this feature is not known, but it is probably precipitated from solutions of varying composition. Pelleted grainstone unit. Banff et al. Asquith 13-1-38-8 (Lsd. 13-1-38-8 W 3), depth 3763 feet.
PLATE 8

Figure 1. Polished core slab: Roofed-over cavity (boundstone) plugged by a mosaic of rhombic dolomite (D) in the lower part and clear gypsum (G) in the upper part. Pelleted grainstone unit or peripheral organic unit. Pheasant Shell Molewood 3-15-48-15 (Lsd. 3-15-48-15 W 3), depth 3093 feet.

Figure 2. Photomicrograph: Tiny rhombs of dolomite (D) concentrated along bands within the radiaxial fibrous mosaic, crossed-nicols. Pelleted grainstone unit. UOHL Parkside no. 8-5 (8-5-47-4 W 3), depth 2490.5 feet.

Figure 3. Photomicrograph: Tiny black rhombs of dolomite enclosed in gypsum (G), crossed-nicols. Note crystallotopic anhydrite (A) in upper right-hand corner. All the gypsum is a single crystal. Pelleted grainstone unit. Banff et al. Asquith 13-1-38-8 (Lsd. 13-1-38-4 W 3), depth 3763 feet.

Figures 4 and 5. Polished core slab: Two rock types of the peripheral organic unit. Alveolites sp. (A) is the dominant frame-building organism. The matrix varies from a pelleted biofragmental grainstone (Figure 4) to an argillaceous lime-mud (Figure 5). Figure 4 is from Pheasant Sun Birch Lake 16-10-51-15 (Lsd. 16-10-51-15 W 3), depth 3027 feet. Figure 5 is from Canadian Seaboard Divide no. 1 (Lsd. 16-10-56-14 W 3), depth 2021 feet.

Figure 6. Polished core slab: Algal oncolith. Note the spherical shape and encrusting habit. Fore-bank unit. Imperial Barnes no. 1-33 (Lsd. 1-33-61-17 W 3), depth 1931.5 feet.

Figures 7 and 8. Polished core slab and photomicrograph: Eble or nodule of anhydrite which displaces and replaces lime-mud. Note (Figure 8) that light-colored needles of anhydrite are growing into the lime-mud matrix and replacing it. The irregular and uneven black band in the anhydrite is pyrite (P). Fore-bank unit. Ceepee Keppell Forest no. 8-3 (Lsd. 8-3-40-14 W 3), depth 4458 feet.
Figure 1. Polished core slab: Stromatolite algal boundstone, with pisolites, at the top of the fringing cap rock unit. Note the thin, wavy encrusting laminae. The overlying anhydrite (A) is in the Shell Lake Member of the Lower Prairie Evaporite Formation. Pheasant BarriF Dunfermline 16-20-37-8 (Lsd. 16-20-37-8 W 3), depth 3625 feet.

Figure 2. Polished core slab: Boundstone, fringing cap rock unit. Note the wavy encrusting laminations. Note that the coatings on oncoliths (O) are preferentially developed on the upper side. These are probably of an algal origin. Pheasant Noel et al. Dundurn 14-8-32-4 (Lsd. 14-8-32-4 W 3), depth 4025 feet.

Figure 3. Polished core slab: Coarse pisolite grainstone, fringing cap unit. Note how the polygonal pisoliths appear to lock together and have a "fitted" polygonal appearance. Note the graded bedding in the lower part and reverse graded bedding in the upper part. Pheasant Noel et al. Dundurn 14-8-32-4 (Lsd. 14-8-32-4 W 3), depth 4025 feet.

Figures 4 and 5. Polished core slab: Interlaminated carbonate mudstone and "enterolithic" anhydrite, which is now entirely calcite (C), Ratner Member. All the pre-existing anhydrite has been replaced by calcite. Note the presence of several stylolites in the samples. Seaboard Meadow Lake Crown no. 2 (Lsd. 9-21-63-8 W 3), depths 1540.5 and 1543.5 feet, respectively.

Figure 6. Photomicrograph: Void-filling, granular calcite cement (coarse crystals) surrounded by more finely crystalline calcite, crossed-nics. Ratner Member. Hudson's Bay Green Lake no. 2 (Lsd. 16-21-61-10 W 3), depth 1301.5 feet.

Figure 7. Photomicrograph: Contact between brown, pseudo-pleochroic calcite crystals (top) and jagged inter-locking calcite crystals showing ralict anhydrite needles (bottom), plane polarized light. Note clear calcite rims (C) in upper part and vague relict laths (L) in the lower part. Ratner Member. Seaboard Meadow Lake Crown no. 2 (Lsd. 9-21-63-8 W 3), depth 1550.75 feet.