DEPOSITIONAL ENVIRONMENTS OF THE UPPER DEVONIAN BIRDBEAR FORMATION, SASKATCHEWAN

STEPHEN PHILIP HALABURA

1983

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Stephen Philip Halabura
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ABSTRACT

The Upper Devonian, Upper Frasnian Birdbear Formation of Saskatchewan is the uppermost carbonate-evaporite cycle of a thick carbonate sequence deposited in a shallow, epicratonic sea. The formation is equivalent to the Birdbear (Nisku) Formation of North Dakota and Montana, and approximately equivalent to the Nisku sequences of Alberta. It is divided into an upper and lower member, with the dividing boundary at the base of the first anhydrite bed.

In the lower member, six lithofacies are discriminated. They are the products of the last and most exclusive incursion of the Frasnian seas into Saskatchewan and beyond, and the ensuing period of standstill. This final flooding had started already in late Duperow and continued into earlymost Birdbear time. The rocks are primarily limestones, dolomitized limestones, dolomite, and some anhydrite which were laid down in environments ranging from moderate-high energy subtidal and intertidal, to low energy, backshoal-lagoonal.

The upper member is characterized by seven lithofacies dominated by various types of micritic and pelletoidal limestones, dolomites and anhydrites, and some intraformational breccias. The sequences formed during the regression of the Frasnian sea and, as a result, are the record of ever-decreasing water depth and increasing salinity. The depositional environments range from restricted-lagoonal to supratidal.

Mapping of the thicknesses of various units within the Birdbear, coupled with core examination from certain key wells, allow the reconstruction of the paleogeography of the Saskathcewan Shelf during Birdbear time. This shelf was broken into two distinct depocentres by two large platforms, one centered in west-central Saskatchewan, the other in eastern Saskatchewan. The rocks of the depositional center to the northwest of the platforms are very similar to those of the Nisku Formation of eastern Alberta and are correlated with them. To the south of the platforms, the rocks are similar or identical to those found in the Williston Basin area of the North American Plains. These are the "typical" Birdbear rocks.

During the final phase of the Frasnian transgression in earlymost Birdbear time, an argillaceous, lowermost unit was deposited across Saskatchewan. After the transgression peaked, a period of sea level standstill occurred during which high-energy, open-marine carbonates were deposited, including mechanically-piled shoals and mounds in some locations. The platforms were the sites of tidal-flat to supratidal (sabkha) environments. Following this interim period, the regression of the sea began and evaporites, both supratidal and subaqueous, with algal and chemically precipitated carbonates, filled the basin. The only area to escape the effects of this regression was the northwest, where sedimentation continued to be primarily subtidal to intertidal.

The Birdbear Formation has been post-depositionally altered by early and late dolomitization and by secondary anhydritization. The dolomitization is significant from an economic viewpoint, as selective dolomitization has led to the development of porosity and possibly to the accumulation of hydrocarbons in stratigraphic traps. To date, the only production, however, is from structural traps.

DEDICATION

This work is dedicated to all the wellsite geologists, older and younger, who had the pleasure or misfortune of having to pick boundaries and core points somewhere within the complex tangle of evaporites, dolomitic limestones, and calcareous dolomites of the Upper Devonian subsurface sequences of Saskatchewan. To them I owe the primary source of my data. They must have been heroes.

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INTRODUCTION

General Remarks

In this study, the stratigraphy, sedimentation, and diagenesis of the Birdbear Formation in Saskatchewan will be examined. This formation is the uppermost unit of the Upper Devonian (Frasnian) Saskatchewan Group, a sequence of carbonates and evaporites found throughout the Williston Basin region of North Dakota, Montana, and southern Saskatchewan, and the eastern portions of the Alberta Basin including western Saskatchewan and eastern Alberta.

The study area extends from Township 1 north to the erosional edge of the Birdbear sequence; it is bound on the east and west by the Manitoba-Saskatchewan and the Alberta-Saskatchewan boundary respectively. This encompasses an area of 2145 townships (see Figure 1). Approximately 1000 wells either terminate within or pass through the Birdbear Formation, with the greatest density of wells found in southeastern Saskatchewan, and following the "potash trend". In western Saskatchewan, many wells are concentrated in the areas of heavy oil occurrences.

The sedimentary sequence under study represents a package transitional between the deeper water sediments of the Alberta Basin to the west and the shallow-water carbonates of the Williston Basin to the east

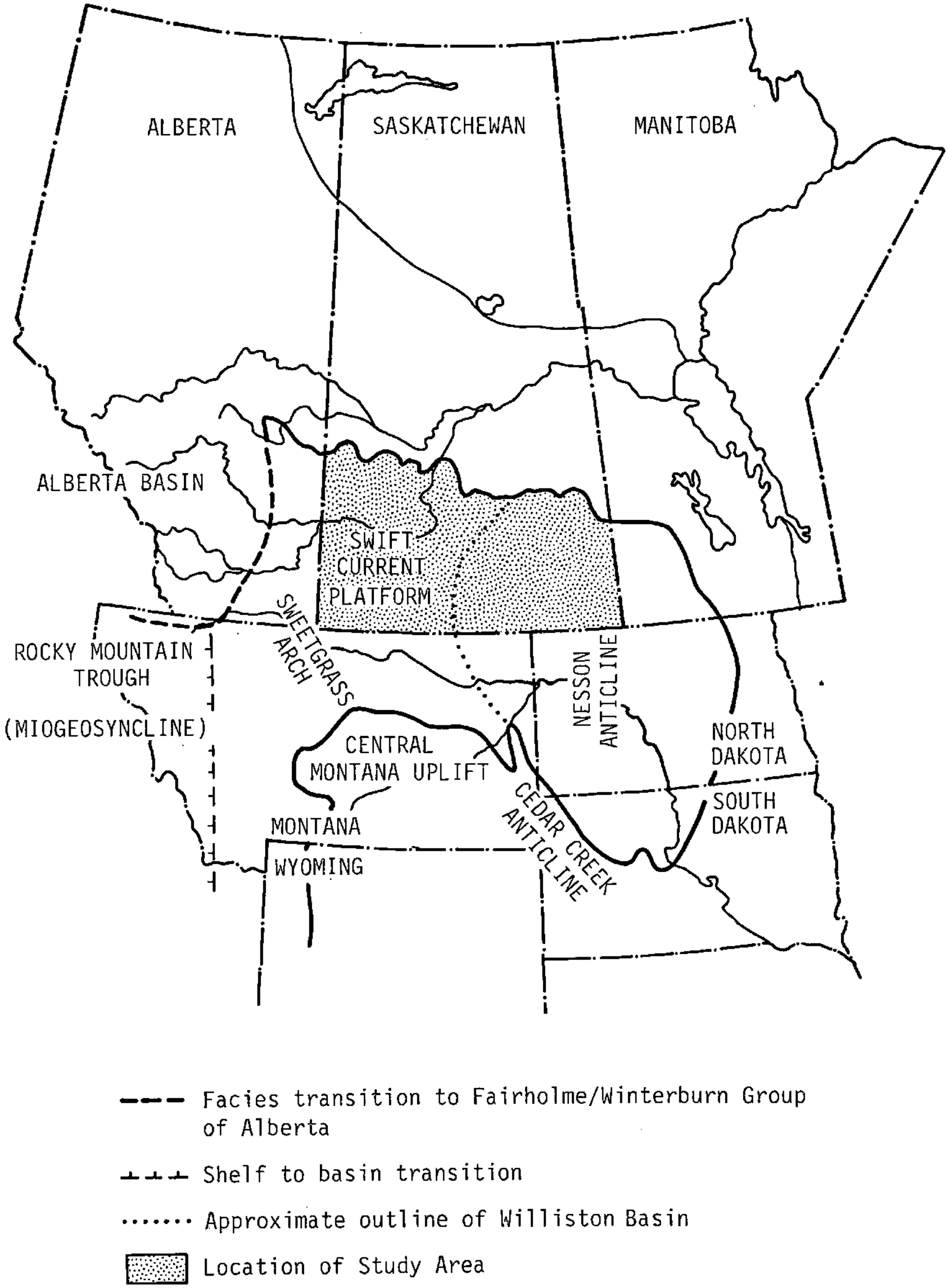


FIGURE 1 LOCATION OF STUDY AREA AND MAJOR TECTONIC ELEMENTS

and southeast. It must be emphasized that the term "Williston Basin" as used in this study does not denote a discrete sedimentary basin. Rather, it is used in a geographic sense. It is doubtful whether a distinct, unified depositional basin existed during Frasnian times (W. K. Braun, pers. comm.); instead the paleotopography was one of a very broad, vast shelf with numerous sedimentary depocenters. Although not a prolific oil producer, the Birdbear sequence nevertheless is important in deciphering stratigraphic and facies relationships within the last and major Frasnian transgressive cycle, and the rapid retreat of the Frasnian sea towards the end of Birdbear time.

The Saskatchewan Group is a cyclic sequence of shoaling-upward carbonates and anhydrites, divided on the basis of argillaceous and evaporitic marker horizons. These sequences are similar to those found at present day along the Trucial Coast of the Persian Gulf region, the Platform of the Caribbean, and other areas of shallow- and warm- water sedimentation.

Objectives of Study

The sedimentary rocks of the Birdbear Formation were studied for the following purposes:

1) to determine the stratigraphic relationships of the Birdbear

sequences with respect to equivalent rocks in Alberta and the southern Williston Basin subsurface;

2) to determine the depositional enviroments of the Birdbear sequences in Saskatchewan;

3) to determine the vertical and lateral extent of the carbonate and evaporite units within the sequences and to document fabric, composition, and characteristic features of these units;

4) to try to determine the diagenetic history of the same units and outline subsequent changes in porosity and its distribution.

Answers to the above questions are valuable from the point of view of oil exploration and aid in defining reservoir parameters, trends, and prospective traps.

Methods of Study

Most of the information for this study was obtained from detailed examination of cores. Cuttings were found to be of relatively little value, in particular for reconstruction of paleo-environments, because of their small size and the problem of uphole contamination and mixing. Approximately 5800 feet of core were examined during the months of July and August 1981, and selected sections were re-examined later for greater details.

Samples were taken from the various rock types and lithofacies, and from most a 2x3 inch plaquette was cut. One side of the plaquette was polished while the opposite side was etched in a solution of 10% HCl. A number of the plaquettes were stained with a solution of potassium ferricyanide and Alizarine Red S, two dyes well suited for the selective staining of limestones and dolomites. In addition, fifty thin sections were cut from the plaquettes and stained, mainly to observe in more detail certain types of carbonate cement and the partial dolomitization of grains and matrix.

In any subsurface study, mechanical, electrical, and other assorted geophysical logs are of vital importance as tools providing indirect information on lithology, porosity, clay content, and other parameters used in correlation and interpretation of rock sequences. The most useful log combination was found to be the gamma-ray and the sonic log; however, various density indicators such as the neutron, compensated neutron, and formation density log were also of value. In contrast, electrical logs, induction logs, and various induction and laterologs were found to be of little value, as were the self-potential (SP) logs. Various methods of log interpretation such as the Pickett crossplot method (Asquith 1979), and the Dresser Atlas 'Reconnaissance R_{wa}' log interpretation method were utilized in order to ascertain reservoir characteristics.

Acknowledgements

Two people made this study possible and to them are owed many thanks. Dr. W.K. Braun of the Department of Geological Sciences acted as faculty advisor during the course of the study and was always quick to provide advice, assistance and constructive criticism. This study was suggested to me by Mr. A.E. Calverley, Petro-Canada Exploration Inc., who also showed much faith in the suitability of this project in the early formative stages.

Financial assistance to the writer in the form of a research grant was provided by Petro-Canada Exploration Inc. Petro-Canada also provided base maps, laboratory services, and drafting facilities during the course of this research. Additional funding was provided by the University of Saskatchewan in the form of a Graduate Research Scholarship, and research funds made available to D.R. W.K. Braun. The typing was done by Dianne Theisen.

Thanks are also due to Dr. D.F. Paterson and the staff of the Saskatchewan Mineral Resources Subsurface Laboratory, Regina Saskatchewan, for allowing the writer access to cores, well logs, and photocopy facilities at the lab.

The writer would like to thank the many industry geologists and companies who freely offered information, encouragment, and advice with respect to the Upper Devonian of Saskatchewan. These include H.T. Hornford, B. Mazurkewich, and J. Lee, of Petro-Canada Exploration Inc. Others include Dr. D.M. Kent, University of Regina, D. Tough and A. Hartling, Saskoil, and Dr. J. Kaldi, formerly of Saskatchewan Energy and Mines, currently with Shell Canada Resources.

Finally, thanks to P. Loeffler, University of North Dakota, for advice on log correlations, provision of well maps of North Dakota, plus many interesting discussions concerning the Devonian of the Williston Basin.

REGIONAL GEOLOGICAL AND STRATIGRAPHIC SETTING

General Remarks

The Frasnian is characterized by a widespread marine transgression across western Canada, including Alberta and Saskatchewan and reaching as far south as the American northern Plains. This transgression may have been the result of worldwide eustatic adjustment of sea levels, the product of differential subsidence within the cratonic basins or, as is assumed for this discussion, a combination of both. Carbonates deposited during the various transgressive pulses overstep the boundaries of the Alberta-Williston Basins and are found as far north as the Canadian Arctic and Alaska and as far south as the Transcontinental Arch of South Dakota and Nebraska. The height of the transgression was reached approximately in early Late Frasnian time, followed by a rapid regression of the sea. It seems that the Birdbear sequences under study were laid down during the last pulse of the transgression and during the first phase of the regression.

In view of the vast expanse of the shelf sea, the shallow-water conditions, and a very low bottom slope, the ordinary current regimes would not have been sufficient to maintain normal salinity levels across the entire shelf. Consequently, restricted to evaporitic conditions developed preferentially in the more landward portions of the seaway, that is in a southeasterly direction towards southeastern

Saskatchewan. That such restrictions were accentuated by the intermittent growth of reef barriers in central Alberta is quite conceivable and plausible. However, the influence of such obstacles may have been overemphasized in the older literature and in some depositional models.

Aside from the distinctly "restricted" nature of the Middle- and Upper Devonian rock record in Saskatchewan, the second characteristic feature is its "rhythmic" nature. In the Middle Devonian and lower Frasnian, two "basinwide", vast scale, and distinctive "cycles" prevail. Each cycle starts with a redbed sequence followed by carbonates which become progressively more restricted, giving way to evaporites mainly of the chloride grade, which are followed again by younger redbeds. This pattern changes markedly under the influence of strong transgressive pulses and some local, tectonic adjustments in middle to late Frasnian time, and as a result of the late Frasnian regression. The basinwide evaporites have all but disappeared and are confined to smaller, localized areas and to the lower sulphate grade. The lithologic marker beds are not any longer the redbeds but widespread argillaceous units. The alteration pattern is from argillaceous carbonates to non-argillaceous units, with sabkha-type evaporites appearing in the uppermost part of the Frasnian pile as an unmistakeable sign of the impending regression.

The pronounced cyclicity of these Devonian units (the same applies for the Ordovician-Silurian pile) was probably caused by only minor eustatic and/or tectonic adjustments; it reflects also on the flat and "regular" nature of the shelf itself. All the while, the warm-water, tropical to subtropical temperatures and climatic conditions prevailed and influence from the adjoining land areas remained minimal.

The Upper Devonian Birdbear Formation

Following the discovery of oil in Upper Devonian carbonates near Leduc in west-central Alberta and close to the city of Edmonton in 1947, exploration geologists expanded their search for this precious resource all over western Canada, reaching Manitoba in 1953 with the discovery of oil at Virden and North Dakota in 1951 with the discovery of oil in the Nesson Anticline. As much as the Leduc discovery stimulated development in the Alberta Basin, so did did the latter two finds initiate a frantic search for oil in the Williston Basin.

The first subsurface study of the Devonian rocks of Saskatchewan was prepared by Powley in 1951. The Birdbear Formation was designated the M-3 unit at that time and assigned to the Moose Jaw Group. Andrichuk (1951), Baillie (1953), and Allan and Kerr (1952) also acknowledged the presence of the Birdbear sequence but referred to it as the "Nisku" after its correlative unit in the Alberta Basin, as did other authors. Problems, however, arose when this term was applied right across the Alberta and Williston Basins, for it was soon debated whether the units in question might not be exactly time equivalent. Belyea (1955, 1957), for instance, pointed out that the Nisku Formation of the Edmonton and type area was different from that in southeastern Alberta, and that it certainly is not equivalent to the "Nisku" of Saskatchewan. To eliminate this ambiguity, Sandberg and Hammond (1958) proposed the name "Birdbear"

Formation for the carbonate-evaporite unit between 10,130' and 10,400' in the Mobil Producing Co. No. 1 Birdbear Well (see Figure 2).

MOBIL PRODUCING CO NO 1 BIRDBEAR WELL

C SE¼ NW¼ SEC 22 TWP 149 RGE 91 W DUNN CO., N.D.
Depth: 10,310 - 10,400 feet
Thickness: 90 feet

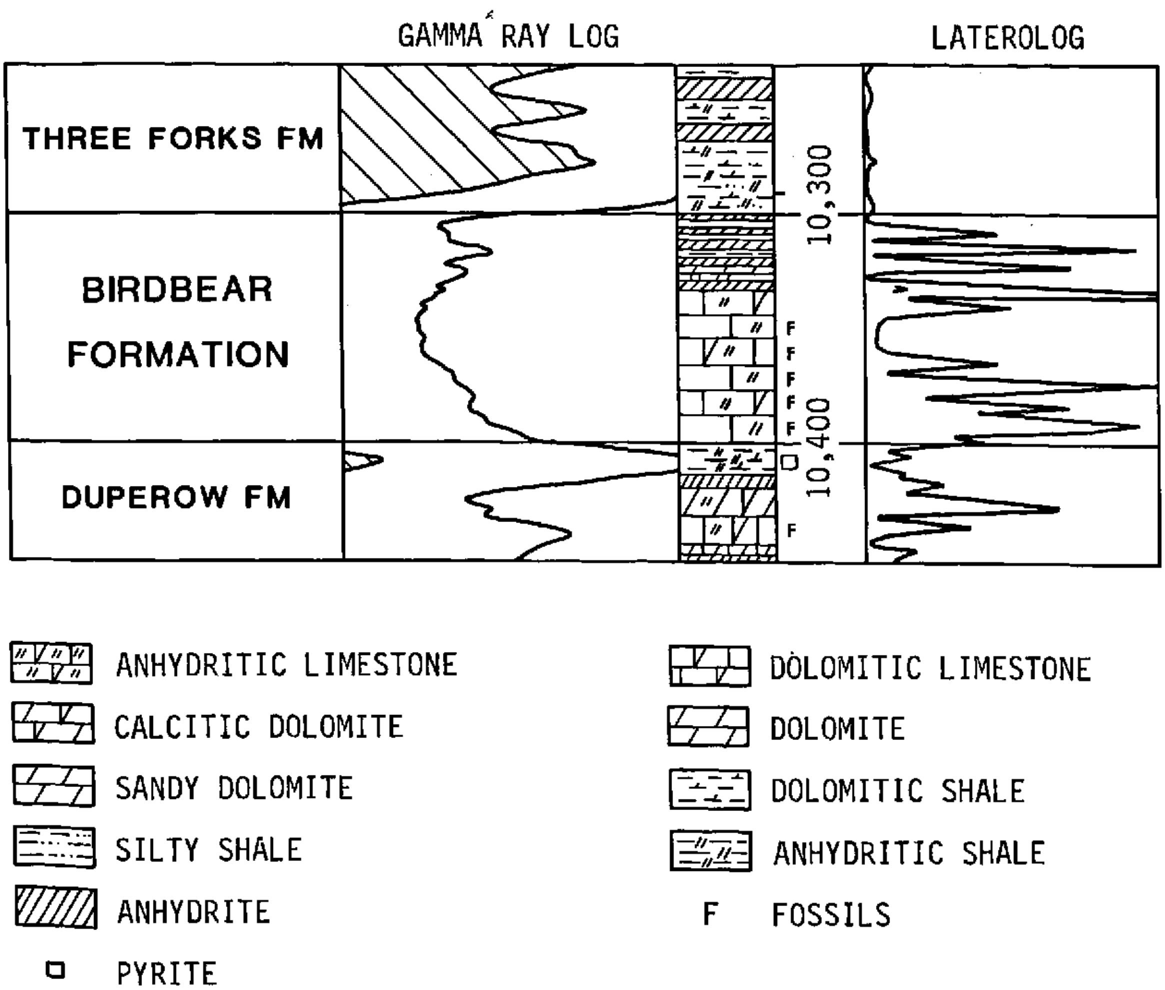


FIGURE 2 TYPE SUBSURFACE SECTION OF BIRDBEAR FORMATION
(from Sandberg and Hammond, 1958)

Meneley (1958) reviewed the correlation problem in general and the Nisku of Saskatchewan in particular and concluded that the unit was indeed correlative with the type Nisku of the Edmonton area, calling it a "format". A "format" he defined (p. 5) as a "Marker-defined operational unit that are segregations of strata sandwiched between markers which can be traced through facies changes affecting the enclosed strata". He did not agree with Belyea's conclusions on the Nisku of the southern Alberta Shelf and the Birdbear of Saskatchewan either, believing that she miscorrelated the lower boundary of the Nisku. Kent (1968), however, drew the opposite conclusion in his study of the Upper Devonian of western Saskatchewan and adjacent areas. Due to lithological transitions within the Birdbear and underlying sequences (Duperow Formation) in southeastern and eastern Alberta, it is difficult to establish firm boundaries, and he concluded therefore that the "Nisku" of Saskatchewan and the type Nisku of the Edmonton area were not precisely correlatable.

Correlations of the Nisku-Birdbear units did not appear to be problematic to American researchers studying the formation in the Williston Basin; however, most concentrated their efforts on the Nisku-Birdbear of the Williston Basin, this interval being most productive from the point of view of oil and gas exploration. The type Birdbear log responses can be recognized over all of this portion of the basin. Only in western Montana does the ambiguity, which is present in eastern Alberta, become noticeable.

To this date, the Nisku-Birdbear problem still figures prominently in geological literature and bears heavily on geologists' minds.

Numerous workers have discussed the stratigraphy of the Birdbear Formation in the Williston-Alberta Basin region, among them Kent (1963, 1968, 1973), Nichols (1970), Loeffler (1982), and Halabura (1982). Studies with respect to hydrocarbon accumulations in the Birdbear sequences have been made by Meneley (1958), Wilson, Surjik and Sawatsky (1963), Sampsel (1964), Swenson (1967), Smith and Pullen (1968), Bishop (1974), and Sawatsky (1975). These sources and some others will be quoted frequently.

The Birdbear Formation is the uppermost unit of the Saskatchewan Group, a relatively thick sheet of Upper Devonian carbonates and evaporites found in the subsurface of North Dakota, South Dakota, eastern Montana, southwest Manitoba, and southern to central Saskatchewan (see Figure 3). These sequences were deposited in a vast epicratonic sea extending southeastward and beyond the Cooking Lake platform and Leduc reefs of the eastern Alberta Basin (Wilson 1975). They display cyclicity in the form of widely traceable marker units and repeated lithofacies patterns.

At the type section, the Birdbear well of North Dakota, the Birdbear Formation consists of an upper unit of interbedded anhydrite and dolomite with minor limestone, and a lower unit of locally anhydritic fossiliferous dolomite and limestone (see Figure 2).

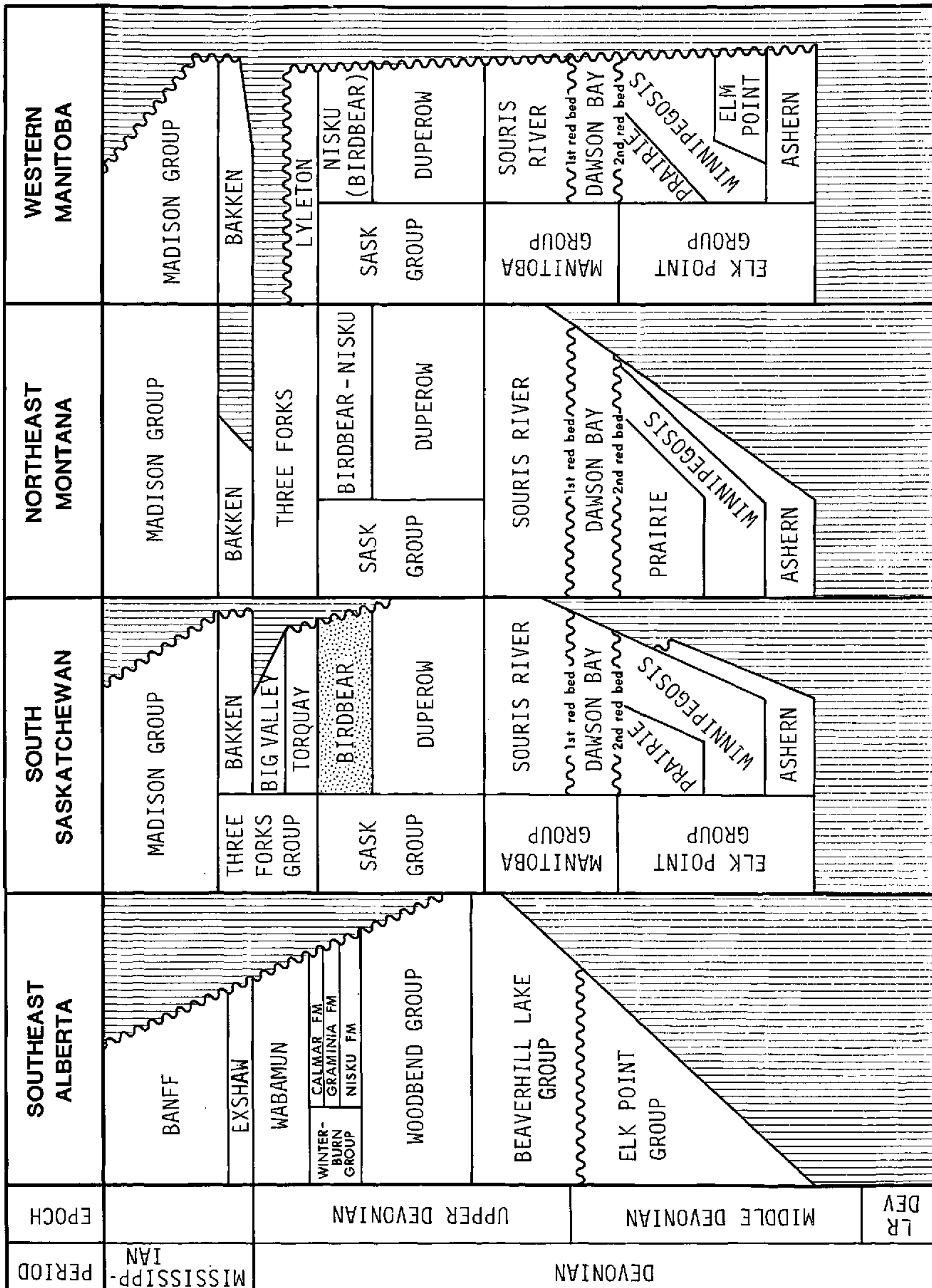


FIGURE 3 STRATIGRAPHIC CORRELATION CHART, SASKATCHEWAN AND ADJACENT AREAS (after Kent et al, 1973)

Overlying the Birdbear Formation in the Mobil No. 1 Birdbear well are the rocks of the Upper Devonian to Mississippian Three Forks Formation. The lithology of this unit consists primarily of dolomitic shale, anhydritic shale, silty and argillaceous anhydrites, and very argillaceous dolomites and limestones. The Three Forks Formation, as described by Sandberg and Hammond, is correlative with the Torquay Formation of southeastern Saskatchewan and the Big Valley - Torquay Formations of the Three Forks Group further to the north and the west. The Big Valley and Torquay Formations remain lithologically consistent with the Three Forks of Montana and North Dakota until facies changes occur in western Saskatchewan where the entire sequence becomes less argillaceous and much more evaporitic.

In southern Saskatchewan, the Birdbear Formation overlies a distinctive sequence of redbeds, breccias, and highly argillaceous, dolomitic mudstones comprising the top of the Duperow Formation. This unit has been named the "B3 subunit" of the Seward Member of the Duperow Formation by Kent (1968), and is informally known as the "Ireton marker" in the subsurface of the American portion of the Williston Basin (Loeffler, 1982 pers. comm.). It forms a most distinctive marker on gamma ray and SP logs and is readily distinguishable throughout the map area (Figures 4, 5). The boundary is placed at the changeover from the argillaceous B3 beds to the overlying, non-argillaceous carbonates of the Birdbear Formation.

The boundary between the uppermost strata of the Birdbear and the overlying Torquay Formation in Saskatchewan is more gradational, irregular, and thus more difficult to delineate. As a rule of thumb, the boundary is placed at the transition from the non-argillaceous carbonates of the Birdbear to the redbeds and shales of the Torquay. In many cases this boundary is quite sharply developed, however it can also be gradational over several feet. In certain regions of western and southwestern Saskatchewan, the Torquay redbeds and shales change to evaporites, in which case it becomes difficult to delineate the boundary on logs. A similar difficulty exists also in northwestern and north-central Saskatchewan where the terrigenous clastics of the basal Cretaceous directly overlie the Birdbear sequence, causing similar signatures on the logs.

The Birdbear has been divided into two members by Kent (1968) and Nichols (1970); however, in Saskathcewan, the boundary between the upper and lower member has been placed at two different stratigraphic intervals by these workers. Nichols (1970), working exclusively in southeastern Saskatchewan, placed the contact at the base of the first anhydrite bed. This boundary is relatively easy to pick from geophysical logs when a combination of logs such as gamma-ray sonic, and CNL-FDC are available. However, in older wells without the more modern logs, this boundary is much more difficult to delineate, and it can only be considered reliable when either core or drill cuttings are examined in addition. In the western areas of south-eastern Saskatchewan, the task of selecting the boundary is made

A
SOCONY W P IMP CARIEVALE 1
16-4-3-32 W2
KB: 1690 ft
TD: 8326 ft
SHELL SOUTH OXBOW
13-24-2-3 W2
KB: 1871.5 ft
TD: 5257 ft
BA CAN DEV QUINN
9-34-3-4 W2
KB: 1935 ft
TD: 9420 ft
DOME WILLMAR
11-8-6-3 W2
KB: 1955 ft
TD: 8634 ft
SCURRY WORDSWORTH
11-36-6-4 W2
KB: 1981.1 ft
TD: 5350 ft
IOE WEIR HILL
3-16-6-6 W2
KB: 1667.8 ft
TD: 7580 ft
PAGE VIEWFIELD
7-17-7-8 W2
KB: 612 m
TD:
FRANCANA ET AL VIEWFIELD
3-33-7-8 W2
KB: 2006 ft
TD: 5598 ft
BA GRIFFIN GEIGER
7-11-8-10 W2
KB: 2006 ft
TD: 5598 ft
CANSO TENN INNES
5-6-8-10 W2
KB: 1986 ft
TD: 5945 ft
CDR ET AL WEYBURN
4-13-7-14 W2
KB: 1915 ft
TD: 7616 ft
2.5 mi
12.0 mi
15.0 mi
4.5 mi
15.5 mi
15.0 mi
3.0 mi
10.5 mi
17.0 mi
7.5 mi
DATUM TOP OF BIRDBEAR FORMATION
Upper Member
Lower Member
DUPEROW FM
ireton marker
B
B A MOORE
6-27-15-6 W3
KB: 2411 ft
TD: 7759 ft
ARCO MORSE
13-11-17-8 W3
KB: 2383 ft
TD: 6200 ft
HUSKY ARCO MORSE
10-3-19-9 W3
KB: 2489.7 ft
TD: 6047 ft
ZD HB BEECHY
6-32-21-10 W3
KB: 2106 ft
TD: 5650 ft
PEYTO GERC ET AL BURRELL
4-11-23-10 W3
KB: 2379 ft
TD: 4504
INC HUSKY WISETON
10-16-25-13 W3
KB: 1964.5 ft
TD: 4690 ft
BARNWELL ET AL PLATO
4-3-25-17 W3
KB: 2394 ft
TD: 2870 ft
BIGHART PLATO
4-2-26-9 W3
KB: 672.1 m
TD: 1050 m
14.5 mi
13.5 mi
18.0 mi
8.5 mi
24.5 mi
24.0 mi
12.5 mi
21.0 mi
DATUM TOP OF BIRDBEAR FORMATION
Upper Member
Lower Member
argillaceous subtidal unit
DUPEROW FORMATION
ireton marker
? NDE
? NDE

ANCANA ET AL VIEWFIELD
3-7-8 W2
2006 ft
5598 ft
BA GRIFFIN GEIGER
7-11-8-10 W2
KB: 2006 ft
TD: 5598 ft
CANSO TENN INNES
5-6-8-10 W2
KB: 1986 ft
TD: 5945 ft
CDR ET AL WEYBURN
4-13-7-14 W2
KB: 1915 ft
TD: 7616 ft
IOE CDR TATAGWA
15-29-7-15 W2
KB: 1908.6 ft
TD: 6902 ft
FINA RADVILLE
13-4-6-18 W2
KB: 2186 ft
TD: 9854 ft
TENN CAN SUP CEYLON A1
13-17-5-20 W2
KB: 2524 ft
TD: 7209 ft
TENN HB BEAD LAKE
6-8-4-21 W2
KB: 2417 ft
TD: 9291 ft
FINA RONCOTT
13-15-5-25 W2
KB: 2224 ft
TD: 6279 ft
FINA READLYN
1-36-7-26 W2
KB: 2550 ft
TD: 6549 ft
FINA CRANE VALLEY
14-12-9-28 W2
KB: 2343 ft
TD: 8735 ft
HB SPRING VALLEY
6-24-12-26 W2
KB: 2296 ft
TD: 7574 ft
10.5 mi
17.0 mi
7.5 mi
10.5 mi
19.5 mi
13.5
9.0
23.0 mi
16.0 mi
15.0 mi
22.5 mi
15.5 mi
DATUM
Upper Member
Lower
Member
DUPEROW FM
?
B'
INC HUSKY WISETON
10-16-25-13 W3
KB: 1964.5 ft
TD: 4690 ft
BARNWELL ET AL PLATO
4-3-25-17 W3
KB: 2394 ft
TD: 2870 ft
BIGHART PLATO
4-2-26-9 W3
KB: 672.1 m
TD: 1050 m
MURPHY ET AL KINDERSLEY
7-19-28-21 W3
KB: 2370 ft
TD: 3427 ft
PAGE BEADLE
7-31-29-22 W3
KB: 722.4 m
TD: 963.5 m
RGAC DISPOSAL WELL #1
15-31-31-23 W3
KB: 2326 ft
TD: 3951 ft
PENNANT SMILEY
14-24-31-26 W3
KB: 2391 ft
TD: 3249 ft
INC HUSKY N HOOSIER
13-21-32-28 W3
KB: 2399 ft
TD: 4005 ft
INC HUSKY SOUTHCOURT
6-3-33-28 W3
KB: 2407 ft
TD: 4790 ft
24.5 mi
24.0 mi
12.5 mi
21.0 mi
10.0 mi
14.5 mi
13.5 mi
14.5 mi
4.5 mi
? NDE
NDE?
DATUM TOP OF BIRDBEAR FORMATION
Upper Member
Lower Member
argillaceous
subtidal unit
ireton marker
DUPEROW FORMATION

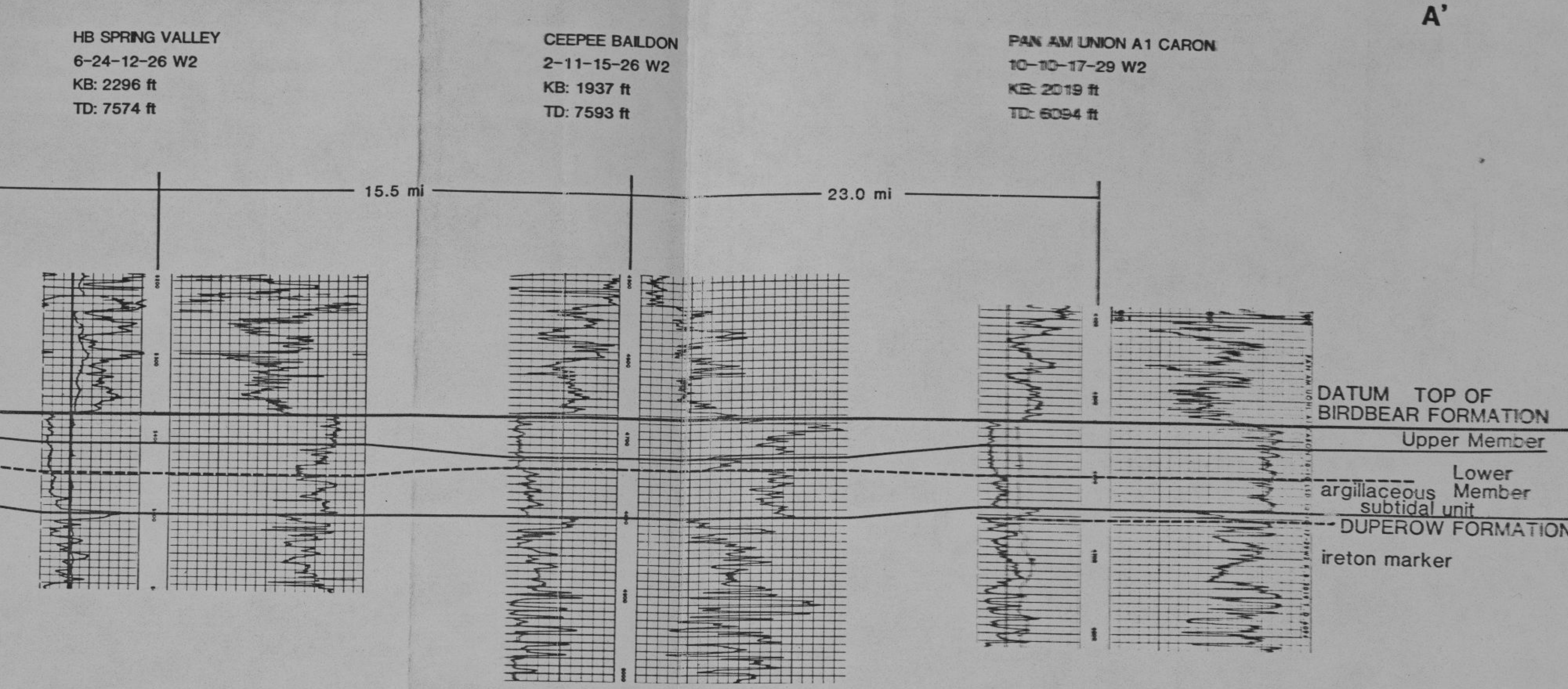


FIGURE 4 STRATIGRAPHIC CROSS SECTION A-A'

FIGURE 5 STRATIGRAPHIC CROSS SECTION B-B' near to impossible because of the occasional absence of anhydrite beds within the entire sequence. In such wells, the upper member is absent by definition; however, a facies equivalent, in the form of a dense lime mudstone, may be present.

Kent (1968), working exclusively in the western portion of Saskatchewan, placed the boundary between both members at the point of transition from the argillaceous beds of the lower member to the poorly argillaceous beds of the upper member. This contact unfortunately is somewhat gradational, although it can be recognized over most of western Saskatchewan. This "argillaceous" lower member is correlatable with the argillaceous "subtidal" unit of the Williston Basin. This apparent discrepancy in the definition of members will be dealt with in a later section.

In the context of this thesis, the contact between the upper and lower member of the Birdbear is placed at the base of the first anhydrite in the stratigraphic sequence. The various reasons and ramifications, however, are explained in the following sections. Figures 4 and 5 illustrate the correlation of various markers across the province from the southeast to the western portion of Saskatchewan.

Towards the west and northwest and in the eastern part of the Alberta Basin Complex, the argillaceous, lower portion of the Birdbear Formation becomes part of the Upper Ireton Formation, whereas the upper portion can be traced as far as the Southern Alberta Marginal Reef Complex where it becomes part of the Woodbend-Winterburn Group (Kent, 1968). In Montana, the Birdbear loses its distinctive character westwards towards the Sweetgrass Arch and Central Montana Uplift, and becomes indistinguishable from the underlying Duperow sequences. In western Montana, the lithologic equivalent of the Birdbear and Duperow Formations is considered to be the Jefferson Formation. The southern margin of the Birdbear Formation is determined by non-deposition along the flanks of the Central Montana Uplift and Transcontinental Arch, and by erosion along the edge of the Cedar Creek Anticline and its extension (see Figure 1). The northern edge in Saskatchewan, the eastern edge in western Manitoba, North Dakota, and northern South Dakota all are erosional features and the location of the depositional boundaries are not known.

DESCRIPTION OF LITHOFACIES

General Procedures

In order to reconstruct environments of deposition and a stratigraphic framework within any given carbonate sequence, certain features of the rocks must be carefully and consistently noted. These features include the following:

- the type of grains present and their relative proportions;
- the packing of the grains and the grain-to-grain contact;
- the amount and nature of the incorporated matrix material;
- the thickness and regularity of bedding;
- mineralogical composition; and
- distribution and development of porosity.

Terminology

Dunham's carbonate classification scheme is employed with modifications as outlined by Kent (1974) and by Smith (1980) (Figure 6). This modified scheme was found to be particularly suitable for the examination of core due to its ease of usage and emphasis upon fabric as opposed to composition.

MUD SUPPORTED				GRAIN SUPPORTED
LESS THAN 10% GRAINS	10-50% GRAINS	GREATER THAN 50% GRAINS		NO MUD
LIME MUDSTONE	WACKESTONE	MICRITIC PACKSTONE	CEMENTED PACKSTONE	GRAINSTONE

FIGURE 6 CARBONATE CLASSIFICATION SCHEME (from Smith 1980)

Dolomite is herein defined as a carbonate rock containing more than 50% dolomite, as determined from visual inspection under a binocular microscope after etching with acid or from the examination of thin sections. Calcareous dolomites are defined as containing 10% to 49% calcite with the remainder being dolomite. Similarly, anhydritic dolomites contain 10% to 49% anhydrite with the remainder being dolomite, and anhydritic limestones contain 10% to 49% anhydrite with the remainder being calcite or its equivalent.

With respect to crystal size, the following terms are used.

(a) cryptocrystalline - no crystallinity visible to the naked eye;

(b) microcrystalline - crystallinity visible, though single crystals not discernable; and

(c) sucrosic - individual crystals visible to the naked eye.

The porosity is described following the scheme of Choquette and Pray (1970), and the various grades are defined as outlined below:

(a) dense - no porosity visible;

(b) trace - less than 1%;

(c) very poor - 1%;

(d) poor - 2%;

(e) fair - 3%;

(f) good - 4%-7%;

(g) very good - 8%-10%; and

(h) excellent - greater than 10%.

The porosity grade was estimated from core and polished sections visually, and calculated from sonic logs where available.

The problem in determining depositonal environments is largely one of identifying energy levels, basin configuration, and sediment supply. Since these controls also affect carbonate accumulation and carbonate genesis and differentiation (Wilson, 1975), the detailed delineation and observation of lithofacies would enable one to unravel the problem of their depositional history and environments of deposition.

The following major rock types or lithofacies have been identified in the lower member:

A - Bedded to nodular lime mudstone to wackestone;

B - Bioclastic lime wackestone to packstone;

C - Intraclastic to pelletoidal lime wackestone to packestone;

D - Laminated to massive dolomite;

E - Laminated to massive lime mudstone; and

F - Argillaceous carbonate mudstone to shale.

The lower member of the Birdbear Formation is characterized by rocks and fossils typical of marine, low- to medium-energy environments. Individual lithofacies can generally be correlated over greater distances, as compared to individual units of the upper member (Halabura, 1982). The lithologies are dominated by limestones and dolomites, with some minor argillaceous mudstones to calcareous shales.

The following lithofacies have been identified in the upper member:

G - Nodular mosaic to bedded nodular anhydrite;

H - Massive to laminated/bedded anhydrite;

I - Laminated to massive dolomite;

J - Laminated to algal dolomite;

K - Laminated to massive lime mudstone;

L - Bioclastic/pelletoidal lime wackestone to packstone; and

M - Intraformational breccias.

This member of the Birdbear Formation is characterized by rapid lateral and vertical changes of lithology, perhaps best illustrated in the core log of the Transempire Imperial Welby No. 14-16 (Lsd. 14-16-18-30 W1M) borehole of east-central Saskatchewan (see Figure 7). In this well, the upper member consists of approximately 63 feet of thinly interbedded limestones, dolomites, and anhydrites.

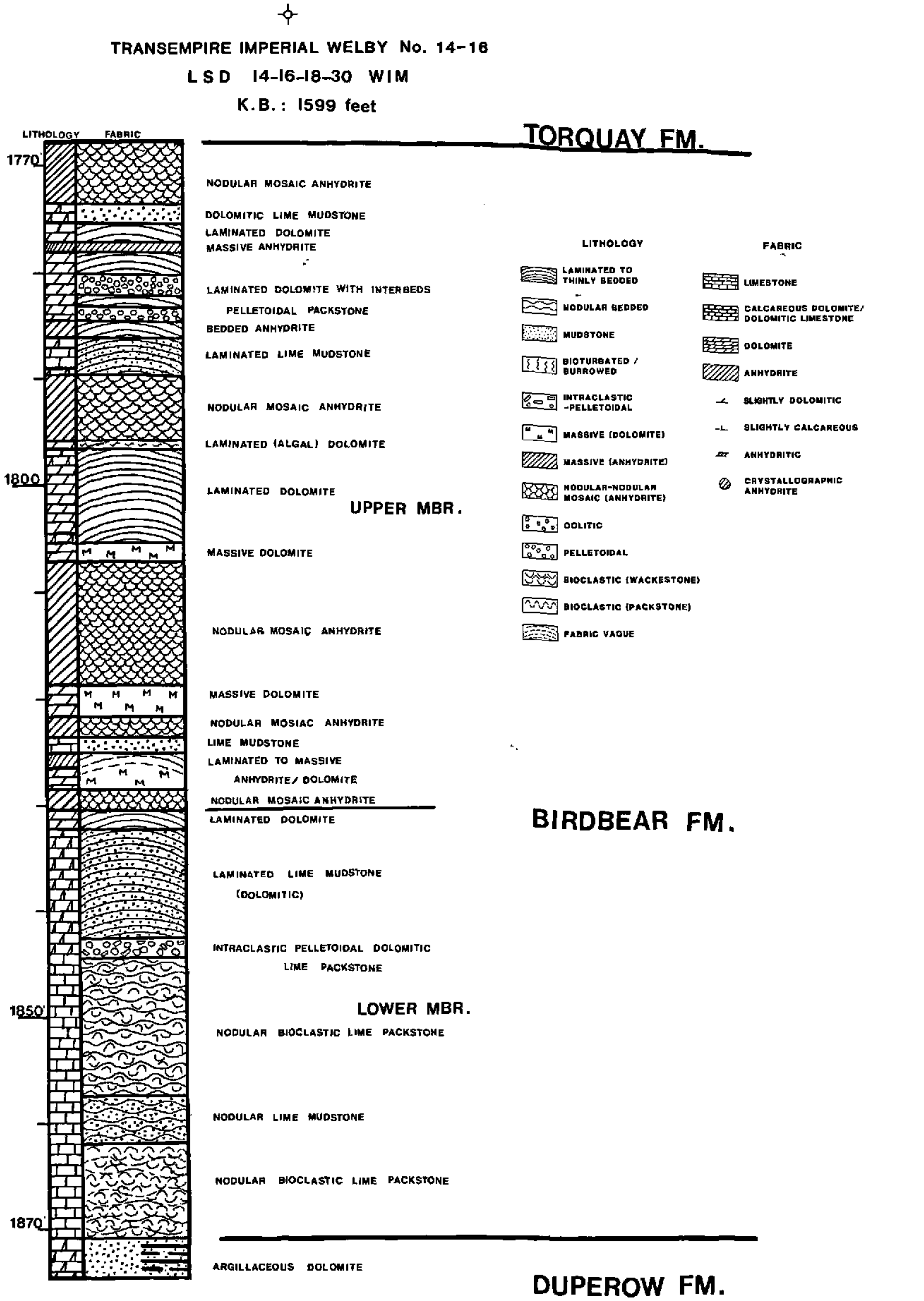


FIGURE 7 DETAILED CORE SUMMARY OF COMPLETELY CORED BIRDBEAR FORMATION, SOUTHEASTERN SASKATCHEWAN

WESTERN SASKATCHEWAN

STRATIGRAPHIC CORRELATIONS

I.N.C. HUSKY N. HOOSIER
13-21-32-28W3
EL:2399'KB

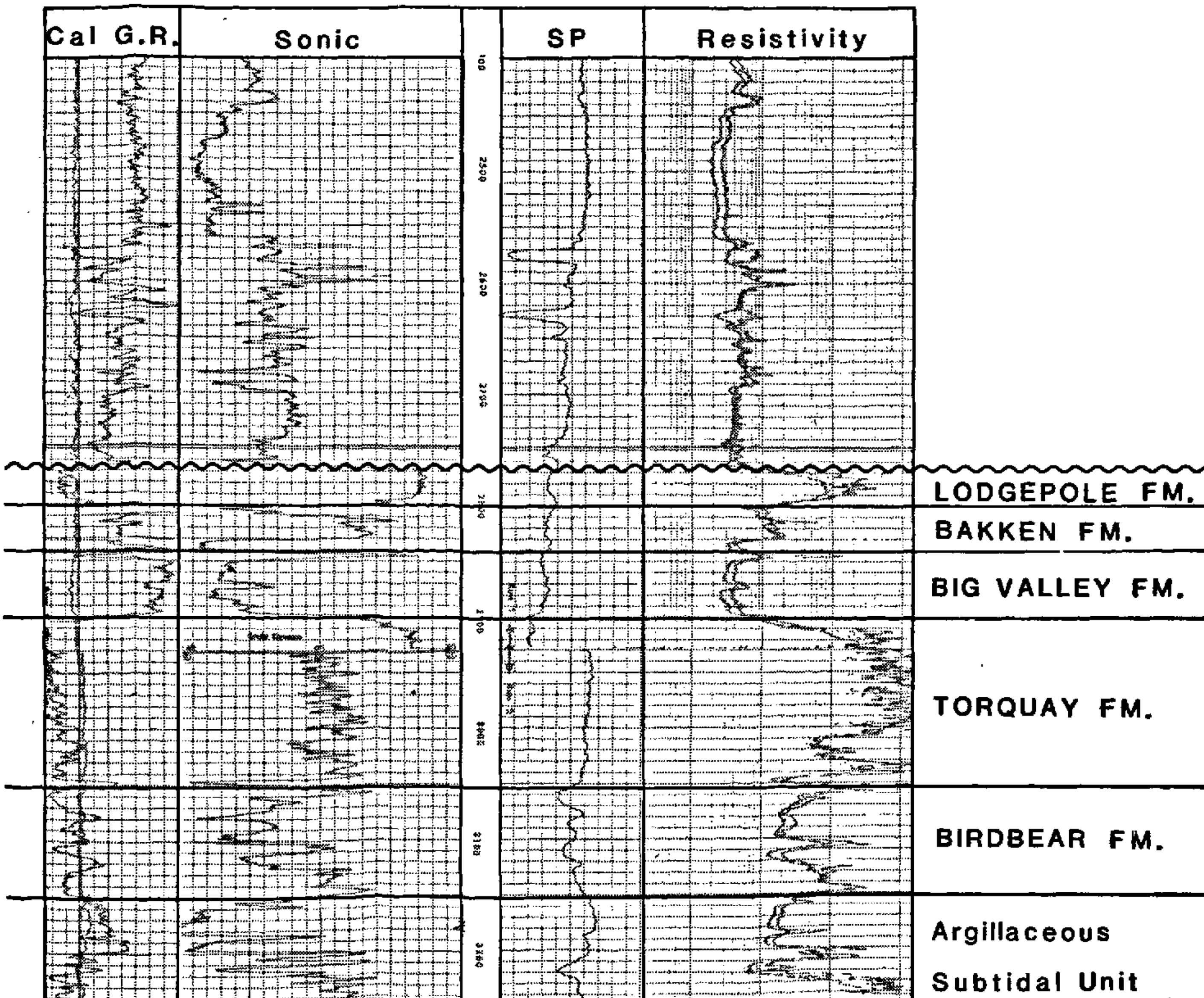


FIGURE 8

Lithofacies of the Lower Member

A. Bedded to Nodular Lime Mudstone to Wackestone

Plate 1, Figures 1-4

Lithofacies A, bedded to nodular lime mudstones to wackestones, is commonly found in the lower portion of the lower member. It may be readily recognized on geophysical logs by its slightly higher content of argillaceous material which causes a shift in the gamma ray curve (see Figures 4 and 5). In core, it is as easy to recognize due to the development of nodular bedding, often referred to as "pinch and swell" bedding, sedimentary boudinage (McCrossan, 1958), or nodular (Type A) bedding (Kaldi, 1980).

The limestone is light to medium brownish-grey in color, microcrystalline, and is frequently slightly to moderately dolomitic. The nodular beds are commonly bound on the upper and lower surfaces by organic and/or argillaceous microstylolites (often referred to as "horsetail" stylolites). Development of nodular beds can often be seen to progress through several stages of development from very slight waving of discrete, primary beds, to regular wavy bedding and minor development of stylolites, to quite distinct nodules often ovoid in form reaching finally a stage where nodules are completely pinched-off and present as discrete bodies, bounded by distinct microstylolites. In units with well-developed nodules, the matrix, as opposed to the nodule itself, is often more dolomitic, with the degree of dolomitization decreasing toward the center of the nodule.

The bioclastic content of this lithofacies ranges from zero up to a maximum of about 20%. The most common fossils are ostracodes, disarticulated brachiopod valves, and rare calcispheres. The bioclasts are in all cases mud and not grain supported. Some pelletoidal material, commonly structureless micrite pellets, is found in isolated cases. In some wells such as Socony Carievale No. 1 (Lsd. 16-4-3-32 W1M), a nodular, bedded lime wackestone may be present in which the prime grain constituents are pelletoids with minor amounts of ooids; however it is believed that such a lithofacies is atypical and that it may represent a local deposit.

Besides varying degrees of dolomitization, the most significant diagenetic alteration of this lithofacies is in form of white, crystalline anhydrite infilling vertical fractures. The fractures are believed to have formed quite late and after deposition and compaction.

B. Bioclastic Lime Wackestone to Packstone

(Plate 2, Figures 1-4)

Bioclastic lime wackestones to packstones comprise the dominant lithofacies of the middle portion of the lower member, and are also quite common in the lower portions of the lower member where they are commonly interbedded with rocks of Lithofacies A. A subtype includes rocks of this lithofacies which have been partially to completely dolomitized. Excellent examples of this lithofacies occur in the Francana Viewfield 3-33-7-8 W2M well, at approximately 5470 feet, and in H.A. Chapman Kisbey 1-28-7-6 W2M at approximately 5352 feet.

Rocks of this lithofacies are usually very fossiliferous, with a bioclastic content up to 50%. The dominant fossils include disarticulated brachiopod valves, gastropods, ostracodes, foraminifera (represented by the genera Parathurammina and Tikhinella), bryozoans, pieces of Amphipora and other stromatoporoids, and coralline algae. In addition, there are abundant intraclasts of structureless micrite. The presence of surface fractures and deformation of the intraclasts suggests that they originated as torn-up pieces of bedded lime mud. In the Steelman well, a thick unit of intraclasts is present, capped by a thin Amphipora bed.

Bedding in this lithofacies, as far as can be detected in core, ranges from randomly sorted bioclasts and intraclasts in a muddy matrix to simple parallel to sub-parallel beds up to 3/4 inches thick. Nodular bedding, as typical for Lithofacies A, may occasionally be developed. Regular and definable bedding, however, is not the norm for this lithofacies; random distribution of bioclasts and other grains is the most common. The percentage of bioclasts versus intraclasts also varies.

Rocks of this lithofacies have been affected to some degree by post-depositional dolomitization, with the percentage of dolomitization ranging from very low to complete in a few instances. Where the rock has been partially dolomitized, the dolomite is best developed in the micrite matrix as opposed to the grains. Where dolomitization is well progressed, the presence of primary grains can only be inferred from vague outlines and "fossil shadows". Dolomite crystal size ranges from microsucrosic to sucrosic. It is within these dolomitized, bioclastic wackestones to packstones that the best porosity trends within the lower member are found.

C. Intraclastic to Pelletoidal Lime Wackestone to Packstone (Plate 3, Figures 1-4)

The intraclastic to pelletoidal lime wackestone to packstone (Lithofacies C) is a common unit within the lower member, and can be divided into two sub-facies: wackestones and packstones composed of grains whose major components are coated particles, and those composed of non-coated particles or lumps. The non-coated pellets are hereafter referred to as pelletoids, as opposed to pellets or fecal pellets, since the affinity of these grains cannot be determined with any amount of accuracy.

The pelletoids are composed of extremely fine-grained micrite, and display no internal lamination or zonation. They are usually sub-rounded to ovoid in shape, though they can also occur as irregular lumps suggestive of intraclasts. Where the grain shape is flat to tabular with sharp, irregular grain edges, the term "intraclast" is more suitable.

The pelletoids and intraclasts are often concentrated in thin, vaguely defined laminae with micrite as the matrix; rarely, the matrix may be calcite cement (as opposed to micritic packstone).

Coated grains are much more rare than the non-coated ones and rarely occur in individual laminae. Lamination is quite vague and not as distinctive as it would be if true ooids were present. The shape of the coated grains is commonly sub-rounded, though they may also be ovoid.

An unusual form of coated grain was found in Tenneco Canadian Superior Salt Lake 11-3-4-20 W2M (Plate 3, Figure 4). Large grains composed of successive layers of algal material are found in conjunction with structureless micrite intraclasts. Smaller grains of 1 to 2 inches in diameter, which may also have an algal affinity are found in very minor amounts in this lithofacies also. The large coated grains are believed to be onkoids.

The grains within these rocks are often in grain-to-grain contact with one another. No apparent deformation of one grain by another is evident; therefore one may assume that the grains were deposited in a solid form and not subjected to deformation by overburden pressure during lithification.

D. Laminated to Massive Dolomite

(Plate 4, Figures 1-3)

Laminated to massive dolomites of Lithofacies D are most commonly found in the upper portion of the lower member. The dolomites are similar to the laminated to massive dolomites of the upper member (Lithofacies I). The dolomite is cryptocrystalline to microsucrosic, commonly calcareous in varying degrees. Bedding character ranges from submillimeter-thick laminations to very thinly bedded, with beds no thicker than a few millimeters. Laminae are defined by variation in crystal size and may be bound on the upper and lower surface by very thin organic and argillaceous layers. Common to these dolomites are thin needles of crystallographic (also known as crystallotopic or metasomatic) anhydrite. Laminae often can be seen to form interlinked anastomosing patterns similar to the intertwined patterns of the black films of microstylolites (horsetail stylolites).

Closer examination of these massive to laminated dolomites reveals in certain cases the vague outline of pelletoids, though most commonly the microscopic texture appears grumelous to indistinct. Relic outlines of bioclastic grains are common and suggestive of primary fossil fragments. The even horizontal form of the laminae are suggestive of varves or algal laminites. The fine and even nature of the laminations, along with a lack of well-developed birdseye textures and fenestral porosity are more suggestive of chemical precipitates, however, than of algal laminites. True algal laminates display characteristic, small-scale wrinkling and development of fenestrae, often infilled with anhydrite.

In view that the laminated dolomites of Lithofacies D lack these features, they can at best be described as "cryptalgal".

Porosity is well developed in this lithofacies as intercrystalline "slits" between adjoining rhombic dolomite crystals. Intercrystalline porosity of this form gives the dolomite the texture of grainy to chalky carbonate.

E. <u>Laminated to Massive Lime Mudstone</u>

(Plate 5, Figures 1-4)

The laminated to massive lime mudstone of Lithofacies E are most common in the uppermost portion of the lower member, and are similar to the laminated to massive limestones (Lithofacies K) of the upper member. The lime mudstones are dolomitic to varying degrees and can often be found closely interbedded with the laminated to massive dolomites of Lithofacies D. These limestones are very fine grained, micritic, and rarely recrystallized. Under a binocular microscope, the microfabric commonly appears clotted or grumelous, suggesting original deposition as pellets or agglutinated lumps of calcareous mud. In some wells, such as Imperial Frys (4-35-7-31 W1M), very small (less than 1 mm in diameter), structureless "pelletoids" appear to comprise the fabric of this lithofacies. The laminae, often with submillimeter-thick laminations, are usually even, sub-parallel and most devoid of features indicating soft-sediment deformation. There are, however, a few contorted and deformed beds suggesting soft-sediment loading. The laminae are bound in most cases by dark, organic-rich and argillaceous films. Dark, organic-rich surfaces cutting across sets of laminae, often rich in pyrite, can be frequently observed and are interpreted to be minor erosional truncation surfaces indicating a period of sediment non-deposition. The individual laminae often form an interwoven, anastomosing pattern.

The lime mudstones are commonly dolomitized to varying degrees with no apparent selectivity or preference of dolomite for certain beds. The other significant diagenetic alteration in this lithofacies is the development of crystallographic anhydrite needles. These needles are often present in thin beds, further defining and accentuating the lamination of the original sediment. Porosity is absent in rocks of this lithofacies except for zones where dolomitization is advanced.

F. Argillaceous Carbonate Mudstone to Shale
(Plate 6, Figures 1 and 2)

This lithofacies is quite rare in southeastern Saskatchewan. It is not to be confused, however, with the lower member of the Birdbear becoming increasingly more argillaceous in western Saskatchewan, which is the result of an increase in clay and silt material in all lithofacies rather than the presence of Lithofacies F.

When present in southern Saskatchewan, the argillaceous carbonate mudstone to shale occurs as thin beds in gradational contacts with other lithofacies. In Socony Imperial Carievale No. 1 (16-4-3-32 W1M), a greenish-grey shale with light, reddish-grey anhydrite nodules is present at the top of the Birdbear Formation. The interfingering of this greenish shale unit with the reddish siltstones of the overlying Torquay Formation and the underlying anhydrites of the upper member of the Birdbear suggest that sedimentation across the boundary was continuous. A similar lithofacies is found in the Imperial Oxarat 14-7-5-27 W3M of southwest Saskatchewan. In Tidewater Glenbain Crown No. 1 (8-22-10-8 W3M), a light-grey, very dolomitic claystone with very thin and even bedding is developed in the lower member and suggests a localized site of deposition of fine-grained, terrigenous clastics. In other wells, very thin shale to argillaceous lime/dolomite mudstones occur sporadically in both the upper and lower member.

Various marker units with log responses similar to those caused by thin shales are found throughout southeastern Saskatchewan. These log markers are distinctive enough to be used for establishing local, stratigraphic markers and lines of correlation. Upon examination of core it was found, however, that these markers do not represent argillaceous beds or shales at all. They may be due either to more radioactive dolomites, minor amounts of disseminated sand grains, or finely disseminated quartzose silt.

Lithofacies of the Upper Member

G. Nodular Mosaic to Bedded Nodular Anhydrite

(Plate 7, Figures 1 and 4)

The anhydrite lithofacies found within the upper member fall into two broad genetic categories, each indicative of a specific depositional environment. The most common form of anhydrite is the nodular mosaic to bedded nodular anhydrite (Lithofacies G). The characteristic feature of this lithofacies is the development of well-defined, discrete nodules of anhydrite, often coalesced into interlinked masses of nodules (known as nodular mosaic texture; see Bebout and Maiklem, 1973).

The voids between individual nodules consist in all cases of dolomite. This matrix dolomite varies in abundance from 50% of the lithofacies to minute wisps, the amount appearing to be dependent upon the stage of development of the nodule growth. In most cases, the matrix dolomite displays parallel to sub-parallel, even laminations rich in dark organic material which are suggestive of algal laminites. The disruption, folding, and rupturing of individual laminated units by anhydrite nodules suggests growth of the nodules within a soft, primary dolomite substrate. This is further supported by the observation that individual laminae can often be traced through the contorted spaces between individual nodules.

Several stages of nodule development and growth can be recognized. The first stage involves the growth of discrete nodules within the laminated matrix causing only buckling and distortion of the beds. Further growth causes the internodular voids to become much smaller and increasingly convoluted. The final stage of nodule growth involves the complete obliteration of the discrete matrix dolomite fabric, and the total coalescence of nodules leaving a vague, shadowy patterning to the rock. Enterolithic fabric is extremely rare, possibly being present in only a few wells such as Imperial Tidewater Climax No. 6-10 (6-10-3-18 W3M). A gradation between nodular mosaic to bedded nodular anhydrite and massive to bedded or laminated anhydrite was observed in some wells such as Barnwell Kendal 4-20-14-12 W2M at the depth of 4330 to 4350 feet. In this borehole, wavy bedding can be seen to be intimately associated with true, nodular mosaic anhydrite.

The bedded-nodular variant of Lithofacies G is similar in appearance to the nodular mosaic texture. The difference lies in the fact that, in the case of nodular mosaic anhydrite, the coalescence of individual nodules appears to be caused by the growth of individual nodules leading to a very subtle interpenetration and commingling of nodules. The bedded-nodular anhydrite, in contrast, consists of nodules in contact with one another yet showing distinct internodular boundaries.

H. <u>Massive to Laminated/Bedded Anhydrite</u>
(Plate 7, Figures 2 and 3)

The second anhydrite lithofacies comprises the massive to laminated and bedded fabric (Lithofacies H). This lithofacies is characterized by laminated to thinly bedded anhydrite with minor amounts of dolomite. The laminations appear to be the result of variations in color as opposed to variations in the amount of enclosed organic matter. The anhydrite is dark-grey to dark brownish-grey in color, often enriched in argillaceous and organic material encapsulated within the crystal mesh. Kirkland and Evans (1981) have suggested that evaporites may contain significant amounts of organic matter and could possibly have potential as hydrocarbon source rocks; therefore it is plausible that the dark color of the anhydrites of the Birdbear is the result of entrapped organic matter.

As mentioned above, dolomite forms a minor constituent of this lithofacies. However, massive anhydrite showing no internal structure and grading to laminated anhydrite is often closely interbedded with cryptocrystalline, massive to laminated dolomite with no evidence of soft sediment deformation. The anhydrite does not appear to be invasive, as are the anhydrites of Lithofacies G. Also the contacts between anhydrite and dolomite is often gradational, suggesting syndeposition. On a larger scale, individual sequences of massive to laminated anhydrite with inter-laminated cryptocrystalline dolomite are bound between well-defined truncation surfaces. These truncation surfaces are dark in color, often appearing highly organic and argillaceous. In Saskoil Moose Valley 10-15-12-6 W2M, pyritized rinds appear to outline several nodules within an essentially massive-patterned anhydrite. Both these features point to reducing conditions during deposition.

I. Laminated to Massive Dolomite

(Plate 4, Figures 1-3)

Rocks of this lithofacies are similar to the laminated to massive dolomites in Lithofacies D. The main difference between these two lithofacies is the greater preponderance of extremely fine-grained, dense dolomites. A large proportion of the dolomites of Lithofacies I are cryptocrystalline, vaguely laminated, and of a dark-brown to very dark, brownish-grey color. Soft sediment deformation may or may not be present. Scattered needles of crystallographic anhydrite are common; where they occur in proportions greater than 10% of the rock, they commonly are found collected in poorly defined beds separated from adjoining beds by a zone free of acicular crystals.

J. Laminated (Algal) Dolomite

(Plate 8, Figures 1-3)

The algal laminated lithofacies comprises a group of rocks which seem to have been precipitated as the direct result of algal activity. This distinguishes these rocks from the laminated sediments of Lithofacies I, K, D, and E which may have resulted from chemical, as opposed to organic, precipitation. The following observations were used to distinguish between the two groups of precipitates:

- algal laminates display crenulation and dramatic waving of individual beds, with the amplitudes and positions of waves within a bed not coincident with those in adjacent beds; non-algal laminites (cryptalgal laminites) display even waving of a much more subdued nature, with amplitudes and positions of waves coincident over wide intervals;

- algal laminites display teepee structures;

- algal laminites display voids between adjacent beds which may be filled with either sparry cement, micrite, or anhydrite, this texture being called "fenestral" or "birdseye" texture;

- clearly developed, stacked hemispherical columns of laminites suggest stromatolites.

The algal laminites may be either horizontally laminated sediments, or columnar stromatolites. An excellent example of stromatolites of the laterally linked variety can be found in Socony Imperial Carievale No. 1 (16-4-3-32 W1M) from 5040 to 5045 feet (see Figure 3, Plate 8). The stromatolites can be seen to be separated by a narrow unit filled with intraclasts of algal material, pelletoids, and micrite. Within this unit are also beds of horizontally laminated algal dolomites with characteristic algal features. Abundant intraclasts, disrupted algal beds, and surface cracks in individual beds suggest a moderate to high energy zone of deposition. The fenestral pores in the horizontally laminated sediments are filled with white, semi-translucent anhydrite.

The algal laminates are generally medium-brown to medium brownish-grey in color. Most are dolomite with varying degrees of calcite. Since the grain size ranges from cryptocrystalline (as in the Carievale algal laminites and stromatolites) limestones to dolomites to microsucrosic dolomites, some degree of post-depositional recrystallization has occurred.

K. Laminated to Massive Lime Mudstone

(Plate 5, Figures 1-4)

The rocks of Lithofacies K are identical to the rocks of Lithofacies C of the lower member. In the upper member, however, the beds are generally much thinner and poorly defined. The degree of dolomitization is generally much greater, with closer intergradation of dolomite versus limestone making precise subdivision of Lithofacies I and K very difficult.

L. Bioclastic/Pelletoidal Lime Wackestone to Packstone

(Plate 3, Figures 2 and 3)

The rocks of Lithofacies L are identical to the rocks of Lithofacies C of the lower member of the Birdbear Formation. The only significant differences are as follows:

- more bioclastic as opposed to intraclastic material is present;
- the beds are much thinner and more poorly defined; and
- the rocks are generally more dolomitic.

M. Intraformational Breccias

Two types of intraformational breccias have been encountered in the Birdbear Formation. The first is present in both the upper and lower member and consists of irregular angular, usually tabular intraclasts of micrite set in a micritic matrix. A good example of the lithofacies can be found in Champlin Brightmore 11-18-9-16 W2M and Tidewater Braddock Crown No. 1 (5-7-14-10 W3M). In the Brightmore well, the rock consists of approximately 60% bluish-grey to brownish-grey, angular, slightly deformed intraclasts bedded sub-horizontally. The matrix consists of micrite and minor sparry calcite. In the Braddock well, the fabric is similar though much more argillaceous material is present. This form of intraformational conglomerate is considered to be sedimentary in origin.

The second form of intraformational breccia is much more rare, yet forms striking occurrences when present. In Tidewater Elbow Crown 2 (1-25-23-6 W3M) and Quasar Francana Trossachs (4-2-9-17 W2M), the Birdbear sequence is virtually indistinguishable on logs. In core, however, the formation consists of large, angular clasts of Birdbear rock set in a shale to finely comminuated carbonate matrix. It is believed that this breccia is tectonic in origin.

INTERPRETATION OF LITHOFACIES

General Remarks

By carefully studying features of various rocks and lithofacies, one may obtain an understanding of the depositional energy level, paleotopography, and configuration of the sedimentary basin in question. Studies on Holocene carbonate-dominated depositional regimes have shown that certain distinctive features characterize each sedimentary environment of sub-environment. By analyzing similar features in ancient depositional sequences allows, therefore, to reconstruct within reasonable limits, the depositional environments for ancient rocks. The Present is thus a valuable key to the Past, and the carbonate-evaporite rocks of the Upper Devonian Birdbear are no exception.

At least one problem, however, exists in this approach, for there are simply no Holocene analogs for the vast, intracratonic and shallow-water seas, and for the extensive Devonian carbonate and evaporite deposits of western Canada. All models can be approximations only, and the problem become most evident when trying to unravel the paleotopography and basinal mechanics of a sequence such as the one under consideration in this thesis.

It also should be remembered that in an ancient sequence, the rock record preserved may not contain all sediments deposited in the original sequence of deposition as a continuum, but rather may be a fragmented record reflecting on the preservation of unusual circumstances (Ager, 1981).

Therefore, any attempt to "precisely" reconstruct a depositional environment for any particular lithofacies must not get bogged down in pinpointing the precise position within a depositional regime, but rather in focusing on a broader depositional zone in which several distinct processes may have been at work.

The sedimentary rocks of the lower member of the Birdbear can be characterized by the following features:

- mud-supported as opposed to grain-supported and cemented fabrics;
- open-marine to slightly restricted depositional conditions;
- the presence of mechanically-piled banks and/or shoals; and
- nodular bedding and compaction effects, especially prominent in the lower portion of the lower member.

Two features distinguish the lithofacies of the upper member of the Birdbear Formation from the lower one. The first, the evaporitic nature of the sediments, points to a basin-wide attainment of hypersalinity in the later period of Birdbear deposition. The second, the remarkable lack of preserved organisms, may be a function of the first condition. The poor lateral persistence of many individual lithofacies units on a regional scale suggests that the depositional environments were more complex than those of a typical supratidal (sabkha) evaporitic sequence, or that of a basinal, hypersaline sea. Distinguishing characteristics of the upper member include laminated sediments (both algal and cryptalgal laminites), thinner individual lithofacies units, and abundant primary anhydrites and dolomites. Tables 1 and 2 summarize the diagnostic features of both lithofacies.

TABLE 1 SUMMARY OF LITHOFACIES OF LOWER MEMBER

LITHOFACIES NAME	GRAIN TYPE/ CRYSTAL SIZE	GRAIN PACKING & MATRIX	BEDDING	POROSITY TYPE & DISTRIBUTION	DIAGENESIS	DEPOSITIONAL ENVIRONMENT
A. BEDDED TO NODULAR LIME MUDSTONE TO WACKESTONE	bioclasts 0-20%; rare pelletoids; very rare ooids	mud supported, micrite, often preferentially dolomitized	nodular bedding microstylolitic; organic laminae	rare intrapart-icle, mainly intercrystalline, fracture, minor moldic	slightly to moderately dolomitic; secondary anhydrite	normal marine to slightly restricted; low energy subtidal
B. BIOCLASTIC LIME WACKESTONE TO PACKSTONE	bioclasts 50% & greater; micrite intraclasts	grain supp. 50% mud supp. 50% micrite matrix; often prefer. dolomitized	parallel to sub-parallel, up to 3/4' thick; minor nodular bedding	intrapart, moldic, interpart, primary & secondary enlargement, inter crystalline, minor fracture	dolomitization of matrix, bio-clasts; secondary crystalline anhydrite	normal marine, relatively high energy, subtidal to intertidal, also mechanically-piled mounds
C. INTRACLASTIC TO PELLETOIDAL LIME PACKSTONE TO WACKESTONE	coated (ooids) non-coated (pelletoids) irregular intraclasts; rare algal beds	grain supp. 50% mud supp. 50% micrite matrix	not character istic; often crude, thin bedding; rare imbrication	interparticle, rare fracture	minor dolomitiz-ation, secondary crystalline anhydrite	quiet water, backshoal shelf, restricted; minor storm deposits
D. LAMINATED TO MASSIVE DOLOMITE	micro-crystal line to sucrosic; rare bioclast outlines	crystalline	laminations sub-millimeter to several millimeters; microstylolitic; organic laminae	intercrystalline	varying degrees of calcite; crystallographic anhydrite	dolomitized version of Lithofacies E, monor C, B; diagenetic
E. LAMINATED TO MASSIVE LIME MUDSTONE	crypto-crystalline		laminations sub-millimeter to several millimeters; microstylolitic, organic laminae	very rare inter-crystalline	dolomitic to varying degree; crystallographic anhydrite	restricted, shallow water low energy lagoons
F. ARGILLACEOUS CARBONATE MUDSTONE TO SHALE	anhydrite; carbonate clasts	mud supported	thin, subparallel to parallel, even bedding	none	secondary crystalline anhydrite	storm deposits & "irregular" events

TABLE 2 SUMMARY OF LITHOFACIES OF UPPER MEMBER

LITHOFACIES NAME	GRAIN TYPE/ CRYSTAL SIZE	GRAIN PACKING & MATRIX	BEDDING	POROSITY TYPE & DISTRIBUTION	DIAGENESIS	DEPOSITIONAL ENVIRONMENT
G. NODULAR MOSAIC TO BEDDED NODULAR ANHYDRITE	minor anhydrite nodules	—	nodular mosaic; crude thin to medium beds, rare enterolithic bedding	—	—	supratidal
H. MASSIVE TO LAMINATED/BEDDED ANHYDRITE	—	—	laminated to thinly bedded; thin argillaceous/ organic laminae; truncation surf.	—	—	very restricted, quiet water, shallow lagoons
I. LAMINATED TO MASSIVE DOLOMITE	cryptocrystalline	—	vaguely laminated; rare soft sediment deformation	intercrystalline	scattered crystallographic anhydrite	precipitation & diagenesis in very shallow, hypersaline ponds & lagoons
J. LAMINATED ALGAL DOLOMITE	microcrystalline to sucrosic; rare intraclasts		typical algal form: wavy bedding crenulation; soft-sediment deformation	intercrystalline	white secondary anhydrite	tidal flats, intertidal to supratidal
K. LAMINATED TO MASSIVE LIME MUDSTONE	similar to lithofacies E			—		
L. BIOCLASTIC/ PELLETOIDAL LIME WACKESTONE TO PACKSTONE	similar to lithofacies C					
M. INTRAFORMATIONAL BRECCIA	intraclasts	matrix of micrite, minor sparry clacite	bedded sub-horizontally	—	sparry calcite	tidal channels, storm-sheet flows, possible evaporite-solution breccias

Interpretation of Lithofacies of the Lower Member

A. Bedded to Nodular Lime Mudstone to Wackestone

The features of this lithofacies which aid in the environmental interpretation are the relatively sparse fauna of a somewhat limited variety, nodular bedding, and slightly higher argillaceous content with respect to other lithofacies.

The bedded to nodular lime mudstone to wackestone of Lithofacies A is similar to Lithofacies B; however, it can be distinguished by the much more limited amount of bioclastic material in facies A as opposed to B. The most common fossils found were ostracodes and brachiopods; gastropods and calcispheres are rare. Distribution of ostracodes is primarily controlled by temperature, salinity, and substrate conditions (Tasch, 1980). Most of their marine species occur in the shallower waters from the lagoon, the inner neritic zone, to about middle neritic water depths. They may be taken, therefore, to be as shallow-water indicators, unless proven otherwise. Some taxa also populate the brackish and freshwater environments and are tolerant of restricted conditions.

Brachiopods were exclusively marine, benthonic, epifaunal, and sessile organisms (Tasch, 1980). Calcispheres remain rather enigmatic as to their origin and may have been derived from algae (Nichols, 1970). It should be noted that the above fossils occur in uniform distribtuion throughout this lithofacies, showing no apparent preference for particular beds. They indicate subtidal, shallow-marine environments. Some restrictions must have been present, however, judging by the sparsity and limited variety of the faunas.

Nodular bedding has been interpreted in several ways by various authors. The pattern of lighter colored, limy layers and nodules within surrounding darker colored muds, with variations occurring between undeformed laminae and thin beds to discrete, completely pinched-off nodules, has been named by McCrossan (1958) 'sedimentary boudinage structures'. This form of bedding has also been informally defined as 'pull-apart' structures or 'pinch-and-swell' bedding. McCrossan interpreted this form of bedding to be the result of pressure loading. Alternating beds of limestone and argillaceous limestone or shale were deposited and, upon compaction, flowage of the less competent beds occurred. This flowage caused tension cracks to form in the more competent, non-flowing beds and the competent beds to crack or form nodules. This mechanism was first postulated by Ramberg (1955). Burrowing was not considered in the case of the Birdbear nodules as a viable mechanism of formation, because burrowing would not explain tension cracks in the nodules, nor would burrowing lead to linked sequences of pinch-and-swell beds but rather to discrete nodules.

Nodular bedding is a very common feature also in the limestones and dolomitic limestones of the Ordovician Red River Formation of the Williston Basin. The development of this nodular bedding has been attributed in most cases to the activity of burrowing organisms (Carroll 1978, Kohm and Louden,1978, Kendall 1976, among others). The mechanisms postulated for the formation of the nodular fabrics involve the following stages:

- the burrows are either preferentially dolomitized or lithified as opposed to the non-burrowed sediments;
- post-depositional compaction causes non-burrowed, non-lithified material to compact preferentially, leading to the draping of these softer beds around the more competent burrowed nodules;
- further compaction leads to pressure solution along the boundary between competent nodules and less competent surrounding beds.

Continuing solution, in turn, leads to the accumulation of argillaceous and organic material along these boundaries.

Nodular structures similar to those found in the carbonates of the Williston Basin were described also by Kaldi (1980) from the Permian Lower Magnesian Limestone of Yorkshire, England. Kaldi distinguished between two forms of nodules. The first type, termed Type A, is similar to the nodular beds of the Devonian Birdbear and Ordovician Red River sequences. Type B nodules, in the form of discrete, irregular nodules are similar however to intraclasts and ruptured beds. Type A nodules occur in distinct or laterally-linked bodies of microspar surrounded by argillaceous matrix, commonly showing signs of deformation around nodules. Kaldi suggested further that these nodules are similar to those described from Mediterranean sediments by Müller and Fabricius (1974). The mechanism involved in their formation requires a low rate of marine sedimentation, allowing abundant subaqueous marine cementation. Preferential cementation leads to beds which are more competent than the surrounding beds. The non-competent beds are considered products of rapid sedimentation, with concomitant reduction in rate of marine cementation. Lithostatic loading of the variably cemented pile in turn leads to flowage of non-competent, as opposed to the competent beds. This flowage enhances the wavy, nodular character of the beds and leads to initiation of pressure solution along the top and bottom of nodules.

The slightly higher argillaceous content of Lithofacies A is obvious not only in core and cuttings, but also from the slightly higher radioactivity of the rocks of Lithofacies A in southeastern Saskatchewan, as shown by the gamma ray curve on logs. In western Saskatchewan, this argillaceous character is amplified and makes the unit a dominant stratigraphic unit (see Figure 8). The settling of such fine, argillaceous material must have occurred in relatively low energy environments as opposed to high energy conditions under which this material would have remained in suspension and be swept into the basin proper. The increased argillaceous content thus points to conditions of relatively low energy.

Considering all features, it may be summarized that the rocks of Lithofacies A were deposited under close to normal marine, but slightly restricted, shallow-water conditions, and under lower energy regimes.

The nodular bedding is believed to be indicative of early marine cementation, preferential lithification, and subsequent flowage and deformation of competent and non-competent beds. These features suggest deposition and lithification in a subtidal marine environment.

B. Bioclastic Lime Wackestone to Packstone

The following features of this lithofacies aid in interpretting the depositional environment: nodular bedding, fossil abundancy and diversity, and nature of grain packing and support. The bioclastic lime wackestone to packstone of Lithofacies B most commonly occurs within the middle portion of the lower member. In core, it forms a conspicuous and easily identifiable rock type, relatively thickly developed, and with only some minor beds of other lithofacies interspersed. Quite often it is dolomitized to a certain degree.

A diverse faunal assemblage characterizes this lithofacies. Fossils observed include stromatoporoids, disarticulated brachiopods, gastropods, ostracodes, Foraminifera (including Parathurammina and Tikhinella), fragments of Amphipora, and varieties of bryozoans. It is worthwhile stressing that these fossil remains are often present as fragments (the corals and bryozoans), as disarticulated valves (the brachiopods and ostracodes), and that they are infilled with micrite (unarticulated brachiopods and gastropods). Bioclasts are often closely associated with intraclasts composed of micrite. Many of the quoted organisms flourish in environments of warm water, normal-marine salinity, and nonturbid water. The broken nature of the organisms suggests high depositional energy levels, as does the abundant and close association of micritic intraclasts. Algal material is also present in the form of laminated pieces as opposed to encrusting forms, suggesting high energy transport.

Despite the richness in stromatoporoids and bryozoans, the thicker accumulations in Lithofacies B are not considered true reef structures but rather mechanically-piled bioclastic mounds. Gerhard (1978) described such structures from the Tague Bay reef of Saint Croix Island in the Caribbean. The reef-building organisms are the typical Caribbean coral faunas. However, the reef is largely a pile of sand with abundant unbound,skeletal fragments. These "sandpile reefs" occur back from the shelf edge in environments of somewhat lower wave energy (Gerhard 1978), while organic framework reefs occur directly on shelf edges with good circulation and higher wave energy. Wilson(1974) placed similar lime-sand shoals, beaches, and dunes on the uppermost part of the shelf margin well within the turbulent zone. All these deposits have in common that they form on shallow shelves and that they are circular or elliptical in planar view. They contain few or no frame-building, sediment-trapping organisms and form in the shoals and lagoonal environments by the trapping and baffling of fine debris by various types of organisms.

The nodular bedding present in this lithofacies is similar to the one discussed for Lithofacies A. The bedding is, however, more sporadic and usually confined to isolated portions of the unit, as opposed to being uniform throughout. The mechanism is considered to be more or less the same as postulated for Lithofacies A. The fact that bedding is not as widespread may simply indicate higher rates of sediment accumulation, as the non-bedded sections were deposited at rates exceeding the rates of precipitation for marine cementation (Kaldi, 1980). Material that is covered up by rapidly deposited sediment does not have the opportunity to remain at optimum depths and subsurface fluid conditions for the precipitation of marine cement. Therefore, the sporadic development of nodular bedding within the rocks of Lithofacies B suggests deposition in a shallow, subtidal environment, with sedimentation rates higher than those envisaged for Lithofacies A.

Not surprisingly, the rocks of this lithofacies are also rich in bioclasts. In most cases, these are present in a mud-supported matrix, as opposed to an organically bound or cemented matrix. When bioclasts are in contact with one another, and the intergrain voids are infilled with micrite. In a few wells, however, on rare occasions it was observed that cement filled the intergrain voids instead of mud. The type of matrix material may give additional clues as to the environment of deposition. The major matrix constituent in Lithofacies B is micrite, as opposed to calcite cement. Several different types of calcite cement have been documented in literature; however, all have certain characteristics in common.

Calcite cement is a precipitate from waters saturated with respect to calcium carbonate (Longman 1982). It is also a diagenetic phenomena controlled by temperature, salinity, CO_2 vapor pressure, and fluid movement. The greatest rate and amount of calcite cementation occurs in the freshwater, phreatic zone, i.e. in rocks which are constantly within the realm of fresh (meteroic) subsurface waters. The rate and amount of cementation decreases away from this zone or where the water becomes stagnant. Becher and Moore (1979) suggested similar effects for the cementation of the Upper Jurassic Smackover "trend" of Louisiana. The absence of cement in the bioclastic wackestones and packstones of Lithofacies B would suggest, therefore, that these sediments were never within this zone of freshwater, phreatic cementation. If they were, one would expect extensive blocky, equant calcite cement as opposed to micrite. Longman (1982) summarized that, in a marine phreatic zone, little cementation can be expected due to relatively stagnant flow regimes, flat bottom conditions, and muddy primary sediments. In the case of Lithofacies B, the preponderance of micrite over cement as matrix material thus implies low energy conditions, poor subsurface water flow, low levels of rainwater and freshwater influx, and muddy primary sediments.

From even cursory observations of the fossil assemblage, bedding characteristics and grain to matrix relationships, the following depositional environment can be postulated for Lithofacies B of the Birdbear Formation. Abundant and diverse faunal assemblages suggest normal-marine salinity levels and clear, warm, shallow waters.

The bioclastic nature of the preserved fossil record, coupled with the presence of intraclasts, suggests a high degree of wave energy. The muddy matrix, as opposed to sparry matrix, points to the lack of freshwater early diagenesis, relatively flat basinal topography, and muddy primary sediments. It is postulated, therefore, that these sediments were deposited in a zone of relatively high energy conditions, resulting in the creation of mechanically-piled mounds and banks. The large amount of micrite and broken nature of the bioclasts means that the organisms perhaps flourished at a location other than the place of deposition of their hard parts. Wave energy, however, was not sufficient to winnow-out the micrite matrix material, or perhaps the water contained a high amount of suspended, very fine mud.

In summary, the sediments of Lithofacies B were deposited in relatively high energy, subtidal to intertidal position, well back from the slope edge, and they are interpreted to be mechanically-concentrated shelf and mound deposits, fairly irregular in outline, distribution, and morphology. The word "intertidal" is used in the sense of a broad zone within the limits of the mean high-tide and mean low-tide water level. Sediments within the high energy subtidal and intertidal zones could undergo periods of subaerial exposure due to water level fluctuations within the basin. Similar shelf and mound sequences have been observed in the Birdbear Formation in North Dakota (P. Loeffler, pers. comm. 1982) and have been reported in other Williston Basin formations such as the Duperow (Wilson, 1967; Hoganson, 1978), where the banks have been interpreted to be stromatoporoid bioherms. The scattered occurrences of Amphipora found within this lithofacies may be isolated thickets and meadows of thin, dendroid and euryhaline stromatoporoids, similar to those found by Wilson (1974) in muddy back reef lagoons in the Swan Hills outer reef platform complex.

In many cases, the micritic matrix of Lithofacies B has been preferentially dolomitized, with bioclasts dolomitized to only a small degree or, if completely dolomitized, observable as relict fragments or 'ghosts'. This preferential dolomitization is due to the smaller size of the micrite grains allowing more surface to surface contact of grains to dolomitizing fluids (Asquith 1978, Longman 1982).

C. Intraclastic to Pelletoidal Lime Wackestone to Packstone

The features of this lithofacies which aid in the interpretation of depositional environments include the preponderance of non-coated grains, as opposed to coated grains; the form and nature of non-coated grains; and the bedding and grain to grain contacts.

The dominant grain found within Lithofacies C is the structureless pellet or pelletoid. Minor amounts of poorly formed ooids are present. In most cases, the core appears rather nondescript, with the pellets visible only on slabbed, polished sections of core and when viewed under a hand lens or microscope. Wilson (1975) defines pelletoids as "fecal pellets and coated grains of other origin", as opposed to "spherical multiple coated particles in which laminae are smooth and constitute a relatively thick coating" (p. 12). Grains which have only one or two laminae coating a nucleus of structureless material are defined by Wilson as "superficial ooids". From observing numerous Holocene and ancient carbonate settings, Wilson (1975) outlines three depositional environments for pelletoids and related grains:

- laminated to bioturbated pelletoidal lime mudstone to wackestone, also containing ostracodes and peloids, deposited in very restricted bays and ponds;
- hardened fecal pellets, in places mixed with carapaces of ostracodes and tests of foraminifera, forming a pelsparite which may grade into a peloidal wackestone. This lithofacies is found on tidal flats and natural levees;
- grapestone pelsparite or grainstone, a mixed facies of isolated peloids, agglutinated peloids, some coated grains, and lumps in which are small intraclasts formed in warm, shallow water with moderate circulation.

Purdy (1963) was the first to study in detail the sediments of the Great Bahamas Bank, he described a pellet mud to mud lithofacies near Andros Island. The pellet mud facies is characterized by abundant fecal pellets and particles smaller than 1/8 mm. Minor amounts of skeletal material is also present. This lithofacies was found to contain appreciable amounts of ooids which apparently were carried into the area by storm waves from regions of oolitic lithofacies. Deposition takes place in shallow waters (between 6 and 24 feet) with stable bottom conditions, and a lack of bottom traction in areas most sheltered from trade winds and furthest from strong tidal activity, generally shoreward from the coralgal reef edge. The fine-grained nature of the sediments is due to the relatively low energy level. The pelletoids in this case are formed by the activity of holothurians and gastropods such as the genus Batillaria (Purdy 1963).

The pelletoidal rocks of the Birdbear sequence most closely resemble Wilson's (1975) laminated to bioturbated pelletoidal lime mudstone to wackestone lithofacies of his 24 standard microfacies. The minor amounts of ooids found, usually in thin, isolated beds, may have been carried into the area by storm processes. The lack of well formed ooids anywhere within the study area suggests that wave energies were never sufficient to result in the agitation necessary for ooid formation, nor that the proper chemical conditions for the precipitation and subsequent formation of these grains were present. The pelletoids are, therefore, interpreted to have formed in quiet water, shallow, backshoal environments.

The intraclasts present appear to be gradation from the rounded pelletoids. They are also constructed of structureless micrite; however, they lack the rounding of the pelletoids. Purdy (1963) described the formation of similar intraclasts within his pellet mud lithofacies. Disaggregation of soft, friable pellets by bottom, storm-induced disturbances leads to the formation of irregular-shaped, often agglutinated grains similar in composition to the round pelletoids. The lack of selective bedding among the two grainforms suggests that current activity and wave-induced sorting were negligible influences on the distribution of these sediments.

Fossils are sparse within Lithofacies C and confined generally to a few ostracode carapaces, though rare forms suggestive of gastropods have been found. The lack of other fauna points to severe restrictions and greater or lower degrees of salinitiy. Ostracodes are known from both hypersaline and brackish-water lagoons, and gastropods are known to occur everywhere as well.

In summary, Lithofacies C, the intraclastic to pelletoidal lime wackestone to packstone, is interpreted to have been deposited under low energy conditions with rare storm disturbances, under moderate to severe restriction, and on a relatively flat, regular shelf where bottom traction was lacking. This latter condition explains the scarcity of ooids. A quiet-water, backshoal shelf region is envisaged with low levels of wave and tidal current activity.

D. Laminated to Massive Dolomite

The features which aid in the interpretation of a depositional environment for this lithofacies include the form and type of bedding and the mineralogical composition. The laminated to massive dolomites are similar in both members of the Birdbear Formation, the significant difference being the finer crystal sizes in the upper member and their more intimate association with anhydrites. The laminated to massive dolomites of the lower member are commonly associated with the laminated to massive lime mudstones of Lithofacies E, and are not associated with anhydrites.

The laminated to massive dolomites of Lithofacies D are formed by a finely intergrown mesh of dolomite crystals generally less than 10 mm and poorly developed. Often they are laminated to thinly bedded and associated with thinly bedded lime mudstones. These dolomites are similar to Fisher and Rodda's (1969) "massive dolomite", a fine-grained to thinly bedded variety which, however, is slightly coarser. The dolomite crystals form a loosely knit mass of euhedral crystals. The massive dolomites which Fisher and Rodda (1969) discussed were found in the Lower Cretaceous Edwards Formation of Texas. They suggest that the dolomites formed as a secondary diagenetic rock from a host which may have been a carbonate grainstone or coarse bioclastic limestone deposited in a high energy rather than low energy marine environment. The dolomitization occurred due to the flowage of magnesium-rich brines through originally permeable sediments, causing recrystallization and porosity development. The denser fluids migrated from restricted lagoons rich in saline brines along topographic depressions and escaped to the main sea body along permeable facies. Fisher and Rodda generalized that thick sequences of massive dolomites found adjacent to lagoonal evaporites are the result of secondary dolomitization by seepage refluxion, according to the classic model first proposed by Adams and Rhodes (1960).

Laminated to massive dolomites found within the Ordovician Red River Formation of the Williston Basin have been interpreted to have been formed subtidally and in a restricted, penesaline sea of regional extent by Kohm and Louden (1978). The laminations are the record of primary depositional units and are preserved because of the absence of organisms which would normally burrow and homogenize the sediment. The absence of mudcracks, burrows, and oxidation films suggests deposition in a hypersaline to penesaline sea. Asquith (1978) also adopts this general model, further suggesting that the dolomite is the result of the dolomitization of lime mud. Kendall (1979) stated that these laminated to massive dolomites, termed by him 'laminated microdolomites', are deposited in a hypersaline lagoonal environment.

In the Birdbear Formation, the laminated to massive dolomites are characteristically found in the upper portions of the lower member, and often closely interbedded with laminated to massive dolomites or rocks of Lithofacies A and/or B. As mentioned previously, examination of polished slabs of this lithofacies often reveals the vague outlines of denser, pelletoidal-shaped bodies or vague outlines of bioclasts. It is believed, therefore, that these laminated to massive dolomites are the result of the dolomitization of laminated to massive lime mudstones, bioclastic wackestones to packstones, and minor pelletoidal lime wackestones to packstones. Dolomitization would have been the result of seepage refluxion following the pathway outlined by Adams and Rhodes (1960) in their model.

If one can clearly ascertain the primary depositional fabric of a dolomite, one may call that particular unit a 'dolomitized' version of a particular lithofacies. If, in contrast, the primary texture is obliterated or difficult to determine, the lithofacies would be placed in Lithofacies D. Laminated dolomites may be the result of dolomitization of a lime mudstone, and this interpretation is further supported by the observation that laminated lime mudstones which have been dolomitized to a certain degree often occur in conjunction with laminated dolomite. The dolomitization occurred in a downward manner for, originally, the sedimentary rocks were impermeable lime mustones. The flowage of dense brines over this unit caused the uppermost layers to gradually undergo dolomitization. As these upper layers were dolomitized with concurrent creation of porosity, the newly developed pore system allowed the brines to seep further down into the lime mudstone. The process terminated when the enriched brines were either depleted, or the brines were routed through a more porous and permeable conduit system such as a bank or shoal.

E. Laminated to Massive Lime Mudstone

The features of this lithofacies which aid in environmental interpretation are the form and type of bedding, and evidence of bed disturbance. The laminated to massive lime mudstones of Lithofacies E within the lower member of the Birdbear Formation are similar to those described by Wilson (1967) from the underlying Duperow Formation. He described an unfossiliferous, non-pelletoidal laminated lime mudstone displaying submillimeter-thick laminations and parallel layers. The laminated to massive limestones of the Duperow are dark brown in color, dense, with fine anastomosing bedding, few irregular laminae, and microlaminar slump structures. Wilson did not observe any textural differences between laminae, and considered this rock to have been originally a carbonate mud deposited in quiet, shallow ponds of water with higher salinity and no agitation of water.

Purdy (1963) noted the abundance of uniform mud in the sediments west of Andros Island. The water covering these mudflats tends to be less than 9 feet deep, prone to greater fluctuations in salinity as compared to the water over the pellet mud facies, and lacking in pellet-producing organisms. Alternately, the abundance of very fine-grained material could also be the result of the disintegration of soft pellets, or the deposition of muds due to extremely low levels of current agitation.

In the Bahamas, this facies is most frequently found in the higher salinity, low energy lagoonal environments.

Fisher and Rodda (1969) deduced that the carbonate mud and evaporite facies of the Lower Cretaceous Edwards Formation of central Texas was deposited within a lagoonal environment. The carbonate mudstone is described as being thinly bedded to nodular, with one variant of this facies being thoroughly bioturbated. The presence of evaporites are inferred due to the presence of extensive beds of evaporite-solution breccias.

Kendall (1979) stated that laminated micrites from the Ordovician Red River Formation are lagoonal in origin. He also described a scenario where sabkhas found bordering hypersaline lagoons are underlain by laminated carbonate sediments. Again a situation involving both increased salinity, very low energy, and consistent water cover is suggested.

The microfabric of Lithofacies E may occasionally be found to be composed of "clots", a texture also referred to as "grumelous". The clots at times suggest a certain similarity with the intraclasts and pelletoids of Lithofacies C; however, their very poor development and lack of well formed pelletoids requires that these rocks be placed in a separate lithofacies.

The laminations found within this lithofacies are quite even, with only minor amounts of bedding disturbances such as microslumping and soft-sediment distortions. The disturbances are not sufficient to be suggestive of brecciation or evaporite solution; therefore one may assume that no evaporites were deposited along with the carbonate mudstones. The bed disruption may have been more due to periods of elevated wave energy such as storms or rapid flooding of the sediment surface.

In summary, the rocks of Lithofacies E are considered to be result of deposition of very fine-grained carbonate mud in shallow-water lagoons. A higher than normal level of salinity is suggested, due to the lack of fossils and bioturbation and the absence of well-formed pelletoids. However, salinities were not high enough to result in the precipitation of evaporites. These rocks represent the endphase of the transgressive carbonate deposition before the onset of hypersaline and regressive conditions and the regional deposition of anhydrite.

F. Argillaceous Carbonate Mudstone to Shale

Rare, thin beds of dark brown to black shales occur sporadically in the lower member of the Birdbear, and are separated as Lithofacies F. These argillaceous layers are not to be confused with the generally more argillaceous sequences developed in western Saskatchewan and in the Alberta Basin. True shales are very rare in the Upper Devonian of eastern Saskatchewan, and it is for these rare occurrences that the biofacies is established.

According to Wilson (1967), terrigenous and authigenic clastic material in the form of insoluble residues make up less than two percent by weight of the limestone facies and less than 0.5 percent of the evaporite facies of the Duperow Formation. The thin shales may therefore represent the record of severe storms which deposited thin films of terrigenous dust on the surface of the sediment. In a carbonate-dominated shelf environment such as that found during Birdbear time in southern Saskatchewan, any significant influx into the system of terrigenous material would have greatly inhibited the deposition of carbonate. Therefore any clastic material would have to be brought into the system by "irregular" processes or what could be termed non-sequential events.

Thicker shale units, such as those found in Quasar Francana Trossachs 4-2-9-17 W2M or Tidewater Birsay Crown No. 1 (13-4-25-8 W2M), are enigmatic. The shale unit in the Trossachs well appears to be related to severe brecciation and, as such, may represent a younger shale which became mixed with Birdbear clasts during the collapse of overlying material into a cavern created by solution of Prairie Evaporite salts. Alternatively, they may represent younger terrigenous clastics deposited within a localized cave created by karst solutioning. Some of the clasts found within this well are similar to the reddish siltstones of the overlying Famennian Torquay Formation, thus suggesting that the breccia may represent a younger deposit containing clasts and a matrix of varying ages. The shale and highly argillaceous carbonates of the Birsay well appear primary in nature as there is no apparent association of breccia with the shales; also the contacts with over- and underlying units suggests that deposition across the shale unit was continuous. This lithofacies may therefore be the result of terrigenous clastics being deposited in localized basins, although the source of the clastics is unknown.

Interpretation of Lithofacies of the Upper Member

G. Nodular Mosaic to Bedded Nodular Anhydrite

The features which aid in interpreting the depositional environment for this lithofacies include the nature and form of bedding, and the fabric of the anhydrite beds. This anhydrite Lithofacies G is characteristically found in intimate association with anhydrite and dolomite. The dolomite is present either as highly distorted beds "woven" among nodules of anhydrite or as wispy patches distributed throughout the apparently massive anhydrite. Dolomite content ranges from less than 10% to approximately half the sediment. Bedding, when present within the dolomite, is thin and crinkly and is interpreted as representing an algal laminite (see discussion of Lithofacies J) with minor amounts suggestive of cryptalgal laminites (Lithofacies I). Individual dolomite beds are often deformed around anhydrite masses; when the nodules of anhydrite appear to be bedded, the dolomite is massive as opposed to laminated.

This nodular to nodular mosaic anhydrite fabric, with varying amounts of disturbed interlaminated dolomite, can be explained either by the growth and coalescence of gypsum crystals within a soft-sediment substrate, or as a result of post-depositional conversion of gypsum to anhydrite. The model for this type of anhydrite formation are the sabkhas along the Trucial Coast of the Persian Gulf which have been described by numerous authors. In thse salt flats, the sequence consists of cemented sediment layers and abundant algal mat material. Gypsum precipitation occurs not on the surface but within the sediment itself and at the boundary with the groundwater surface. In the Abu Dhabi sabkha, anhydrite first appears one kilometer inland from the high water mark according to Kendall (1979), and is present as small discrete nodules. Further precipitation onto these nodules causes them to grow causing the displacement of the host sediment.

Nodular mosaic anhydrites were described as well from carbonate-evaporite sequences of the Upper Devonian (Famennian) Stettler Formation of central Alberta (Fuller and Porter 1969). Laminated dolomites and nodular anhydrites were interpreted to represent the sediments of an ancient sabkha that developed peripherally is a carbonate-dominated basin.

Dean (1975) examined the differences between nodular and laminated anhydrites and suggested that workers in the field of anhydrite deposition and diagenesis apply the sabkha model too frequently and in some cases uncritically. He believed that the close association of the two types of anhydrite fabrics could mean, alternatively, that the laminated and nodular anhydrites have formed subaqueously, in shallow to deep bodies of water, and side by side.

Rocks of Lithofacies G occur most frequently in the northeastern portion of the study area, corresponding to the most shoreward zone of sediment accumulation. Within this zone, the nodular mosaic to bedded nodular anhydrite lithofacies forms the bulk of the anhydrite present. The environment is interpreted to be that of supratidal, shoreline (sabkha) with the anhydrite having formed within the sediment by the growth and coalescence of gypsum nodules. The dolomite may have originated as irregular masses of algal material and storm-washed intertidal to subtidal material.

H. Massive to Laminated/Bedded Anhydrite

The feature which distinguishes this anhydrite lithofacies from the previously described lithofacies is the even, subparallel nature of the bedding. The beds typically display only the slightest amount of crinkling and bed distortion. Nodule development is absent. Interlaminated carbonate in the form of dolomite is typically cryptocrystalline and dense, lacking in features which would suggest algal growth.

Kent (1968) recognized a bedded or banded anhydrite, and an interlaminated dolomite-anhydrite in the Birdbear Formation of western Saskatchewan. In both cases the beds are thin, display minor crenulation, and may be separated by shaley or carbonaceous partings. Kent concluded that the bedded, banded, and interlaminated anhydrites were deposited as the last phase of anhydrite deposition and that they may indicate flooding of the sabkha by marine waters.

Bebout and Maiklem (1973) and Kendall (1976) both described laminated to thinly bedded anhydrites from numerous ancient sequences. Bebout and Maiklem thought that this form of anhydrite may have been deposited subaqueously in very shallow water, calm lagoons. Kendall also gave as a site of deposition a subaqueous environment. Individual nodules in contact with and distorted by each other are interpreted to have been deposited in shallow water. If any distortion of beds is present, the distortion is due to the deformation of semi-solidifed or plastic sediments.

Dean (1975) stated that the even, subparallel laminations of anhydrites and associated carbonates seen in many ancient sequences was due to subaqueous precipitation instead of subaerial exposure and agglomeration within a host sediment. The lack of deformation or disruption he interpreted to point to deposition in deeper, permanently stratified water. Shallow-water or tidal flat sediments should display storm layers, burrows, shrinkage cracks, and flat-pebble conglomerates in his opinion. A subaqueous depositional environment for laminated anhydrites is also suggested by Asquith (1978) and Wilson (1975) for anhydrites of the Ordovician Red River Formation and the Upper Devonian Birdbear Formation respectively.

Holocene examples of tidal pond sediments were documented by Hagan and Logan (1975) from Shark Bay, Western Australia. These sediments contain abundant algal mats and laminites, particularly the 'C-mat' fabric.

From a perusal of these and other examples, the following environment of deposition is suggested for the anhydrites of Lithofacies H. The laminations and lack of soft-sediment deformation on algal laminites suggest precipitation of both anhydrite and carbonate within shallow, low energy lagoons or ponds. The ponds contained hypersaline brines which were periodically flushed and recharged with smaller amounts of normal saline, marine water. Thus, restriction never reached the point where salt and other chlorides would precipitate. The minor amount of sediment disturbance may have been caused either by storm activity or by the slumping of semi-solid material. While some of the laminated anhydrites do contain abundant laminated carbonates, which may be algal in nature and thus compare to the Hagan and Logan model, most of the massive to bedded anhydrites are devoid of carbonate interlaminations. This, coupled with lack of sediment disruption, suggests that the pools were devoid of organisms and were chemically unsuited for the precipitation of appreciable amounts of carbonate.

I. Laminated to Massive Dolomite

Features which aid in interpreting the depositional environment for this lithofacies are the nature of the bedding and crystal size. In certain respects, the dolomites of Lithofacies I are similar to the ones of Lithofacies D of the lower member. One significant difference is that cryptocrystalline, dense dolomites make up a greater proportion of the lithofacies in the upper member than in the lower member. Also, the dolomites of the upper member are closely associated with anhydrites, which they are not in the lower member.

Wilson (1967) suggested an early, pre-lithification dolomitization phase for several of the dolomite types found within the Upper Devonian Duperow Formation of Saskatchewan and North Dakota. Dolomites, which are unusually fine-grained (individual crystals 10 to 20 μm) were believed by Wilson to be evaporitic in nature, representing mineral phases which were deposited syngenetically with closely interbedded anhydrites.

Besides describing a massive dolomite lithofacies from the Edwards Formation of central Texas, Fisher and Rodda (1969) also describe a "stratal" dolomite. This dolomite consists of a tightly knit network of very small (less than 10 μm) poorly developed dolomite rhombs. Porosity and permeability in these stratal dolomites is nonexistent. The dolomite beds tend to be quite thin, generally less than two feet in thickness. In Fisher and Rodda's view, the stratal dolomite was deposited on carbonate-mud tidal flats within a mud of aragonite or calcite with associated amounts of gypsum or halite. The dolomite formed very early in the diagenetic history of the sediment, probably before lithification of the host sediment. These sediments were considered resistant to any later dolomitizing and refluxing Mg-rich brines.

Many workers tend to consider most laminated dolomites as being the remains of algal laminites and mats. This characterization may, in some cases, lead to misinterpretation of the proper environment. There are, however, differences between the algal and non-algal laminites which will be discussed in more detail in the description of Lithofacies J, the laminated algal dolomite.

The question arises if the non-algal (or "cryptalgal") laminites may or may not represent primary dolomite which has directly precipitated from highly hypersaline brines. Dolomite-like carbonate minerals called "protodolomites" have been reported from several areas such as the Bahamas, south Florida, Bonaire, the Gulf of Eilat, and the Persian Gulf (Patterson and Kinsmen 1982). This protodolomite is present as a diagenetic, rhombohedral variety, non-stoichiometric with respect to calcium content, and partly or completely disordered with respect to the distribution of calcium and magnesium (Patterson and Kinsman 1982). This mineral phase was termed by them 'diagenetic dolomite' and was found to form by dolomitization in the subsurface of the sabkha under precise ion ratios and flow rates of fluids, flooding frequency, sediment permeability, and shoreline configuration. The maximum development occurs in the high intertidal sediments composed of fine aragonitic mud.

Obviously, this dolomite did not form as a direct precipitate but rather as a very early, diagenetic event.

Dolomitization of surface sediments was reported from the Florida Keys by Shinn (1968). The dolomites were found as mudd,y desiccated crusts in the lower supratidal zone and associated with zones of lithification. Again, these dolomites are more likely very early diagenetic products, as opposed to primary precipitates. The span of time between sediment deposition and dolomitization may be quite short however, for Patterson and Kinsman (1982) report that at the Bahamas, Florida, and Bonaire sites, dolomitization was essentially concomitant with sedimentation. Therefore, when ancient dolomites are described, and even though the dolomite is not a primary precipitate, it may still be considered to have formed quasi-syndepositionally with other carbonate sediments.

In summary, the cryptocrystalline, anhydritic, laminated to massive dolomites found within the upper member of the Birdbear Formation are considered to be largely the product of very early precipitation and diagenetic growth of dolomite in very shallow, hypersaline ponds or lagoons. The salinity was great enough to inhibit the growth of any benthonic forms of organisms and algal mats other than planktonic organisms which left no fossil record. Yet organic material must have been plentiful, for these dolomites are often dark brown in color and give off a fetid smell when dissolved in acid. Kirkland and Evans (1981) report finding highly saline ponds in the Rann of Kutch often teeming with phytoplankton. Therefore, the laminated to massive dolomites of the Birdbear are believed to have been formed in similar saline, very evaporitic lagoons and ponds, possibly within an intertidal zone or landward of restricting shoals and/or banks.

J. Laminated Algal Dolomites

Features which suggest an algal origin for these dolomites include:

- wavy, crinkled bedding and lamination;
- the development of fenestrae, often filled with anhydrite or acting as sites for the development of secondary (crystallographic) anhydrite;
- evidence of soft-sediment deformation features such as rupture of beds, development of dessication cracks, and teepee structures;
- the presence of stromatolites.

As mentioned earlier, some geologists assume many laminated dolomites reflect on the preservation of algal mats. Algal laminites can be distinguished from cryptalgal laminites by the following subtle but identifiable features.

Logan (1961), in his study of the algal laminites of Shark Bay (Western Australia), gives an excellent summary of the characteristics of true algal laminites, features which were acknowledged to be diagnostic by numerous later workers. The algae form sequences of layered algal mats in sheltered, intertidal zones (such as protected re-entrant bays and tidal flats behind barrier ridges and islands), and in the supratidal zone. Mats in the supratidal zone display desiccation cracks, and often are disrupted because they were broken apart in storms to form flat-pebble conglomerates. The actual mat is formed as the result of filaments binding together the trapped sediment particles. Three forms of algal laminate are described by Logan:

- flat-lying algal laminites underlying an active mat surface;
- low sinuous domes and discs of detrital material formed in zones of slight wave energy;
- club- and columnar-shaped structures displaying the form of the classic 'Cryptozoan' type stromatolite.

Carozzi (1960) gives the following petrographic characteristics of algal laminites:

- laminated, wavy texture with an almost imperceptible gradation between the bottom of an algal layer and the underlying limestone;
- laminae ranging from 0.06 mm to 5 mm in thickness with an average of 0.25 mm;
- persistence of individual laminae;
- the presence of domes with synclinal troughs between individual domes;
- extremely small crystal size;
- indistinct laminae with only birdseye texture apparent;
- birdseye pores (fenestrae) filled either with clear calcite

or with anhydrite;

- rare forms displaying anastomosing networks of bedding planes with individual laminae often intersecting and bifurcating in an irregular manner.

The reported occurrences of ancient algal laminated dolomites are too numerous to mention. Zenger (1972) gives a set of characteristics by which an algal affinity was inferred for Paleozoic dolomites in the Appalachians. These characteristics are also frequently mentioned by other workers. The dolomites occur closer to sources of terrigenous material, suggesting proximity to a paleoshoreline. Desiccation cracks, birdseye texture, intraclasts, evaporite crystal molds, vertical burrows, algal stromatolites, dolomite rhombs in a lime micrite, and the paucity of fossils -- all these and other features are suggestive of sediments that formed in an intertidal to supratidal, periodically flooded are of deposition. Extreme evenness of laminae, excellent sorting of any particles (such as silt or sand grains) within individual laminea, and the orientation of elongate grains parallel to the bedding are indicative of non-algal origin and therefore could be characterized as being indicative of cryptalgal laminites.

Limestones and dolomite beds displaying most of the features described above are numerous in the sediments of the upper Birdbear member and contrast markedly with the laminated to massive dolomites of Lithofaices I. Therefore, it is suggested that the laminites of the upper member are the result of algal precipitation in an intertidal to supratidal depositional setting. The association of nodular mosaic anhydrite and laminated to bedded anhydrite with algal laminities aids in further pinpointing the depositional environment. The two forms of anhydrite allow differentiation of sediments into those deposited subaqueously in very shallow water, and those deposited supratidally in a sabkha-type environment. Both stromatolites (as in Socony Imperial Carievale No 1, 16-4-3-32 W1M) and horizontally laminated algal structures are present within the upper member of the Birdbear. The generally larger crystal size of the dolomites associated with the algal sediments points to a greater degree of post-depositional diagenetic recrystallization of the dolomite, or perhaps the early dolomitization of calcareous algal beds. This greater degree of secondary dolomitization was perhaps due to greater primary porosity in the algal units as opposed to the much denser impermeable dolomites of Lithofacies I. Such dolomites would correspond to surficial dolomites found in the Persian Gulf sabkhas (Patterson and Kinsman, 1982).

K. Laminated to Massive Lime Mudstone

Features useful in identifying this lithofacies are similar to those described for Lithofacies E of the lower member. The environment of deposition of these limestones is considered similar or identical to the one reconstructed for the rocks of Lithofacies E. Some laminated lime mudstones which display the typical features of algal affinity are placed, however, within Lithofacies L; they represent calcareous algal laminites which escaped the process of dolomitization. It is suggested that Type-K limestones are the result of deposition of extremely fine-grained muds in shallow waters, perhaps bodies of water such as lagoons. These bodies of water may represent episodes in the normally highly restricted Birdbear shelf of fresher waters entering the basin, preventing the deposition of significant amounts of evaporites or dolomites.

L. Bioclastic/Pelletoidal Lime Wackestone to Packstone

The identifying features and environment of deposition for rocks of this lithofacies is believed to be similar to those described for the rocks of Lithofacies C of the lower member. As with Lithofacies K, the occurrence of rocks with significant amounts of bioclastic material and pelletoids points to a localized freshening of the waters on the Birdbear shelf. This freshening may have been due to a short-lived influx of marine waters with more normal salinities, or in areas of increased circulation and mixing. The occurrence of these rocks, however, is quite rare, with individual beds rarely traceable over anything more than very small lateral distances. In a few rare cases, thin beds of pseudo-ooids are found within this lithofacies; however, their presence is not considered to have any significance.

M. Intraformational Conglomerate and Breccias

As mentioned earlier, two forms of intraformational breccias can be recognized. The first form is clearly sedimentary in origin, while the second form is tectonic in nature and not related to any event of deposition during Birdbear time.

In the first type, tabular clasts of micrite can be seen embedded sub-horizontally in a muddy matrix. Two modes of origin can be postulated for these breccias:

- breccias and conglomerates with crude bedding and imbrication, suggesting deposition under flowing water, possibly in tidal channels or storm sheet flows;
- non-bedded breccias composed of jumbled intraclasts and severely broken and deformed beds which may have been the result of solution of evaporites and subsequent collapse of overlying beds.

Fisher and Rodda (1969) described an evaporite-solution breccia from the Edwards Formation of central Texas. This unit is composed of a lower zone of highly brecciated or conglomeratic rocks, succeeded by a sequence of beds dipping in random directions, commonly at steep angles. The brecciated rocks are typically very altered due to their high original porosity and permeability. Overlying beds are frequently undisturbed, suggesting that solution and collapse occured intermittently at the time of deposition.

In the Champlin Brightmore 11-18-9-16 W2M well, the intraclasts are quite irregular and angular. They are commonly sub-horizontally bedded, though the beds display signs of severe soft-sediment deformation. Also, abundant sparry calcite, secondary crystalline anhydrite, and tripolitic chert are found in the matrix. It is suggested that this form of intraformational breccia is the result of the solution of evaporite beds with subsequent collapse of overlying beds. The activity occurred soon after the deposition of the primary sediment, for the overlying units are unaffected by any form of collapse features. The intraformational breccias found in Tidewater Braddock Crown No. 1 (5-7-14-10 W3M) are more difficult to explain, since the clasts are more regular and they form and display even horizontal to sub-horizontal bedding with rare occurrences of imbrication. This fabric is interpreted to reflect on a storm flood deposit spread over a tidal flat. The onrushing waters caused the desiccated and cracked surface to break up and result in a mass of intraclasts which settled-out later when the storm waters receded.

This lithofacies is placed within the upper member, for this solution-collapse breccia had obviously been associated with evaporites at one time or another even though at present it may occur below the first preserved evaporite bed (as in the Brightmore well).

The tectonic breccias are much more dramatic in appearance and generally affect the entire stratigraphic column, not being confined to any particular beds or formations. Within the Birdbear Formation, tectonic breccias have been found at Quasar Francana Trossachs 4-2-9-17 W2M and the Tidewater Imperial Elbow Crown 1 and 2 wells (Twp. 23, Rge. 6, W2M).

The Elbow structure was analyzed by deMille (1956). The pre-Cretaceous section appears to be repeated by faulting and to have been severely crushed and jumbled, often mixed with fragments from underlying Silurian and Ordovician rocks. The Devonian cannot be correlated from logs or cores with surrounding wells and with undisturbed sections. The zone of disturbance is approximately 10 sections in size and is underlain by an area devoid of Prairie Evaporite salts. Also, the structure seems to be located at the edge of the Devonian stable platform. De Mille postulated that the structure was formed by a cryptovolcano erupting in a zone of crustal weakness. His reasons for postulating an eruptive event include the circular nature of the structure, the presence of a ring depression extensively folded and faulted around a severely disturbed core, and the upward displacement of Silurian and Ordovician rocks into younger strata. The above features, except, perhaps, for the upward displacement of older rocks, could also be explained by a meteorite impact.

The Trossachs well displays features very similar to those found in the Elbow wells. Again, it cannot be correlated with surrounding wells and the entire Devonian section appears to be severely disturbed.

There are a number of explanations for the structures. They are simply listed without further discussion because not enough regional data is available to allow any weighing of the pros and cons of the alternative explanations. The alternatives are:

- solution of Prairie Evaporite salts with subsequent collapse of overlying beds into the salt-free cavity;
- an eruptive event such as a cryptovolcano (an igneous feature which vents large amounts of extremely hot gases but little or no magma);
- infilling of a karst solution system with younger sediments;
- an astrobleme;
- fault breccias associated with deep-seated basement fault movements.

What is clear is that the tectonic breccias were not the result of syndepositional forces, but that they formed at later times as a result of any of the events outlined above. Therefore, the isolated occurrences of these tectonic breccias are not discussed as part of the depositional history of the Birdbear Formation but are rather mentioned as structural oddities.

DEPOSITIONAL ENVIRONMENTS AND PALEOGEOGRAPHY OF THE BIRDBEAR FORMATION

Deposition Within an Epeiric (Intracratonic) Sea

Saskatchewan, during the Frasnian and for that matter during all of Middle and Upper Devonian time, was an extensive shelf area bordered by the Precambrian craton to the north and east, and the Alberta Basin-Cordilleran Geosyncline to the west. This shelf was separated from the Cordilleran geosyncline and the Alberta Basin by a positive area composed of the Sweetgrass Arch and the Swift Current Platform. The shelf itself rested on a stable, intracratonic platform situated at or close to the western border of the Devonian North American continent. Therefore one may consider sedimentation within this intracratonic area to follow the pattern predicted by the epeiric model (see Figure 9). Within this intracratonic sea sedimentation remained remarkedly constant, consisting almost entirely of carbonates and evaporites. The only exception to this sedimentary tendency towards autochthonous deposits are the terrigenous clastics of the Deadwood-Winnipeg Formations, the shales of the Ordovician (Gunton and Stoney Mountain), the Devonian redbeds (Ashern, First, and Second), and the Three Forks Group, including the Bakken Formation. Terrigenous clastics become much more common in younger sediments, especially during the Cretaceous. The alteration between autochthonous and allochthonous sediments is probably due to crustal stability, epeirogenic events, and climatic influences.

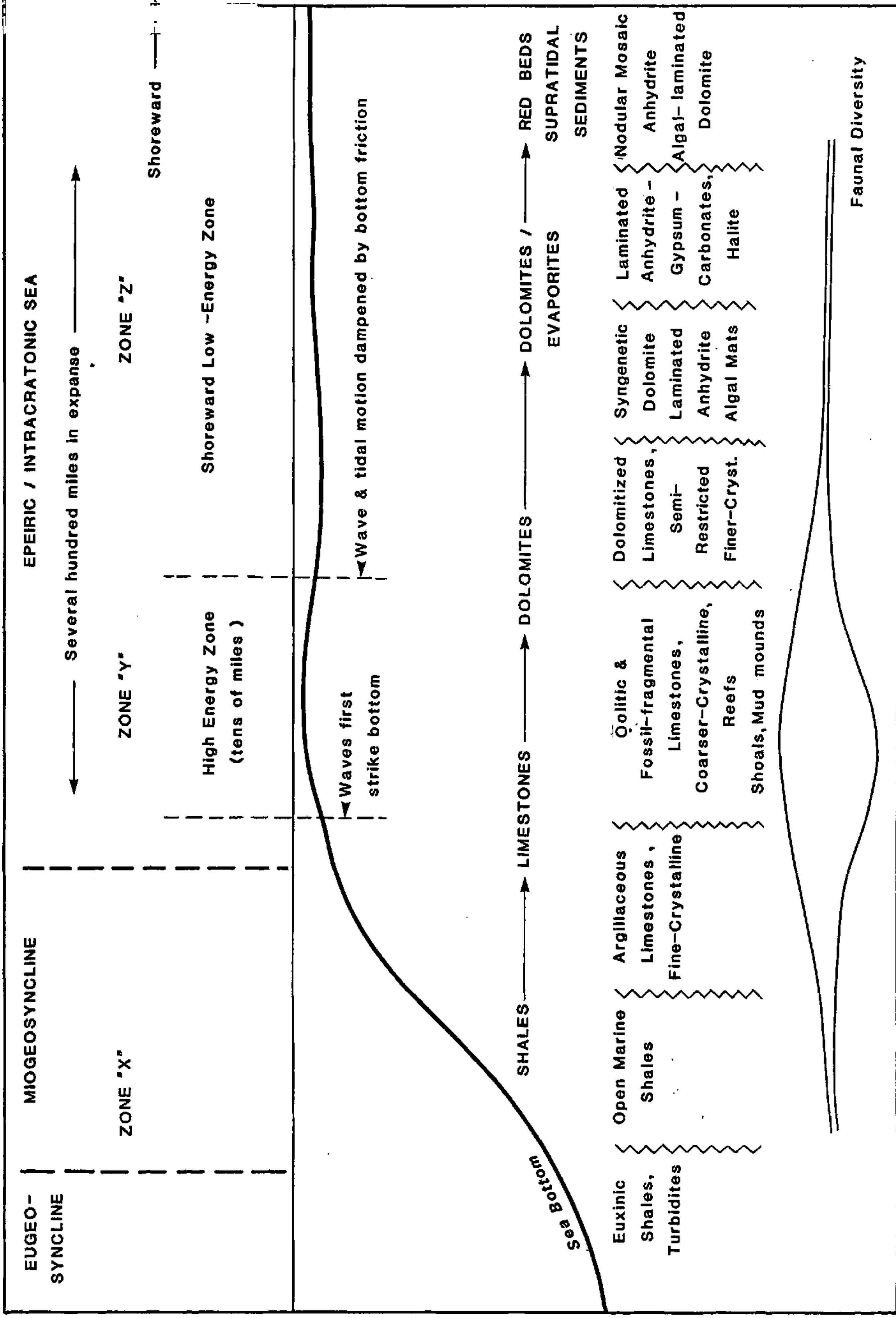


FIGURE 9 SEDIMENTATION ZONES IN AN EPEIRIC SEA

(after Irwin, 1965; Braun, pers. comm.)

Sedimentation in an epeiric sea is perhaps best summarized in the works of Irwin (1965) and Shaw (1965), although many other geologists have dealt with this fascinating topic. The principles of epeiric sea sedimentation are quite simple and are based on a few common denominators:

- lack of terrigenous clastics and minor influences from land areas;
- great width of shelves;
- abundant shoaling;
- low order of slope coupled with extreme shallowness; and
- restricted circulation and low energy levels.

Figure (9) also illustrates Irwin's concept of 'energy zones'. Zone 'X' is the area where deeper water sediments collect; this zone is always below wave base and, as a result, is one of low energy. In Zone 'Y', the wave and current energy comes in contact with bottom sediments and dissipates there. It is therefore a zone of high energy and well-aerated waters. It is in this zone where the greatest amount of biogenic activity occurs which, in turn, leads to one of the greatest rates in sediment accumulation. Zone 'Z', shoreward of Zone Y and often of vast expanse, has relatively low energy levels for most of the wave energy has been expended in Zone Y and whatever remains is slowly but surely dissipated in Zone Z by bottom friction. Also, due to the lack of major circulation and mixing and increased rates of evaporation, Zone Z is also one of increased salinity.

Bioclasts and grains derived from plant and animal material are significant indicators of both salinity and energy levels, as previously mentioned. Grains are found preferentially in the vicinity of marine banks in shallow, turbulent, well-aerated marine waters, and are usually skeletal in origin (bioclasts). These grains are deposited as the result of mechanical energy. Peloclasts (Irwin 1965) are precipitated particles formed either as chemical coatings or as fecal debris. Peloclasts occur in a zone landward of the high energy, bioclastic zone of deposition. Mud occurs within this facies. Lithoclasts (Irwin 1965) are broken pieces of existing carbonates and are found on the tidal flat. They are formed by periodic desiccation-flooding cycles.

Sedimentation is controlled by the physical-chemical conditions and biological activities in the three energy zones, by the topography of the shelf, any by minor "external" influences from the surrounding land area which must have been very subdued in topography and only undergoing chemical erosion. The sediment character thus was largely established within the system.

Three major types of sediments are found and to be expected according to the model: shales (including black shales), carbonates, and evaporites, each showing a progressive change in facies within each unit from the "seaward" to the "landward" side.

Another important control on sedimentation is the topography of the basin and depositional area. If the basin floor was perfectly flat, the pattern of lithofacies stacking would be highly regular, following the contour of basin depth above or below wavebase. If, however, the basin floor was not perfectly flat, minor deviations would result in an irregular distribution of facies patterns due to certain portions of the basin floor ("paleohighs") being in the range of a higher energy zone as opposed to surrounding lower portions ("paleolows"). A "crazy quilt" distribution of lithofacies would occur (Shaw 1965).

There is another and third kind of control mechanism, the dynamic nature of the transgression-regression itselt which too often is overlooked in geologic reconstructions. As outlined earlier, the lowermost Birdbear sequence was strongly influenced by a transgression, the strongest perhaps of Devonian times, which was building-up momentum all through the Frasnian time (Braun 1983, pers. comm.). In contrast, the upper two-thirds of the Birdbear sequence is marked by stagnating, highly restrictive influences which indicate a long-lasting regression.

During a transgression and regression, energy zones will fluctuate rapidly and continuously, and their effect will be accentuated by irregularities of the basin floor. As a result, lithofacies patterns will change continously, and the rapid changes in lithology both in a vertical and lateral sense will be the most difficult to unravel, and equally difficult to describe, because of their four-dimensional complexities.

Basin Topography and Isopach Maps

Up to now, only the lithologic and facies aspects have been considered and interpreted. For the writing of the geological history of Birdbear time and deposition it is, however, equally important to attempt to reconstruct the major trends in basin and shelf topography. Major insight can be gleaned from a series of isopach maps which were specifically constructed for this purpose.

It has been stressed several times that the investigator's aim should not be necessarily the "precise" reconstruction of all and the most minute details, but the recognition of "trends" and the attainment of plausible results. The final goal is impossible to achieve anyway considering the "state of the art" in geological exploration and the level of refinement in knowledge acquired to date. Furthermore, the writer does not subscribe to the idea that the summation of many small, detailed and precise points and observations automatically translates into a coherent large-scale picture. Far from it; there is the old proverb that still holds true that in geology it is sometimes more advantageous to be "vaguely right" than "precisely wrong". All these and many other painful truths are particularly pertinent to the construction and interpretation of isopach maps from subsurface data.

The following isopach maps were constructed:

A. Total isopach of the Birdbear Formation;

B. Isopach of the argillaceous lower unit (corresponding to

8) lower member and the argillaceous subtidal unit of southeastern Saskatchewan of this study);

C. Isopach of the lower member;

D. Isopach of the upper member; and

E. Isopach of the interval between the base of the upper member and the top of the argillaceous lower unit (called the "Intertidal Unit").

The isopach intervals were chosen for several reasons. The total thickness of the Birdbear Formation is a reflection of rates of sediment accumulation and as such is indicative of the rate of sediment supply and basin downwarp. Since the base of the first anhydrite encountered in the stratigrpahic sequenc marks the attainment of hypersalinity within the basin, an isopach map of the interval from the base of this first anhydrite to the top of the formation should indicate zones of increased anhydrite deposition and thus zones of increased salinity. Likewise, an isopach of the lower member -- those sediments below the base of the first anhydrite -- should indicate areas of increased accumulation of normal-marine rocks. An isopach of the argillaceous lower unit reflects on thicker accumulations of this unit and anomalously thin deposits in the underlying subtidal unit. This subtidal interval is the record of the first transgressive pulse across the basin after the numerous Duperow transgressions and regressions. Thick isopach values should indicate paleotopographic depressions which received a greater amount of sediment than the thin units deposited over paleotopographic highs. An isopach map of the interval between the base of the upper member and the top of the argillaceous lower unit records the amount of sediment deposited in an intertidal zone, and perhaps also in a hypersaline lagoonal zone.

A. Total Isopach of Birdbear Formation

Map A illustrates the total thickness of the Birdbear sequence across Saskatchewan. Attention should be paid to the following features:

- position and orientation of thin areas (areas with less than 100 feet of sediment, colored in blue on map);
- position and orientation of areas greater than 120 feet and less than 150 feet in total thickness (colored in yellow on map); and
- differences in thicknesses between northwest and southeast corners of the map area.

Within the area of study, three broad regions are distinguishable where the Birdbear sequence is less than 100 feet in thickness. Between Ranges 17 W2M and 3 W3M, and from the International Border (Township 1) north to approximately Township 7 exists a roughly semicircular area of Birdbear sediments less than 100 feet thick. This regional trend in thinness is broken in the vicinity of Township 4 Range 26 W2M by a local, oval-shaped feature trending approximately north-south. In this broad area, the sequence is as thin as 77 feet, as in the Socony Sohio East Popolar No. 1, 1-15-1-25 W2M well for instance.

A second region in which the Birdbear Formation is regionally thin is in the southwestern part of the province. This area is elongate, trending northeast to southwest and extends as far west as Range 24, W3M and as far north as Township 25. This feature is named the "Swift Current Platform" for its coincidence with a tectonic feature of the same name and in the same area (Kent 1968).

The third region with a thin Birdbear sequence lies in the northeastern portion of the study area. This region is defined by the 100-foot contour and the feature is named the "Punnichy Platform" after a settlement near its center. This area of thin Birdbear trends in a northwest to southeast direction, the Birdbear being as thin as 54 feet in Altana North Wapella 11-35-15-33 W1M.

The Swift Current Platform is of a somewhat semi-circular shape and appears to link-up at its northern end with the western margin of the Punnichy Platform, suggesting some sort of continuity. Both platforms appear to surround the semi-circular thick representing the Williston Basin in the southeast of the province. To the northwest of the Swift Current Platform, the Birdbear Formation thickens markedly.

The regions of intermediate thickness -- by definition between 120 and 150 feet -- form two well-defined belts. The first is centered in southern Saskatchewan and in turn shows two sub-belts. The southernmost one seems to be composed of a series of discontinuous bodies, roughly oval in shape. The strike of the bodies changes from northeast to southeast in the western portion, to approximately northwest to southeast in the eastern parts. The position and shape of these bodies suggests an arcuate pattern similar to the outline of a basin. The southernmost sub-belt is flanked to the north by a more continuous belt trending in a northeast to southwest direction which approximates the strike of the edge of the Punnichy Platform. It crosses to the north of the edge of the Swift Current Platform and abruptly changes strike to a northeast to southwest direction, aligning itself parallel to the western edge of the Swift Current Platform. A third region of intermediate thickness and forming the second belt is found in the northwest corner of the study area west of Range 24 W3M and north of Township 29. This region is oriented in a northwest to southeast direction.

To the northwest of the Swift Current Platform is a region where the Birdbear Formation exceeds 150 feet in thickness. In three areas, the thickness is in excess of 200 feet. These areas of maximum thickness are located as follows:

- between Townships 25 and 30, west of Range 26 W3M;
- between Townships 28 and 31, Ranges 21 to 23 W3M; and
- between Townships 31 and 34, Ranges 13 to 15 W3M.

These areas are oval to elongate in shape, without any preferred orientation or well-defined isopach trends other than a semi-circular form bounded by the Swift Current Platform to the southeast and the subcrop edge to the north.

In contrast, a series of isopach trends in the northcentral portion of the map area shows distinct northwest to southeast orientation, especially the easternmost one. The significance of these trends will be discussed in the following section.

B. Isopach Map of the "Argillaceous" Lower Unit

As discussed earlier, this unit is slightly more argillaceous than upper sediments, and tends to be composed of rocks of Lithofacies A and B. It is interpreted to primarily reflect a low to high energy subtidal in environment.

Three broad trends can be recognized on this map. The first is a large, irregularly shaped region in the southwestern part of the province where the unit is regionally thin. The eastern boundary of this area is approximately Range 5 W3M, and the northern edge approximately Township 25 in the eastern portion, and Township 18 in the western portion. This regionally thin area is situated in approximately the same position as the Swift Current Platform, with its overall thin Birdbear sequence. Contours within this region, although somewhat irregular in outline, show no major changes in thickness. This would suggest that the area was one of relative constant topography with a low rate of subsidence.

A broad region centered in southcentral and southeastern Saskatchewan is characterized by elongate trends of 'thicks' (greater than 50 feet) and 'thins' (less than 30 feet). In the southeast they are oriented in a roughly northwest to southeast direction, about parallel to the southern edge of the Punnichy Platform. In the western portion, the strike is in a more northerly direction. Again, the overall orientation and shape of these trends suggest a semicircular pattern.

The third trend is a regional 'thick' extending across the entire province along the northern subcrop edge. This trend is interrupted in the easternmost portion by a local 'thin' centered in Township 17 W1M. In the westernmost portion of this area, two local regions exceed 100 feet in thickness.

Isopach trends in the northwest corner of the study area appear to be influenced by the orientation of the indentations noticeable on the Total Isopach Map (A). These identations occur at the northern end of the Swift Current Platform and may represent localized sub-basins resulting possibly from basement fault movements. The close spacing of the individual contour lines is indicative of rapid sedimentation within these fault-controlled sub-basins.

Overall, the isopach contours of this unit and within the various regions tend to form rather irregular patterns with the exception of some contours in the northwest region. This irregularity would suggest that the basin floor was relatively irregular in topography, though displaying an overall constancy of that of a flat shelf.

C. Isopach Map of the Lower Member

Examination of cores and certain geophysical log responses, and the discrimination of lithofacies and reconstruction of their mode of deposition allow the delineation of a number of depositional zones for both the lower and upper members. It cannot be emphasized enough, however, that such an undertaking is highly subjective and speculative. The difficulties start already when examining the core, multiplying as the study proceeds, and they are most pronounced in units where lithologic changes are frequent and drastic, as in the upper Birdbear member.

One, and probably the only, way to solve these multilayered problems is tp try to detect and outline first- and second-order influences, possibly even third-order ones, which will enable to differentiate between primary depositional environments and secondary to tertiary sub-units thereof. This was done for each and any borehole examined in this study. The results were then plotted on a map, using symbols and colors for the various depositional zones and subzones. If a pattern develops that shows large scale trends and what could be called a "predictable" sequence, one might assume that the assumptions made and procedures followed are valid as research approaches, and that the interpretations are reasonable.

The isopach of the lower member reflects the influence of the Swift Current and Punnichy Platforms, and the seaway linking the Williston and

Alberta Basin. Three areas of interest can be mapped:

- subtidal zones along the southern and the northwest margins of the map area;
- lagoonal zones over the Punnichy and Swift Current Platforms;
- intertidal to high-energy subtidal zones between those zones mentioned above.

The subtidal zones colored in green in Map C are found in two widely separated portions of the map area. Two distinct lobes of this zone occur in southern Saskatchewan, the first lobe centered over the previously described total isopach 'thin' of the Roncott area immediately east of the Swift Current Platform, and the second in the extreme southeastern corner of the map area. These subtidal zones are characterized by the preponderance of rocks of Lithofacies A. It should be remembered that subtidal sedimentary rocks are found across the province (the 'argillaceous' unit/marker); in areas where this form of lithofacies is dominant the lower member consists entirely of the subtidal unit. In areas not shaded in green on the map, other depositional zones intervene. In the northwest of the study area, the subtidal unit corresponds to the zone of thickest total sedimentation and thickest portions of the lowermost 'argillaceous' member of Kent (1968). In the south of the province, this zone approximately corresponds to the area full of evaporites in the upper member.

The Swift Current and Punnichy Platforms manifest themselves strongly as zones of low energy, lagoonal to tidal-flat sedimentation. This suggests that both were positive, paleotopographic features covered by very shallow waters and ephemeral standing bodies of water. In Imperial Oxarat 1-1-5-25 W3M, the entire Birdbear sequence is dominated by a supratidal facies, though the lowermost subtidal unit is present as a thin zone. The trend of the isopach contours follow this platform and its positive nature quite closely.

Between the subtidal basins to the south and northwest and the flanking platforms to the northeast and southwest lies a zone dominated by intertidal to high-energy subtidal sediments. Isopach trends define a channel or seaway between the Swift Current and Punnichy Platforms, suggesting a link between the Williston and Alberta Basins. In south-eastern Saskatchewan, the contours again become irregular and reflect on the influences of local, paleotopographic highs instead of following the more regional basin trends. Shoal zones tend to correspond to areas of thicker accumulations of the lower member, suggesting that the increased Birdbear interval may be the result of mechanically piled intertidal to high energy supratidal mounds. This generalization does not hold in western Saskatchewan, where total thicknesses reflect thick sections of the argillaceous lower unit (the subtidal unit).

In general, the isopach contours tend to follow the broad structural elements visible in the previously discussed isopach maps. The decrease in the definition of the patterns in the upper member may be the result of destruction of basin topography due to sediment infilling, The isopach contours of the lower member, however, reflect on sedimentation during the height of the initial transgression, the stagnation phase, and the beginning of the final regression. They follow the "normal" pattern of epeiric sedimentation more closely. The supratidal zone indicated for the Oxarat locality suggests that the Swift Current Platform began to exert its influence already from earliest Birdbear time onward and may, in fact, have not been influenced to any great degree by the Frasnian transgression responsible for the Birdbear.

D. Isopach Map of the Upper Member

In constructing Isopach Map D, the same technique used in constructing Isopach C was applied. By use of a symbol and symbol colors, the dominant depositional environment and the most influential of the other depositional environment, as deduced from core and geophysical log examination, are shown. The color scheme is self-explanatory.

In map D, there are three areas of interest:

- a sabkha zone where the dominant mode of sedimentation is supratidal and where secondary influences are those of the shoreface (thin intraclasts beds) and backshoal to shelf-lagoon;
- a backshoal to shelf-lagoon area under the primary influence of low energy conditions with modifying, secondary influences coming from lagoons and tidal ponds, and intertidal to high energy subtidal environments; and

- a zone in which the upper member is absent due to either change in facies or due to post-depositional solution of evaporites.

Two extensive supratidal zones are recognizable in Saskatchewan where rocks of Lithofacies G and J, or the algal laminites and nodular mosaic anhydrites respectively, are the characteristic sedimentary sequences. These areas also contain a larger proportion of thin, argillaceous or shaley beds than zones which were in closer and more continuous contact with the sea, as greater amounts of terrigenous wind-blown clastics may have been deposited.

In the eastern portion of the map area, a large supratidal zone is centered in the northeast corresponding to the location of the Punnichy Platform.

Anhydrites are absent from only two of the northernmost wells (Seaboard Devil's Lake Crown No. 1, 16-11-28-6 W2M; Tidewater Wishart Crown No. 1, 13-21-30-12 W2M). The depositional edge of the supratidal zone corresponds with the isopach edge of the thin region in the area. The region is underlain by a relatively thick argillaceous unit. In this region, the major percentage of the upper member is of supratidal origin.

A second major supratidal zone is situated in the southwest corner of the province. Again, the region dominated by supratidal sediments coincides with a total Birdbear 'thin', the Swift Current Platform. Obviously, the Swift Current Platform remained a positive feature during late Birdbear time, as it had started out in the early Birdbear. The northern extension of the Swift Current supratidal zone is tenuous at best due to poor well control, though evaporites have been found in core as far north as the Husky Whiteside 11-22-30-26 W3M well.

Lying between the Swift Current and Punnichy sabkhas and extending to the southeast is a broad region mapped as a backshoal-shelf lagoon zone. Within this zone, the rocks of Lithofacies B, L, C, D, K, E, H, and I were found with only minor supratidal components. These latter anomalies are considered to represent supratidal localities developed on the exposed landward side of shoal complexes. The dominant type of lithofacies are those of the low energy, lagoon and tidal pond environment. Other lithofacies types occur more sporadically. Within this zone, lithologies change rapidly both in the vertical and horizontal dimension. The isopach contours are quite irregular and suggest irregular rates of sedimentation. In comparison to Map B (the argillaceous marker/member), it appears that many thin regions of the upper member correspond to areas of increased total Birdbear thickness which, in turn, also seem to correlate with local 'thins' in the argillaceous unit.

Two highly irregular-shaped areas in southcentral Saskatchewan are free of evaporites located between Townships 1 and 4 and Ranges 20 to 29 W2M. Within these regions, extremely dense lime mudstones and dolomites may represent a facies equivalent to the evaporites.

Evaporites are also absent from the northwest corner of the map. This region, shaded in green on Map D, represents a region where the dominant lithofacies types are subtidal to intertidal. Being closest to the slightly deeper water and more normal-marine Alberta Basin, it is only natural to assume that the green-shaded area remained submerged during deposition of the upper member, forming the transition zone between the Alberta and Williston Basins.

In summary, the isopach contours of the upper member are quite irregular across the map area and only very vague trends are definable. The contours do not form the well-defined patterns that Maps A, B, or C exhibit. This irregularity may be due to the process of infilling of the basin and the progradation of the intertidal to sabkha zones, as pointed out earlier.

E. Isopach Map of the 'Intertidal' Unit

Map E illustrates the thickness of the unit between the basal argillaceous subtidal unit, and the base of the upper member. It represents therefore the thickness of what is referred to as the 'Intertidal' unit. This intertidal unit is defined following the same guidelines as those of the other depositional zones. There is a dominant facies and subordinate ones reflecting on first-order influences and minor secondary ones.

Three features on this map are significant. The first one is the pattern of regional 'thins' over the Swift Current and Punnichy Platforms. This suggests that both platforms were positive during the time of active, intertidal deposition. Consequently, the sequences over these areas are of a lagoonal character, as opposed to the more bioclastic sediments of the normal-marine, high-energy to intertidal zones which are common in the surrounding areas.

The second feature is the series of irregularly shaped 'thicks' in southeastern Saskatchewan, clustered in the Williston Basin. These 'thicks' correspond to 'thins' in the lowermost subtidal units and 'thicks' in the total thickness isopach maps. In the cores examined, the dominant lithofacies is Type B, the bioclastic to intraclastic lime packstone. Consequently, the blue-shaded areas shown on Map E are considered to represent regional zones of 'potential' shoaling. These potential shoal areas are expressed also within the intertidal zone on the isopach map of the lower member. As such, they represent the zone of highest wave energy in the Birdbear sequence. Their irregular shape points to the fact that basin topography was not perfectly flat but rather had gentle undulations which controlled the position of the intertidal strandline.

The third feature of significance is the wide, elongate isopach trend in the central part of the map area approximately between the Swift Current and Punnichy Platforms. The position of this regional, thick accumulation corresponds with the intertidal zone of Map C and therefore defines a zone of active marine sedimentation within the seaway linking the Alberta and Williston Basins. At Tidewater Placid Hawarden Crown No. 1 (12-10-29-5 W3M), situated almost astride the seaway, the core of the lower member shows a predominantly bioclastic lime packstone to stromatoporoidal boundstone from 3155 to 3165 feet. The presence of this highly fossiliferous, high energy, open-marine facies points to the well-agitated, non-restricted nature of the sea in this area. The correspondence of this dominant lithofacies with the center of the mapped isopach trend is further evidence for the existence of the interconnecting seaway. That true bioherms may exist within this zone, especially near the entrance to the seaway, raises interesting possibilities with respect to oil exploration. They may not be of the same magnitude as the 'Nisku reefs' of the Edmonton area but they still might be worth examining and searching for.

Other isolated wells that display a high-energy, intertidal shoal or bank facies include the following:

- Kissinger Moose Valley 16-9-12-6 W2M, which appears to be an oolitic to pelletoidal bank;
- Transempire Imperial Welby No. 14-16, 14-16-18-30 W1M; and
- Tidewater Parkbeg Crown No. 1, 10-32-18-3 W3M.

The irregularity of these shoals preclude the possibility either of drawing well-defined limits to their occurrence or of determining precise outlines on a regional scale. However, it is safe to generalize that such shoals can be expected anywhere within the intertidal zone, in particular in areas of overlying thin, argillaceous subtidal sequences, and in regions where the Birdbear Formation is thickly developed. These areas represent "paleo-highs" on the Birdbear shelf.

Paleogeography and Sedimentology of the Saskatchewan Shelf

As previously stated, Saskatchewan and most of North Dakota and Montana were the sites of vast epicratonic seas on the stable continental platform. For purposes of description, the geographic location of the shelf in Saskatchewan during the Upper Devonian is hereby named the 'Saskatchewan Shelf'. The paleogeography and sedimentation patterns of the Birdbear Formation on this shelf is interpreted by means of the isopach maps constructed for the various units, in addition to two stratigraphically drawn stratigraphic cross-sections. These visual aids also aid in reconstructing the shape and form of the two sedimentary basins which were discrete entities, yet connected at the time of Birdbear deposition. A map illustrating paleogeographic structures is shown in Figure 10. The stratigraphic cross-section A-A' and B-B' are also useful for understanding sedimentation patterns across this broad shelf. The presence of consistent, correlative markers enables the division of the Birdbear Formation on a regional scale, such markers being the argillaceous unit at the top of the Birdbear Formation, the argillaceous subtidal unit, and the "Ireton" marker. Other markers are also found; however, most are useful for correlation only on a local, as opposed to regional level. Such markers are especially common in the upper member of the Birdbear Formation in southeastern Saskatchewan, and are often used by industry geologists to correlate individual porous beds, for example the 'A', 'B', and 'C' markers shown on Cross-section E-E' (Figure 16).

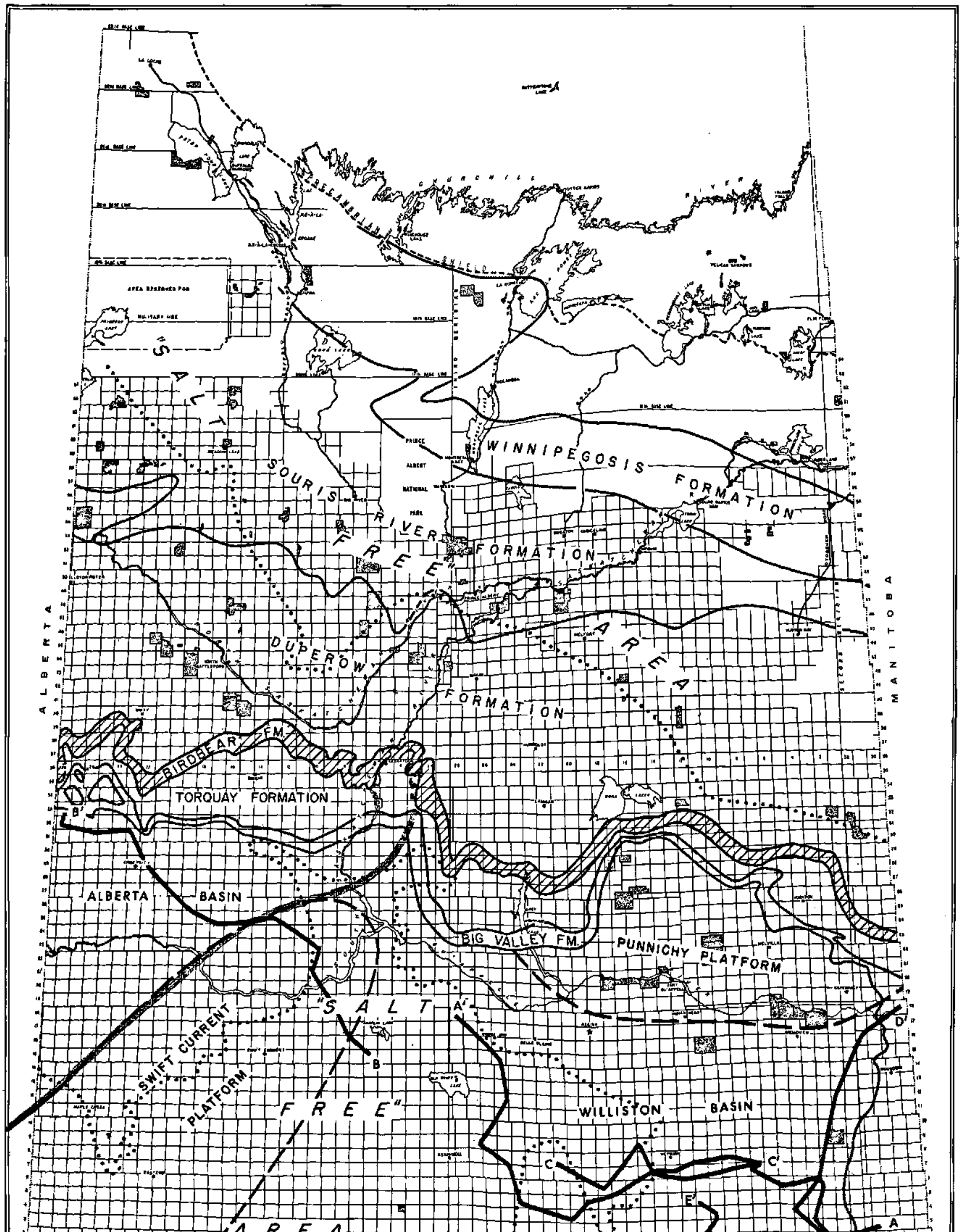


FIGURE 10 DETAILED MAP OF UPPER DEVONIAN SUBCROP EDGES AND PALEOTECTONIC FEATURES (modified from Nichols, 1970)

The abundance and dominance of low-energy carbonate rocks such as pelleted muds, laminated muds, mud-supported bioclastic rocks, and subtle lithofacies variations lead to only one conclusion: that the Birdbear sequences were deposited on a very shallow-water, partially to severely restricted shelf, the 'Saskatchewan Shelf', without any direct influence from land. Wave energy was never sufficient to winnow away and remove the carbonate muds, but adequate to create mechanically piled, mud-supported banks. There was no organic activity at any time at the shelf-basin hingeline which would have resulted in the construction of organic reefs, save for possible rare occurrences in the seaway connecting the two basins. The lack of these organic reefs reinforces the notion that higher than normal salinity levels prevented such sensitive organisms as stromatoporoids and corals to migrate into Saskatchewan in any great numbers. They were not extinct, as yet, for the Nisku reefs of the Edmonton region were built by such groups.

The abundance of evaporites and lack of evidence for freshwater diagenesis and mixed-water cementation points to high levels of aridity over the Saskatchewan Shelf and surrounding regions during the deposition of the Birdbear. Such climatic factors accentuated the stagnating and regressive conditions which developed as a result of the general retreat of the Frasnian seas already in Birdbear time and gaining momentum throughout. In addition, the irregular, poorly defined isopach contours of the upper member, as opposed to the much better defined contours of the lower member, record the final stages of infilling of the shelf sea and the southeastern lobe of the western Canadian

Frasnian seaway.

A quick perusal of the papers by other researchers dealing with the Upper Devonian of the Williston Basin points to the possibility that the Birdbear sequence may simply represent the sixth and last of the Duperow transgressive-regressive cycles. Figure (11), using correlative markers suggested by Burke and Stefanovsky (1982) and Dunn (1975), appears to reinforce this idea. The Duperow Formation is divided on the basis of the presence of thin, argillaceous carbonates and pure carbonate units given the status of members (Dunn 1975, Dean 1982). One may consider the 'Ireton marker', or B3 unit of the Seaward member of the Duperow Formation (Kent 1968) to be such an argillaceous marker, and the lower Birdbear member to be comparable to an argillaceous Duperow member. However, the Birdbear is worthy of its own formational status as opposed to the status of another Duperow cycle, for the lithological differences are too pronounced, as are the thickness differences, especially with respect to the upper Birdbear. Moreover, the lithology changes progressively, shoaling upwards, reflecting on early transgressive and late regressive conditions and indicating a transgressive-regressive couplet. In other words, the Birdbear forms a cycle of its own.

SHELL TABLELAND 12-24
12-24-01-10 W2M
KB: 531.5m
TD: 2456m

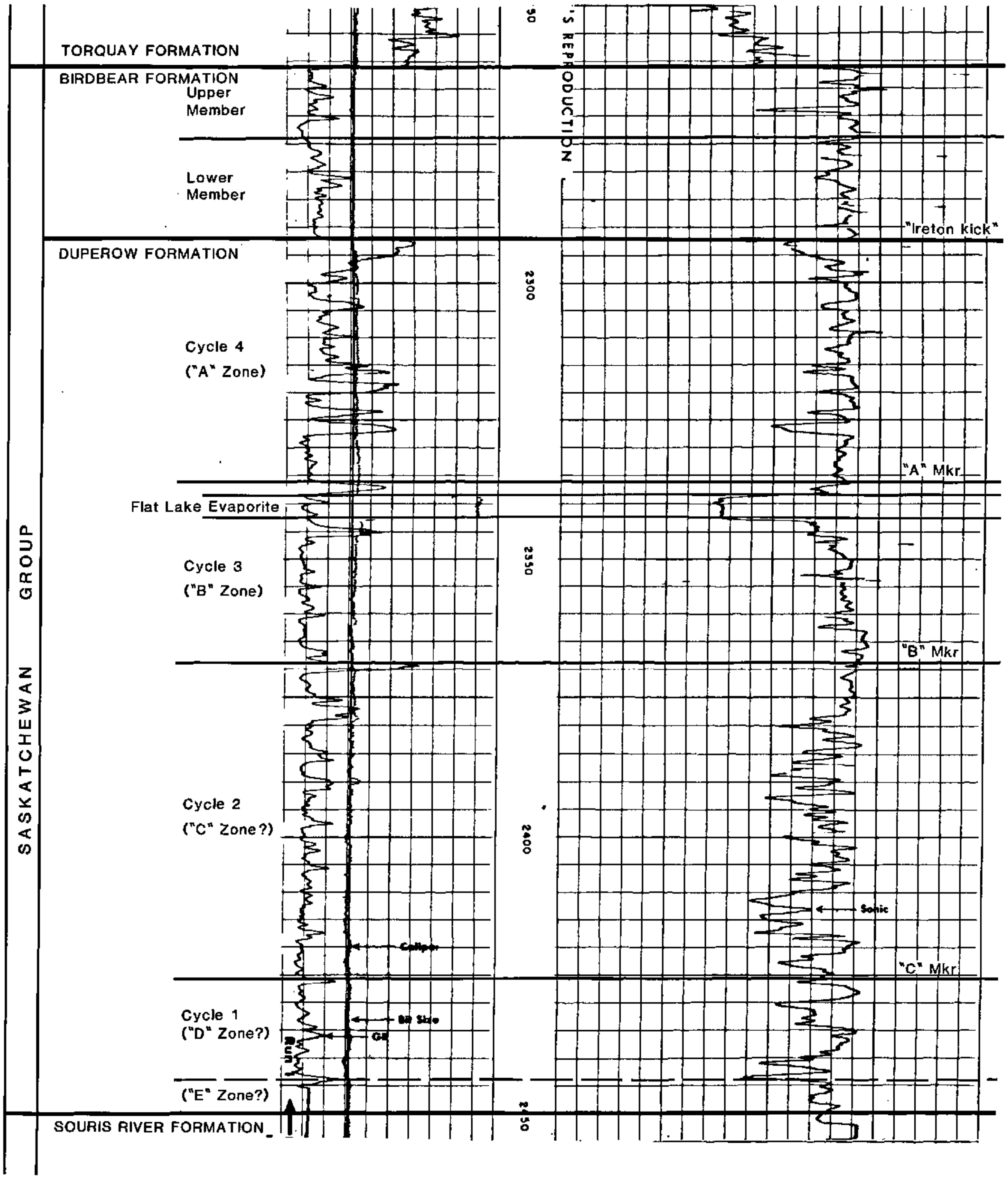


FIGURE 11 DUPEROW AND BIRDBEAR FORMATION DEPOSITIONAL CYCLES

The shallowing-upward sequence of the Birdbear cycle is summarized in Figure (12) from Halabura (1982). Evidence for decreasing wave energy and increasing salinity becomes progressively more manifest upwards in the section, with the restriction and decrease in circulation caused either by an actual drop in sealevel, by a shallowing of the basin floor due to the accumulation of carbonates, or by a combination of both.

Braun and Mathison (1982) place the height of the Frasnian transgression in the uppermost Duperow (Seaward Member) and lower Birdbear member. They reconstructed several pulses for what is collectively referred to as the 'Frasnian transgression', one of the strongest and far reaching in Post-Precambrian history. During each pulse, the sea pushed farther to the southeast and expanded its influence gradually across the International Border and deep into the United States. Towards the end of mid-Frasnian time, a seaway extended uninterrupted from Alaska to Iowa.

On the basis of the distribution of ostracodes and other microfossils, Braun and Mathison concluded that the argillaceous units of the Duperow and lowermost Birdbear were the products of the transgressive pulses. The barren or very poorly fossiliferous "pure" carbonates in between were interpreted to reflect on stillstands, even regressive conditions. The greatest variety in terms of ostracodes occurs in the shaley intervals, reflecting in turn on open-marine conditions. Such generalizations can be substantiated also by certain sedimentary features.

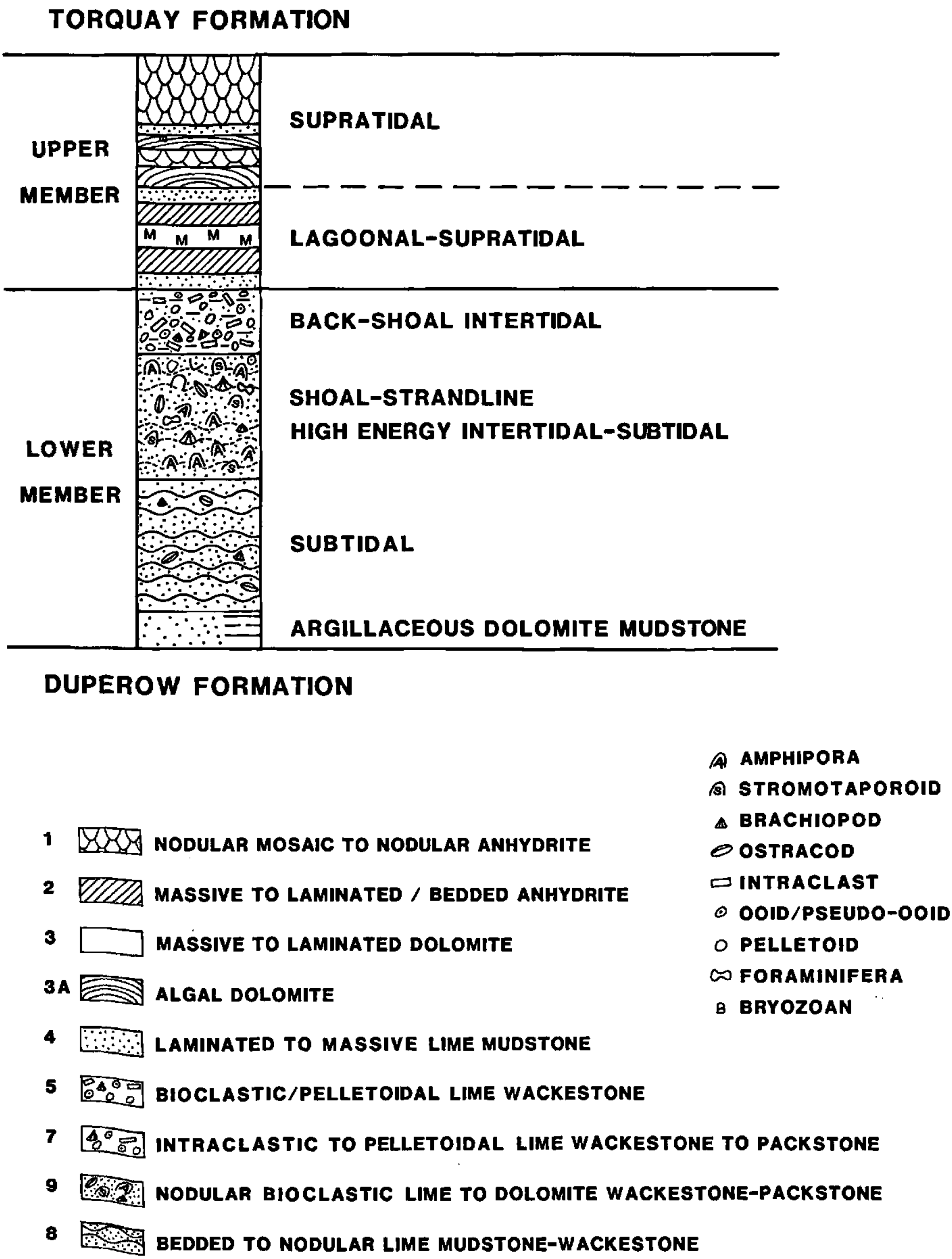


FIGURE 12 TYPICAL BIRDBEAR DEPOSITIONAL CYCLE

The lowermost, argillaceous unit and the carbonates above but below the first anhydrite bed are the most open-marine as far as the Birdbear sequence is concerned. They comrpise the bulk of the lower member. However, indications of shoaling in the middle and upper portions of the lower member point to a stillstand and possibly even to the beginning of a regression. It is here that fossils become more and more rare. The upper member with its anhydrites and dolomites bears without any doubt the imprint of the regression and of increasingly restrictive influences. All what was left of the Frasnian seas were lagoons with their adjoining sabkhas bordering the craton, and only in the northwestern part of the province did the sea linger on for a while.

Cross-section C-C' (Figure 13) is taken across the southern portion of the study area, in an east to west direction, while cross-section D-D' (Figure 14) runs north to south. The progression from the subtidal zone through an intertidally-dominated to a sabkha region can be readily seen in both sections. In C-C;, the thickest section of Birdbear is found in wells with intertidal shoals, namely Jefferson Lake Canoxy Steelman 15A-19-4-5 W2M and Scurry Rainbow Wordsworth 11-36-6-4 W2M. Also, the progradation of the lagoonal and supratidal depositional zones over such intertidal shoals is evident. Cross-section D-D' illustrates the same relationships; however, because it runs about parallel to depositional strike, it intersects several discretely developed shoals within the broad intertidal zone. The various relationships between facies and depositional environments are illustrated in Figure (15), which is a diagrammatic representation of the supratidal to low energy subtidal zones across the Saskatchewan Shelf.

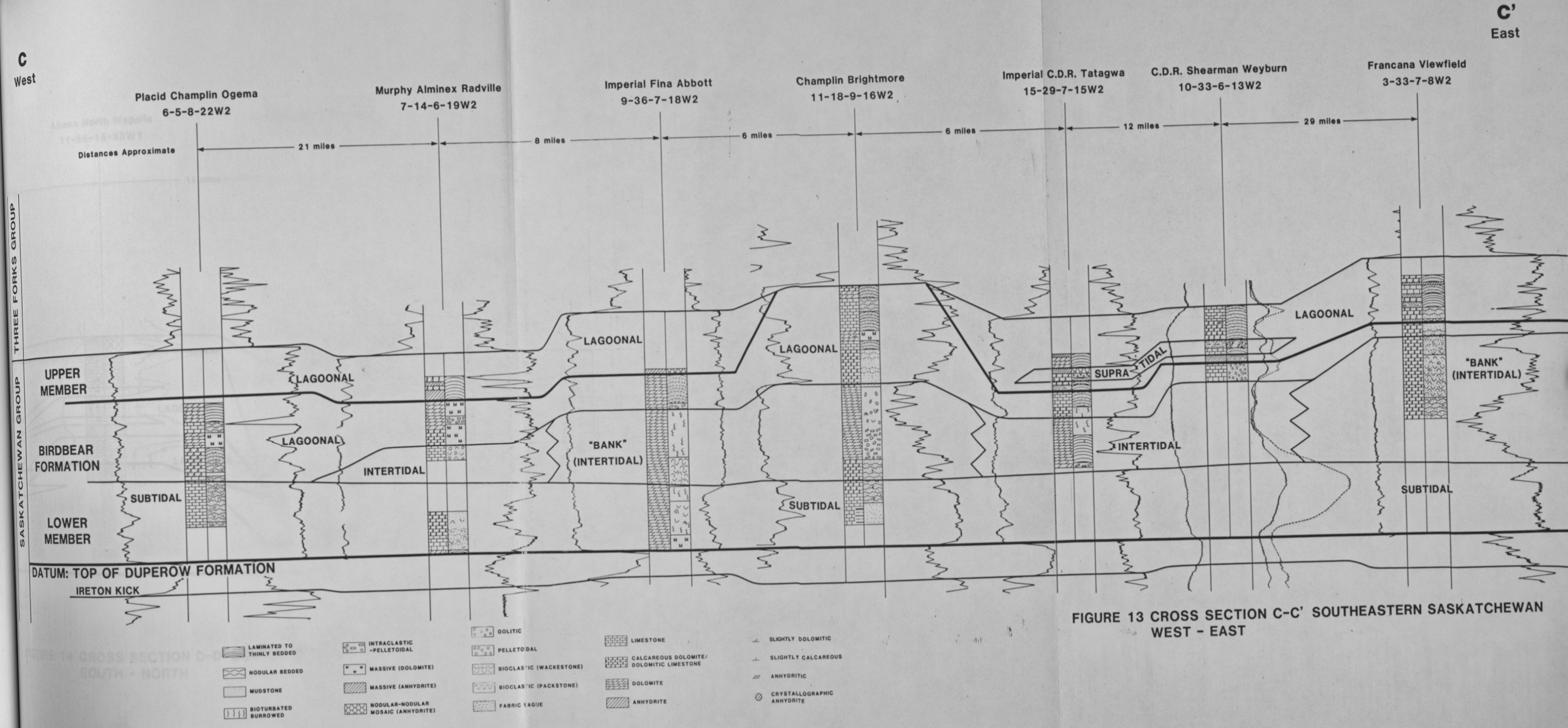


FIGURE 13 CROSS SECTION C-C' SOUTHEASTERN SASKATCHEWAN
WEST - EAST

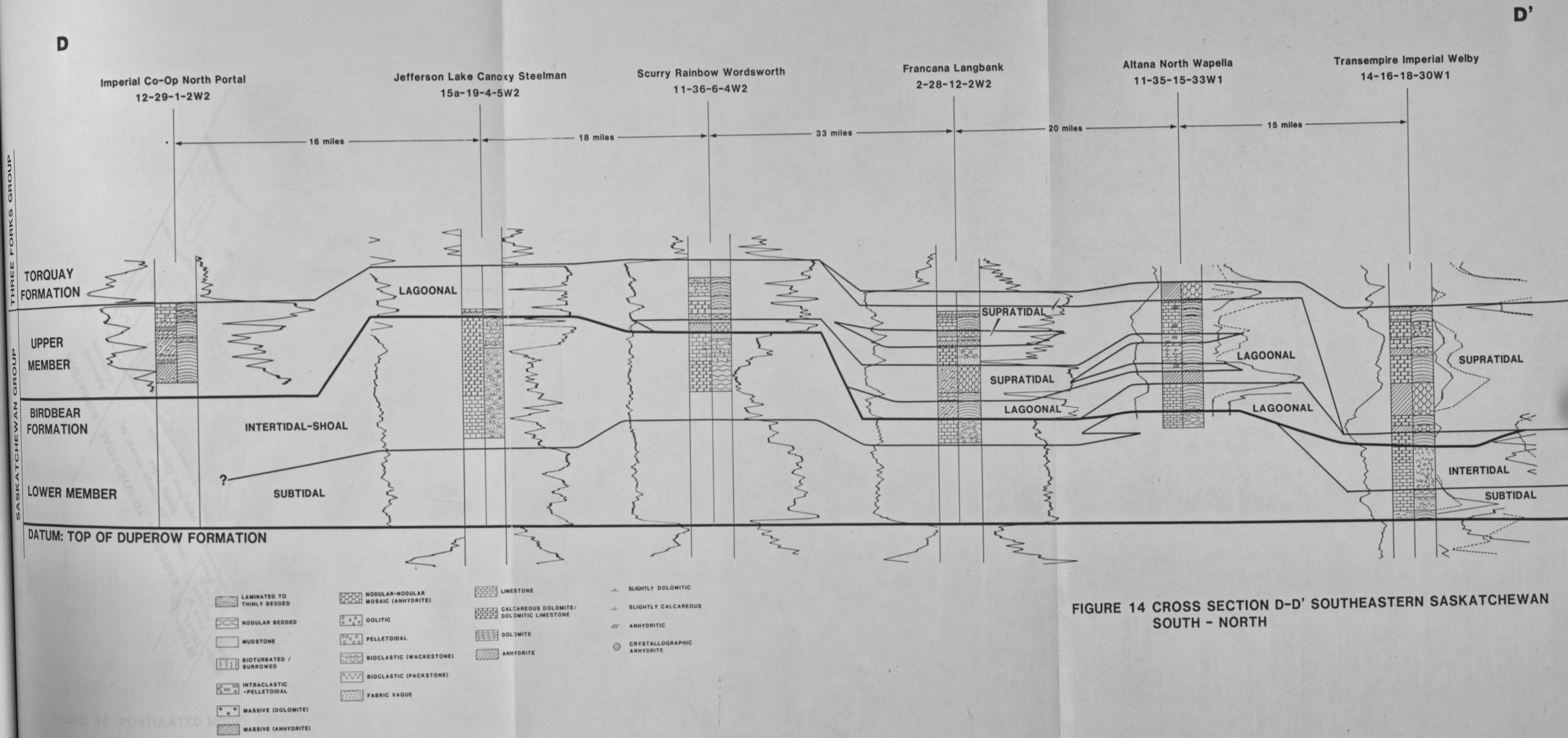


FIGURE 14 CROSS SECTION D-D' SOUTHEASTERN SASKATCHEWAN SOUTH - NORTH

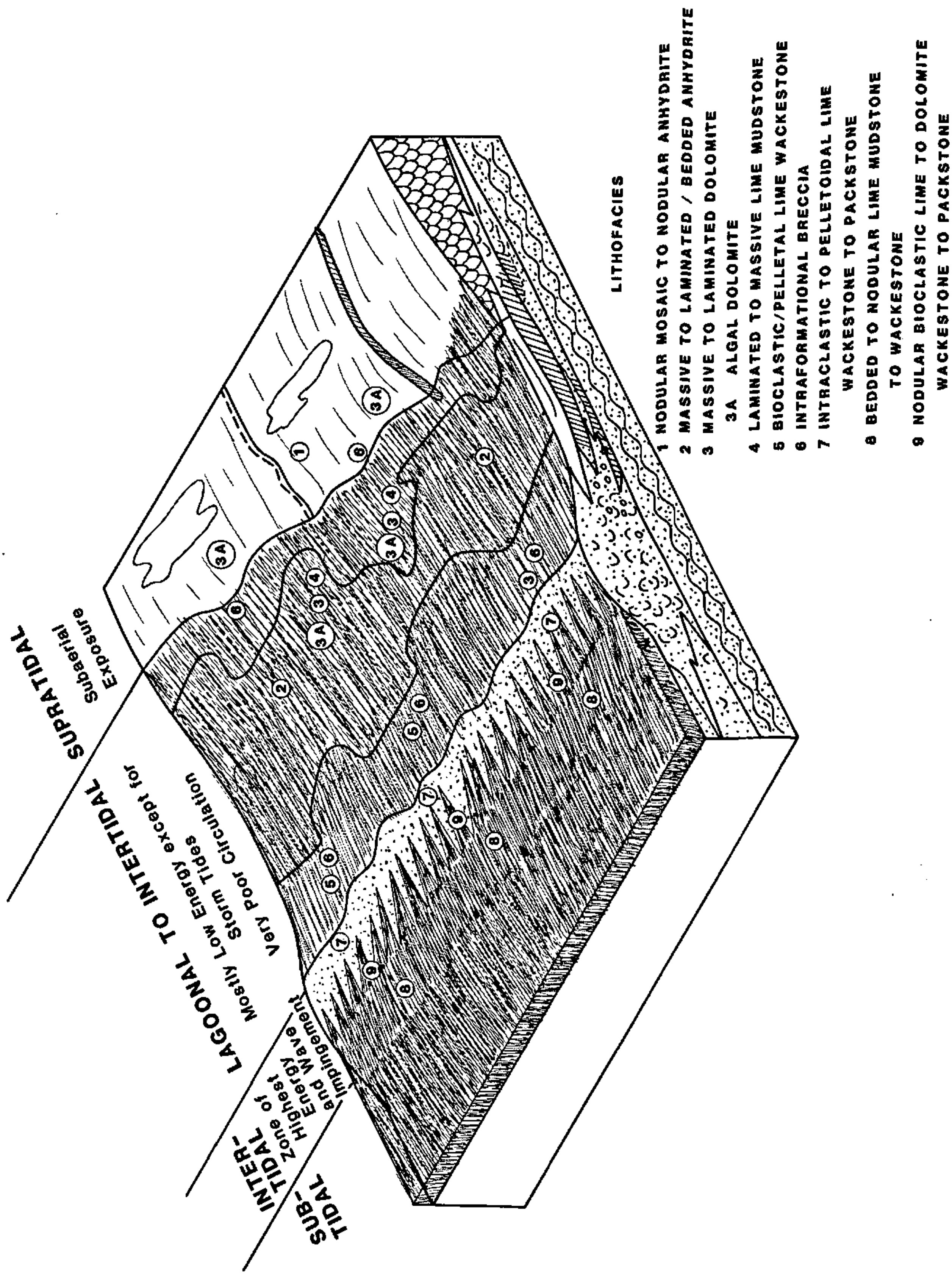


FIGURE 15 POSTULATED MODEL FOR DEPOSITION OF BIRDBEAR FORMATION

The isopach maps show various structural features which have influenced deposition of sediments on the Saskatchewan Shelf. As discussed previously, two broad positive areas were present: the Swift Current Platform in the southwest, and the Punnichy Platform in the east-central portions of the map (see Figure 10). Over these areas, regionally thin units of the Birdbear Formation were deposited, displaying the features of low-energy lagoonal to supratidal sedimentation. The two embayments situated on the north flank of the Swift Current Platform suggest that its development may have been influenced by movement along basement faults. However, there is no direct evidence that these were active during the deposition of the upper portions of the lower Birdbear and the upper member, for the isopach contours of both these units do not reflect on any embayments.

Perhaps the most significant deductions that can be made from studying the isopach maps is the definition of the Williston and Alberta Basins. These basins were separated by two positive areas which, in turn, were dissected by a narrow seaway in the central part of the study area which served as a connecting link. The Alberta Basin, evident in the northwestern part of the study area, is characterized by several features. Not only does the total thickness of Birdbear sediments increase gently with respect to the thicknesses found in southern Saskatchewan, but also the lower portion of the Birdbear becomes quite argillaceous, and the rocks become darker in color. Furthermore, the upper member is absent over much of this region, suggesting that normal marine conditions prevailed throughout the deposition of the Birdbear.

The higher argillaceous content of the Alberta Basin portion of the Birdbear simply reflects on the abundance of terrigenous clastic material brought in from the deeper, more unstable Alberta Basin. As suggested by Smith (1978), stable shelf areas are characterized by light-colored, fragmental carbonates displaying shallow-water characteristics. Sediments of the more unstable areas are supposedly argillaceous, dark-colored carbonates. It seems plausible therefore, that the northwestern portion of the study area was in a hinge area with higher mobility, while the less argillaceous, shallow-water carbonates of the central to southeastern portion of the map area were laid down on the most stable part of the shelf.

The Williston Basin portion of the Saskatchewan Shelf is characterized by the following features. Most of the isopach contours in this area display a roughly semi-circular isopach pattern; however, on a local scale, the isopach contours tend to be quite irregular. This feature suggests that the Williston Basin portion of the shelf had a much more variable basinal topography. Also, there is much evidence for aridity and restriction, such as the abundance of evaporites and the presence of a thick upper member. The carbonates tend to be lighter in color, and much less argillaceous than the carbonates of the Alberta Basin shelf.

The green line drawn on the map in Figure 10 outlines the eastern extent of the Alberta Basin. The Williston Basin portion of the

Saskatchewan Shelf is bounded on the northwest by the Swift Current Platform and on the northeast by the Punnichy Platform. In the north-central portion of Saskatchewan is found the seaway connecting the Williston Basin with the Alberta Basin. This means that the Birdbear sequences of Saskatchewan occur in two distinct, depositional basins, an observation that offers a solution to the Nisku-Birdbear controversy. It is proposed that the name 'Birdbear; be used for the sequences in the Williston Basin and over the two platforms. In the northwestern portion of the map area, to the west of the green line, and in the region where the sediments were influenced by the Alberta Basin, the name 'Nisku' should be employed.

In summary, the following depositional history is suggested for the Birdbear-Nisku Formations of Saskatchewan. The deposition of these two units began as the last phase of the Frasnian transgression gained momentum, reaching its height shortly thereafter. The waters surged into Saskatchewan from the northwest, spreading the argillaceous sediments of the subtidal unit and lowermost part of the lower member across the whole region, leaving a thicker sequence in the northwest of the shelf, with gradual attenuation to the southeast. The irregular pattern of 'thicks' and 'thins' was established at this time, the latter being deposited over paleohighs and the former in paleolows. This sedimentary pattern was no doubt influenced by the structural expression of the underlying Duperow and older rocks at the time of deposition.

The transgression came to a rapid halt after deposition of the argillaceous, subtidal unit. A time of "stillstand" followed during which restrictions over the Saskatchewan Shelf increased slightly, and during which extensive deposits of bioclastic wackestones and packstones were deposited throughout the Alberta and Williston basins. This indicates that the sedimentary pile had reached wave base and that it accumulated in the more turbulent zone of wave action. There were no signs, as yet, of the impending and longer-lasting regression, for no evaporites were laid-down in the basins proper. The Swift Current and Punnichy platforms, however, exerted ever increasing influences. They became the site of lagoonal sediments, minor carbonate mounds and shoals, and eventually of vast sabkhas. The connecting channel between the Alberta and Williston basins -- the connecting link between the Nisku and the Birdbear sea -- had high energy intertidal to subtidal, shallow water conditions, whereas on and behind the shoals, the water was calm, very shallow, and of higher salinities. The highest "spots" turned into supratidal sabkhas.

After the time of stillstand and "infilling", signs of a final retreat of the sea appear in the sedimentary record of the upper portions of the lower member, and become most conspicuous in the evaporitic upper member. In late Birdbear time, the Birdbear sea became a vast brine "pond", toally dead save for the hardiest of algae and isolated "islands" of organisms. The intertidal zone, quite important and exclusive at the peak of the transgression and the following stillstand, now became a very flat, featureless plain dotted with many intermittently flooded tidal ponds and lagoons. The platforms, still above normal sea level were only occasionally flooded by seawater during severe storms, but remained the preferred sites of vast sabkhas.

It was only in the regions of the northwest, the Alberta Basin extension, or in the Nisku sea that sedimentation of subtidal carbonates continued throughout early and late Birdbear time. Obviously, the effects of the regression were far more pronounced in the Williston Basin than in its counterparts in Alberta and northwestern Saskatchewan and essentially confined to the Birdbear sea. The Torquay Formation, generally a sequence of intraformational conglomerates, highly restricted carbonates, evaporites, and siltstones, overlies the Birdbear sequence. On the basis of conodonts and ostracodes it is dated as Famennian to Mississippian in age, and the uppermost Frasnian does not seem to be represented anywhere in Saskatchewan. This suggests that the Birdbear-Torquay contact is unconformable, and that the seas withdrew completely at the end of Birdbear time or that they simply dried-up. In Alberta and the Northwest Territories, however, the Nisku or late Frasnian sea lingered on until it too retreated.

In an overall sense, the Birdbear Formation is the record of the end of an outstanding era, a geological graveyard and final resting place. It marks the beginning of the end of a grand seaway that affected vast areas of western Canada in Frasnian time. When the sea returned in Mississippian time, the paleogeographic picture had changed profoundly, and so had the animals. In earlymost Birdbear time, the Saskatchewan

Shelf was still under the impact of the strong, transgressive surge that started in the late Duperow, and during which the Frasnian seas reached their maximum extent. Soon thereafter, a longer period of stillstand followed which developed into a full-fledged retreat in late Birdbear time during which the Birdbear sea turned into a "brine pond" and eventually into a vast sabkha.

DIAGENESIS OF BIRDBEAR FORMATION

An important feature of any shelf carbonate-evaporite sequence is the diagenetic history of the rocks following deposition and subsequent burial. This diagenetic history may be much more complex than the depositional history of any other sequence, for not one but several distinct diagenetic environments may have existed at different times during the burial history of the rocks.

Two of the most significant diagenetic modifications of the original lithofacies of the Birdbear Formation are extensive dolomitization and post-depositional precipitation of anhydrite cement within pores, vugs, and fractures. Less common diagenetic alterations include silicification of bioclasts and precipitation of acicular metasomatic or crystallographic anhydrite.

Dolomitization

Dolomite is present in significant quantities within the Birdbear Formation, both as syngenetic to very early post-depositional dolomite (Lithofacies, D, I, and J), and diagenetic dolomite. The distribution and formation of diagenetic dolomite is of vital importance to the oil industry, for the process of dolomitization leads to the creation of porosity, and hence potential oil reservoirs.

From the core study it is apparent that the lithofacies most commonly dolomitized are B, C, and to a lesser extent L, K, and E. These lithofacies are most prevalent in the upper portion of the lower member and commonly are found deposited within the intertidal zone. This zone, representing the period of stillstand, usually contains the greatest amount of bioclasts, intraclasts, and other high-energy indicators, and it is the zone in which mechanically-piled mounds and shoals are found. Correlation of logs and core usually shows that the best dolomitization is found in thick accumulations of intertidal sediments, with an increase in lagoonal and/or supratidal evaporites in a more shoreward position. This relationship is shown in Cross-section D-D' and E-E' where an increase in dolomitization and resultant porosity is found closest to the restricted lagoonal sediments.

The degree of dolomitization ranges from slight to nearly complete, with dolomitization prevalent in the micrite matrix as opposed to within grains. This relationship has been noted by Longman (1982) in other carbonate sediments of the Williston Basin. The fine crystal size of the micrite particles allows dolomitizing fluids greater surface contact, and hence sites of dolomite nucleation.

Examination of thin sections (see Plates 10, 11, and 12) reveals several interesting facts with respect to the occurrence of dolomite within the Birdbear Formation. Dolomite crystals are usually found as rhombic crystals scattered randomly within the micrite matrix. Crystal sizes range from 1 millimeter to 0.2 millimeter. As the degree of dolomitization increases, the number of crystals within the matrix increases until, in the case of a "pure" dolomite, the crystals form an interlocking mesh in which individual crystals are indistinguishable.

Dolomite also occurs as crystals lining pores, vugs, and within the centers of particles, often forming an interlocking film lining the void and pore. This form of dolomite cement is not as prevalent as the dolomitized matrix. In some sediments the lamination observable in core is due to preferentially dolomitized laminae, often bound by organic films.

Numerous mechanisms have been postulated to explain the occurrence of dolomites within carbonate sequences. The following characteristics of the dolomites of the Birdbear Formation are useful in interpreting their formation:

a) Localization of most dolomitized sediments in the upper portions of the lower member;
b) Great lateral extent of dolomitized units; and
c) Association of dolomite with zones rich in evaporites.

If the dolomites occurred as isolated pods within the limestone sediments, the source of Mg^{2+} ion-rich fluids might have been local in origin (Kendall 1977); however, the ubiquitous presence of a dolomitized horizon in the upper portion of the lower member, often correlatable on a regional scale, suggests that an external source rich in Mg^{2+} was present. Also, the association of dolomite with intertidal zone sediments suggests that dolomitization occurred soon after deposition and that it was controlled by the lithofacies distribution of the host sediment (Morrow 1982). The seepage refluxion dolomitization model of Adams and Rhodes (1960) is well suited to explaining the occurrence of dolomite in the Birdbear Formation. Evidence previously discussed, such as the abundance of evaporites in the upper member (the 'regressive' unit), suggests that the sea during the final stages of Birdbear deposition was hypersaline. Such hypersaline waters are enriched in Mg^{2+} ions and hence are ideal dolomitizing fluids. The widespread occurrence of dolomite in the intertidal sediments is due to early diagenetic dolomitization, as a result of dense, hypersaline brines percolating through the sediments soon after their deposition and the attainment of basin-wide hypersalinity.

Petrographic evidence supports this interpretation. In his summary of dolomitization, Morrow (1982) differentiates between finely crystalline (10 μm to 20 μm) and more coarsely crystalline dolomite, the finer crystalline variety having formed in a primary or 'pre-burial' diagenetic environment, and the more coarsely-crystalline dolomite in a 'secondary' or 'late replacement' diagenetic environment. As stated previously, the dolomite crystals of the Birdbear Formation have an average size of 20 to 30 m. This points to an early, as opposed to late, episode of dolomitization. Gebelein et al. (1980) document the occurrence of euhedral, micrometer-sized dolomite rhombs scattered in the fine-grained muds. They interpret this to indicate early dolomitization from marine fluids. The interlocking rhombic dolomites are the result of the progressive growth of these original rhombs during subsequent burial diagenesis.

In summary, the above features point to early diagenetic, post-depositional dolomitization due to the reflux and percolation of hypersaline brines through shelf sediments during the latest phase of Birdbear deposition. The mixed-water dolomitization model (Badiozamani, 1973; Choquette and Steinen, 1980) would explain some of the above-mentioned features; however, the abundance of evaporites associated with the dolomites rules out the mixed-water model, for obviously the waters were highly saline as opposed to brackish as required by the mixed-water model.

Anhydritization

Two forms of anhydrite are present within the Birdbear Formation. The first variety consists of white, chalky to translucent, coarsely crystalline to massive, euhedral to subhedral anhydrite crystals infilling pores, fractures, vugs, and solution cavities. In thin sections, these anhydrite masses are seen to be formed by large and blocky, interlocked crystals of anhydrite. The presence of this form of anhydrite within pore systems, in addition to their coarsely crystalline nature, suggest that the anhydrite precipitated quite late and after the deposition and burial of the sediment.

The second form of anhydrite consists of dark brown rosettes and clumps of needle-like anhydrite scattered throughout the host rock. This form of anhydrite, known as 'metasomatic' or 'crystallographic' anhydrite, often is most common in fine-grained, laminated lime to dolomite mudstones. Kent (1968) reported this form of anhydrite within the Birdbear Formation of western Saskatchewan. Kent suggested also that it is the result of precipitation of anhydrite from sulphate-rich formation waters which circulate through the more porous and permeable sediments after lithification.

SIGNIFICANCE TO OIL AND GAS EXPLORATION

Exploration for hydrocarbons in the Birdbear Formation has been rather disappointing and difficult to pursue. The only fields of significance, located at Hummingbird and Kisbey, are related to salt-solution collapse structures. In the case of the Hummingbird field, early and local solution of the salts of the Middle Devonian Prairie Evaporite Formation led to the creation of a localized depression which was filled in by an extra thick section of Souris River and Duperow sediments. A normal thickness of Birdbear sediments was deposited over the filled depression, but subsequently a regional removal of salt in the Prairie Evaporite led to widespread collapse of the overlying beds. Upon collapse, the extra-thick Duperow and Souris River sections formed a local structural high with subsequent closure on the surface of the Birdbear Formation.

At Kisbey, only one major period of salt solution and its effect can be recognized. This field is the result of a structural reversal against the southern edge and wall of the solution sink and does not involve the presence of thickened Devonian units. Both the Kisbey and Hummingbird fields were discovered with the aid of seimsic reflection surveys and are capable also of production from the Mississippian formations.

The main pay zone at both Hummingbird and Kisbey is found within the dolomitic Lithofacies B rocks and in thin, microsucrosic dolomites (Lithofacies D and I). The packstones and wackestones are confined to the lower member, while the laminated dolomites are found in the uppermost portion of the lower member and interbedded with anhydrites in the upper member. In both fields, production is from the dolomitized lithofacies of the intertidal shoal-mound zone.

Hummingbird and Kisbey are both fields with significant structural expression and, as a result, were not too difficult to discover. The fields which produce from the Birdbear in northeastern Montana, such as Volt, Benrud, and Tule Creek, are also salt-solution collapse structures and were detectable by seismic surveys. However, numerous oil and gas shows have been documented where no structural disturbance is present; these potential stratigraphic traps are far more difficult to explore for and to find.

Longman (1982) gives several excellent examples of stratigraphic traps within the Ordovician Red River, Upper Devonian Duperow, and various Mississippian formations in the Williston Basin. It is becoming apparent with increased levels of exploration that the norm for hydrocarbon traps in the Williston Basin is stratigraphic. It is not inconceivable, therefore, that similar stratigraphic traps might have been formed within the Birdbear Formation. Exploration to date for hydrocarbons in the Devonian sequence of Saskatchewan has been concentrated on the delineation of structures, as opposed to detailed litho-stratigraphic mapping. Depositional environments control the distribution of lithofacies and to a certain degree the subsequent diagenetic processes. There are hints, therefore, in the rock record to be evaluated in the search for the elusive stratigraphic trap.

Within the Birdbear sequences are many of the prerequisites for the creation of excellent stratigraphic traps. There are abundant primary anhydrites which could act as impermeable caprocks and sources of Mg-rich brines, and many rocks with secondary porosity, especially in the dolomite facies. There seems to be an adequate supply of organic and bituminous argillaceous material to form source rocks, and there seems to be a lack of evidence for breached reservoirs, save for the subcrop region in the northwest of the study area. Porosity development is linked to the general trends of the regional lithofacies, although the mechanisms of dolomitization have yet to be studied in detail.

The scarcity of oil and gas in the Birdbear may reflect not so much on its absence or presence as on our inability to unravel its complex depositional and diagenetic history. Maybe, well control is not close enough, as yet, to have reached the threshold to enable explorationists to use techniques developed by their American counterparts in the more densely drilled U.S. portions of the basin. However, the following hints may be of use.

Within Saskatchewan, the best reservoir properties are developed within the dolomitized lithofacies. These include Lithofacies D, B, I, J, and to a lesser extent C, A, and L, in order of decreasing importance. Porosity is commonly found at the top of the lower Birdbear member, and it is everywhere developed in the Williston Basin portion of the Saskatchewan Shelf. This porosity is developed within the 'Intertidal' unit. Cross-section E-E' shows the


E
Jeff Lake et al
East Oungre 12-12
12-12-2-13 W2
KB: 1962 ft
TD: 7766 ft
Shell
South Torquay 1-29
1-29-2-12 W2
KB: 598.4 m
TD: 2400 m
Banff et al
Torquay North 7-29
7-29-3-11 W2
KB: 19 2 ft
TD: 7500 ft
Jeff Lake et al
Torquay 2-4
2-4-4-11 W2
KB: 1864 ft
TD: 5616 ft
3.75 mi
8.25 mi
2.10 mi
4.00 mi
Datum: Top of Birdbear
Upper Member
Lower Member
'INTERTIDAL' UNIT
'SUBTIDAL' UNIT
70 µsec
55 µsec

FIGURE 16 CROSS SECTION E-E' ILLUSTRATING DISTRIBUTION OF POROUS UNITS WITHIN BIRDBEAR
SOUTHEASTERN SASKATCHEWAN

the stratigraphic distribution of these porous units. Porosity increases with proximity to the anhydrite-rich lagoonal and supratidal environments. The porosity in the lower member pinches out to the south with increasing distance from the evaporitic regime. Cross-section C-C' shows the increase in porosity within the inter-tidal shoal facies (represented by the Steelman and Wordsworth wells) lying immediately basinward of an anhydrite-rich, lagoonal environment. Similar porosity is developed in wells of the Alberta Basin portion of the Saskatchewan Shelf.

Unfortunately, the ubiquitous porosity zone at the top of the lower member may be more of a drawback than a blessing with respect to hydrocarbon trapping. Regionally connected pore systems encourage the widespread flushing of the porous unit by subsurface waters, driving the oil from all but the well-developed structures or those best protected by impermeable seals. The exploration problem thus becomes one of defining porous zones and mapping their updip pinchout or termination against an impermeable, undolomitized lagoonal facies. In addition, the exploration geologits could search for broad, structural upwarps which would capture a certain amount of the migrating hydrocarbons within its closure.

That widespread and regional flushing may have occurred in western Saskatchewan is deduced from the experience that wells in western Saskatchewan produce fresh water in drillstem tests, indicating meteoric water invasion and circulation. There is also widespread occurrence of very heavy, biodegraded oil along the northwest subcrop edge which must have come from somewhere, including the Birdbear. In the North Hoosier field of northwestern Saskatchewan, two wells were completed in the Birdbear Formation and for a time produced 17^{o} A.P.I. oil.

Altogether, the following points may be worth considering when exploring for hydrocarbons in the Birdbear Formation. From a stratigraphic point of view, geologists should:

a) watch for rapid terminations of regionally porous zones against impermeable lagoonal or supratidal sediments, or for pinchouts of favorably dolomitized units;
b) examine DST and resistivity logs for sudden indications of saline water in western Saskatchewan, for the saline water may indicate a local updip barrier to regional flushing; and
c) carefully map thicknesses of the upper member and the lowermost subtidal lithofacies, as 'thins' in the lowermost subtidal unit may indicate paleohighs upon which shoaling conditions could have developed; similarly, 'thins' in the upper member could indicate thinning and drape-over of intertidal shoals.

In summary, the most prospective area to search for hydrocarbons within the Birdbear Formation would be in the intertidal lithofacies of the

Williston Basin portion of the Saskatchewan Shelf. The best reservoirs would be developed in an updip position and in the dolomitized portions of the intertidal shoals. Minor porosity development is in the high-energy subtidal and laminated to massive dolomite lithofacies units which could become secondary targets. From a structural exploration point of view, the best prospect would be within the area of regional salt collapse in southcentral Saskatchewan. Within this area, many other structural traps may be found as those of Hummingbird, Tule Creek, Volt, and Benrud oilfields of Saskatchewan and Montana.

SUMMARY AND CONCLUSIONS

1) The Birdbear Formation is the uppermost formation of the Frasnian (Upper Devonian) Saskatchewan Group and is approximately correlatable to the Nisku Formation of the Winterburn Group of Alberta. The Birdbear Formation consists of two members. The lower member is a sequence of dolomites and limestones, non-argillaceous in the south of the province, but becoming more argillaceous towards the western portion of the province. Range in thickness is from 38-143 feet. The upper member is a sequence of dolomites, anhydrites, and limestones ranging in thickness from 0 to 77 feet. The boundary between the upper and lower members is placed at the base of the first anhydrite bed encountered in the stratigraphic sequence.

2) Six lithofacies are recognized in the lower member:

A. Bedded to nodular lime mudstone to wackestone;

B. Bioclastic lime wackestone to packstone;

C. Intraclastic to pelletoidal lime wackestone to packstone;

D. Laminated to massive dolomite;

E. Laminated to massive lime mudstone;

F. Argillaceous carbonate mudstone to shale.

3) Seven lithofacies are recognized in the upper member:

G. Nodular mosaic to bedded nodular anhydrite;

H. Massive to laminated anhydrite;

I. Laminated to massive dolomite;

J. Laminated algal dolomite;

K. Laminated to massive lime mudstone;

L. Bioclastic to pelletoidal lime wackestone to packstone;

M. Intraformational breccia.

4) The following depositional environments are suggested for the various lithologic units of the lower member. Lithofacies A was deposited in a normal to slightly restricted, low energy, muddy environment. The nodular bedding developed as a result of submarine cementation and compaction. Lithofacies B was deposited in a high-energy, normal-marine, subtidal to intertidal environment. This lithofacies is rich in bioclastic material. Also present in this lithofacies are mechanically-piled, bioclastic banks formed where wave energy was dissipated. Lithofacies C was deposited in a low-energy, moderately restricted backshoal-shelf environment. Lithofacies D and E were deposited in a similar environment of moderate to high-salinity, very shallow, low-energy lagoons or tidal ponds situated back of the intertidal shoal areas. Lithofacies F is interpreted to be the result of influx of terrigenous clastics by windstorms.

5) The following depositional environments are postulated for the lithofacies of the upper member. The rocks of Lithofacies G were formed supratidally in a subaerial environment, and in a setting similar or identical to the sabkhas of the Persian Gulf. Lithofacies H and I were deposited within highly restricted, very low-energy lagoons and tidal ponds. Type I rocks are the result of algal growth in a high intertidal to supratidal environment. The environment of deposition of Lithofacies K is similar to the one postulated for Lithofacies L, which is similar also in origin to that of Lithofacies C of the lower member. Rocks of Lithofacies M formed as the result of evaporite solution or storm-driven floods.

6) The lithofacies of the upper and lower members are grouped into depositional zones. Due to the close proximity and mixing of various lithofacies of different environments, the dominant depositional environment has been selected to represent the depositional zone, but secondary influences from other environments are demonstrated and discussed as well. The following depositional zones, each with a set of characteristic lithofacies are outlined below:

- subtidal: Lithofacies A;
- intertidal to high-energy subtidal: Lithofacies B, L, M, and D;
- lagoonal (backshoal shelf to lagoon): Lithofacies C, D, E, H, K; and
- supratidal: Lithofacies G, J.

7) From the construction and interpretation of isopach maps, coupled with observations from selected cores, several structural features are believed to have influenced sedimentation during the deposition of the Birdbear Formation. The Swift Current Platform in the southwest of the province, and the Punnichy Platform in the northeast separated the broad Saskatchewan Shelf into two distinct depositional basins. To the south lay the Williston Basin, extending south into North Dakota and Montana. To the northwest of the Swift Current Platform lay an extension of the Alberta Basin. The Birdbear-Nisku sequences of the Alberta Basin are more argillaceous than those of the Williston Basin. The increased amounts of sediment deposited in the Alberta Basin portion of the shelf, coupled with the dominant subtidal character of the rocks, suggests that the northwest portion of the shelf was an area of greater mobility and subsidence. The two depositional basins were connected by a narrow seaway extending across the center of the province between the two positive platforms.
It is proposed to refer the 'Birdbear' sequences in the northwest of the Swift Current Platform to the Nisku Formation of Alberta, with which it shows greater affinity than to the true Birdbear of the Williston Basin.

8) The height of the Frasnian transgression was reached during deposition of the lower member of the Birdbear, followed by a

rapid regression. As a result, the Birdbear Formation is partly transgressive but mostly regressive in nature. The sediments of the lower member were deposited under a transgressive setting without the effects of an impending regression. During the ensuing regression and deposition of the upper member, the entire shelf attained moderately saline to hypersaline conditions (except for the far northwest corner) resulting in the deposition of abundant nodular mosaic and laminated anhydrites.

9) The Birdbear carbonates of the Saskatchewan Shelf should provide a target for the exploration of stratigraphically-trapped hydrocarbons. The fields discovered to date, however, are structural in nature and the result of multistage salt solution of the underlying Prairie Evaporite Formation. Porosity is best developed in the sediments of the intertidal zone, particularly within bioclastic shoals formed in the high-energy zone of wave impingement. Dolomitization by seepage refluxion enhanced the porosity within this unit. Possible plays include the shoreward termination of porosity against nonporous and impermeable lagoonal sediments.

10) The primary diagenetic effects modifying sediments of the Birdbear include dolomitization due to seepage refluxion, and precipitation of secondary anhydrites.

REFERENCES CITED

Adams, J.D., and M.L. Rhodes, 1960, Dolomitization by seepage refluxion: AAPG Bull., v. 44, p. 1912-1920.

Ager, D.V., 1981, Nature of the stratigraphical record: 2nd edition, Halsted Press, New York, 136 p.

Allan, J.D., and L.B. Kerr, 1950, Oil and gas exploration in Manitoba: The Precambrian, v. 23, p. 8-10.

Andrichuk, J.M., 1951, Regional stratigraphic analysis of Devonian System in Wyoming, Montana, and southern Saskatchewan: AAPG Bull., v. 35, p. 2368-2408.

Asquith, G.B., R.L. Parker, C.R. Gibson, and J.R. Root, 1978, Depositional history, Ordovician Red River C and D zones, Big Muddy Creek Field, Roosevelt County, Montana: in Montana Geological Society Guidebook, Williston Basin Symposium, p. 71-76.

Asquith, G.B., 1979, Subsurface carbonate depositional models: Petroleum Publishing Co., Tulsa, Okla., p. 79-94.

Badiozamani, K., 1973, The Dorag dolomitization model-application to the Middle Ordovician of Wisconsin: Jour. Sed. Petrology, p. 965-984.

Baillie, A.D., 1953, Devonian System of the Williston Basin Area: Manitoba Mines Branch, Publication No. 52-5, 105 p.

Bebout, D.G., and W.R. Maiklem, 1973, Ancient anhydrite facies: Bull. Canadian Petroleum Geology, v. 21, p. 287-343.

Becher, J.W. and C.H. Moore, 1979, The Walker Creek Field: A Smackover diagenetic trap: in Gulf Coast Assoc., Geol. Soc. Trans., No. 26, p. 34-56.

Belyea, H.R., 1955, Cross-sections through the Devonian System of the Alberta Plains: Geol. Survey Canada, Paper 55-3, 29 p.

Belyea, H.R., 1957, Correlation of Devonian subsurface formations, Southern Alberta: Geol. Survey Canada, Paper 55-38, 16 p.

Bishop, R.A., 1974, Hummingbird structure, Saskatchewan: single vs. multiple stage salt solution collapse: in Parslow, G.R. (ed.), Fuels-A Geological Appraisal, Sask. Geol. Soc., Spec. Publ. No. 2, p. 179-197.

Braun, W.K. and J.E. Mathison, 1982, Ostracodes as a correlation tool in Devonian studies of Saskatchewan and adjacent areas: in J.E. Christopher, J. Kaldi (eds.), Fourth International Williston Basin Symposium, p. 43-51.

Burke, R. and G. Stefanovsky, 1982, Porosity types, geometry and interpore minerals of the Lower Duperow Formation, Billings Nose area, Williston Basin, North Dakota: in J.E. Christopher, J. Kaldi (eds.), Fourth International Williston Basin Symposium, p. 93-101.

Carozzi, A.V., 1960, Microscopic sedimentary petrography: John Wiley and Sons, New York, 485 p.

Carroll, W. K., 1978, Depositional and paragenetic controls on porosity development, Upper Red River, North Dakota: in Montana Geological Society Guidebook, Williston Basin Symposium, p. 79-94.

Choquette, P.W. and R.P. Steinen, 1980, Mississippian non-supratidal dolomite, Ste. Genevieve Limestone, Illinois Basin: evidence for mixed-water dolomitization: in D.H. Zenger, J.B. Dunham, and R.L. Ethington, (eds.), Concepts and Models of Dolomitization: SEPM Mineral, Spec. Publ. 28, p. 168-196.

DeMille, G., 1960, The Elbow structure of South-Central Saskatchewan: Jour. Alta. Soc. Petrol. Geol., v. 8, p. 154-162.

Dean, K., 1982, Devonian Dawson Bay Formation in Northwestern North Dakota: in J.E. Christopher, J. Kaldi (eds.), Fourth International Williston Basin Symposium, p. 89-93.

Dean, W.E., G.R. Davies and R.Y. Anderson, 1975, Sedimentological significance of nodular and laminated anhydrite: Geology, v. 3, p. 367-372.

Dunn, C.E., 1975, Devonian Duperow Formation in southeastern Saskatchewan: Saskatchewan Department of Mineral Resources, Report 179, 151 p.

Fisher, W.L. and P.U. Rodda, 1969, Edwards Formation (Lower Cretaceous), Texas, dolomitization in a carbonate platform system: AAPG Bull., v. 53, p. 55-72.

Fuller, J.G.C.M. and J.W. Porter, 1969, Evaporite formations with petroleum reservoirs in Devonian and Mississippian of Alberta, Saskatchewan and North Dakota: AAPG Bull., v. 53, p. 909-926.

Gebelein, C.D. et al, 1980, Subsurface dolomitization beneath the tidal flats of central west Andros, Bahamas: in D.H. Zenger, J.B. Dunham and R.L. Ethington (eds.), Concepts and Models of Dolomitization: SEPM Spec. Publ. 28, p. 31-49.

Gerhard, L.C., 1978, Some modern carbonate studies applied to the Williston Basin: in Montana Geological Society Guidebook, Williston Basin Symposium, p. 35-53.

Hagan and Logan, 1975, Prograding tidal-flat sequences: Hutchinson Embayment, Shark Bay, Western Australia, in Tidal Deposits: A Casebook of Relevant Examples and Fossil Counterparts, R.N. Ginsburg (ed.), Springer Verlag, New York, p. 215-222.

Halabura, S.P., 1982, Depositional environments of the Upper Devonian Birdbear Formation, Saskatchewan: in J.E. Christopher, J. Kaldi (eds.), Fourth International Williston Basin Symposium, p. 113-125.

Hoganson, J.W., 1978, Microfacies analysis and depositional environments of the Duperow Formation (Frasnian) in the North Dakota part of the Williston Basin: Montana Geological Society Guidebook, Williston Basin Symposium, p. 131-143.

Irwin, J.L., 1965, General theory of epeiric clear water sedimentation: AAPG Bull., v. 49, p. 445-459.

Kaldi, J., 1980, The origin of nodular structures in the Lower Magnesian Limestone (Permian) of Yorkshire, England: Contribution to Sedimentology, v. 9, p. 45-60.

Kendall, A.C., 1976, Ordovician carbonate succession (Bighorn Group) of southeastern Saskatchewan: Saskatchewan Department of Mineral Resources Report 180, 186 p.

Kendall, A.C., 1977, Origin of dolomite mottling in Ordovician limestones from Saskatchewan and Manitoba: Bull. Can. Petrol. Geol. v, 25, p. 480-504.

Kendall, A.C., 1979, Facies Models 14: Subaqueous evaporites: in Geoscience Canada Facies Models Reprints, p. 159-174.

Kent, D.M., 1963, The stratigraphy of the Upper Devonian Saskatchewan Group of southwestern Saskatchewan: Saskatchewan Department of Mineral Resources, Report 73, 51 p.

Kent, D.M., 1968, Geology of the Upper Devonian Saskatchewan Group and equivalent rocks in western Saskatchewan and adjacent areas: Saskatchewan Department of Mineral Resources, Report 99, 224 p.

Kent, D.M. et al, 1973, Hydrocarbon potential of Saskatchewan: Saskatchewan Department of Mineral Resources Report, 28 p.

Kent, D.M., A stratigraphic and sedimentologic analysis of the Mississippian Madison Formation in southwestern Saskatchewan: Saskatchewan Department of Mineral Resources, Report 141, 85 p.

Kirkland, D.W. and R. Evans, 1981, Source-rock potential of evaporitic environment: AAPG Bull., vo. 65, p. 181-190.

Kohm, J.A., and R.O. Louden, 1978, Ordovician Red River of Eastern Montana and Western North Dakota: Relationships between lithofacies and production: in Montana Geological Society Guidebook, Williston Basin Symposium, p. 99-116.

Loeffler, P., 1982, Depositional environments and rock fabric, Birdbear (Nisku) Formation (Upper Devonian) Williston Basin, North Dakota: AAPG 1982 Convention Book of Abstracts, p. 76.

Logan, B.W., 1961, Cryptozoan and associated stromatolites from the Recent, Shark Bay, Western Australia: Jour. Geology, v. 69, p. 517-533.

Longman, M.W., 1982, Carbonate diagenesis as a control on stratigraphic traps (with examples from the Williston Basin): AAPG Education Course Note Series No. 21, Tulsa, Oklahoma.

McCrossan, R.G., 1959, Sedimentary boudinage structures in the Upper Devonian Ireton Formation of Alberta; Jour. Sed. Petrology, v. 28, p. 316-320.

Maiklem, W.R., D.G. Bebout, and R.P. Glaister, 1969, Classification of anhydrite: a practical approach: Bull. Canadian Petroleum Geology, v. 17, p. 194-233.

Meneley, R.A., 1958, The Nisku Format in Saskatchewan: M.Sc. thesis, University of Saskatchewan, 37 p.

Morrow, D.W., 1982, Diagenesis 2. Dolomite - Part 2: Dolomitization models and ancient dolostones: Geoscience Canada, v. 9, No. 2, p. 95-107.

Muller, J., and F. Fabricius, 1974, Magnesium-calcite nodules in the Ionian deep sea: an actualistic model for the formation of some nodular limestones: in K.J. Hsu and H.C. Jenkyns (eds.) Pelagic Sediments: on Land and under the Sea, Spec. Publ. Int. Assoc. Sed., p. 235-247.

Nichols, R.A.H., 1970, Petrology and economic geology of the Upper Devonian Birdbear formation in southeast Saskatchewan: Saskatchewan Department of Mineral Resources Report 125, 94 p.

Patterson, R.J., and D.J.J. Kinsman, 1982, Formation of diagenetic dolomite in coastal sabkha along Arabian (Persian) Gulf: AAPG Bull., v. 66, p. 28-43.

Powley, D., 1951, Devonian stratigraphy of central Saskatchewan: M.Sc. thesis, University of Saskatchewan, 98 p.

Purdy, E.G., 1963, Recent $CaCO_3$ facies of the Great Bahama Bank 2: Sedimentary facies: Jour. Geol., v. 71, p. 472-497.

Ramburg, H., 1955, Natural and experimental boudinage and pinch-and-swell structures: Jour. Geol., v. 63, p. 512-516.

Sampsel, W.H., 1964, Structural evolution of the Tule Creek area of eastern Montana: in Third International Williston Basin Symposium, p. 200-203.

Sandberg, C.A., and C.R. Hammond, 1958, Devonian System in Williston Basin and Central Montana: AAPG Bull., v. 42, p. 2293-2334.

Sawatsky, H., 1975, Astroblemes in the Williston Basin: AAPG Bull., v. 59, p. 694-710.

Shaw, A.B., 1965, Time in stratigraphy: McGraw-Hill, New York, 365 p.

Shinn, E.A., 1968, Selective dolomitization of recent sedimentary structures: Jour. Sed. Petrology, v. 38, p. 612-616.

Smith, D.L. 1972, Depositional cycles of the Lodgepole Formation (Mississippian) in central Montana: in Montana Geological Society 21st Annual Field Conference, p. 29-35.

Smith, D.G., and J.R. Pullen, 1967, Hummingbird structure of southeastern Saskatchewan: Bull. Canadian Petroleum Geology, v. 15, p. 468-482.

Smith, S.R., 1980, Petroleum geology of the Mississippian Midale Beds, Benson oil field, southeastern Saskatchewan: Saskatchewan Department of Mineral Resources Report 215, 98 p.

Swenson, R.E. 1967, Trap mechanics in Nisku Formation of northeast Montana; AAPG Bull., v. 51, p. 1948-1958.

Tasch, P., 1980, Paleobiology of the invertebrates: Data retrieved from the fossil record: Wiley and Sons, New York, 975 p.

Wilson, J.L., 1967, Carbonate-evaporite cycles in Lower Duperow Formation of Williston Basin: Bull. Canadian Petroleum Geology, v. 15, p. 230-312.

Wilson, J.L., 1974, Characteristics of carbonate-platform margins: AAPG Bull., v. 58, p. 810-824.

Wilson, J.L., 1975, Carbonate facies in geologic history: Springer-Verlag, New York, 471 p.

Wilson, W., D.L. Surjik, and H.B. Sawatzky, 1963, Hydrocarbon potential of the south Regina area, Saskatchewan: Saskatchewan Department of Mineral Resources, Report No. 76, 17 p.

Zenger, D.H., 1972, Significance of supratidal dolomitization in the geologic record: Geol. Soc. America Bull., v. 83, p. 1-12.

PLATE 1

Lithofacies A: Bedded to Nodular Lime Mudstone to Wackestone

Figure 1. Light brownish-grey, mottled, bioclastic, nodular-bedded lime wackestone with slightly dolomitized matrix. The bioclasts include broken pieces of algal mats and corals. Fina Readlyn 1-36-7-26 W2M, 6455 feet.

Figure 2. Well developed nodular beds are present in this well. Rocks of Lithofacies A also contain thin beds of very small, poorly formed pseudo-ooids and pelletoids. Nodules are selectively dolomitized. Socony W.P. Carievale No. 1, 16-4-3-32 W1M, 5082 feet.

Figure 3. The lighter colored nodules are generally more calcareous than the darker colored beds in this sample. Ostracode carapaces and rare brachiopod valves are scattered throughout Tenneco Canadian Superior Salt Lake 11-3-4-20 W2M, 7484 feet.

Figure 4. Dolomitized bioclastic lime wackestone with thin interbedded lime packstone beds. The nodules are more dolomitic than the matrix. Peloids and minor amounts of algal rip-up clasts are also common in this interval. Jefferson Lake Canoxy Steelman 15-19-4-5 W2M, 6148 feet.

PLATE 1

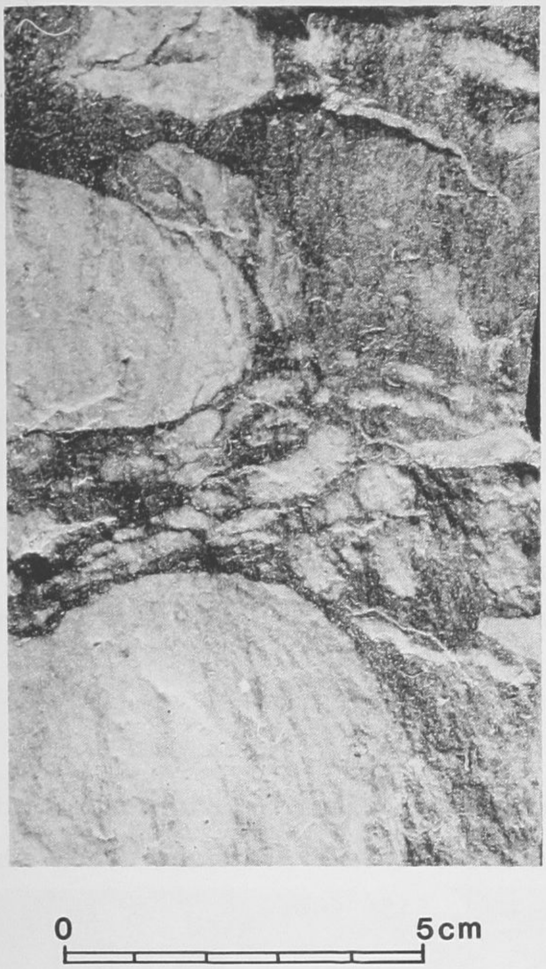


FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

PLATE 2

Lithofacies B: Bioclastic Lime Wackestone to Packstone

Figure 1. Bedded bioclastic lime packstone with beds very rich in Amphipora. The Amphipora are poorly developed and often present as broken fragments. This sample directly overlies a shoal sequence and is interpreted as being the final shoal deposit. Jefferson Lake Canoxy Steelman 15-19-4-5 W2M, 6128 feet.

Figure 2. This sample contains abundant coral fragments, Amphipora, algal and micrite rip-up clasts, and other bioclasts. Dolomitic. Tenneco Canadian Superior Salt Lake 11-3-4-20 W2M, 7476 feet.

Figure 3. Bioclastic lime packstone with minor amounts of micrite intraclasts in a dolomitic matrix. Abundant coral fragments. Fina Readlyn 1-36-7-26 W2M, 6454 feet.

Figure 4. Very bioclastic lime packstone, with abundant micrite and algal intraclasts. Abundant secondary anhydrite, often infilling intergrain pores and vugs. Slightly dolomitic. This sample is an example of a shoal development. Francana Viewfield 3-33-7-8 W2M, 5477 feet.

PLATE 2

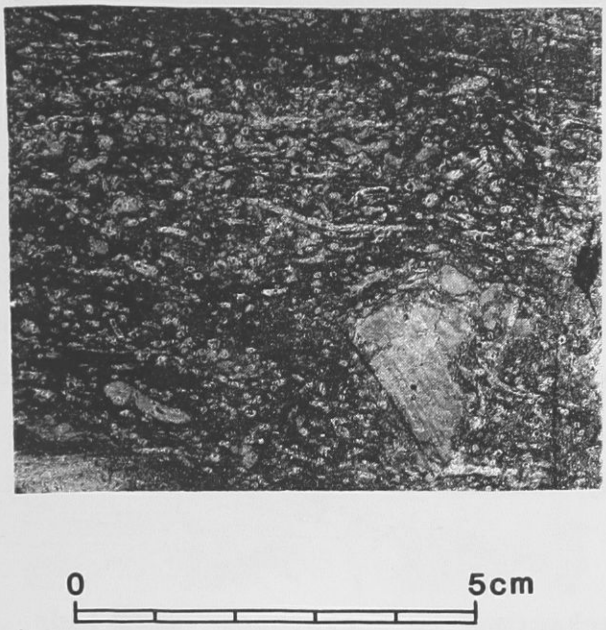


FIGURE 1

FIGURE 2

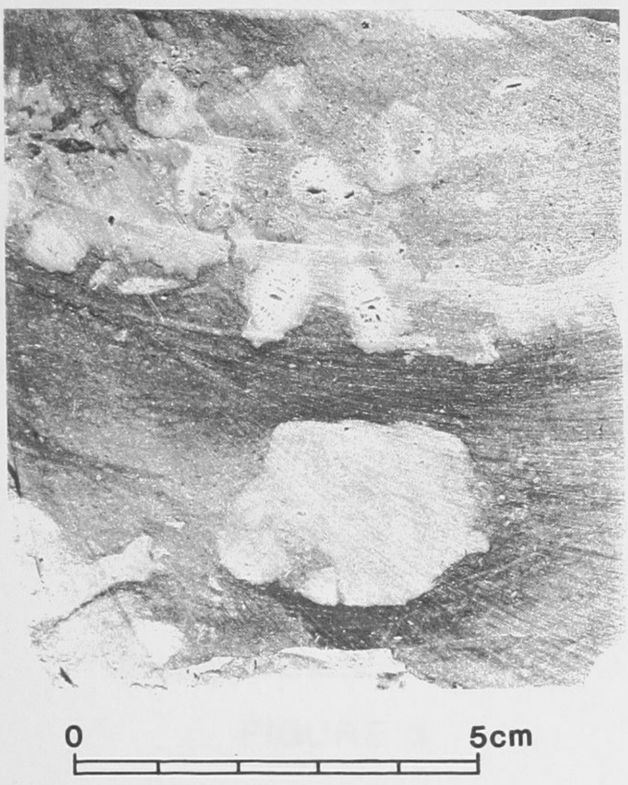


FIGURE 3

FIGURE 4

PLATE 3

Lithofacies C and L: Intraclastic to Pelletoidal Lime Wackestone to Packstone

Figure 1. Well-developed fractured intraclasts composed of micrite. The fracturing, shrinkage cracks, and bed disruption point to high levels of water energy. Some scattered bioclasts are present. Porosity ranges from poor to very good. Jefferson Lake Canoxy Steelman 15-19-4-5 W2M, 6136 feet.

Figure 2. Laminated oolitic wackestone to packstone. Rare beds cemented as opposed to matrix-supported. Ooids poorly developed. Tenneco Canadian Superior Salt Lake 11-3-4-20 W2M, 7430 feet.

Figure 3. Intraclastic lime wackestone. Intraclasts range from irregular structureless micrite clasts to flattened, oval pelletoids. Traces of ooids. Tenneco Canadian Superior Salt Lake 11-3-4-20 W2M, 7441 feet.

Figure 4. Laminated intraclastic lime wackestone. Onkoids are also quite common in this sample, as are algal mat intraclasts. Very dolomitic. Tenneco Canadian Superior Salt Lake 11-3-4-20 W2M, 7465 feet.

PLATE 3

FIGURE 1

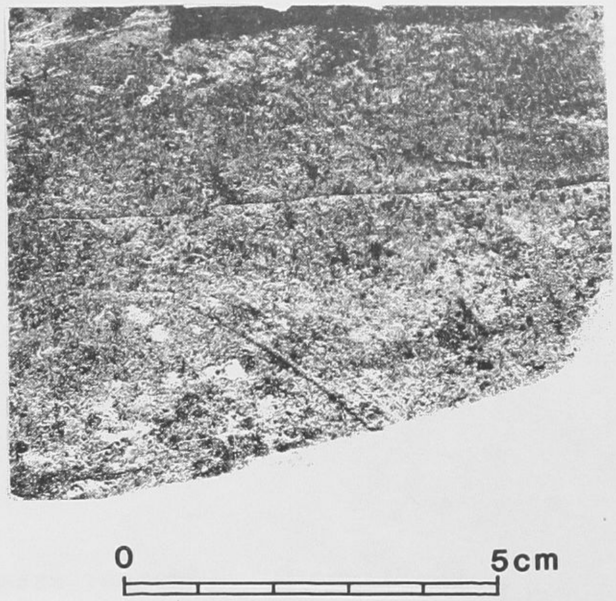


FIGURE 2

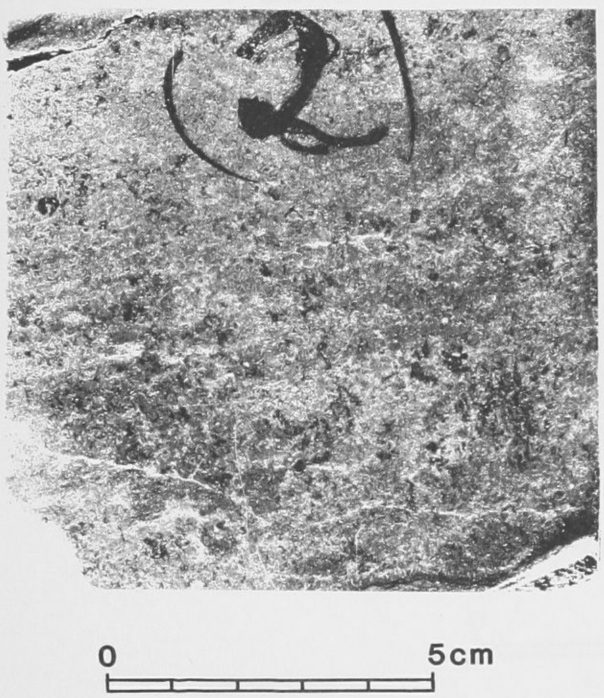


FIGURE 3

FIGURE 4

PLATE 4

Lithofacies I and D: Laminated to Massive Dolomite

Figure 1. Bedded dolomite. This sample is cryptocrystalline, anhydritic, and laminated to thinly bedded. It is anhydritic, and varies from calcareous to very calcareous. Also present are thin beds of dark, organic-rich anhydrite. Saskoil Moose Valley 10A-15-12-6 W2M, 4540 feet.

Figure 2. Another example of the laminated to bedded dolomite. Saskoil Moose Valley 10A-15-12-6 W2M, 4537 feet.

Figure 3. Laminated to bedded dolomite. Some of the beds in the lower portion of this interval display features suggesting algal bedding. Saskoil Moose Valley 10A-15-12-6 W2M, 4542 feet.

PLATE 4

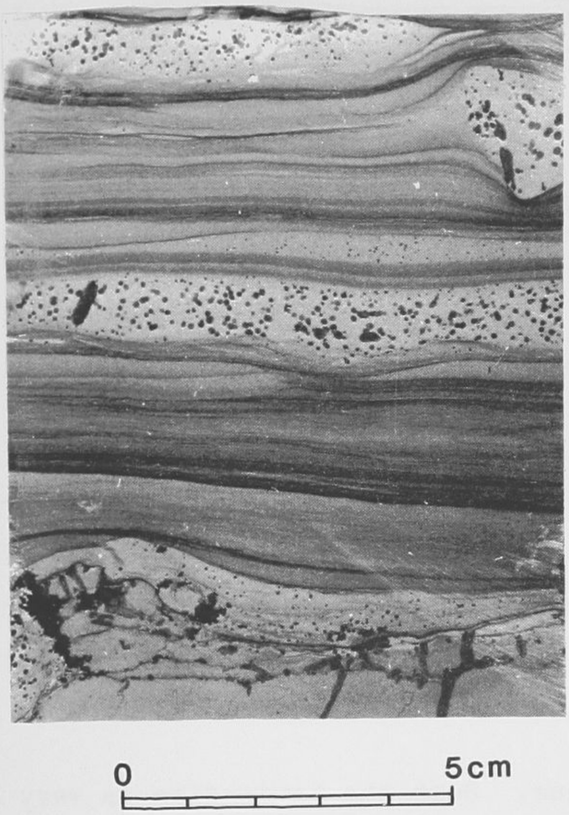


FIGURE 1

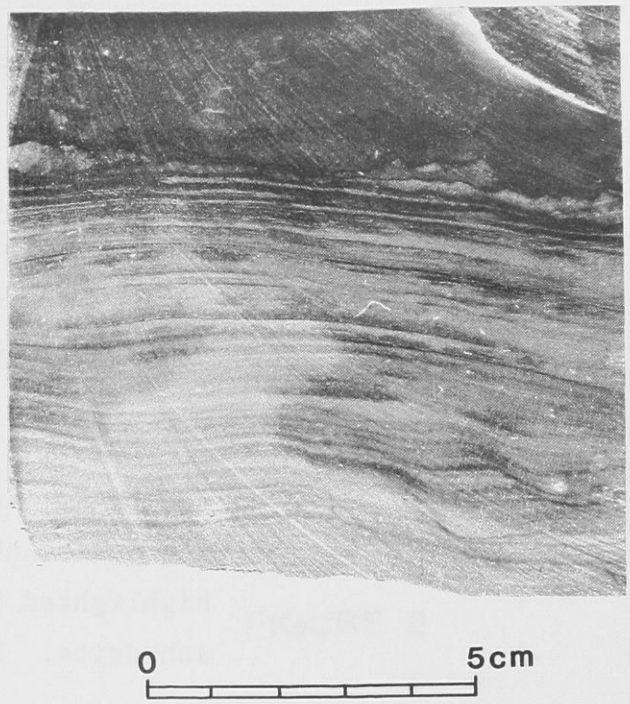


FIGURE 2

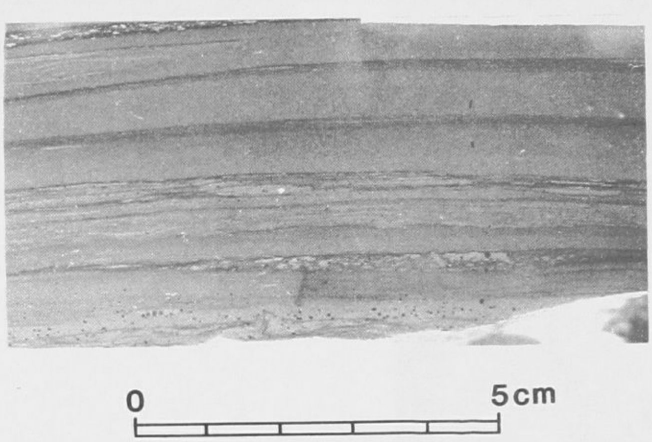


FIGURE 3

PLATE 5

Lithofacies K and E: Laminated to Massive Lime Mudstone

Figure 1. Laminated lime mudstone. One of the rare occurrences in which the bedding is disturbed by actual vertical burrowing. Tenneco Canadian Superior Salt Lake 11-3-4-20 W2M, 7450 feet.

Figure 2. Laminated lime mudstone with minor amounts of crystallographic anhydrite. Bedding parallel, uneven, and often highlighted by thin concentrations of crystallographic anhydrite. Francana Viewfield 3-33-7-8 W2M, 5434 feet.

Figure 3. Laminated lime mudstone. Here the lamination is very even, highlighted by thin films of organic and argillaceous matter. This sample is moderately dolomitic. Socony W.P. Carievale No. 1, 16-4-3-32 W1M, 5044 feet.

Figure 4. Massive lime mudstone. Laminations very vague to nonexistent. Tenneco Canadian Superior Salt Lake 11-3-4-20 W2M, 7450 feet.

PLATE 5

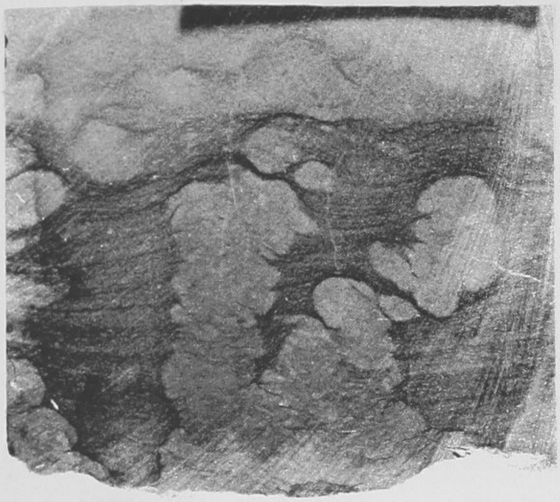


FIGURE 1

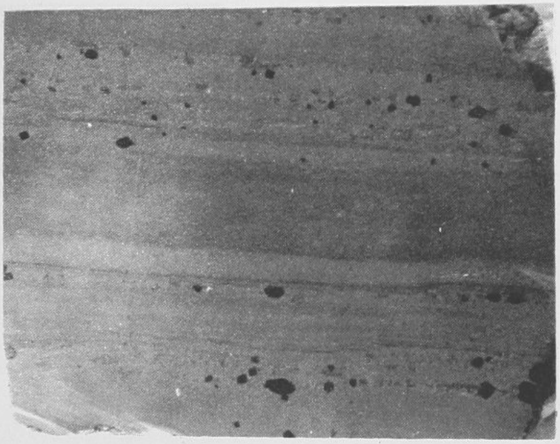


FIGURE 2

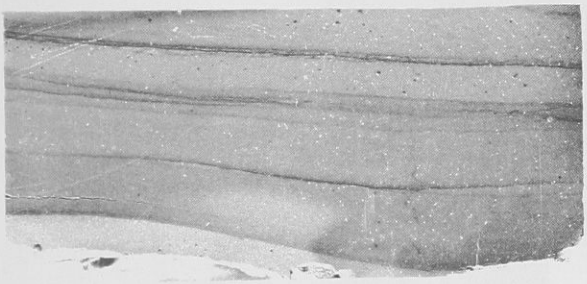


FIGURE 3

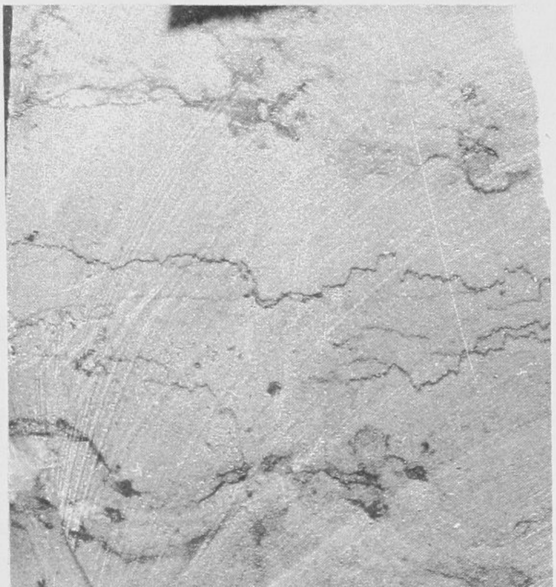


FIGURE 4

PLATE 6

Lithofacies F: Argillaceous Carbonate Mudstone to Shale

Figure 1. Thin to medium bedded very calcareous shale mudstone, light greenish grey in color. Abundant nodular anhydrite. From the top of the Birdbear Formation, near the Birdbear-Torquay contact. Socony W.P. Carievale No. 1, 16-4-3-32 W1M, 5030 feet.

Figure 2. Argillaceous nodular to brecciated lime wackestone. Socony W.P. Carievale No. 1, 16-4-3-32 W1M, 5082 feet.

PLATE 6

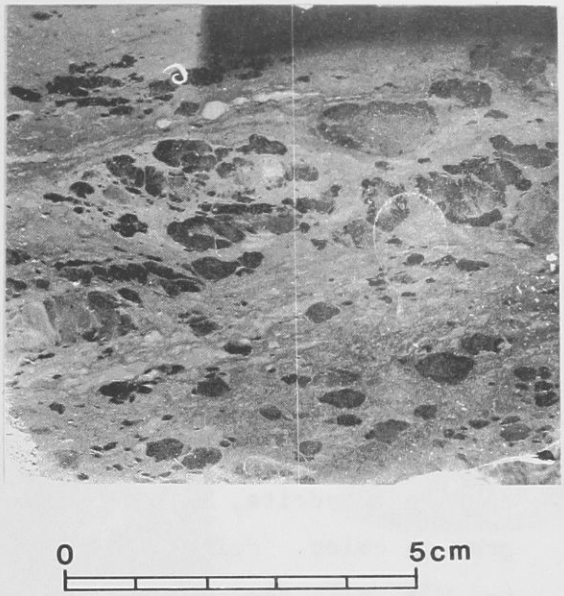


FIGURE 1

FIGURE 2

PLATE 7

Lithofacies G: Nodular Mosaic to Bedded Nodular Anhydrite
and
Lithofacies H: Massive to Laminated/Bedded Anhydrite

Figure 1. Nodular mosaic anhydrite. Dolomite matrix completely disturbed by coalesced nodules, no discernable bedding. Saskoil Moose Valley 10-15-12-6 W2M, 4585 feet.

Figure 2. Massive anhydrite, vaguely laminated. Light greenish grey in color. Jefferson Lake Canoxy Steelman 15-19-4-5 W2M, 6114 feet.

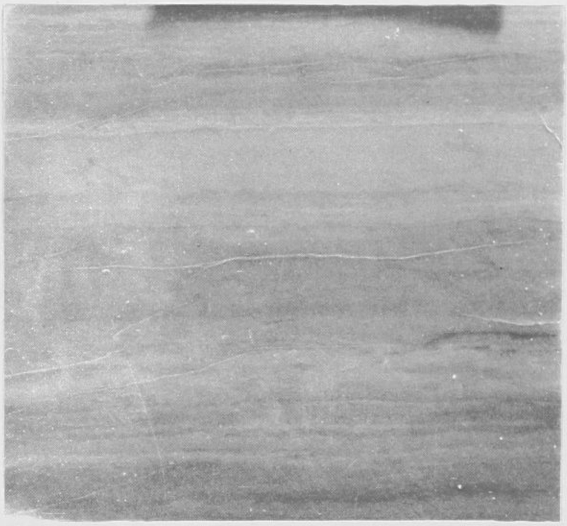
Figure 3. Bedded to massive anhydrite. This sample displays some algal laminations which are slightly contorted and wavy. Fina Readlyn 1-36-7-26 W2M, 6413 feet.

Figure 4. Transition from vaguely bedded anhydrite to massive anhydrite. Jefferson Lake Canoxy Steelman 15-19-4-5 W2M, 6113 feet.

PLATE 7

0 5cm

FIGURE 1

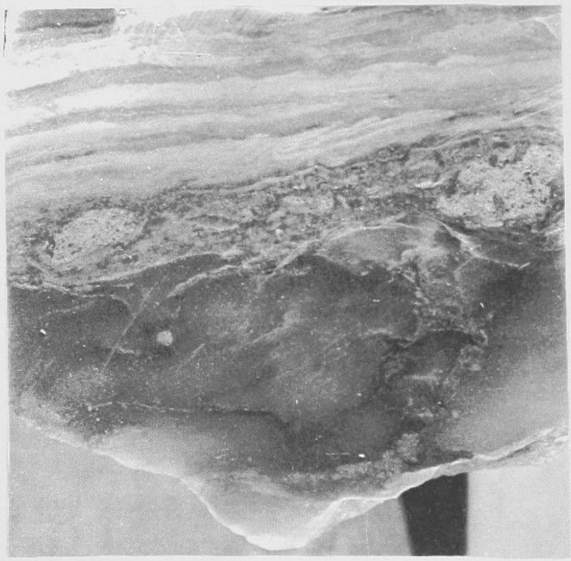


0 5cm

FIGURE 2

0 5cm

FIGURE 3



0 5cm

FIGURE 4

PLATE 8

Lithofacies J: Laminated (Algal) Dolomite

Figure 1. Well-developed algal laminite. Bedding very even and parallel. Abundant crystallographic anhydrite, present as very small nodules scattered randomly throughout sample. Socony W.P. Carievale No. 1, 16-4-3-32 W1M, 5041 feet.

Figure 2. Laminated algal beds disrupted by syndepositional fault plane. Socony W.P. Carievale No. 1, 16-4-3-32 W1M, 5073 feet.

Figure 3. Two vertical algal stromatolites beads, with interstack void filled with mixture of micrite, pelletoid, and fragments of algal material. Socony W.P. Carievale No. 1, 16-4-3-32 W1M, 5042 feet.

PLATE 8

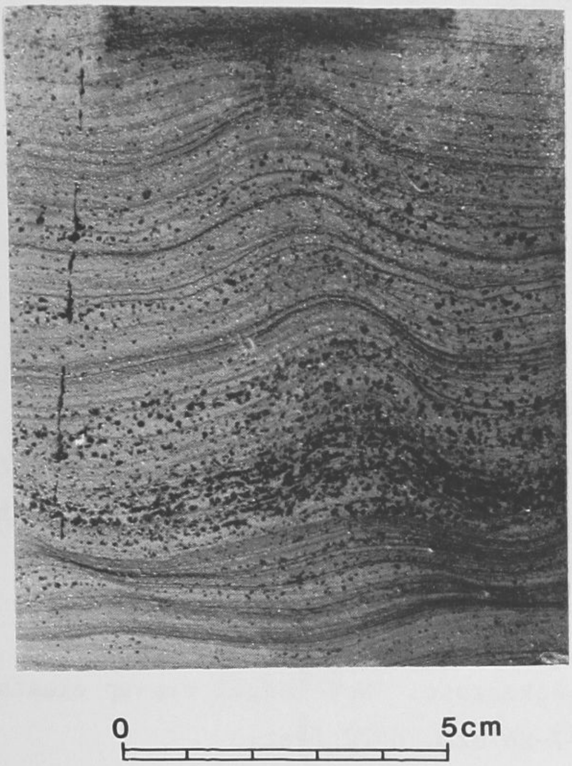


FIGURE 1

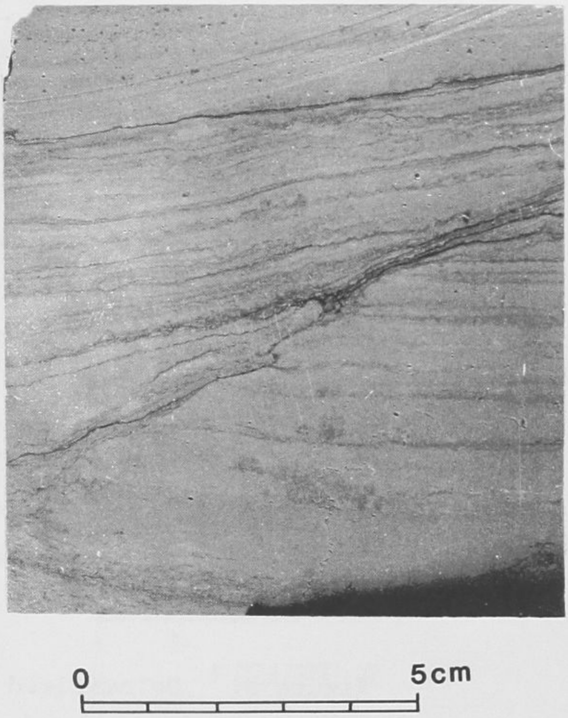


FIGURE 2

FIGURE 3

PLATE 9

Examples of Dolomites from Birdbear Formation

Figure 1. Dolomite with vague bioclastic outlines. Bedding vaguely discernable. Dolomitization not complete. Tenneco Canadian Superior Salt Lake 11-3-4-20 W2M, 7441 feet.

Figure 2. Nodular bedded dolomite. Note gastropod in lower left center. Bioclasts and pelletoidal texture still visible. Francona Viewfield 3-33-7-8 W2M, 5468 feet.

Figure 3. Dolomitized lime wackestone. Note algal rip-up clasts. Fina Readlyn 1-36-7-26 W2M, 6472 feet.

PLATE 9

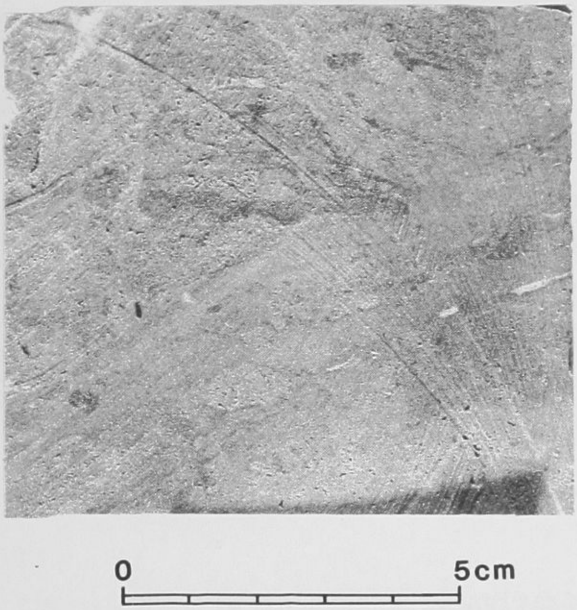


FIGURE 1

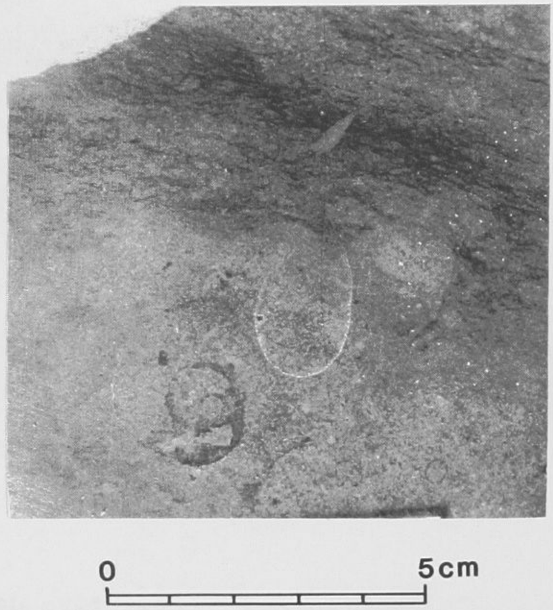


FIGURE 2

FIGURE 3

PLATE 10

Early Diagenetic Dolomite

Figure 1. Selective dolomitization of micrite. Note very fine grained dolomite crystal mesh and scattered coarser-grained crystals. Very fine-grained pyrite crystals also present. 25x.

Figure 2. Same view as Figure 1 under higher magnification. Note rhombic dolomite crystals. 100x.

Figure 3. Selective dolomitization of irregular micrite pelletoid. 25x.

Figure 4. Medium to coarse grained dolomite crystals within algal laminite. Abundant black, crinkly, organic laminae throughout sample. 25x.

Figure 5. Low degree of selective dolomitization within a bioclastic wackestone (Lithofacies B). The dolomite is present as a poorly developed cement in the thin pelletoid bed on the right of the photo, and as a cement infilling bioclast molds. 25x.

Figure 6. Close-up of bioclasts (probably ostracodes) infilled with rhombic dolomite cement. 100x.

PLATE 10

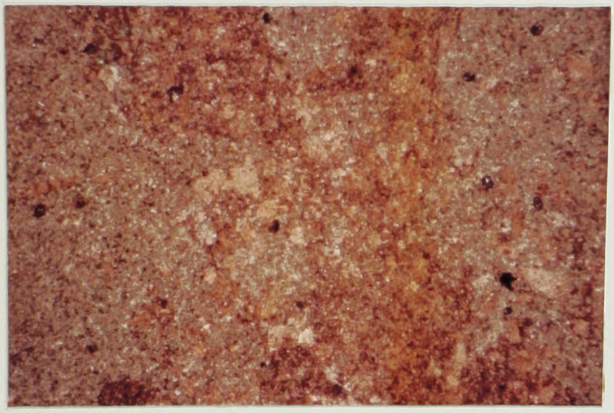


FIGURE 1

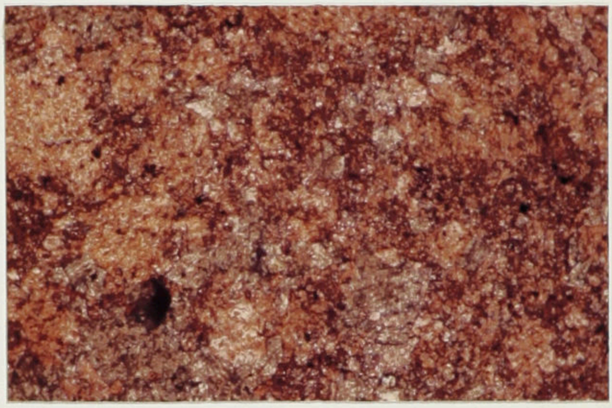


FIGURE 2

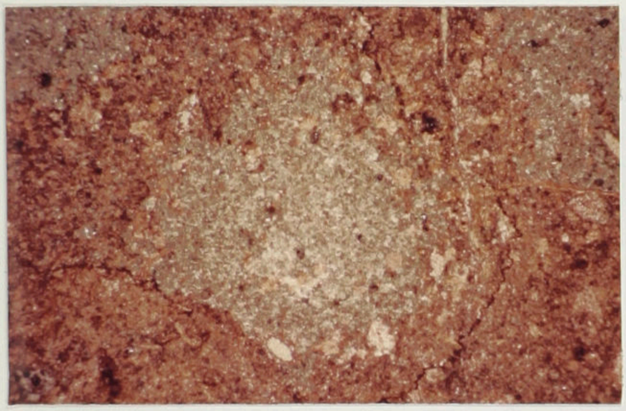


FIGURE 3

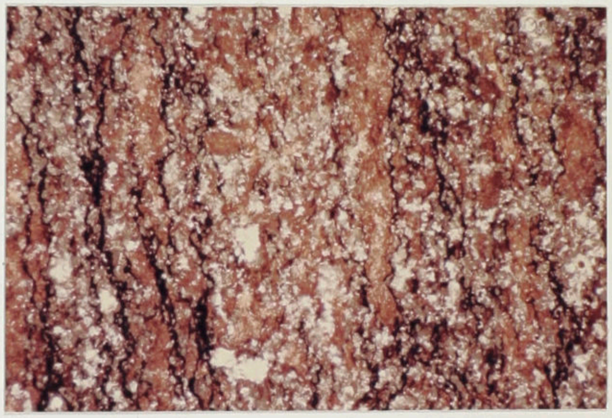


FIGURE 4

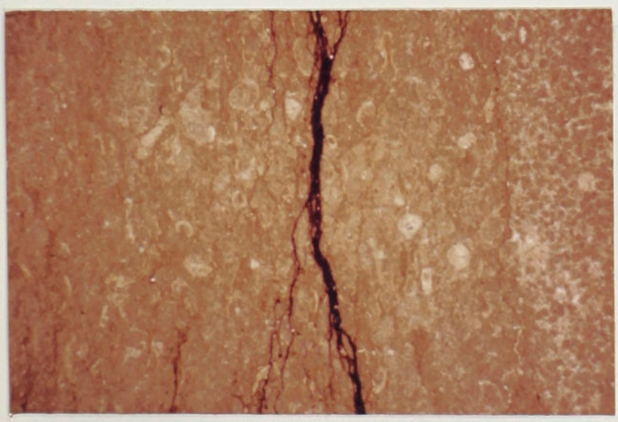


FIGURE 5

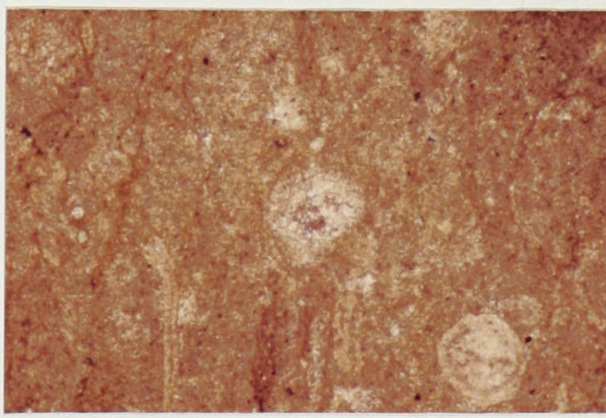


FIGURE 6

PLATE 11

Late Diagenetic Dolomite

Figure 1. Very fine-grained dolomite grains with only minor amounts of calcite present. Pattern of dolomitization vaguely suggestive of randomly oriented patches. 25x.

Figure 2. Rhombic dolomite crystals with evidence of post-diagenetic solution. Note the corroded centers of dolomite crystals in center of picture and pore system between crystals, now completely plugged with heavy oil. This feature may be due to solution of dolomite in a vadose diagenetic environment, such as at an erosional subcrop. 100x.

Figure 3. Interlocking mosaic of dolomite crystals. The dark circular objects are collections of pyrite dust. 25x.

Figure 4. Same view as Figure 3, 100x.

Figure 5. An interlocking mosaic of dolomite crystals; however, these crystals are coarser in size than those in Figure 3.

Figure 6. Same view as Figure 5, 100x.

PLATE 11

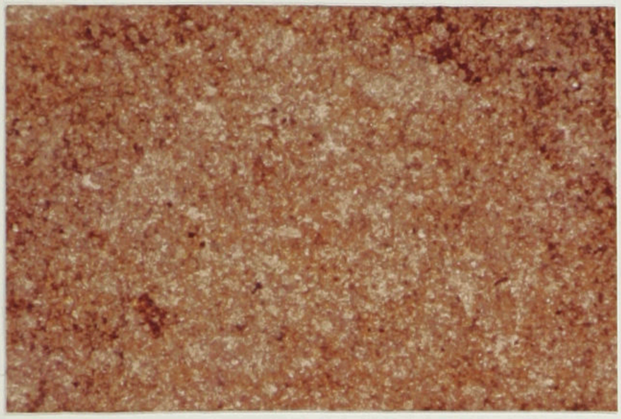


FIGURE 1

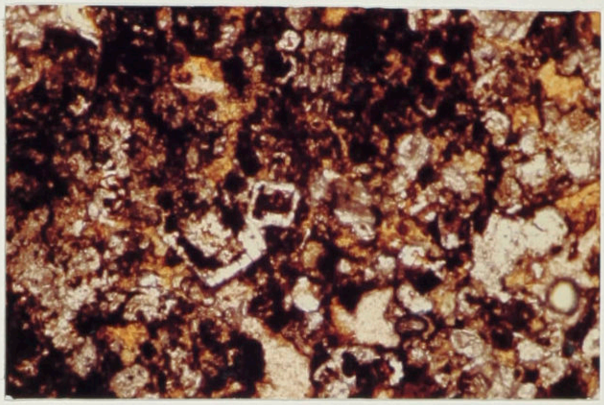


FIGURE 2

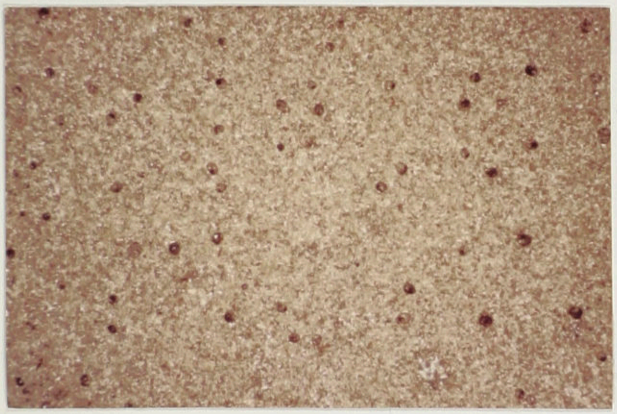


FIGURE 3

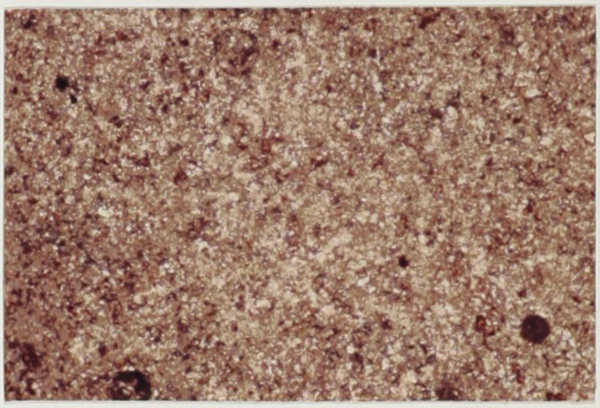


FIGURE 4

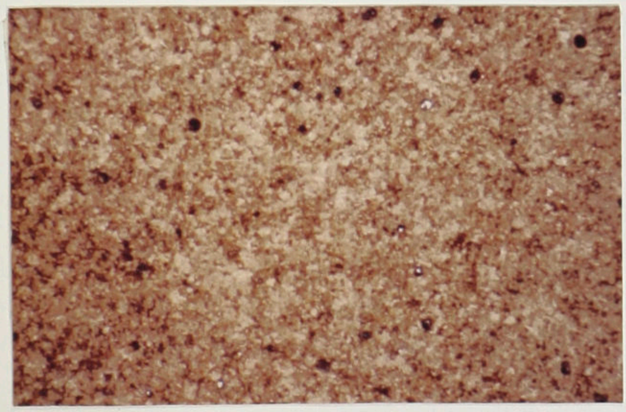


FIGURE 5

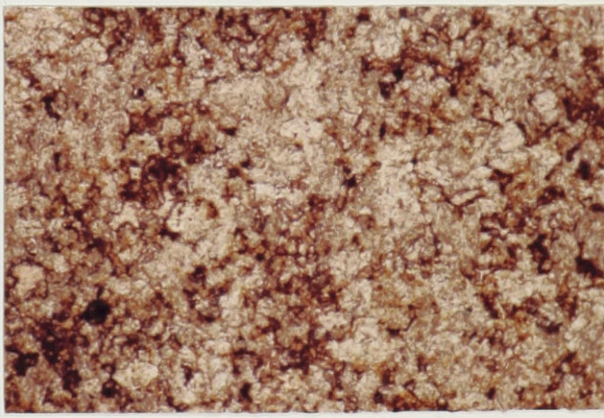


FIGURE 6

PLATE 12

Diagenetic (Secondary) Anhydrites

Figure 1. Coarsely crystalline anhydrite infilling pore throats. 25x.

Figure 2. Same view as Figure 1, however under polarized light. 25x.

Figure 3. Mesh of interlocking subhedral to irregular anhydrite crystals, infilling and possibly replacing micrite matrix. 25x.

Figure 4. Close-up of Figure 3. Note lath-like crystal habit and abundance of black organic material between crystals. 100x.

Figure 5. Same view as Figure 3, however under polarized light. 25x.

PLATE 12

FIGURE 1

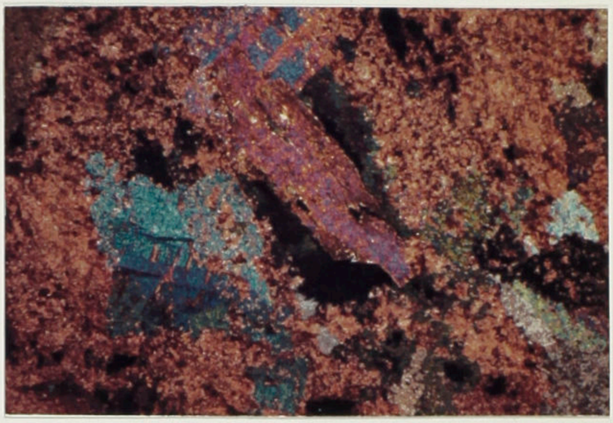


FIGURE 2

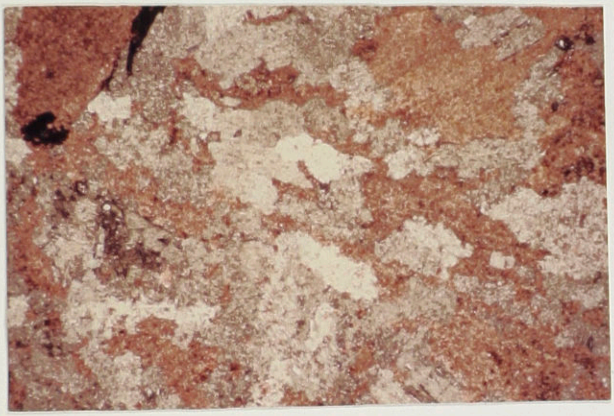


FIGURE 3

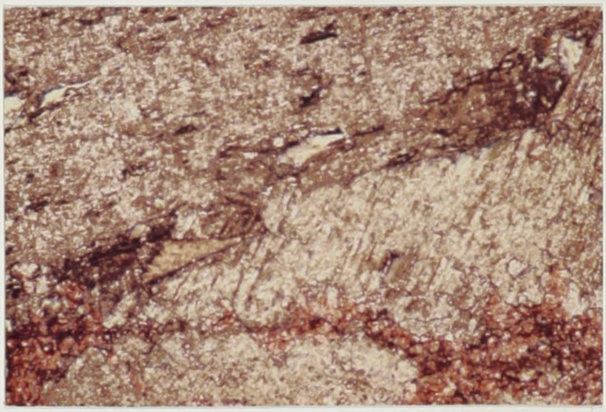


FIGURE 4

FIGURE 5

APPENDIX B: WELL DATA SUMMARY

Note: all depths in feet and measured from below kelly bushing (K.B.)

* denotes well in which identification of marker tops difficult

NDE: Not deep enough

- : no thickness available

Well Data		Subsurface Depths (Depth measured below K.B.)								
Well Name & Location (Well Number)	K.B.(ft.)	Top of Birdbear	Top of Duperow	Top of Lower Member	Top of "subtidal" interval	Total Isopach	Isopach of Upper Member	Isopach of Lower Member	Isopach of "subtidal" interval	Isopach of "intertidal" [illegible] interval
Socony Carievale 16-4-3-32 W1M (1)	1690	5026	5136	5072	5084	109	45	64	52	
Imperial Frys 4-35-7-31 W1M (2)	1895	3838	3950	3870	3912	112	32	80	38	
Herkules Fairlight 6-32-10-31 W1M (3)	1938	3427	NDE	3452*	-	43+	25	-	-	
Royalite Northgate 15-29-1-2 W2M (4)	1860	6365	NDE	6406	6406	101+	41	60+	60+	
Imperial North Portal 12-29-1-5 W2M (5)	1900	6926	NDE	NDE		36+	36+	-	-	
Gulf Neumann 12-29-2-2 W2M (6)	1722	5911	6018	5955	5955	107	44	63	63	0
Imperial Oxbow 15-36-2-3 W2M (7)	1887	6076	6186	2120*	6123	110	44	66	63	3
Calstan Frobisher 5-21-2-4 W2M (8)	1875	6442	6543	6483*	6500	101	41	60	43	17
Shell South Oxbow 13-24-2-3 W2M (9)	1870	6170	6280	6213	6213	110	43	67	67	0
B.A. Quinn 9-34-3-4 W2M (10)	1935	5978	6092	6026*	6057	114	48	66	35	31
Jeff Lake Steelman 15-19-4-5 W2M (11)	1947	6089	6211	6108	6152	122	19	103	59	44
B.A. Charlotte 12-30-4-4 W2M (12)	1940	5914	6026	5950*	5985	112	36	76	41	35
Imperial Douglaston 12-6-5-3 W2M (13)	1938	5580	5705	5621*	5631	125	41	84	74	10
Dome Willmar 11-9-6-3 W2M (14)	1955	5260	5380	5288	5336	120	28	92	44	48

Well Data		Subsurface Depths (Depth measured below K.B.)								
Well Name & Location (Well Number)	K.B.(ft.)	Top of Birdbear	Top of Duperow	Top of Lower Member	Top of "subtidal" interval	Total Isopach	Isopach of Upper Member	Isopach of Lower Member	Isopach of "subtidal" interval	Isopach of "intertidal" interval
urry Wordsworth -36-6-4 W2M (15)	1981	5176	5298	5208	5256	122	32	90	42	48
perial Wier Hill 16-6-6 W2M (16)	1968	5700	5822	5733	5765	122	33	89	57	32
ancana Viewfield -33-7-8 W2M (17)	2006	5424	5557	5452	5515	133	28	105	92	63
idwater Carlyle 5-23-7-3 W2M (18)	1941	4830	NDE	NDE	NDE	28+	28+	-	-	-
age Viewfield -17-7-8 W2M (19)	2007	5625	5750	5658	5684	125	33	92	66	26
amoil Benson 1-12-7-9 W2M (20)	2003	5650	NDE	5689	5710	80+	39	41+-	20+	21
larathon Arcola 1-11-8-4 W2M (21)	2014	4886	NDE	4906*	NDE	50+	20	30+	-	-
Comaplex Stoughton 15-11-8-8 W2M (22)	2026	5356	5472	5390*	5429	116	34	82	43	39
Shell Tableland 12-24-1-10 W2M (23)	1907	7417	7518	7461	7463	101	44	57	55	2
Dome Tableland 11-14-2-9 W2M (24)	1874	7044	7145	7082*	7082	101	38	63	63	0
Imperial Halkett 15-7-3-8 W2M (25)	1923	6778	6896	6815	6837	118	37	81	59	22
Shell Macoun 8-1-4-9 W2M (26)	1923	6582	6698	6612	6642	116	30	86	56	30
Shell Bryant 16-33-4-9 W2M (27)	1948	6310	6426	6340	6373	116	30	86	53	33
Shell East Elswick 13-20-4-11 W2M (28)	1878	6526	6635	6553	6590	109	27	82	45	37

Well Data		Subsurface Depths (Depth measured below K.B.)								
Well Name & Location (Well Number)	K.B.(ft.)	Top of Birdbear	Top of Duperow	Top of Lower Member	Top of "subtidal" interval	Total Isopach	Isopach of Upper Member	Isopach of Lower Member	Isopach of "subtidal" interval	Isopach of "intertidal" interval
ıell Torquay -29-2-12 W2M (29)	1975	7284	7392	7323	7323	108	39	69	69	0
DR Flat Lake East 3-3-1-15 W2M (30)	2240	7850	7953	7881*	7920	103	31	72	33	39
DR Oungre .5-9-2-14 W2M (31)	2155	7530	7635	7555*	7607	105	25	80	28	52
:POG Oungre)-34-2-15 W2M (32)	2174	7412	7519	7434*	7472	107	22	85	47	38
Jeff Lake East Oungre 12-12-2-13 W2M (33)	1962	7340	7449	7376*	7422	109	36	73	27	46
CFP Outram 1-19-3-10 W2M (34)	1856	6773	6883	6812*	?	110	39	71	-	-
Banff North Torquay 7-29-3-11 W2M (35)	1900	6807	6909	6833*	6805	102	26	76	44	32
I.O.E. Tribune 2-8-3-14 W2M (36)	2027	7274	7380	7303	7328	106	29	77	52	25
Jeff Lake Torquay 2-4-4-11 W2M (37)	1863	6896	7000	6921*	6958	104	25	79	42	37
I.O.E. Jewel 8-20-4-14 W2M (38)	2006	6665	6763	6742	6718	98	77	21	45	0
CDR Elswick 1-7-5-12 W2M (39)	1850	6314	6414	6468	6368	100	54	46	46	0
Francana Medicine Wheel 11-26-9-6 W2M (40)	2444	5206	5330	5263	5290	124	57	67	40	27
Tidewater Whitebear 5-15-10-2 W2M (41)	2464	4591	4691	4644	4654	100	53	47	37	10
Francana Dumas 13-19-11-1 W2M (42)	2220	4023	4132	4087	4087	109	64	45	45	0

Well Data		Subsurface Depths (Depth measured below K.B.)								
Well Name & Location (Well Number)	K.B.(ft.)	Top of Birdbear	Top of Duperow	Top of Lower Member	Top of "subtidal" interval	Total Isopach	Isopach of Upper Member	Isopach of Lower Member	Isopach of "subtidal" interval	Isopach of "intertidal" interval
Amroc Fletwode [illegible]-33-3 W2M (43)	2444	4549	4670	4623	4632	121	74	47	38	9
[illegible]inger Moose Valley [illegible]-12-6 W2M (44)	2395	4565	4680	4619	4642	115	54	61	38	23
[illegible]coil Moose Valley [illegible]15-12-6 W2M (45)	2420	4528	4651	4596	4618	123	68	55	33	22
[illegible]ll Midale [illegible]8-6-10 W2M (46)	2006	5991	6102	6003	6023	111	12	99	79	20
[illegible] Geiger [illegible]1-8-10 W2M (47)	1975	5455	NDE	5500	5515	95+	45	50+	35+	15
[illegible]skoil Creelman [illegible]-27-9-10 W2M (48)	2018	5053	5176	5089	5133	123	36	87	43	44
[illegible]skoil Griffin 2-9-11 W2M (49)	3014	5330	5457	5374	5412	127	44	83	45	38
Kanata Griffin 7-10-9-11 W2M (50)	2005	5262	5400	5306	5340	138	44	94	60	34
Imperial Hartaven 2-11-10-9 W2M (51)	2054	4987	5104	5002*	5050	117	15	102	54	48
United Canso Innes 5-6-8-10 W2M (52)	1989	5520	5642	5547*	5618	122	27	95	24	71
CDR Weyburn 10-33-6-13 W2M (53)	1877	5840	5946	5871*	5910	106	31	75	36	39
CDR Weyburn 4-13-7-14 W2M (54)	1915	5774	5890	5811*	5857	116	37	79	33	46
Imperial Meadowbrook 16-10-2-15 W2M (55)	1923	5855	5970	5885	5935	115	30	85	35	50
Imperial Tatagwa 15-29-7-15 W2M (56)	1909	5890	5997	5917	5963	107	27	80	34	46

Well Data		Subsurface Depths (Depth measured below K.B.)								
Well Name & Location (Well Number)	K.B. (ft.)	Top of Birdbear	Top of Duperow	Top of Lower Member	Top of "subtidal" interval	Total Isopach	Isopach of Upper Member	Isopach of Lower Member	Isopach of "subtidal" interval	Isopach of "intertidal" interval
King North Weyburn -9-13 W2M (57)	1982	5388	5497	5434*	5467	109	46	63	30	33
erial Lillie Glen 12-10-14 W2M (58)	1990	5100	5210	5153*	5170	110	53	57	40	17
mplin Talmadge ·2-10-13 W2M (59)	1985	5147	NDE	NDE	NDE	53+	-	-	-	-
G Cedoux -20-11-14 W2M (60)	1966	4770	4895	4830	4830	115	60	55	55	0
bil Flat Lake -14-1-16 W2M (61)	2336	7892	7998	7918	7940	106	26	80	58	32
R Lake Alma 14-1-17 W2M (62)	2268	8023	8124	8048	8094	101	25	76	30	46
R Lake Alma -29-1-17 W2M (63)	2363	7753	7859	7782	7827	106	29	77	32	45
GERC Alkali Lake 14-25-1-18 W2M (64)	2342	7928	8031	7955*	8000	103	27	76	31	45
Shell Lake Alma 16-36-1-18 W2M (65)	2371	7914	8012	7937	7979	98	23	75	33	42
Great Basins Hummingbird 8-13-2-19 W2M (66)	2481	7866	7959	7900*	7931	93	34	59	28	31
CDR Beaubier 3-20-2-16 W2M (67)	2339	7578	7681	7604*	7650	103	26	77	31	46
Saskoil Hummingbird 12-13-2-19 W2M (68)	2455	7838	7929	7861*	7900	91	23	68	29	39
H.B. Hummingbird 3-26B-2-19 W2M (69)	2418	7608	7708	7636	7678	100	28	77	30	42
H.B. Hummingbird 11-26B-2-19 W2M (70)	2461	7603	7702	7632	7672	99	19	70	20	40

Well Data	Subsurface Depths (Depth measured below K.B.)									
Well Name & Location (Well Number)	K.B.(ft.)	Top of Birdbear	Top of Duperow	Top of Lower Member	Top of "subtidal" interval	Total Isopach	Isopach of Upper Member	Isopach of Lower Member	Isopach of "subtidal" interval	Isopach of "intertidal" interval
I n Neptune : -3-17 W2M (71)	2352	7116	7218	7158?	7203	102	42	60	15	45
: cana Gladmar] -3-19 W2M (72)	2437	7613	7710	7640	7700	97	27	70	10	60
ıcana Neptune 30-4-16 W2M (73)	2257	6789	6889	6826?	6856	100	37	63	37	30
: Daleview 3-4-19 W2M (74)	2509	7388	7480	7420?	7450	92	32	60	30	30
e Lonetree -1-19 W2M (75)	2344	7913	8012	7940	7982	99	27	72	30	42
Three Lakes 6-1-19 W2M (76)	2284	7645	7745	7669	7715	100	24	76	30	46
ıds Three Lakes 11-1-20 W2M (77)	2291	7575	7677	7608	7648	102	33	69	29	40
CPOG Three Lakes 3-16-1-20 W2M (78)	2315	7564	7659	7590	7628	95	26	65	31	38
B.A. Minton Didrick 11-9-2-20 W2M (79)	2358	7374	7470	7400	7438	96	26	70	32	38
Dome Jim Creek 4-32-2-20 W2M (80)	2399	7204	7297	7234*	7264	93	30	63	33	30
Dome Minton 11-2-3-21 W2M (81)	2542	7168	7260	7194*	7220	92	26	66	40	26
Tenneco Salt Lake 11-3-4-20 W2M (82)	2534	7396	7490	7432*	7481*	94	36	58	9	49
Tenneco Bead Lake 6-8-4-21 W2M (83)	2417	6824	6914	6867*	6867	90	43	47	47	0
Gulf Radville 9-35-5-17 W2M (84)	2067	6294	6394	6322*	6342	100	28	72	52	20

Well Data		Subsurface Depths (Depth measured below K.B.)								
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ıeco Ceylon .7-5-20 W2M (85)	2524	7044	7138	7055	7093	94	11	83	45	38
ı Radville ı-6-18 W2M (86)	2186	6385	6477	6406	6433	92	21	71	44	27
ɔhy Radville 4-6-19 W2M (87)	2391	6626	6722	6646	6686	96	20	76	36	40
C Ceylon 0-6-19 W2M (88)	2325	6526	6630	6562*	6589	104	6	68	41	27
ony East Poplar .5-1-25 W2M (89)	2688	7353	7430	7380*	7380	77	27	50	50	0
)G Big Muddy -1-2-23 W2M (90)	2641	7430	7515	7477*	-	85	47	38	-	0
evron Buffalo Gap ,-17-2-25 W2M (91)	2638	7067	7146	7090*	7090	79	23	56	56	0
CPOG Roanmine 9-22-3-22 W2M (92)	2407	6940	7032	6980*	7015	92	40	52	17	0
B.A. Loucks 9-5-3-28 W2M (93)	2631	6770	6857	6800*	-	87	30	57	-	0
Socony North Roanmine 6-29-4-21 W2M (94)	2426	6740	NDE	-	-	50+	-	-	-	0
Mobil Harptree 6-21-4-26 W2M (95)	2397	6530	6676	6590	-	146	60	86	-	0
Petrofina Roncott 13-15-5-25 W2M (96)	2224	6163	6250	6207*	6237	87	42	45	13	30
Champlin Brightmore 11-18-9-16 W2M (97)	1915	5668	5790	5702*	5760	122	34	88	30	58
Quasar Trossachs 4-2-9-17 W2M (98)	1933	5858?	5914?	-	-	56+	-	-	-	-

Well Data		Subsurface Depths (Depth measured below K.B.)								
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‚inger Moreland ‚-9-19 W2M (99)	2136	5873	5972	5908*	5936	99	35	64	36	28
‚rial Abbott ‚-7-18 W2M (100)	2153	6120	6234	6153	6200	114	33	81	34	47
‚ny Avonlea 7-12-31 W2M (101)	1942	5052	5168	-	5130	116	-	-	38	-
cid Ogema -8-22 W2M (102)	2341	6061	6162	6094	6122	101	33	68	40	28
‚a Readlyn ‚6-7-26 W2M (103)	2551	6400	6497	6424	6454	97	24	73	43	30
‚ncana Langbank ‚28-12-2 W2M (104)	2204	3971	4083	4033	4033	112	62	50	50	0
dewater Bender 13-11-12-5 W2M (105)	2448	4552	NDE	NDE	NDE	NDE	13+	13+	-	-
B.A. Montmartre Paul 9-14-13-11 W2M (106)	2164	4447	4568	4503	4528	121	56	65	40	25
Barnwell Kendal 4-20-14-12 W2M (107)	2173	4284	4407	4345	4370	123	61	62	27	25
Altana North Wapella 11-35-15-33 W1M (108)	1957	2859	2913	2913	2913	54	-	-	-	0
Imperial Broadview 14-17-15-4 W2M (109)	2026	3418	3540	3478?	3490	122	60	62	50	12
Jeff Lake Sedley 12-23-15-14 W2M (110)	2177	4146	4276	4204	4232	130	58	72	44	28
Socony Estlin 1-20-15-19 W2M (111)	1922	4086	4220	4106	4186	134	20	114	34	80
CPOG Baildon 2-11-15-26 W2M (112)	1937	4669	4802	4696	4744	133	30	103	58	48

Well Data		Subsurface Depths (Depth measured below K.B.)								
Well Name & Location (Well Number)	K.B. (ft.)	Top of Birdbear	Top of Duperow	Top of Lower Member	Top of "subtidal" interval	Total Isopach	Isopach of Upper Member	Isopach of Lower Member	Isopach of "subtidal" interval	Isopach of "intertidal" interval
asant Assiniboine 27-16-11 W2M (113)	2282	3974	4095	4036*	4056	121	62	59	39	20
ific Edenwold 2-16-18 W2M (114)	1913	3811	3929	3830	3854	118	19	99	64	24
io Pense ·6-17-22 W2M (115)	1909	4140	4260	4160*	-	120	20	100	-	-
ansempire Welby -16-18-30 W1M (116)	1599	1770	1870	1820	1834	100	50	50	32	14
OG Crooked Lake 30-18-5 W2M (117)	1868	2786	2886	2834	2834	100	48	52	52	0
easant Indian Head 13-18-9 W2M (118)	1998	3048	3148	3098	3104	100	50	50	44	6
IC Yarbo 1-24-20-33 W1M (119)	1690	1874	1942	1885*	1885	68	11	57	57	0
Dillman Keeler 4-34-20-28 W2M (120)	1952	3430	NDE	3457	NDE	614	27	34+	-	-
SWP Bredenbury 11-36-22-1 W2M (121)	1761	1746	1817	-	-	71	-	-	-	-
U.O.H.L. Willowcreek 13-28-25-7 W2M (122)	1893	1934	2024	-	-	90	-	-	-	0
Sohio Strasbourg 4-10-25-23 W2M (123)	1761	2590	2734	2602*	2680	144	12	132		78
Tidewater Stalwart 14-10-27-25 W2M (124)	1692	2362	2450	-	2410	88	-	-	40	-
Seaboard Devils Lake 16-11-28-6 W2M (125)	1656	1450	1544	1468*	1494	94	18	76	50	26
Tidewater Hawarden 12-10-29-5 W3M (126)	2014	3114	3257	3125	3170	143	11	132	87	45

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ewater Wishart 21-30-12 W2M (127)	1961	1905	1990	-	1926	85	-	-	64	-
io Wood Mountain .5-3-3 W3M (128)	3246	6766	6876	6816*	6860	110	50	60	16	44
›erial Climax .0-3-18 W3M (129)	3075	5696	5784	5716*	5756	88	20	66	28	40
›erial Oxarat l-5-25 W3M (130)	3157	5294	5400	5354*	5376	106	60	46	24	22
iewater Glenbain 22-10-8 W3M (131)	2499	5386	NDE	5401	5412	-	15	-	-	11
C Shamrock 22-14-5 W3M (132)	2430	5084	5186	5104	5152	102	20	82	34	48
.dewater Braddock 5-7-14-10 W3M (133)	2654	5118	5213	5150	5168	95	32	63	45	18
Tidewater Morse 16-25-16-8 W3M (134)	2354	4760	4844	4770	4818	84	10	74	26	48
Tidewater Parkbeg 10-32-18-3 W3M (135)		4561	4653	4595	4615	92	34	58	38	20
Tidewater Kyle 3-32-21-13 W3M (136)	2665	4183	4262	4218	4235	79	35	44	27	67
Tidewater Elbow 1-25-23-6 W3M (137)	1945	-	-	-	-	-	-	-	-	-
Tidewater Forgan 4-16-27-13 W3M (138)	1927	2820	2940?	2854	2907	120	34	86	33	53
Husky Whiteside 11-16-30-26 W3M (139)	2365	3164	3308	3181*	3191	144	17	127	117	10
Husky Whiteside 11-22-30-26 W3M (140)	2375	3135 3108	NDE	3256	NDE	-	21	-	-	-

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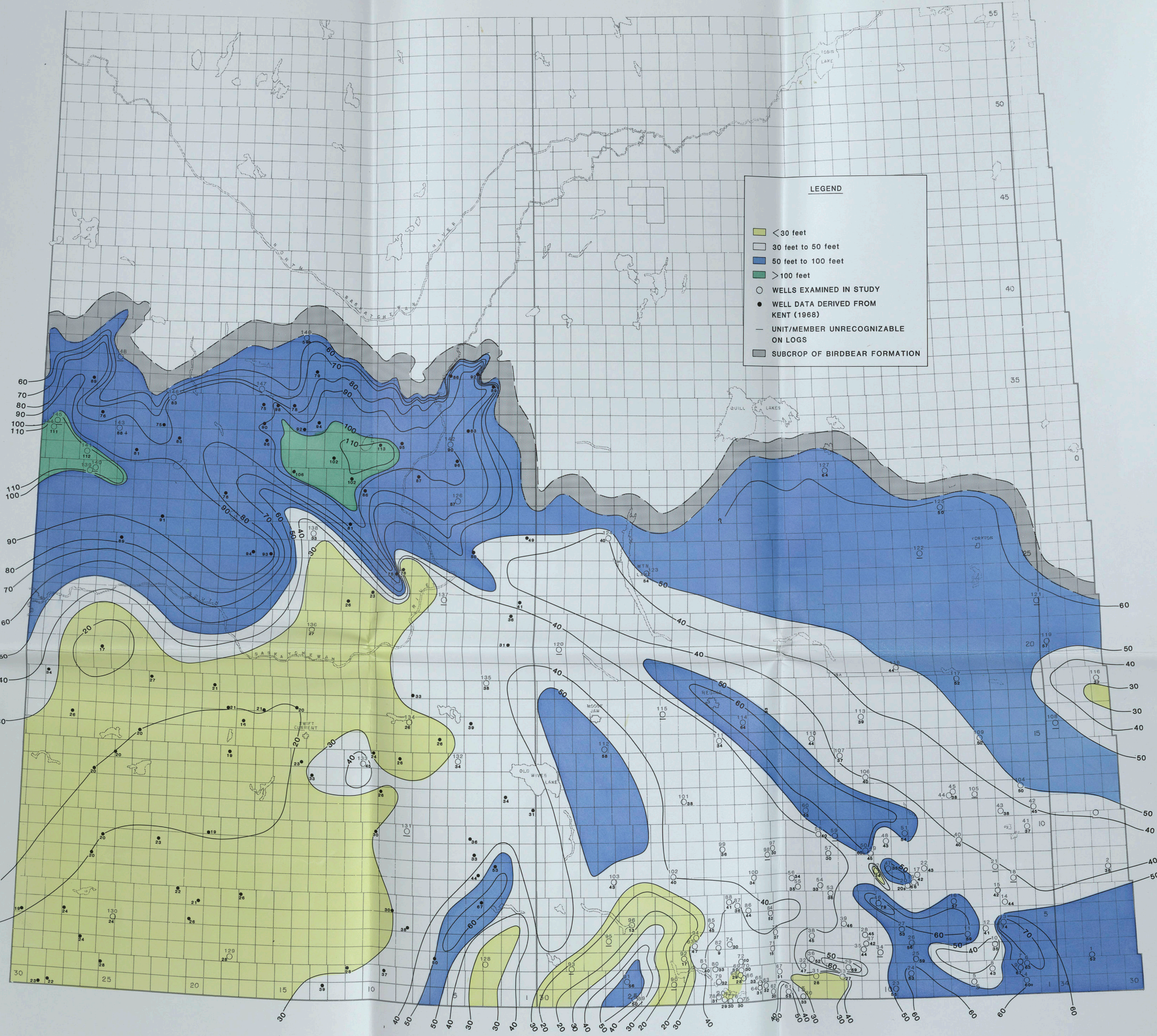
ant Smiley 1-31-26 W3M (141)	2352	3052	3198	3068*	3086	146	16	130	112	18
water Dundurn -32-5 W3M (142)	1726	2123	2272	-	2182	149	-	149	90	-
rcan Buffalo ee 6-32-32-24 (143)	2337	2908	NDE	2930	2930	110+	-2	88+	88+	0
North Hoosier 28-32-28 W3M (144)	2411	3092	3237	3115*	3126	145	23	122	111	111
Southcourt -33-28 W3M (145)	2407									
a Kerrobert 9-34-21 W3M (146)	2235	2614	2775	2632*	2692	161	18	143	83	60
lewater Duperow 4-9-35-16 W3M (147)	2291	2680	2870	-	2791	191	-	190		-
Woods Luseland 13-32-36-24 W3M (148)	2286	2533	2728	-	2626	195	-	195	102	93
Calstan North Biggar 16-12-38-14 W3M (149)	2286	2422	NDE	-	2484	121+	-	121+	39+	62

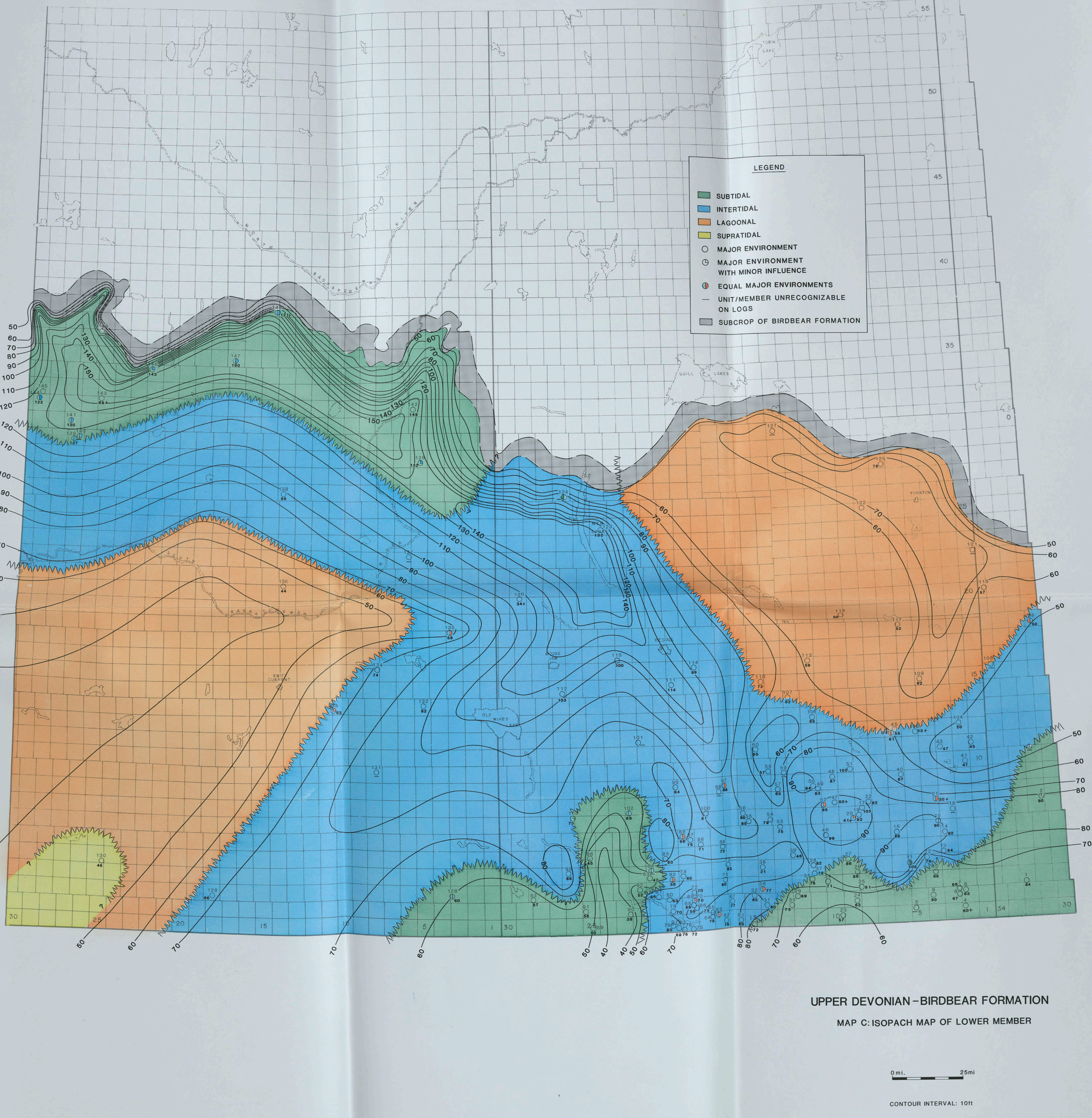


UPPER DEVONIAN–BIRDBEAR FORMATION

MAP B: ISOPACH MAP OF ARGILLACEOUS UNIT/INTERVAL

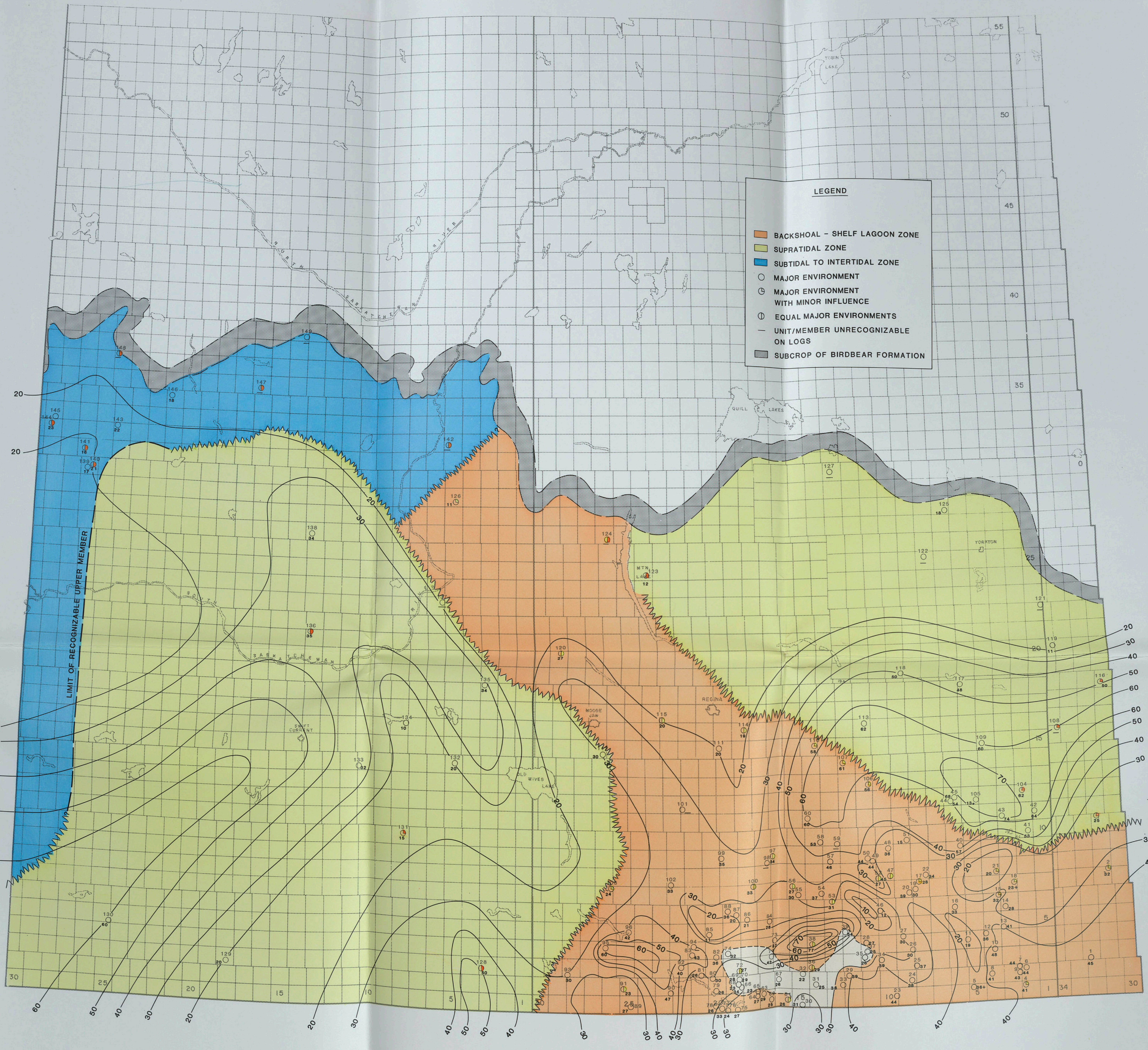
0 mi. 25 mi

CONTOUR INTERVAL: 10ft



UPPER DEVONIAN – BIRDBEAR FORMATION

MAP C: ISOPACH MAP OF LOWER MEMBER

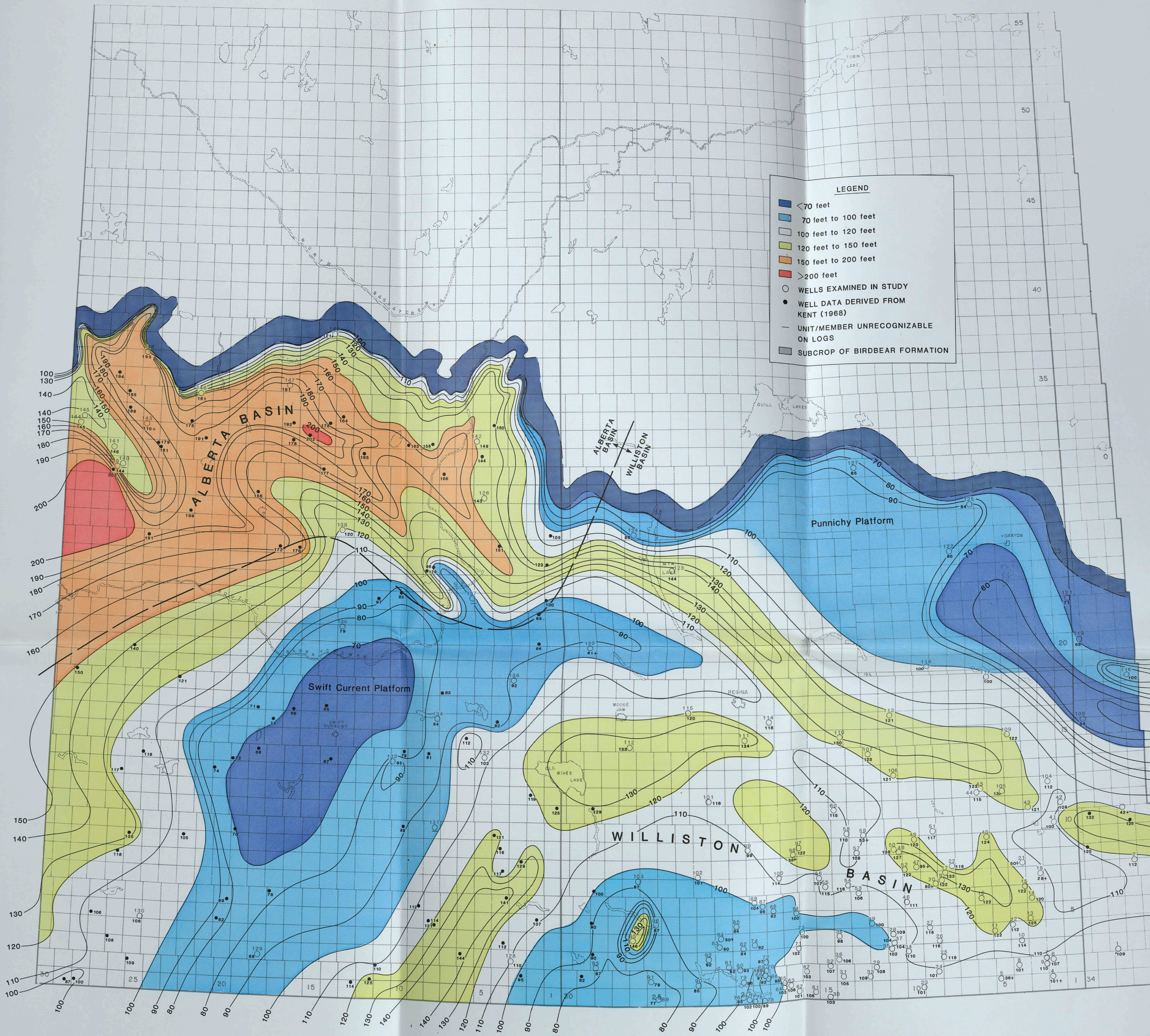


UPPER DEVONIAN - BIRDBEAR FORMATION

MAP D: ISOPACH MAP OF UPPER MEMBER

0 mi. 25 mi

CONTOUR INTERVAL: 10ft



UPPER DEVONIAN-BIRDBEAR FORMATION

MAP A: TOTAL ISOPACH

0 mi. 25mi

CONTOUR INTERVAL: 10ft

UPPER DEVONIAN–BIRDBEAR FORMATION

MAP E: ISOPACH MAP OF INTERTIDAL UNIT

0 mi. 25 mi

CONTOUR INTERVAL: 10ft