Lithofacies and Petroleum Potential of the Birdbear Formation (Upper Devonian), Southwestern Manitoba and North-Central North Dakota

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ABSTRACT

The Birdbear Formation is a widespread carbonate-evaporite unit that was deposited over a broad, shallow Upper Devonian shelf extending from central Alberta to eastern North Dakota. The formation can be subdivided into a lower, carbonate member composed predominantly of non-argillaceous limestones and dolostones and an upper, evaporite-carbonate member of mainly dolostones with interbedded evaporites. It is conformably underlain by the Duperow Formation. Contact with the overlying Three Forks Formation is conformable throughout most of Manitoba and North Dakota.

The Birdbear Formation represents one cycle in the Devonian marine transgressive-regressive sequence. Depositional environments recognized within the Lower and Upper members of the Birdbear Formation range from low energy subtidal to higher energy intertidal, lagoonal and supratidal. Lithofacies that represent these environments can be identified and correlated in southwestern Manitoba and north-central North Dakota.

The Birdbear Formation has produced in excess of 823,527 m^3 (5,182,373 bbls) of oil in the Williston Basin mostly from stromatoporoid banks and biostromes that border the basin in northeastern Montana and from facies associated with basement-related faulting and Late Devonian salt collapse structures in Saskatchewan and northeastern Montana.

Correlative facies within the Birdbear Formation in Manitoba and North Dakota suggests a potential for the exploitation of several different types of stratigraphic traps. Exploration for hydrocarbons also may be directed toward areas of basement-related and multiple stage salt collapse structures. The current edge of the Prairie Formation salt is definable within the study area and may serve as a control on the distribution of reservoir facies, the enhancement of porosity and entrapment of hydrocarbons. Secondary dolomitization, a major control in stratigraphic trapping in other areas of the basin, may also serve the same role in the study area.

INTRODUCTION

This paper summarizes the stratigraphy of the Birdbear Formation and describes the lithofacies identified in the study area (Fig. 1). Depositional environments and distribution of lithofacies are discussed. The main reservoir facies are described in terms of their hydrocarbon potential. The location of favorable structural and stratigraphic trap types in north-central North Dakota and southwestern Manitoba are assessed in the context of maximum observed oil migration distances inferred from known Williston Basin oil-source systems.

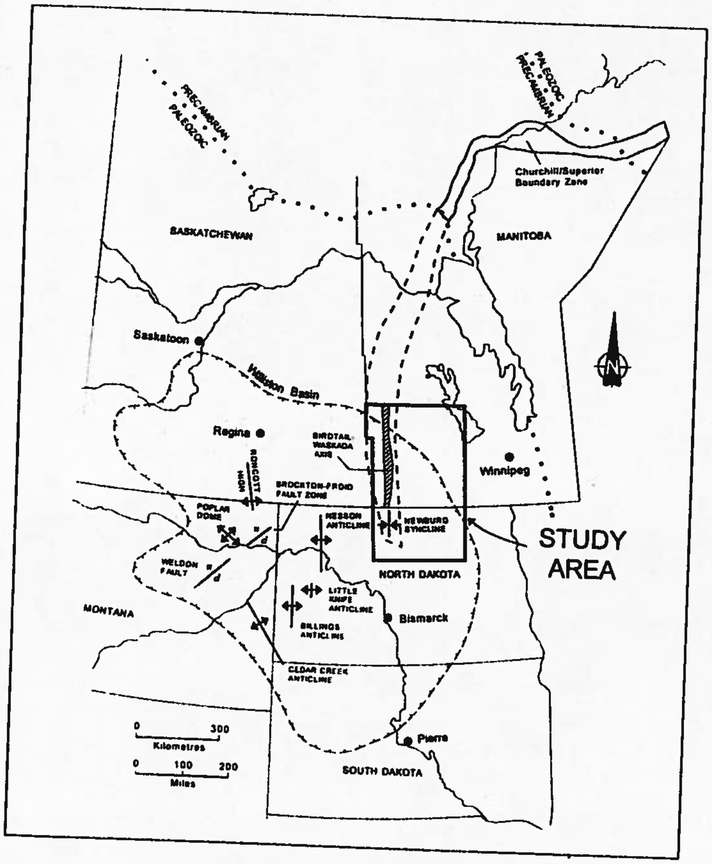

Figure 1. Map of the Williston Basin showing major structural features. Location of study area is shown (after Gerhard et al., 1990).

GEOLOGIC SETTING

The Williston Basin was the southern extension of the Middle Devonian Elk Point Basin (Fig. 2). Sediments deposited during the Late Devonian represent upward shallowing cycles of argillaceous limestones, fossiliferous dolostones and limestones, massive anhydrites interbedded with claystones.

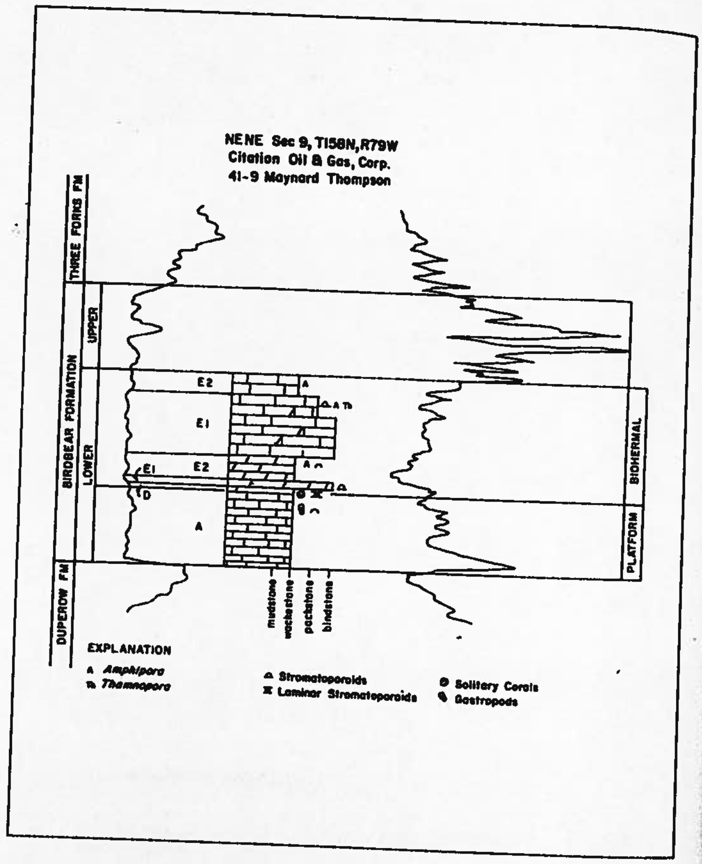

Figure 3. Reference Well – Birdbear Formation

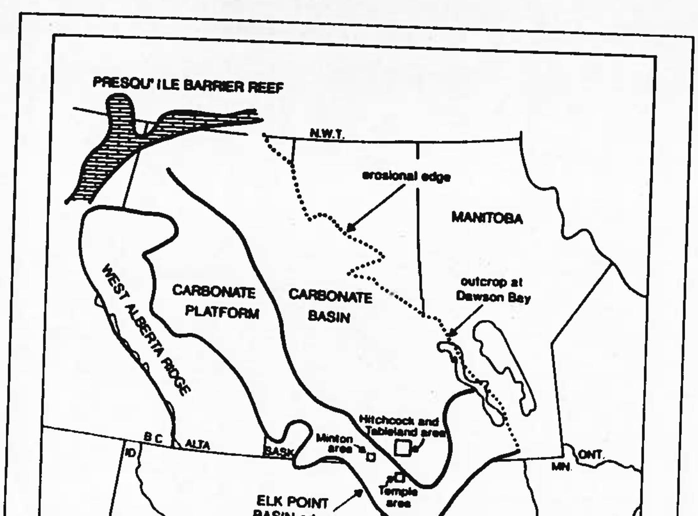

Figure 2. Simplified map of the Elk Point Basin and Presqu'ile Barrier (after Martindale et al., 1991).

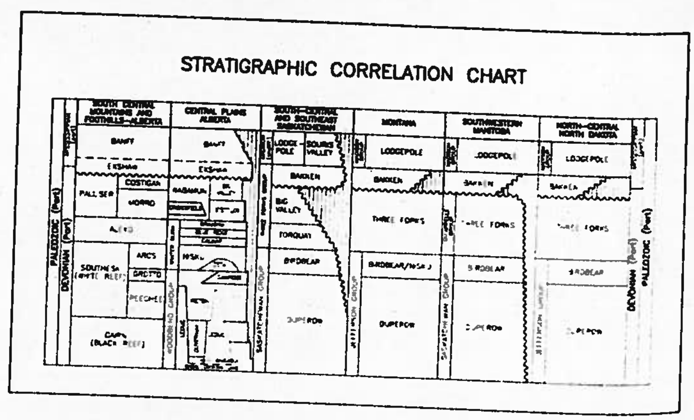

Figure 4. Stratigraphic Correlation Chart. (modified after Saskatchewan Department of Mineral Resources Petroleum and Natural Gas Branch, Drawing Number G-193, 1963, Blumele et al., 1986, and Canadian Society of Petroleum Geologists, 1990)

The maximum advance of the late Devonian sea occurred during deposition of the Duperow Formation. The Initial regressive phase began in Birdbear time during which fragmental, highly fossiliferous limestones and dolostones were deposited over a broad, shallow shelf. Devonian seas became more restricted toward the end of Birdbear time, which resulted in deposition of interbedded dolostones, evaporites, siltstones and shales of the succeeding Three Forks Formation.

STRATIGRAPHY

Sandberg and Hammond (1958) formally defined the Birdbear Formation for 90 ft (27.4 m) of strata that occur from 10,310 to 10,400 ft (3142.5-3169.9 m) below K.B. in the Mobil Oil Producing Co. 1 Birdbear well (C SENW Sec. 22, T149N, R91W, Dunn County, North Dakota). The lower part of the section consists of thick bedded, light to brownish grey, finely crystalline to microcrystalline, anhydritic, slightly dolomitic fossiliferous limestone that contains brachiopods, crinoids and gastropods (60 ft; 18.3 m thick). The upper 30 ft (9.1 m) features alternating thin beds of medium to dark and brownish grey, microcrystalline to dense anhydrite; medium greenish grey, silty, dolomitic shale; and, brownish grey, yellowish grey and greenish grey, microcrystalline to finely crystalline, anhydritic dolostone. The boundary between the Lower Member and Upper Member is placed at the base of the lowest anhydrite bed within the Upper Member (Nicols, 1970) (Fig. 3).

The Birdbear Formation as formally recognized throughout the Williston Basin, is the uppermost formation of the Upper Devonian Saskatchewan Group, and is equivalent to the upper Southesk Formation of the south-central mountains and foothills of Alberta, and the upper Ireton and lower Nisku formations of the Alberta central plains (Fig. 4). It is generally conformable with the underlying argillaceous carbonates of the Duperow Formation in North Dakota, Montana, southern Saskatchewan and southwestern Manitoba, and the overlying argillaceous carbonates and evaporites of the Three Forks Formation in Montana, North Dakota and southwestern Manitoba, and the Torquay Formation of the Three Forks Group in southern Saskatchewan. An angular unconformity separates the Birdbear Formation from younger strata in areas where the Three Forks Formation is absent.

The following is a detailed description of the lithofacies of the Birdbear Formation based on data derived from examination of core and samples from thirteen (13) wells in north-central North Dakota and thirty-five (35) wells in southwestern Manitoba. Dunham's carbonate classification scheme

LITHOFACIES OF THE BIRDBEAR FORMATION
(Southwestern Manitoba and North-Central North Dakota)

UPPER BIRDBEAR

BIOHERMAL OR BANK FACIES	**DOLOSTONE TO DOLOMITIC MUDSTONE TO WACKESTONE,** microsucrosic, finely crystalline, anhydritic, slightly calcareous, light to medium brown. Occasional wispy, bituminous partings. Rare blebs of blue-grey anhydrite. Good to excellent intercrystalline porosity. Oil-stained. Thickness averages 12 ft (3.7 m).	F
BIOHERMAL OR BANK FACIES	**LIME WACKESTONE TO GRAINSTONE,** rare wispy, argillaceous partings, pinkish-light to medium brown. Abundant *Amphipora*, *Thamnopora*, rugose and colonial corals (*Syringopora*), laminar and tabular stromatoporoids, bryozoans(?), ostracods, brachiopods and locally peloids and calcispheres. Interstitial, nodular and stringers of anhydrite. Occasional coated grains. Occasional stylolitic partings. Fair to good intergranular, vuggy (in part, solution enhanced) and moldic porosity. Oil-stained. Thickness ranges from 1 to 21 ft (0.3 to 6.4 m); averages 7.8 ft (2.4 m).	E2
BIOHERMAL OR BANK FACIES	**LIME WACKESTONE TO BOUNDSTONE,** locally dolomitic, occasionally mottled, rare thin bituminous partings, medium to light brown. Predominantly stromatoporoid (laminar, tabular and bulbous), rugose corals, *Thamnopora*, *Amphipora* and occasional brachiopods, locally peloids and calcispheres. Interstitial, nodular and thin-bedded anhydrite. Occasional stylolitic partings. Fair to good moldic, intergranular, vuggy (in part, solution enhanced) and intergranular porosity. Oil stained. Thickness ranges from 2 to 40 ft (0.6 to 12.2 m); averages 21 ft (6.4 m).	E1
BIOHERMAL OR BANK FACIES	**BIOCLASTIC(FRAGMENTAL) LIME WACKESTONE TO PACKSTONE, RARELY GRAINSTONE,** locally dolomitic, light brown to buff, medium brown and grey. *Thamnopora*, abundant fragments of laminar and hemispherical stromatoporoids, *Amphipora*, rugose corals, brachiopods and rare crinoids, locally peloids and calcispheres. Irregular stringers and nodules of anhydrite. Fair moldic, vuggy (in part, solution enhanced) and intergranular porosity. Thickness ranges from 2 to 24 ft (0.6 to 7.3 m); averages 13 ft (4.0 m).	D
	LIME MUDSTONE, recrystallized, occasionally burrow mottled, dolomitic, anhydritic, medium to light brown. Occasional irregular anhydrite inclusions. Thickness ranges from 2 to 9 ft (0.6 to 2.7 m); averages 5.5 ft (1.7 m).	C intra-bank
	LIME MUDSTONE TO PACKSTONE, finely laminated, locally nodular bedded or burrow mottled, recrystallized, anhydritic, light to medium brown. Irregular blebs of anhydrite. Local accumulations of fossils including brachiopods, calcispheres, peloids, ostracods, rugose and colonial corals, stromatoporoids and gastopods. Argillaceous laminae throughout, occasionally marked by stylolites. Thickness range from 2 to 4.5 ft (0.6 to 1.4m); averages 3.3 ft (1.0 m).	B inter-bank
PLATFORM FACIES	**MOTTLED LIME MUDSTONE TO WACKESTONE,** occasionally dolomitic, massive, wispy argillaceous laminae, occasionally burrowed, medium to light brown. Rugose and colonial corals, *Thamnopora*, small gastropods, brachiopods and occasional elongate, laminar stromatoporoids. Scattered small, blue-grey anhydrite nodules. Stylolitic. Intergranular and vuggy porosity. Thickness ranges from 2 to 27 ft (0.6 to 8.2 m); averages 14.5 ft (4.4 m).	A1
PLATFORM FACIES	**BURROW MOTTLED TO NODULAR LIME MUDSTONE TO WACKESTONE,** wispy argillaceous laminae, pinkish- to medium brown. Gastropods, brachipods and rugose corals, peloids, calcispheres and skeletal debris. Localized oil staining. Horse-tail stylolitic partings (birdseye). Algal oncolites. Occasional anhydrite nodules. Thickness ranges from 23 to 60 ft (7.0 to 18.2 m); averages 41.5 ft (12.6 m).	A

DUPEROW FORMATION

Lithofacies of Local Occurrence

MOTTLED LIME WACKESTONE, light to medium brown. *Thamnopora*, laminar and bulbous stromatoporoids, brachiopods and rugose corals. Fair intergranular porosity. Thickness ranges from 1 to 4 ft (0.3 to 1.2 m); averages 2.5 (0.8 m).	STORM DEPOSIT

Figure 5. Composite lithofacies descriptions of the Lower Member of the Birdbear Formation for the study area.

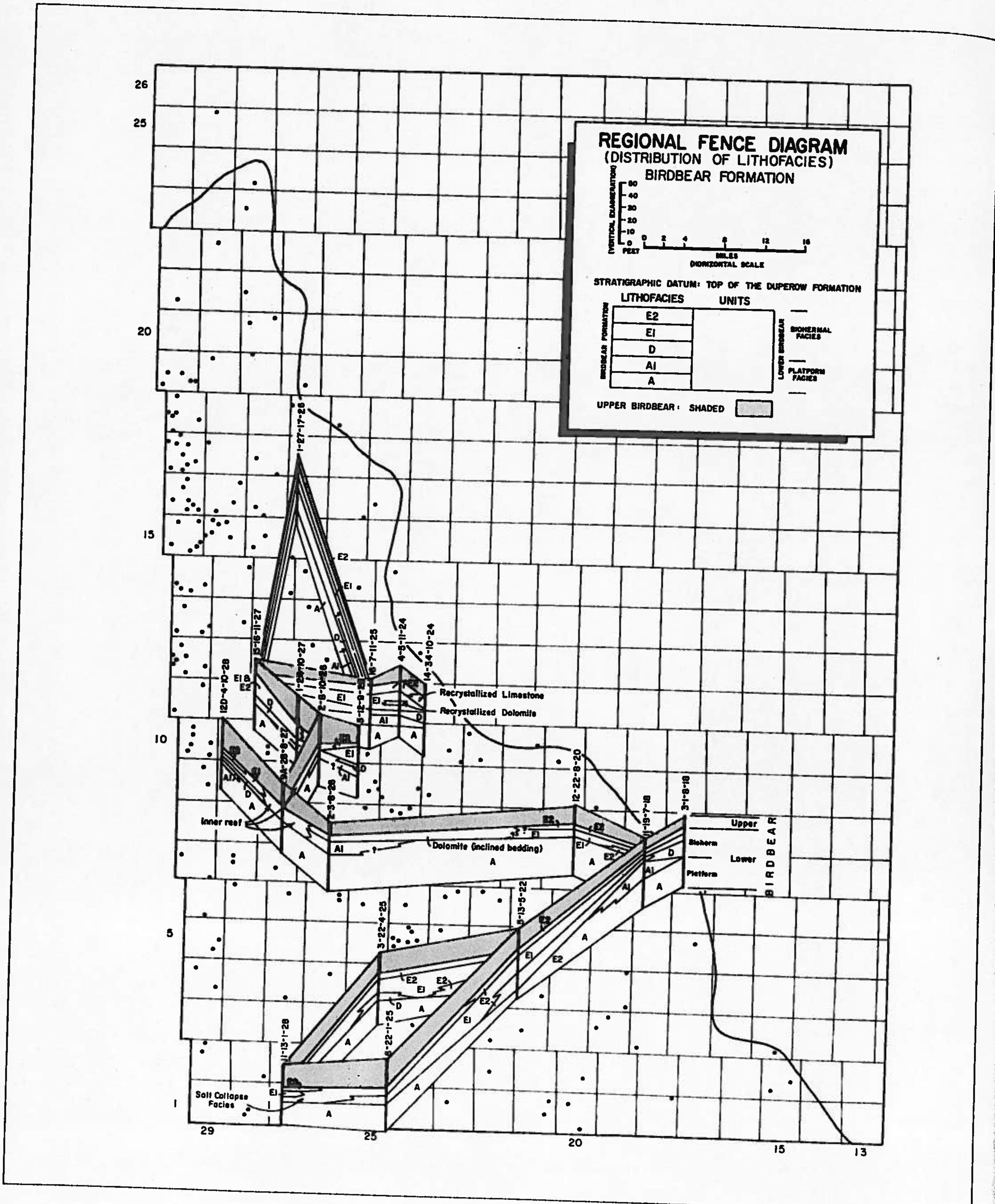

Figure 6. Regional fence diagram showing the distribution of lithofacies of the Birdbear Formation, southwest Manitoba. The Upper Member is shaded. Lithofacies units with their appropriate letter designation are shown.

was used to describe the lithofacies. Composite lithofacies descriptions of the Lower Member are shown in Figure 5. The regional fence diagrams of southwestern Manitoba and north-central North Dakota show the distribution of the various lithofacies over the study area (Figs. 6, 7)

Lower Member

Lithofacies are described as follows:

Lithofacies A and A1

Lithofacies A, basal in the Birdbear Formation, consists of a pinkish to medium brown, burrow mottled to nodular lime to dolomitic mudstone to wackestone with wispy, argillaceous laminations, stylolite partings, and horsetail stylolites (Fig. 8). Fossils generally include gastropods and brachiopods, a lesser number of rugose corals, oncolites, peloids and calcispheres, and local accumulations of skeletal debris include stromatoporoids, ostracods, *Syringopora*, crinoids and *Amphipora*. Anhydrite occurs as cement and nodules. The contact with the Duperow Formation in north-central North Dakota is marked by an olive grey to dark grey claystone under a dolomitic mudstone with scattered intraclasts and locally capped by thin beds of anhydrite and anhydrite nodules. Quartz-filled fractures were noted in one well (SWSE Sec. 35, T161N, R68W, North Dakota) immediately above the Duperow Formation. Solution-enhanced intergranular, pinpoint, vuggy and fracture pores are exhibited in North Dakota. Porosity ranges from 4.3 to 11.0% and permeability from <0.01 to 0.42 md. The rock is oil-stained along fractures and vug linings. In southwest Manitoba, thickness of lithofacies A ranges from 23 to 60 ft (7.0-18.3 m) and averages 43 ft (13.1 m). In north-central North Dakota, it ranges from 33.5 to 42.5 ft (10.2-12.9 m) and averages 38 ft (11.6 m).

Lithofacies A1 consists of medium to light brown, anhydritic, and stylolitic mottled lime mudstone to wackestone. It is massive with wispy, argillaceous laminations, locally

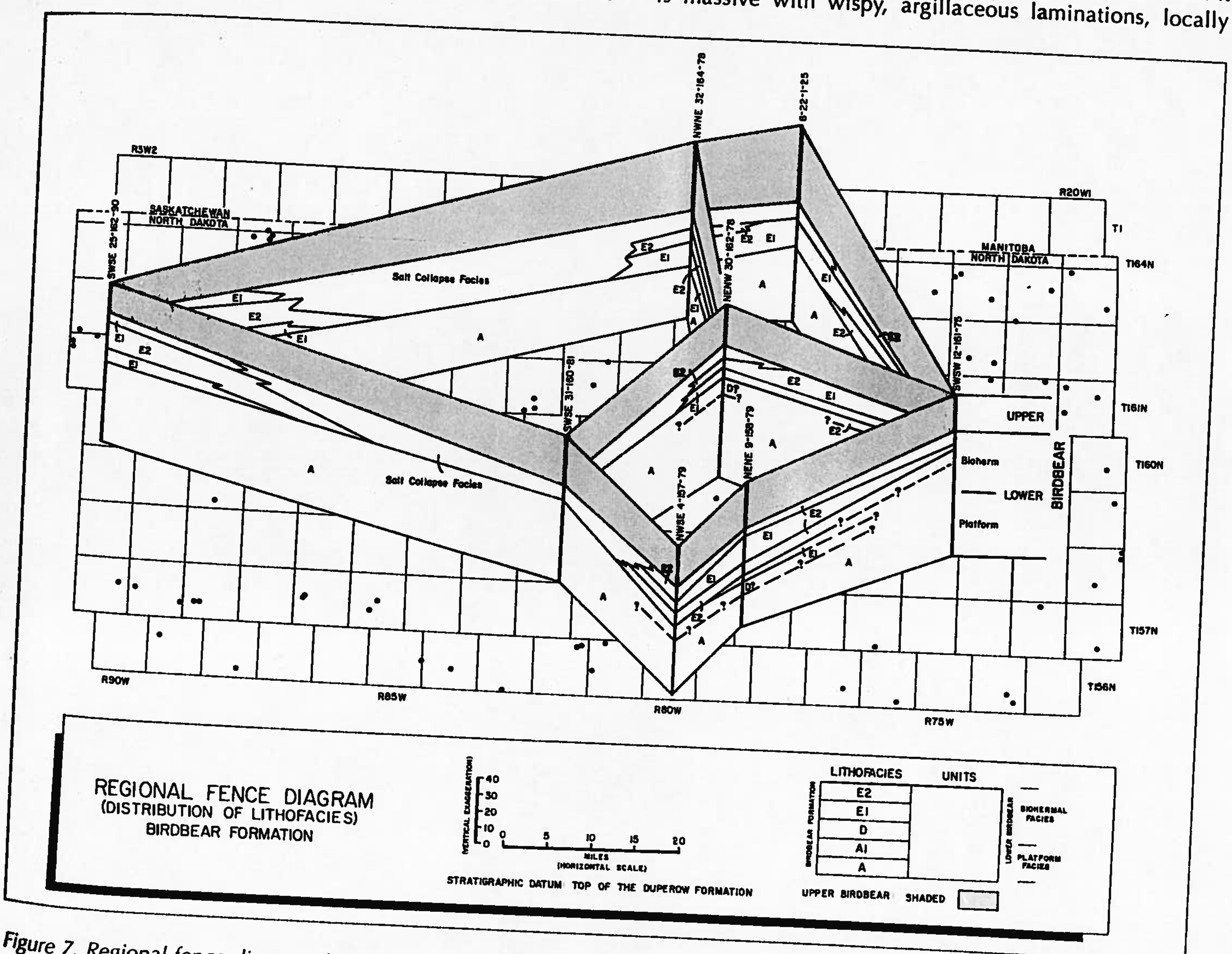

Figure 7. Regional fence diagram showing the distribution of lithofacies of the Birdbear Formation, north-central North Dakota. The Upper Member is shaded. Lithofacies units with their appropriate letter designation are shown.

Figure 8. Photo of Lithofacies A in NWNE Sec. 32, T164N, R78W at a depth of 4107 ft (1251.8 m) below K.B.

Figure 9. Photo of Lithofacies A1 in 14-34-10-24 WPM at a depth of 2149 ft (655.1 m) below K.B. Shows laminar stromatoporoids, corals (arrow) and irregular patches of wackestone in largely dolomitized microspar matrix.
Bar scale = 1 in (2.5 cm).

Figure 10. Photo of Lithofacies D in 1-24-10-27 WPM at a depth of 2615 ft (797 m) below K.B. Shows lime mudstone to wackestone with laminar stromatoporoids, corals and brachiopods.
Bar scale = 1 in (2.5 cm).

Figure 11. Photo of Lithofacies E1 in 4-5-11-24 WPM at a depth of 2187 ft (666.6 m) below K.B. Shows laminar stromatoporoids (arrows) in a wackestone matrix. Irregular patches of replacement anhydrite (A).
Bar scale = 1 in (2.5 cm).

burrowed and nodular bedded. Fossils generally include rugose and colonial corals, *Thamnopora*, gastropods and brachiopods and elongate, tabular stromatoporoids (Fig. 9). Additionally, peloids, calcispheres, ostracods, *Syringopora* and local *Amphipora* fragments are observed in north-central North Dakota. In North Dakota, intergranular and vuggy porosity ranges from 8.0 to 19.5%, permeability from 0.01 to 3.3 md, and thickness from 2 to 27 ft (0.6-8.2 m), averaging 14.5 ft (4.4 m).

Lithofacies B

Lithofacies B represents an interbank facies of the Lower Member and is seen in 9A-28-8-27 WPM and 2-8-10-26 WPM in Manitoba and in SWSE Sec. 25, T162N, R90W of North Dakota (Figs. 6 and 7). It comprises an argillaceous and stylolitic, light to medium or greyish brown, lime mudstone to wackestone (southwestern Manitoba) and lime wackestone to packstone (north-central North Dakota). It is finely laminated in Manitoba and locally nodular bedded or burrowed in North Dakota and anhydrite occurs as cement and irregular blebs. Fossils in North Dakota include brachiopods, calcispheres, peloids, ostracods, rugose corals, occasional laminar stromatoporoids, gastropods and *Syringopora*. In southwestern Manitoba, thickness ranges from 16.5 to 17.75 ft (5.0-5.4 m) and averages 17.1 ft (5.2 m). In north-central North Dakota, thickness ranges from 2 to 4.5 ft (0.6-1.4 m) and averages 3.3 ft (1.0 m).

Lithofacies C

The intrabank lithofacies C represents a medium to light brown, locally burrow mottled, dolomitic and anhydritic recrystallized lime mudstone. Anhydrite occurs as rare inclusions. Brachiopods are rare. The lithofacies is seen in southwestern Manitoba at 1-24-10-27 WPM and 15-16-11-27 WPM. Thickness ranges from 2 to 9 ft (0.6-2.7 m) and averages 5.5 ft (1.7 m).

Lithofacies D

Lithofacies D is constituted of light brown, medium brown and grey, bioclastic (fragmental) lime wackestone and packstone and rarely a lime grainstone, but is dolomitic in north-central North Dakota. Fossils include *Thamnopora*, abundant fragments of laminar and hemispherical stromatoporoids, *Amphipora*, rugose corals, brachiopods and rare crinoids, and calcispheres and peloids (Fig. 10). Anhydrite occurs as cement, metasomatic laths, irregular stringers and nodules and pore filling. Porosity is vuggy, solution enhanced, or moldic and is present where skeletal material is abundant. Porosity at 12D-4-10-28 WPM in Manitoba, ranges from 15.5 to 21.9% and permeability from 5.9 to 29 md. Thickness ranges from 2 to 24 ft (0.6 to 7.3 m) in southwestern Manitoba and is 3.5 ft (1 m) in north-central North Dakota. Strata of this facies is basal to the biohermal rocks of lithofacies E1 and E2.

Lithofacies E1 and E2

Lithofacies E1 and E2 incorporate the main biohermal bodies of the Lower Member (Figs. 6, 7). E1 is stromatoporoid, and characterized by light to medium brown, grey brown, lime wackestone and grainstone (southwestern Manitoba) and lime wackestone and boundstone (north-central North Dakota). Fossils are predominantly stromatoporoids (laminar, tabular, bulbous and digitate), with rugose corals, *Thamnopora*, *Amphipora* and occasional brachiopods (Figs. 11, 12). *Syringopora*, calcispheres and peloids are noted in North Dakota, and locally secondary dolomite, anhydrite and calcite cement. Anhydrite also occurs as thin beds and nodules. Towards the subcrop edge of the Birdbear Formation, lithofacies E1 is extensively dolomitized and reveals horsetail stylolitic partings, rare bituminous partings or wispy laminations and local mottles.

Lithofacies E1 exhibits intergranular, moldic, intraparticle, pinpoint and open and anhydrite lined, or partially filled vuggy porosity. Porosity is commonly solution enhanced and ranges from 10 to 20.4% in southwestern Manitoba, with permeability between 7.1 and 143 md. In north-central North Dakota, porosity ranges from 6.4 to 18.8% and permeability from 0.34 to 237 md. In southwestern Manitoba, thickness ranges from 2 to 40 ft (0.6-12.1 m) and thickness ranges from 2 to 18 ft (0.6-5.5 m) in north-central North Dakota.

Lithofacies E2 consists of pinkish light to medium brown, lime wackestone to packstone (southwestern Manitoba), and lime wackestone to grainstone and locally mudstone (north-central North Dakota). In the northern portion of the study area, it is present above lithofacies E1 (Fig. 6). The main fossil constituent is *Amphipora*, which occurs as concentrations or is scattered throughout the body. *Thamnopora*, rugose and colonial corals (*Syringopora*), laminar and tabular stromatoporoids and bryozoans(?) and scattered skeletal debris are also present. In north-central North Dakota the lithofacies also include ostracods, brachiopods, peloids and calcispheres (Fig. 13). Anhydrite is the main cement, but includes nodules and stringers. There are also local wispy, argillaceous laminae and stylolitic partings. North of Township 17 (Manitoba) the facies is dolomitized. Contact with the overlying Upper Member is sharp.

Lithofacies E2 exhibits intercrystalline, pinpoint, vuggy, solution enhanced vuggy and moldic porosity. In southwestern Manitoba, porosity ranges from 8.4 to 11.1% and permeability ranges from 0.2 to 11.3 md. Trace oil was noted in Manitoba. In north-central North Dakota, the facies is oil-stained. Porosity ranges from 2.5 to 8.7% and permeability ranges from 0.02 to 13 md. Thickness of lithofacies E2 ranges from 1 to 16 ft (0.3-4.9 m) in southwestern Manitoba and from 2.5 to 21 ft (0.8-6.4 m) in north-central North Dakota.

Lithofacies F

Lithofacies F displays a light to medium brown, microsucrosic, finely crystalline, slightly calcareous dolostone (southwestern Manitoba) and dolomitic mudstone to wackestone (north-central North Dakota) (Fig. 14). The lithofacies is associated with areas of multi-stage dissolution of the Devonian Prairie Formation salt and with lithofacies E1 and E2. It is massive, wispy laminated and in North Dakota, nodular bedded, brecciated and burrowed. Anhydrite occurs as nodules or blebs, cement (along bedding planes), fractures and voids fillings and as metasomatic anhydrite. In North Dakota, there are also ostracods, calcispheres, scattered gastropods, brachiopods, *Amphipora*, and peloids.

These rocks exhibit intercrystalline, vuggy, and where associated with fossils, shelter porosity. In North Dakota, porosity ranges from 7.9 to 25.8%, permeability ranges from 0.01 to 79 md (in-part fracture enhanced) and thickness from 9 to 14 ft (2.7-4.3 m). In Manitoba, porosity averages 27.5%, permeability 289 md and thickness 12 ft (3.7 m). Oil staining occurs in Manitoba and North Dakota.

Upper Member

The Upper Member is characterized by an interbedded sequence of rocks attributed to supratidal to sabkha environments. Thickness ranges from 20 to 46 ft (6.1-14.0 m) in southwestern Manitoba and from 0 to 40 ft (0-12.2 m) in north-central North Dakota and the upper contact with the brick-red and grey-green, earthy, massive shale of the overlying Three Forks Formation is sharp.

Seven lithofacies that occur as vertically and laterally discontinuous, 0.5 to 13.6 ft (0.15-4.15 m)-thick beds are identified.

Lithofacies A is a brownish or bluish grey, predominantly massive and chickenwire or nodular mosaic anhydrite, that is locally bedded and nodular with thin shale partings, argillaceous laminae, wispy laminated siltstones and claystones and stromatolitic.

Lithofacies B is represented by thin, interbedded dolostones and blue-grey, massive, and coalesced nodular anhydrite with internodular wisps of dolomite (Fig. 15). Dolostone may constitute 50% of the body, and occurs as thin (< 1.4 in; 3.6 cm), medium to light or greenish brown, finely crystalline, interbeds or wisps. Interbeds of light brown to greenish grey shale may also be present.

Lithofacies C features a light, greenish or medium brown, finely crystalline and microsucrosic, algal laminated dolostone (Fig. 16). Bedding is locally inclined at 10 to 15°. Locally argillaceous partings and nodules (1 to 1.5 in; 2.5-3.8 cm) and discontinuous beds (0.4 to 9.0 in; 1.0-23.0 cm) of anhydrite are also seen.

Lithofacies D is a light brown to greenish-grey, slightly calcareous, laminated to thin bedded, dolostone with local algal laminations. Anhydrite occurs as thin beds (1 in; 2.5 cm) or inclusions.

Lithofacies E occurs as a finely laminated to thin bedded, light to medium brown, slightly mottled lime mudstone to wackestone. Anhydrite as cement, nodules or fracture fill and as local, scattered metasomatic porphyrotopes or blebs also occur. The rocks are locally cross-bedded or graded bedded and exhibit soft sediment deformation. Hairline fractures and horsetail stylolites occur locally. The lithofacies also includes irregular intraclasts 1 to 2 in (2.5-5.1 cm) of lime mudstone or shale, algal stromatolites, peloids, calcispheres and ostracods (Fig. 17). Local intergranular and vuggy (commonly solution enhanced) porosity and oil staining was observed in north-central North Dakota.

Lithofacies F is characterized by medium brown and greenish grey, dolomitic and anhydritic, massive mudstone and shale. Anhydrite is formed as nodules (0.5 in; 1.3 cm), thin beds and scattered metasomatic porphyrotopes. Locally bituminous partings and interbeds of dark grey siltstones are present.

Lithofacies G features a bedded, cross-bedded and planar laminated, tan, siltstone to very fine grained, dolomitic sandstone that occurs locally in north-central North Dakota. Anhydrite infills fractures or forms nodules.

ENVIRONMENT OF DEPOSITION

The Birdbear Formation records deposition of carbonates and evaporites in a shallow epicontinental sea across what is now southwestern Manitoba, southern Saskatchewan, North Dakota and Montana during the early Late Devonian. Sediments accumulated in subtidal, intertidal and supratidal settings during a transgressive-regressive event that began during deposition of the upper Duperow or lower part of the Birdbear Formation (Halabura, 1982; 1983). Overall, the Birdbear Formation represents a shallowing-upward sequence.

Lower Member

The eight different lithofacies of the Lower Member mainly represent low energy subtidal conditions, but also include a higher energy stromatoporoid and *Amphipora* bank regime.

The diverse faunal assemblage of the lowest part of the member suggests deposition in subtidal open marine environments of normal salinity within the photic zone based on the presence of algal oncolites. The abundance of carbonate mud, possibly derived from algal precipitation and disintegration, and the presence of argillaceous laminae indicates low energy conditions. Storm generated waves may have been responsible for the commonly observed fragmentation of skeletal material, although invertebrate and vertebrate bottom scavenging are also a possibility. The platform facies of the Lower Member is slightly more argillaceous, as indicated on wireline logs, than stratigraphically higher parts of the section.

A westward increase in the argillaceous content of this platform facies across Saskatchewan (Nichols, 1970; Halabura, 1982; 1983; Cisyk, 1991) suggests a western source. Although the position of the eastern depositional margin of the basin is unknown, the adjacent land mass was apparently low lying and supplied only small amounts of fine siliciclastic material to the basin in Manitoba and North Dakota.

Overlying deposits probably accumulated in shallower water and under more energetic conditions. Rocks of lithofacies D, typically wackestones and packstones, rarely grainstones, generally form a substrate for the stromatoporoid and *Amphipora* bank facies. Their fauna indicates subtidal

Figure 12. Photo of mottled Lime Mudstone Wackestone to Packstone (storm deposit) in 5-12-9-26 WPM at a depth of 2547.2 ft (776.4 m) below K.B.

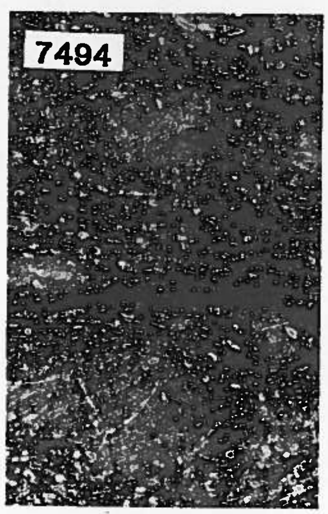

Figure 13. Photo of Lithofacies E2 in SWSE Sec. 25, T162N, R90W at a depth of 7494 ft (2284.2 m) below K.B. Field of view = 2.5 in (6.4 cm).

Figure 14. Photo of Lithofacies F in SWSE Sec. 31, T160N, R81W at a depth of 5505.3 ft (1678 m) below K.B.

Figure 15. Photo of Lithofacies B in 4-36-1-21 WPM at a depth of 3661.2 ft (1115.9 m) below K.B. Shows irregularity of interbedded dolostone (light) and anhydrite. Bar scale = 1 in (2.5 cm).

waters of normal salinity, but under energy conditions that allowed winnowing of some of the fine mud and fragmentation and alignment of benthonic organic remains. On elevated areas of the sea floor removal of carbonate mud led to the preservation of well-washed grainstones (well at 16-7-11-25 WPM).

The middle and upper parts of the Lower Member are represented by the stromatoporoid and *Amphipora* bank facies (lithofacies E1 and E2). The faunal diversity in the stromatoporoid bank facies indicates favorable growth conditions for lime secreting organisms. Energy conditions were probably variable. The paucity of dendroid or bulbous stromatoporoid and the dominance of laminar forms suggests relatively high energy conditions, especially where associated with *Thamnopora* (Loeffler, 1982). The fragmented nature of much of the skeletal debris and the orientation of elongate stromatoporoid fragments at a high angle to bedding suggests reworking of the deposits by wave action. Skeletal grains are typically mud supported, but patches of the grainstone indicates winnowing on shallow subtidal and possibly intertidal areas of the bank.

The stromatoporoid bank facies is well developed in the Virden area (southwestern Manitoba) and in southwestern Manitoba and north-central North Dakota in general. Loeffler (1982) in northwestern North Dakota suggested them to be a series of coalescent banks. Nichols (1970) in southeastern Saskatchewan indicated them to be restricted to local areas. Undoubtedly, the sea floor possessed some relief at this time and slightly elevated areas may have been favorable sites for the establishment of stromatoporoid banks.

Figure 16. Photo of Lithofacies C in 9A-28-8-27 WPM at a depth of 3661.2 ft (1115.9 m) below K.B. Shows algal laminated dolostone and fenestral porosity infilled with anhydrite. Bar scale = 1 in (2.5 cm).

Figure 17. Photo of Lithofacies E in 5-11-11-26 WPM at a depth of 2302.5 ft (701.8 m) below K.B. Shows laminated to thin bedded lime mudstone and intraclastic horizon (arrow). Bar scale = 1 in (2.5 cm).

Given the discontinuous nature of the stromatoporoid banks, environmental conditions varied in their vicinity. Interbank laminated sediments that contain peloids and a variety of skeletal debris (lithofacies B) are recognized in the Virden area (southwestern Manitoba) and in north-central North Dakota. Their laminated nature suggests deposition in a sheltered location leeward of the banks or between them. In the Virden area, periods of increased water depth over the banks are indicated by lime mudstone (lithofacies C) within the normal stromatoporoid-rich sequence. Increased water depth may have been related to local subsidence caused by Prairie salt dissolution. Storm-related deposition may also have occurred within the stromatoporoid bank environment.

The faunal assemblage of the *Amphipora* bank facies indicates continued shallow marine deposition. The presence of abundant amphiporids may indicate higher than normal salinity in a low energy lagoonal setting (Stearn, 1975). Wave and current action was sufficient, however, to detach and align amphiporid remains and to fragment most other types of skeletal forms, commonly to fine size. On more elevated parts of the sea floor, wave and current action may have been more intense, thereby winnowing the carbonate mud and creating thin layers of skeletal, peloidal or intraclastic grainstone.

The *Amphipora* bank facies is widespread and apparently continuous over much of southwestern Manitoba and north-central North Dakota, but areally restricted in western North Dakota (Loeffler, 1982). Nichols (1970) also records the presence of *Amphipora* forming incipient reefs in the Birdbear Formation of southeastern Saskatchewan, although this facies is largely absent just west of the Manitoba-Saskatchewan border.

Upper Member

The upper part of the Birdbear Formation marks a change to evaporitic sediments and therefore restricted intertidal and supratidal environments. Their extensive distribution across Saskatchewan, southwestern Manitoba and north-central North Dakota indicates Late Devonian basinwide hypersalinity during regression of the sea. The lack of continuity and the variety of Upper Birdbear lithofacies suggests deposition on a sea floor of variable relief interspersed with areas at, or just above sea level.

The nodular and nodular mosaic anhydrite, with wispy partings, thin laminae and beds of finely crystalline dolomite (lithofacies A and B) are comparable to those from modern evaporites formed in the supratidal flats of the Trucial Coast. Accordingly, much of the anhydrite in the Upper Member represents sabkha-type deposition, although thick beds of anhydrite without associated dolostone may indicate deposits formed by direct precipitation in shallow, low energy lagoons or ponds.

The sabkha is inimical to most organisms, although green and blue- green algae are characteristic of the intertidal and shallow subtidal zones. Domal algal stromatolites or algal laminites in the Upper Member are thought to indicate extremely shallow subtidal to intertidal conditions. On the other hand, laminated to thin-bedded dolostone with algal laminations (lithofacies C and D), may represent penecontemporaneous dolomitization of lime muds in an intertidal, restricted subtidal and sabkha environment.

Lime mudstone and wackestone of lithofacies E, with their peloids, calcispheres and ostracods, represent deposition of fine mud in a quiet water lagoon. Salinity may have been above normal marine, but was not so high as to inhibit growth of some euryhaline organisms. Periodic storms disrupted weakly lithified bottom muds, leaving intraclast-rich horizons. Some laminated mudstones may have been deposited in quiet water pools of higher salinity as suggested by the continuity of the laminae, lack of current bedding and bioturbation.

The argillaceous laminae and thin shale partings in the Upper Member may have been delivered to the shelf area from continental sources by sheet flooding following periods of heavy rain, however an aeolian delivery cannot be discounted.

Later diagenetic dolomitization of the mud component in mudstones, wackestones and packstones of both the Lower and Upper members is common.

The product of secondary dolomitization varies from the occurrence of scattered dolomite rhombs in a microspar matrix to complete replacement of the matrix (in preference to skeletal material) in wackestones and packstones. In some cases, pervasive dolomitization has completely obliterated original textures (lithofacies F). Partial dolomitization of the matrix in lithofacies E1 and E2 is common and where unreplaced carbonate mud is dissolved, good to excellent intercrystalline porosity is developed. Secondary dolomitization appears to be related to areas of multiple stage salt dissolution.

STRUCTURE

The Newburg syncline is the most prominent structural feature in the North Dakota portion of the study area (Fig. 18). Located immediately south of the Manitoba border, it extends southward for 20 mi (32.1 km). It overlies a zone of structural weakness within the Precambrian basement at the boundary between two terranes, the Churchill and Superior provinces. Fluid movement along this zone has resulted in the dissolution of the Devonian Prairie Formation salt and the subsequent collapse forming the syncline. Other minor struc-

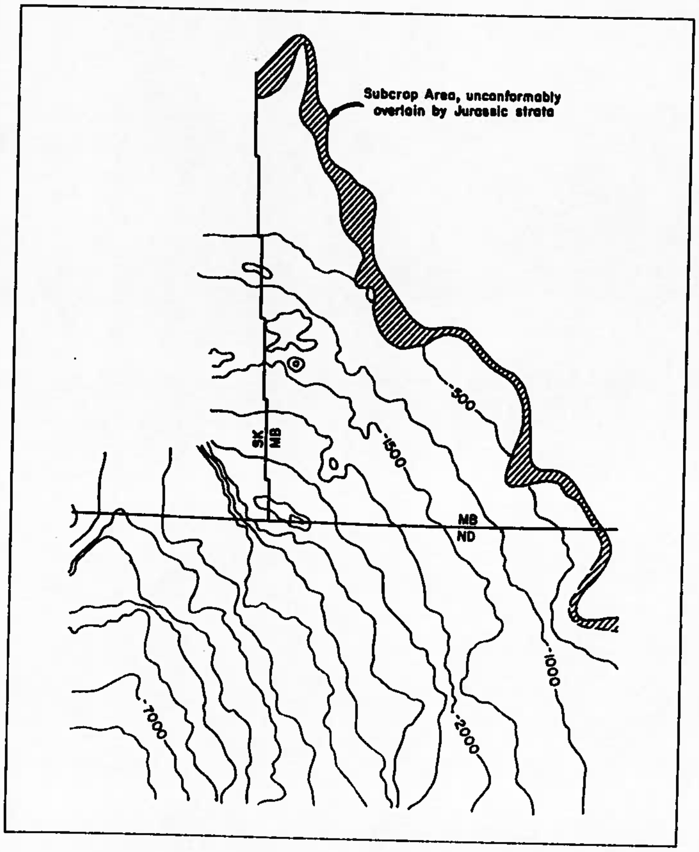

Figure 18. Structure map on top of the Birdbear Formation for the study area. Contour interval is 500 ft (152.4 m). Subcrop area of the Birdbear Formation in southwest Manitoba is shown.

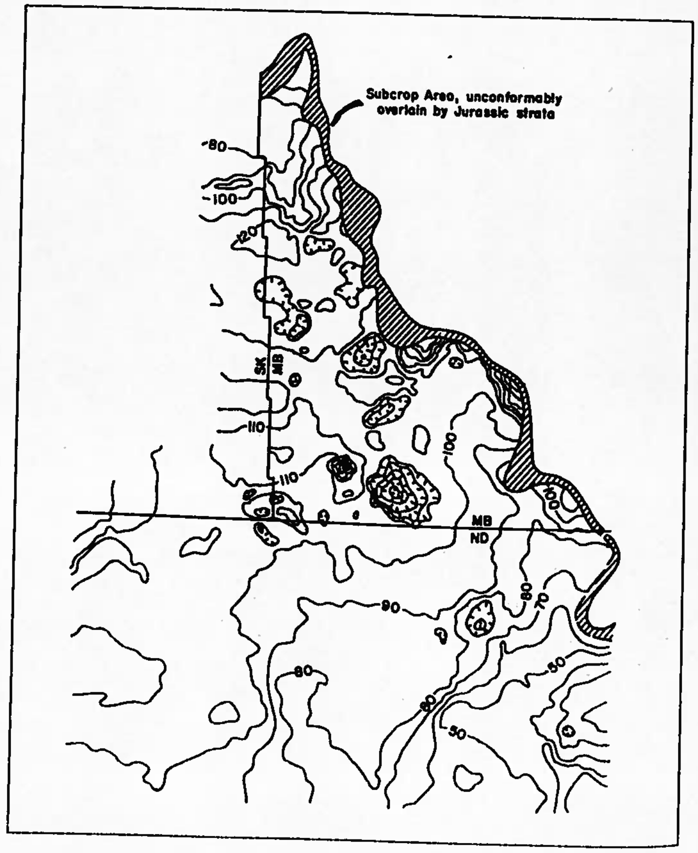

Figure 19. Isopach map of the Birdbear Formation for the study area. Contour interval is 10 ft (3.0 m). Subcrop area of the Birdbear Formation in southwest Manitoba is shown.

tural features are generally related to the dissolution of the Prairie Formation salt.

In Manitoba structure on the Birdbear Formation is fairly regular and depicts the regional Paleozoic tilt toward the southwest (Fig. 18). The most prominent features are a number of north-south aligned structural lows along the Birdtail-Waskada axis. The latter is approximately 20 mi (32.1 km) east of the Saskatchewan border, along which numerous local structural and isopachous anomalies in the Devonian and younger strata are concentrated (Fig. 1). These anomalies may be related directly or indirectly to salt dissolution resulting from minor tectonic movement along the boundary zone between the Churchill and Superior provinces (McCabe, 1966; Green et al., 1985).

ISOPACH

The distribution of the Birdbear Formation throughout the study area is shown in Figure 19. The isopachs show depositional patterns related to the Elk Point Basin sedimentation; the overall pattern is fairly irregular, reflecting the biostromal nature of the formation and the influences of salt dissolution and resulting collapse (Fig. 19). Regional trends are absent, which suggests relative stability of the tectonic framework toward the end of the Devonian depositional cycle (Baillie, 1953; McCabe, 1966). In southwestern Manitoba, the thickness of the Birdbear Formation ranges from 0 to 140 ft (0-42.7 m). The thickness in North Dakota ranges from 0 to 120 ft (0-36.6 m).

Wireline logs enable isopach maps to be constructed for the Upper Member and for the biohermal and platform facies of the Lower Member. Differentiation between the biohermal and the underlying platform facies is recognizable on logs as the change from the clean, gamma-ray response of the biohermal facies to the shaly gamma-ray response of the platform facies (Fig. 3). These provide the only tools for lithofacies determination from wireline logs.

There is a considerable variation in thickness of the individual members of the Birdbear Formation. Most of this variation is related to biohermal development versus platform deposits. The biohermal bank facies (lithofacies E1 and E2) trends north-northeast over most of the study area (Figs. 6, 7). These facies are directly underlain by the bioclastic, fragmental lithofacies D. In the northern portion of the study area, lithofacies E1 occurs as single a stromatoporoid bank. Lithofacies E2 straddles these banks. In the southern portion of the study area, E1 occurs as single or multiple stromatoporoid banks that have developed intermittently on widespread *Amphipora* banks.

EXPLORATION AND DEVELOPMENT POTENTIAL

The Birdbear Formation has produced in excess of 823,527 m^3 (5,182,373 bbls) of oil in the Williston Basin. Much of this production has been from stromatoporoid banks and biostromes bordering the Williston Basin in northeastern Montana and within reservoir facies associated with basement-related faulting and Late Devonian salt collapse structures in Saskatchewan and northeastern Montana. In North Dakota, the Birdbear Formation produces, or has produced, from sixteen fields situated along the northern portion of the Nesson anticline and scattered throughout western North Dakota.

Potential exists for exploration and new discoveries in the Birdbear Formation. In addition to traditional structural trap types, there is potential for the exploitation of several types of stratigraphic settings.

Three main reservoir facies are the stromatoporoid banks of lithofacies E1, the *Amphipora* bank deposits of lithofacies E2 and, the microsucrosic dolomites of lithofacies F. In the northern part of the study area, *Amphipora* banks (lithofacies E2) occur along the flanks of the stromatoporoid banks. Toward the south, the latter are interspersed within *Amphipora* banks. Porosity and permeability within these lithofacies are variable and controlled primarily by lithofacies type and by secondary diagenesis. Reservoir potential also exists within the secondary microsucrosic dolomites of lithofacies F developed within lithofacies E1 and E2.

Salt Dissolution Features

Several of the fields that are associated with known salt dissolution areas produce from the Birdbear Formation, notably Tule Creek Field and surrounding fields in northeastern Montana, and Hummingbird and Kisbey fields in southeastern Saskatchewan. In southwestern Manitoba, salt removal and collapse is most evident in the areas along, or near, the Birdtail-Waskada axis and its extension into north-central North Dakota. The eastern limit of the present Prairie Formation salt dissolution edge is roughly coincident with this axis. Salt re-entrant and subsidence structures occur along this edge and have resulted in numerous structural and isopach anomalies many of which are important in controlling Mississippian (Lodgepole and Mission Canyon formations) oil accumulation within the Daly, Virden and Waskada producing areas of southwestern Manitoba, and the Newburg and South Westhope fields of north-central North Dakota (McCabe, 1963; Anderson and Hunt, 1964; Rodgers, 1986; Martiniuk, 1988, LeFever and LeFever, 1991). Potential for production exists in traps related to salt dissolution in the Birdbear Formation in this area.

Basement-Controlled and Deep Structural Traps

Large reserves of Birdbear Formation production in the Williston Basin occur in areas primarily influenced by basement-controlled structural traps. The majority of fields and pools are located on large structures such as the Nesson and Cedar Creek anticlines, but many of the others are in combi-

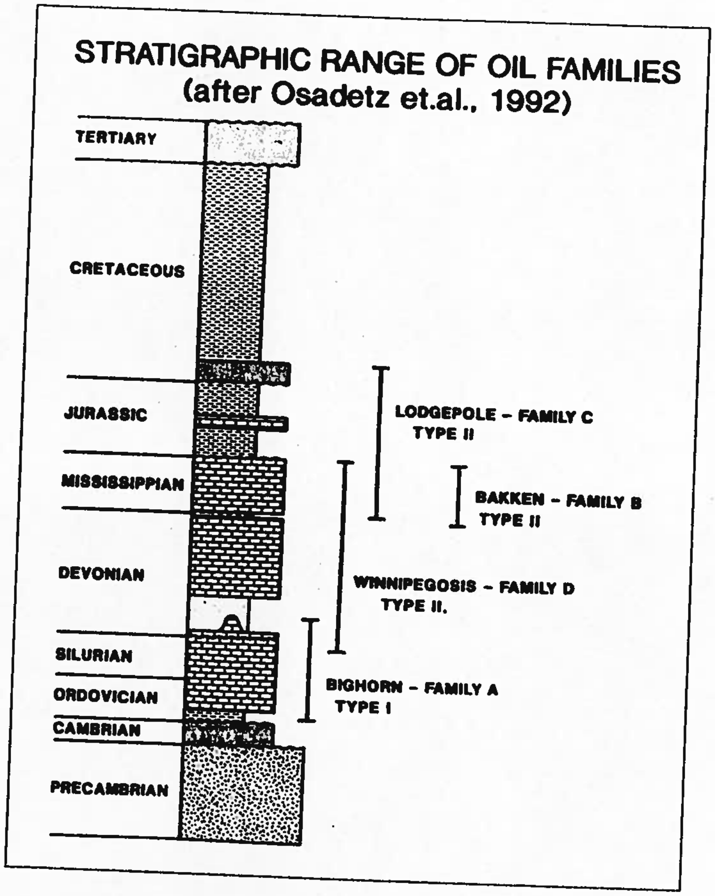

Figure 20. Stratigraphic range of oil families in the Williston Basin (after Osadetz et al., 1992, reprinted by permission).

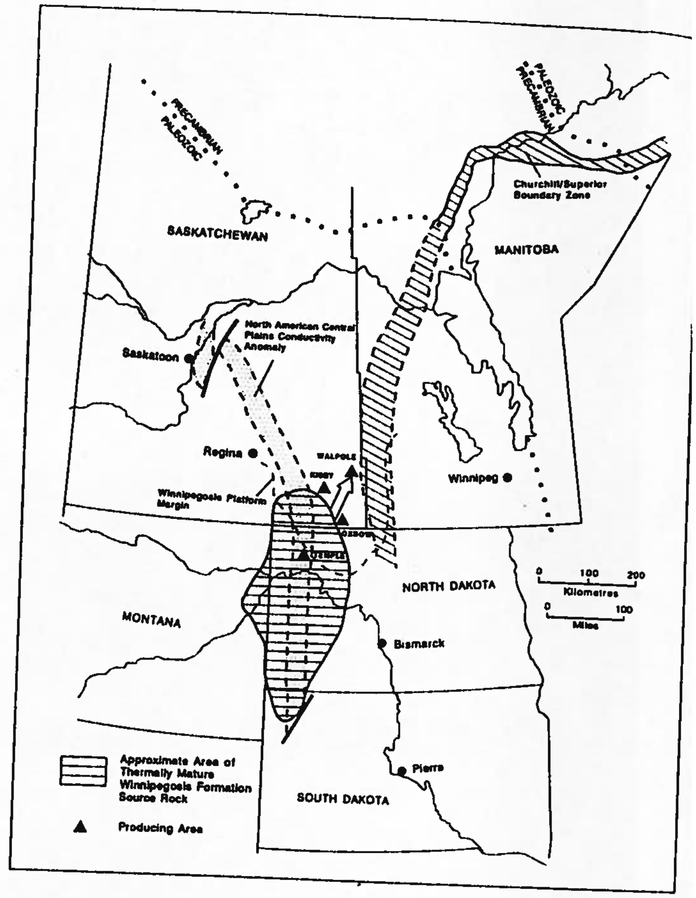

Figure 21. Family D Oil-Source System and migration pathways (after Martiniuk and Barchyn, 1993).

nation stratigraphic-diagenetic and structural traps. Anticlinal structures are generally of less than 640 acres (256 ha) in areal extent and commonly produce from multiple pay zones which range stratigraphically from Ordovician to Mississippian (Martiniuk and Barchyn, 1993). Raymond Field in eastern Montana is a typical example of this type of trap (Parker and Powe, 1982).

Within the study area, along the northeastern flank of the Williston Basin, there is also potential for tectonically-generated structures. This is due primarily to the existence of the crustal boundary zone. In southwestern Manitoba, the Birdtail-Waskada axis is coincident with this boundary zone and is the locus of numerous stratigraphic anomalies throughout the Phanerozoic section (McCabe, 1971). Periodic reactivation of vertical movements along this zone of weakness has resulted in the superposition of isopach, depositional and diagenetic anomalies (Martiniuk and Barchyn, 1993). Most of the study area's Mississippian and Triassic-Jurassic oil production is located along the Birdtail-Waskada axis and its southern extension.

Stratigraphic-Diagenetic Traps

Documented examples of stratigraphic traps within the Ordovician Red River Formation and Devonian Duperow Formation have revealed the presence of these subtle traps within pre-Mississippian reservoirs in the Williston Basin (Longman, 1982). The Birdbear Formation, with its excellent reservoir characteristics, lateral and vertical lithofacies variation and impermeable cap rock, make it an ideal candidate for stratigraphic type hydrocarbon plays.

The search for primary lithostratigraphic trapping may be directed to areas where the porous stromatoporoid bank facies (lithofacies E1) and *Amphipora* bank facies (lithofacies E2) are pinched out against the impermeable lime mudstones to packstones of the interbank facies (lithofacies B). Presence of good biohermal facies versus interbank or biohermal facies is indicated by lithofacies mapping.

The potential for stratigraphic traps within lithofacies E1 and E2 may also exist down dip of the subcrop edge of the Birdbear Formation. In several wells near the subcrop edge, it appears that porosity has been occluded by secondary dolomitization and anhydritization at the Devonian unconformity surface, thus creating an up dip porosity-permeability pinchout.

Diagenetic-stratigraphic traps may exist where locally enhanced porous and permeable zones within lithofacies E1 and E2 are pinched out against tighter, anhydrite or dolomite-cemented zones within the reservoir facies. This type of trap is also exhibited by the finely crystalline dolostone to dolomitic mudstone to wackestone of lithofacies F. The lithofacies is believed to have resulted from the downward percolation of solutioning brines altering the original fabric of the lithofacies E1 and E2 in areas of salt collapse. Exploration for these trap types require detailed lithofacies mapping and thin section examination.

SOURCE ROCK AND MIGRATION PATHS

Recent work by Osadetz et al. (1991; 1992) classifies the stratigraphic distribution of oil families in the Williston Basin (Fig. 20).

Production from the Birdbear Formation is derived from the Family D oil-source system. Family D oils are considered to be sourced from bituminous laminates in the Middle Devonian Winnipegosis Formation. Most Family D oil production to date, has occurred very close to the area of thermally mature source rock (Fig. 21). However, Family D oil pools in the Upper Devonian Birdbear Formation at Kisbey and Walpole in southeastern Saskatchewan suggest that extensive cross-stratal migration can accompany significant up dip migration to the northeastern margin of the basin (Martiniuk and Barchyn, 1993). The Birdbear Pool at Walpole is thought to be sourced from rocks of the Winnipegosis Formation western platform (Osadetz et al., 1992). This suggests lateral migration of a minimum of 106 mi (170 km) and cross-stratal migration into the Birdbear Formation. It is uncertain as to whether the lateral component of migration occurred within the Winnipegosis Formation or in the Birdbear Formation itself.

The study area is well within the maximum area of up dip migration in the Family D oil-source system. The numerous oil shows reported in the Winnipegosis Formation to Birdbear Formation stratigraphic interval may be indicative of migration of Family D oils through these strata. The lack of significant Family D reserves on the northeastern flank of the basin may reflect a lack of exploration directed towards pre-Mississippian strata (Martiniuk and Barchyn, 1993).

CONCLUSIONS

The Birdbear Formation is subdivided into a lower, predominantly non-argillaceous limestone and dolostone member, that represents low energy subtidal and higher energy bank and associated deposits, and an upper dolostone and interbedded evaporite member, that represents restricted intertidal and supratidal deposition.

Three reservoir facies were identified within the Lower Member including a stromatoporoid and *Amphipora* bank facies (lithofacies E1 and E2) and a dissolution-related alteration facies of E1 and E2. The excellent porosity and permeability associated with these rocks in combination with the variety of trap types make the Birdbear an attractive target for hydrocarbon exploration.

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