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THE UNIVERSITY OF ALBERTA

DIAGENESIS OF WINNIPEGOSIS BUILDUPS (GIVETIAN), TABLELAND AREA, SOUTHEASTERN SASKATCHEWAN

by

ROBERT WILLIAM MacDONALD ©

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

EDMONTON, ALBERTA
FALL, 1989

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(SIGNED) Robert W. McDonald

PERMANENT ADDRESS:

11612 32a Ave
Edmonton Alberta
T6J 3G8

DATED Aug. 10, 1989

THE UNIVERSITY OF ALBERTA

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled DIAGENESIS OF WINNIPEGOSIS BUILDUPS (GIVETIAN), TABLELAND AREA, SOUTHEASTERN SASKATCHEWAN submitted by ROBERT WILLIAM MacDONALD in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

Supervisor

Date July 31, 1989

Abstract

The Winnipegosis reservoirs in southeastern Saskatchewan are heterogeneous and largely unrelated to original depositional facies. Reservoir quality is diagenetically controlled, being determined by the nature and extent of cement-lined and sediment-filled, pores, cavities and fractures. These Winnipegosis buildups include five distinct facies. The lower two thirds comprise peloidal packstones and codiacean algal grainstones that were deposited as a series of coalesced shoals or banks. Their flanks were stabilized by early marine cements. The upper third consists of an algal bound peloid packstone facies that is overlain by a coral/algal framestone facies. The framestone facies consists of red algae on the high-energy windward margin, with *Thamnopora* and chaetetids occupying more restricted conditions in the lee of the crest. The buildups are capped by a laminated dolostone which probably formed during restriction of the basin when the buildups became exposed.

Syndepositional cavity and fracture systems in Winnipegosis buildups represent a major relic pore network. Reticulate cavities, with flat subhorizontal bases and irregular roofs, occur in codiacean algal grainstones. They probably formed beneath reoriented and brecciated submarine-cemented grainstone crusts. Isolated cavities, with irregular surfaces, occur in peloidal packstones. These cavities formed contemporaneously with deposition due to early marine cementation or algal binding. Cavities are commonly lined or partially lined by early marine cements. Peloidal marine sediment on the floors of the cavities suggests that they were open to the sea.

Submarine fractures occur within 10 m of the tops, and on the windward margins of the buildups as a result of tectonic fracturing or oversteepening of a semilithified margin. Type II fractures, which occur as networks of thin veins, formed by compaction of, or water escaping through semilithified sediment. Cavity and fracture systems are filled with vadose (?) micrite and silt.

During shallow burial, blocky isopachous, blocky mosaic and syntaxial cements formed, and later, in an intermediate to deep burial enviroment, limpid dolomite and anhydrite cements were precipitated.

Acknowledgements

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I am also grateful to Home Oil Company Limited, for providing financial support for this project as well as providing access to cores, geophysical logs, and seismic. Thanks are also extended to Canadian Hunter Exploration Limited and the Saskatchewan Department of Mineral Resources for providing access to cores.

I am especially grateful to Bill Martindale, of Home Oil, for our many insiteful discussions on different aspects of diagenesis and sedimentology, and to Ian Hunter, Jill Rehman and my other fellow graduate students for their encouragement, helpful suggestions and constructive criticism.

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CHAPTER I — INTRODUCTION

Regional setting

The Winnipegosis Formation was deposited throughout Saskatchewan, western Manitoba, North Dakota, and eastern Montana in the southern Elk Point and Williston basins (Fig. 1).

The Williston Basin is bordered by the Siouxia Arch on the south, the Black Hills and the Mile City Arch on the southwest and the Boudin Dome on the west (Peterson and MacCary 1987; Gerhard *et al.* 1982*b*; Fig. 1). Thomas (1974) suggested that structural control of the Williston Basin was related to large scale "tears" in the edge of the craton. The boundary between the Churchill (1.6 billion years old) and Superior (2.5 billion years old) structural provinces is in the eastern part of the basin and may also have had an important influence on the post-Proterozoic development of the basin. Structures in the basin are north and northwest trending relating to the structural grain in the Rocky Mountain province to the west. Gerhard *et al.* (1982*b*) suggested that structure and hence sedimentation in the basin were controlled by movements of large pre-Phanerozoic basement blocks.

Subsidence of the Williston Basin was continuous from the late Cambrian to the Tertiary. Devonian uplift along the Transcontinental Arch, southeast of the basin, broke the connection between the Williston Basin and the Cordilleran Geosyncline. This also resulted in the Williston Basin being tilted northward. Gerhard *et al.* (1982*b*) suggested that the movement on the Transcontinental Arch was associated with both the Antler and Acadian Orogenies. During the Early Devonian, marine seas transgressed southeastward from the Cordilleran Basin and inundated the subsiding portion of North America which has come to be known as the Elk Point Basin (McGehee 1949). In the Early Devonian (Emisian), sedimentation was restricted to the north part of the Elk Point Basin. Further southward transgression of the sea was prevented by the topographically positive Meadow Lake Escarpment in central Saskatchewan.

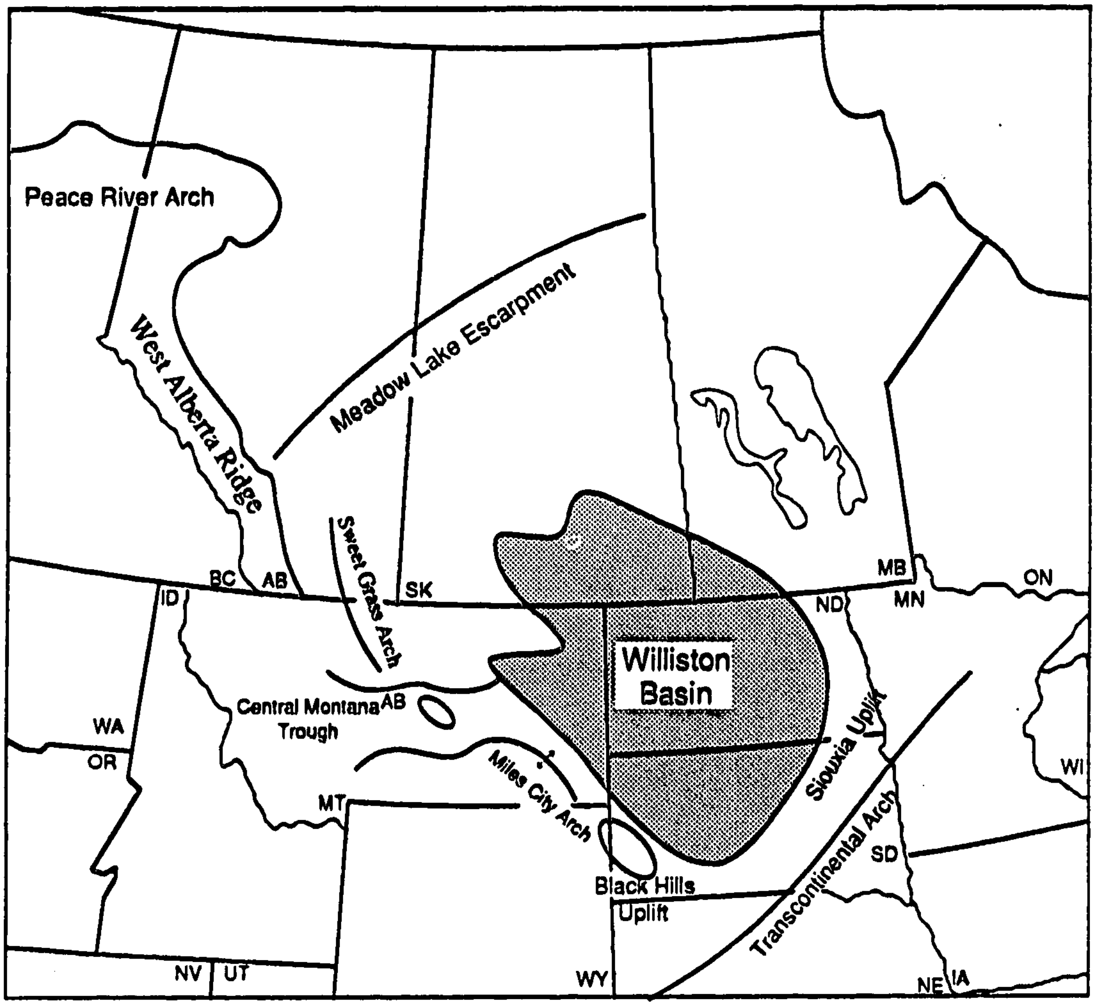


Fig. 1. Structural features surrounding the Williston Basin during the Devonian (modified from Peterson and MacCary 1987; Perrin 1987).

In the Middle Devonian (Eifelian), continued transgression of the Elk Point Sea caused the Elk Point Basin to become connected to the northward tilting Williston Basin (Gerhard *et al.* 1982*a*, 1982*b*). As a result the Elk Point Sea extended from northeastern Alberta to the parts of Montana and South Dakota once occupied by the Williston Basin (Grayston *et al.* 1964; Williams 1984; Perrin and Precht 1985; Fig. 2).

Time stratigraphic relationships in the extended Elk Point Basin, determined from marker bed correlation across the platform and into the basin, indicate differentiation of the broad Prairie Shelf from a carbonate ramp to a distinct platform and basin complex during deposition of the Winnipegosis Formation in the early Givetian.

History of Winnipegosis exploration

The Northwest Company, a subsidiary of Imperial Oil, initiated exploration for oil in Saskatchewan in the early 1900's. It was not until World War II, however, that oil exploration in Saskatchewan began in earnest. Initial drilling was primarily an attempt to understand the stratigraphy in Saskatchewan, with many deep stratigraphic tests penetrating the Prairie Evaporite and Winnipegosis formations. The Middle Devonian evaporites were correlated to the Saline salt of the Michigan Basin and thus assigned a Silurian age. Drilling in the early years was expensive and commonly fraught with problems. Drilling through the "Silurian salt" was one of the greatest problems. These early drilling tests found local shows of oil and gas in shallower zones (above the salt) but nothing was deemed to be of commercial interest. In 1949, McGhee dispelled the belief that the salt and the underlying dolostone (the Winnipegosan Formation) were Silurian in age by correlating them with Middle Devonian evaporites and underlying carbonates in Alberta. After the discovery of oil in the Devonian Leduc Formation in Alberta, similar Devonian reef plays were sought in Saskatchewan with little success.

The Winnipegosis Formation has been of interest as a drilling target and a potential reservoir of hydrocarbons since the mid 1960's though exploration in the Winnipegosis

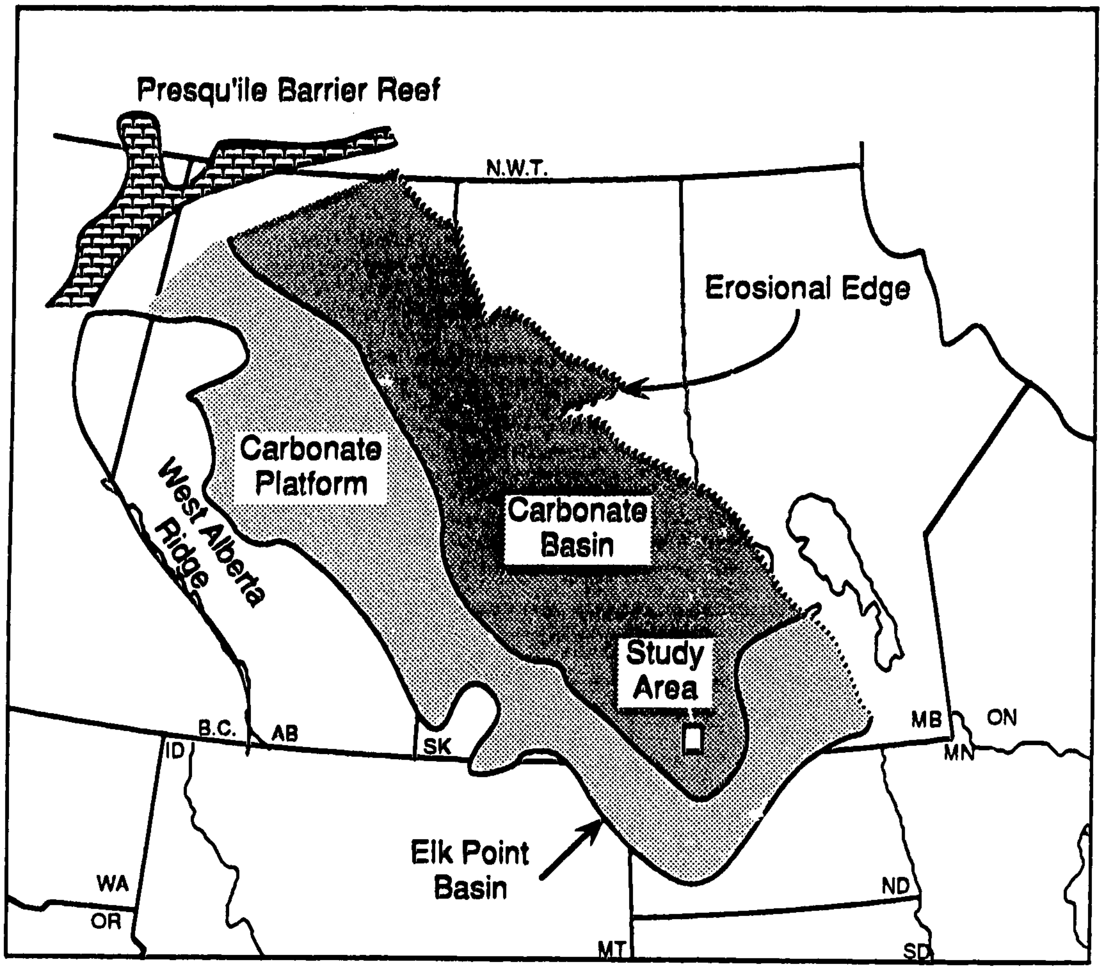


Fig. 2. Elk Point Basin and the Presqu'ile Barrier Reef (modified from Williams 1984; Grayston *et al.* 1964).

dates back to about 1953. Initial probes suggested that the Winnipegosis Formation had the potential for holding large amounts of oil; however, finding the "reefs" was difficult because they were too small to be detected on seismic (Fritz 1988).

By 1967 an extensive Winnipegosis Formation "reef" trend had been delineated in central Saskatchewan; however, there was limited control with only 30 wells drilled (Jordan 1967). Of these wells 15 had "...been drilled close enough to the [reef] front to suggest a number of extremely attractive prospects" (Jordan 1967). However, no reservoirs were located.

In 1968 and 1969 a consortium of oil companies began the "Pheasant Project". The consortium's goal was to locate commercial amounts of hydrocarbons in Winnipegosis Formation reefs. To this end 49 wells, mostly wildcats, were drilled on land held by the companies in the consortium. Though some wells found oil shows and favourable reservoirs, all 49 wells were abandoned (Halabura 1988). This discouraged further exploration for deep oil both in central and southeast Saskatchewan.

On February 10, 1976 the Dome Scurry Tableland 11–14 well, was completed as an oil well in the Winnipegosis Formation in southeastern Saskatchewan (Figs. 3, 4). Initial production was over 19 m^3 of oil per day. However, in 1983 after producing almost 5000 m^3 of oil, the well watered out and it was capped. It would not be until 1986 that a significant reservoir would be discovered in the Winnipegosis Formation. The discovery well, Home et al. Tableland 8A–22, was a wildcat drilled by Home Oil Company Limited and Canadian Hunter Exploration Limited, approximately 3 km northeast of the 1976 Dome Scurry well (Figs. 3, 4).

After Home Oil's success at Tableland the Winnipegosis play became more popular. Between 1986 and 1988, 44 wells were drilled into the Winnipegosis Formation and 11 new fields discovered. Of the unsuccessful wells, several recorded oil shows but none were commercial.

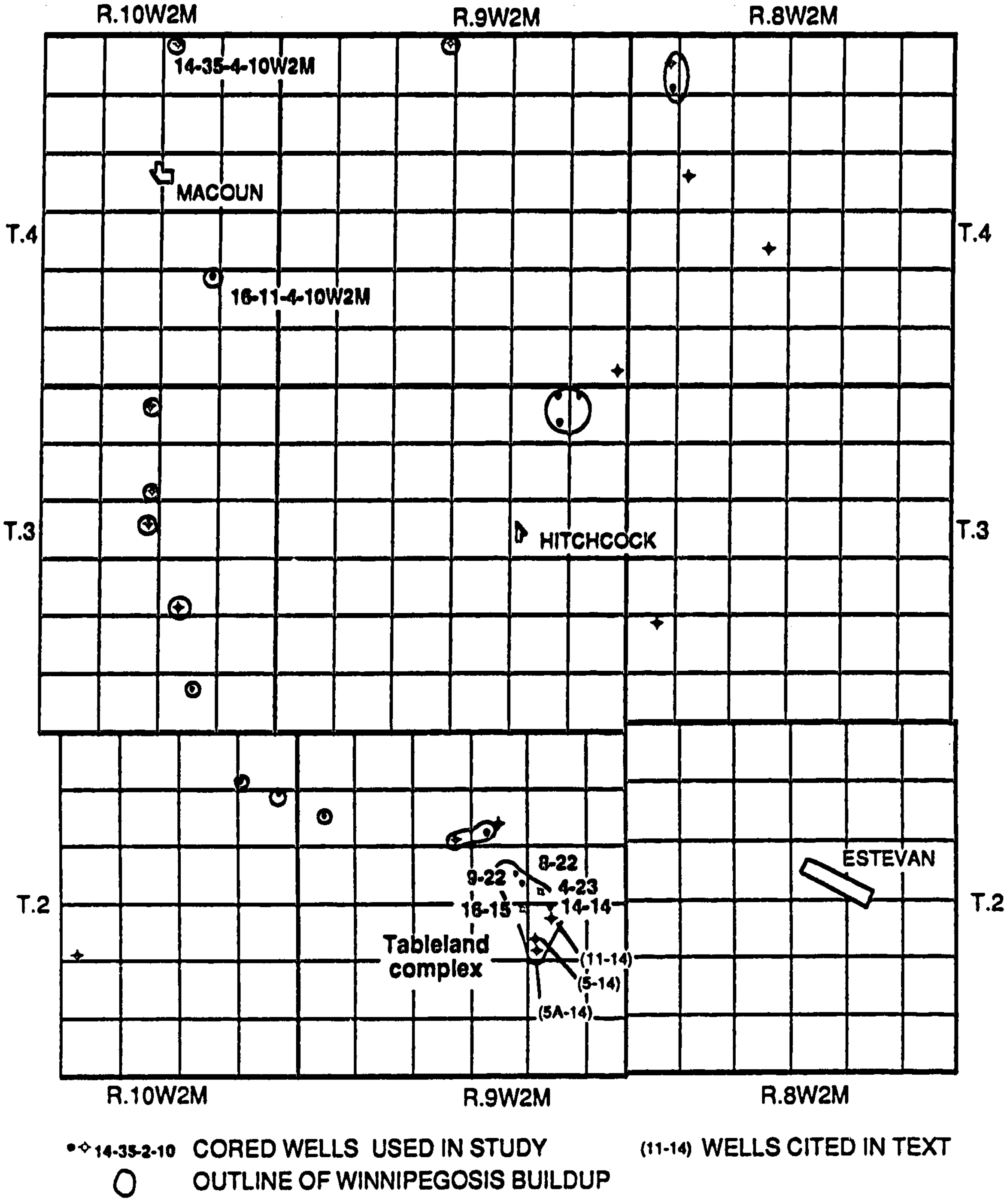


Fig. 3. Location map showing Winnipegosis wells in the Tableland area (modified from Martindale and MacDonald 1989).

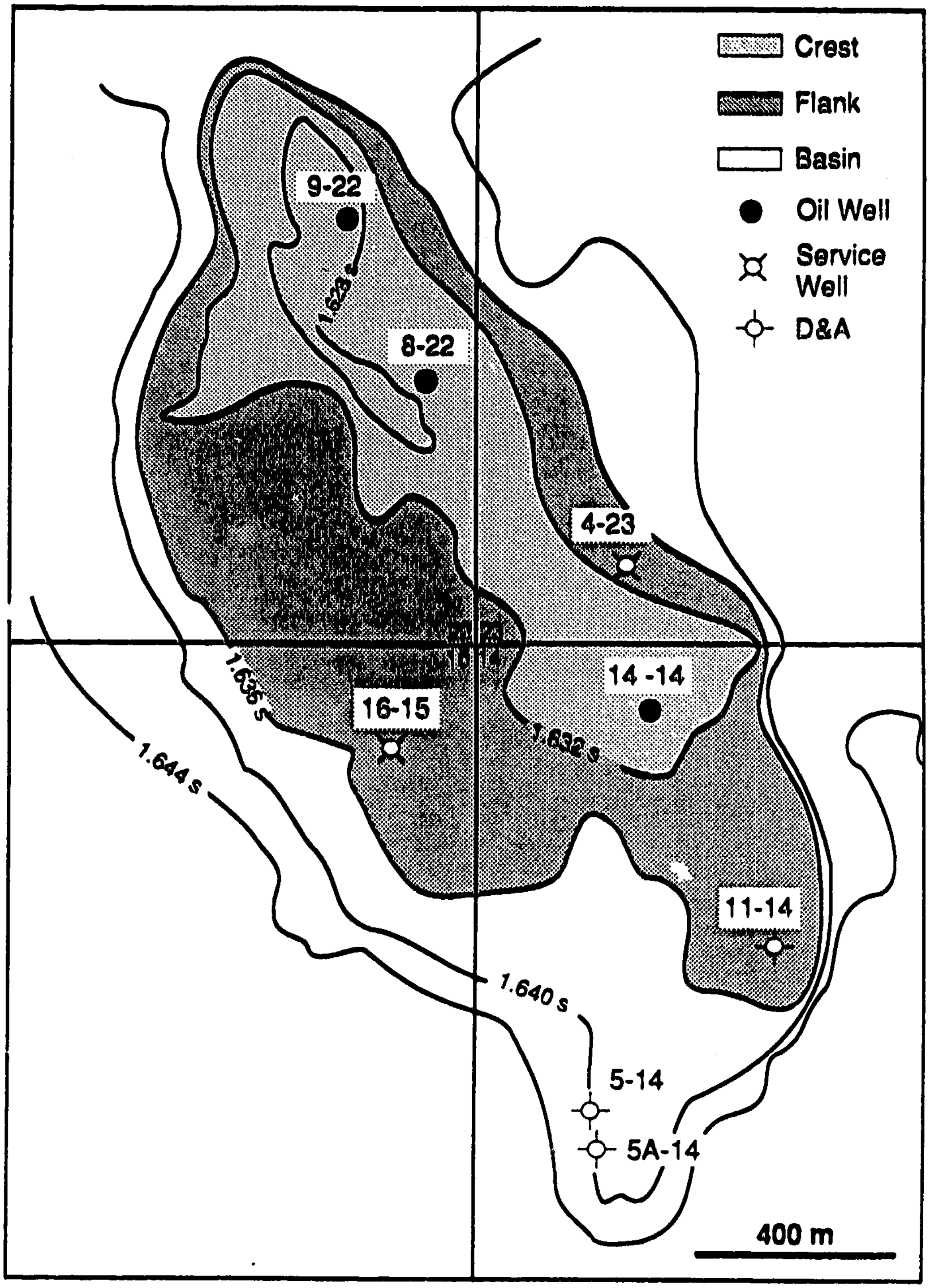


Fig. 4. A seismic structure map (two way travel time) of the Tableland buildup showing the locations of all wells penetrating the buildup (modified from Martindale and MacDonald 1989).

History of Tableland development and production

The Tableland discovery well, Home Souris River 8A-22-2-9W2M, initially flowed 223 m^3/day of 37° API oil (Martindale and Orr 1988a). This was the first Winnipegosis "pinnacle reef" with significant commercial production of petroleum in the Williston Basin (Martindale and Orr 1988*a*; 1988*b*). By August 1988 this well had produced 49 158 m^3 of oil (average of 69.8 m^3/day) and 53 249 m^3 of gas (75.5 m^3/day). Subsequent to the discovery well six step out wells were drilled into the Tableland buildup. The first step-out well, Home SRO Tableland 9-22-2-9W2M (Fig. 4), encountered the crest of the buildup, and was completed on April 6, 1987 as an oilwell. This well produced 15 098 m^3 of oil (average 32.8 m^3/day) between April 1987 and August 1988. The next well, Home *et al.* Tableland 4-23-2-9W2M (Fig. 4), was drilled too far east and only encountered flank and basinal deposits. The well was abandoned in April 1987. Also in April of 1987, Uniglobe International Energy Corporation drilled two wells in 5-14-2-9W2M, approximately 3200 m south of the Tableland complex; they encountered only basinal deposits (Fig. 4).

In August of 1987, Dome Petroleum Limited drilled the Dome *et al.* Tableland 14-14-2-9W2M well, approximately 1800 m southeast of the Home Oil discovery well (Fig. 4). It encountered the Tableland buildup and the reservoir. The well began producing in November 1987 and had produced 6063 m^3 of oil (average 37.1 m^3/day) by May 1988. The last well drilled into the Tableland buildup, CanHunter Inland Tableland 16-15-2-9W2M, was completed on November 6, 1987. This well was drilled approximately 1700 m south of the discovery well (Fig. 4); however, it encountered the flank of the buildup and failed to produce oil.

The location for drilling the discovery well was based on seismic modelling and conventional 2-D techniques. The margins of the buildup were delineated and subsequent well locations were determined by reprocessing the conventional 2-D seismic grid into a pseudo 3-D survey (Fig. 4; Martindale and Orr 1988*a*; 1988*b*). The seismic not only delineated the Tableland reef complex but also located two smaller buildups to the north.

Hunt Tableland 6A-27-2-9W2M penetrated one of these small buildups and was completed in February 1988 as an oil well. Even though the Tableland complex and the buildups to the north are separate entities as seen on seismic, all the wells in both complexes are in pressure communication (W. Martindale, personal communication, 1988).

By mid-1987 pressure decreased in the Tableland buildup and production decreased to less than 47.5 m^3/day and 31.9 m^3/day from the 8A-22 and the 9-22 wells respectively. Water injection began in late 1987 in an attempt to re-establish pressure in the producing wells. Home et al. Tableland 4-23 was completed in the Blairmore Formation as a water production well, and CanHunter Inland Tableland 16-15 was completed in the Winnipegosis Formation as a water injection well. As of August 1988, 50 000 to 100 000 m^3 of water had been injected into the buildup with no increase in pressure (D. A. Wilmot, personal communication, 1988).

Objectives

The increasing interest in Winnipegosis plays, and difficulties in producing from many of the reservoirs has resulted in a desire to understand the formation. Delineation of facies in the Winnipegosis buildup in the Tableland area was undertaken to aid in development of the field and the discovery of new fields. By the summer of 1987 all five wells drilled into the Tableland buildup had been cored. This good core control provides an opportunity to delineate sedimentologic and diagenetic trends in the Tableland buildup, and by extrapolation to other Winnipegosis buildups in southeastern Saskatchewan. This examination will provide a better understanding of the depositional and post-depositional history of these buildups.

This study presents:

(1) a review of the Lower and Middle Devonian stratigraphic nomenclature used in southeastern Saskatchewan,

(2) the stratigraphy of the Ashern, Winnipegosis, and Prairie Evaporite formations,

(3) a discussion of the facies and their distribution in the buildups,
(4) a depositional model,
(5) the preservation and diagenetic alteration of allochems and matrix,
(6) the fabrics and possible origins of the cements,
(7) the distribution and possible origins of cavity systems, and
(8) a diagenetic model.

Materials and methods

In this study, three widely spaced buildups were examined in core (Fig. 3). The Tableland complex (Fig. 4) is represented by cores from wells located at 9-22-2-9W2M, 8A-22-2-9W2M, 4-23-2-9W2M, 14-14-2-9W2M, and 16-15-2-9W2M. Buildups located at 14-35-4-10W2M and 16-11-4-10W2M are each represented by one core. From these cores selected samples were thin sectioned. Eighty two thin sections were made at the University of Alberta and 57 thin sections, from the 8A-22 and 14-35 cores, were provided by Home Oil Company Ltd. All thin sections were polished and described using conventional petrographic, incident fluorescent light and cathodoluminescence microscopy. Selected samples were examined with a scanning electron microscope.

Cathodoluminescence is the light given off by a substance under illumination by a beam of electrons (Nickel 1978). Cathodoluminescence of carbonates is still poorly understood. Most literature considers Mn^{+2} and Fe^{+2} to be the only trace elements responsible for cathodoluminescence (Meyers 1974; Pierson 1981; Fairchild 1983; Grover and Read 1983; Ten Have and Heijnen 1985), with the degree of luminescence controlled by the absolute quantity of Fe^{+2} and the ratio of Mn^{+2} to Fe^{+2} (Fairchild 1983; Grover and Read 1983; Machel 1987). Recently, however, it has been suggested that luminescence in carbonates is caused or inhibited by a number of other trace elements. Machel (1985) showed that Mn^{+2}, Pb^{+2}, and Ce^{+2} enhance luminescence, whereas Fe^{+2}, Ni^{+2}, and Co^{+2} quench luminescence. In the absence of microprobe data it is impossible to assess what elements are causing luminescence, since they are present in quantities to small to be determined with standard staining techniques. An accelerating voltage of 15 kV, current of 600 µA, and a beam area of approximately 1.6 mm^2 was applied to polished thin sections in a Technosyn, model 8200 MkII, cold-cathode luminescence instrument.

Fluorescence is the light given off by a substance under incident illumination by ultraviolet light. Although poorly understood it is becoming a popular tool in carbonate petrology (Dravis and Yurewicz 1985). The color and degree of fluorescence in carbonates appears to be controlled by the distribution of organic material and fluid inclusions. Organic materials tend to fluoresce yellow, and inclusion rich carbonates fluoresces lime green. All thin sections in this study were examined with a Jenamed fluorescence microscope, using a green filter.

Selected samples were sputter coated with gold and examined with a Cambridge Stereoscan 250 scanning electron microscope, at 20 KV, and gross elemental analysis was determined with a KEVEX 7000 Energy Dispersive X-ray analyser (EDAX).

Selected thin sections were stained with alizarin red-S, to distinguish between calcite and dolomite, and potassium ferricyanide, to determine the presence of ferrous iron, as described by Warne (1962) and Dickson (1965,1966). In the Winnipegosis buildups in this study neither alizarin red-S nor potassium ferricyanide produced any stain, indicating the absence of calcite and ferroan dolomite.

Terminology

Organic frameworks represent about five percent or less of the sediments in the Winnipegosis Formation, therefore, in this study, the term "reef" (Lowenstam 1950; Heckel 1974) is not used. The term "buildup" is preferred because it describes a topographic accumulation of organic skeletal debris which may or may not form a rigid framework (Heckel 1974). The dolostones in this study were classified according to

Embry and Klovan's (1971) modified version of Dunham's (1962) limestone classification.

There is considerable confusion surrounding the term "micrite" and its usage. Folk (1959, 1962) defined micrite as a contraction of "microcrystalline calcite ooze", and specified a range in grain diameter from 1–4 µm. It was introduced to refer specifically to the matrix of a rock, as well as a designation for a rock made entirely of microcrystalline calcite. Matrix refers to "mechanically deposited material between grains—as distinct from precipitated cement" (Bathurst 1975). In this study "micrite" is used in a nongenetic sense, to describe carbonate grains 1–4 µm in diameter, despite their being dolomitized and neomorphosed.

"Microspar" was defined by Folk (1965) as a neomorphic crystal mosaic of calcite, with crystals 4–30 µm on a side. The term is used in this study as neomorphic mosaic of any mineralogy, with crystal diameters from 4 µm–50 µm (Bathurst 1975).

The term peloid is used to describe an allochem composed of micrite or microspar with no implication of size or origin (Bathurst 1975). In this study two types of peloids (type I and II) occur, and they vary from 0.2–2.0 mm in diameter. Type I peloids are round to oval and composed of microspar enclosed by a micrite rim. Type II peloids are highly variable in shape from spherical to irregular. They are composed entirely of 5–20 µm dolomite crystals and have a dark brown color, possibly due to organics. There is a gradation between the two types.

CHAPTER II — STRATIGRAPHY

History of Lower Elk Point Group nomenclature (Saskatchewan)

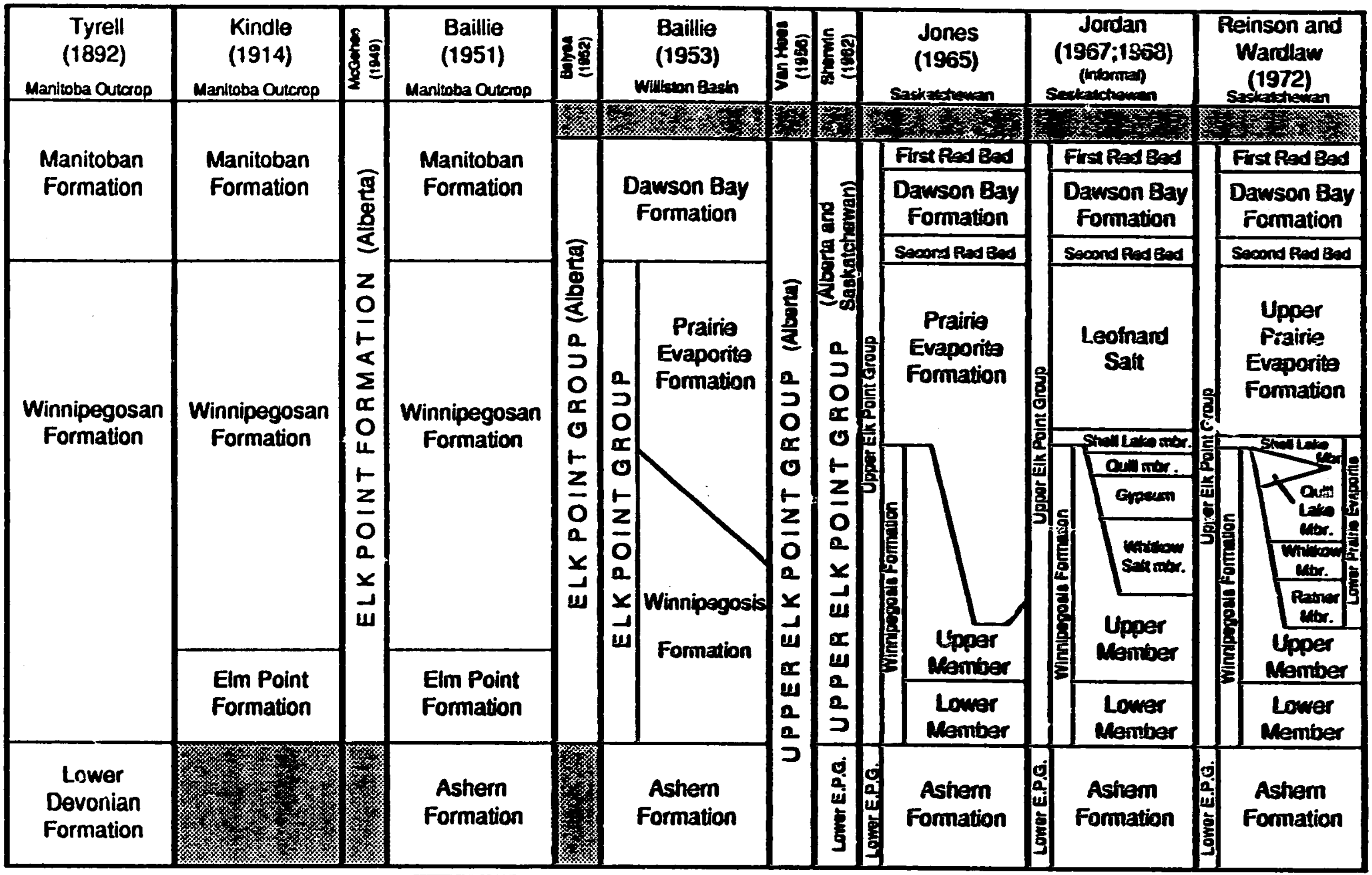
All of the early work on the Devonian strata of Saskatchewan was based on exposures along Lake Manitoba and Lake Winnipegosis in Manitoba. Most of this work was done prior to 1950 when little or no subsurface data were available.

The Winnipegosan Formation was originally defined by Tyrrell (1892) for dolostones exposed on the shores of Lake Winnipegosis in Manitoba. Tyrrell (1892) also proposed the Manitoban Formation for shales and limestones of Devonian age overlying the Winnipegosan Formation (Fig. 5). In 1914, Kindle established the Elm Point limestone as the oldest Devonian formation (Fig. 5). The Elm Point Formation was deposited on the Silurian unconformity and overlain by the Winnipegosan Formation. Baillie (1953) combined the dolostones of the Winnipegosan Formation and the limestones of the underlying Elm Point Formation and renamed them the Winnipegosis Formation, mostly to remove any time connotation implied by the name Winnipegosan (Fig. 5). Jones (1965) divided the Winnipegosis Formation into Upper and Lower members (Fig. 5).

The evaporite beds above the Winnipegosis Formation, not represented in outcrop, went unrecognized until 1953 when Baillie proposed the name Prairie Evaporite Formation (Fig. 5). The Prairie Evaporite Formation is laterally equivalent to the Muskeg Formation anhydrite in Alberta (Law 1955).

The Ashern Formation was initially proposed by Baillie (1951) to describe the brick red argillaceous dolostones, beneath the Elm Point Formation in the outcrop belt of Manitoba. At that time the Ashern Formation was thought to be of Silurian age (Baillie 1951). Baillie (1953, 1955) extended the Ashern Formation into the subsurface of Manitoba, Saskatchewan and North Dakota, and demonstrated that it was of Devonian age (Fig. 5).

In 1949 McGehee named Middle Devonian carbonates and evaporites in Alberta the Elk Point Formation. Later this formation was raised to group status by Belyea (1952).



▨ Indicates that strata were not discussed

Fig. 5. Development of Elk Point terminology in the Williston Basin.

Baillie (1953) proposed that the Elk Point Group of Alberta should include the Ashern, Winnipegosis, and Prairie Evaporite formations in the Williston Basin (Fig. 5). Van Hees (1956) divided the Elk Point Group into the Upper Elk Point and Lower Elk Point subgroups, with the boundary at the base of the Ashern Formation (Fig. 5). However, Sherwin (1962) found that the Ashern Formation, as defined in its type locality, loses its identity northwest of the Meadow Lake Escarpment (Fig. 1), and proposed that the division between the Upper and Lower Elk Point subgroups to be taken as the base of the Winnipegosis and laterally equivalent Keg River formations (Figs. 5, 6).

Jordan (1967, 1968) divided the Prairie Evaporite Formation into the informally named Whitkow Salt, Shell Lake Gypsum and Quill members (Fig. 5). These names were applied throughout the central and south-central portion of Saskatchewan. Reinson and Wardlaw (1972) raised the Whitkow Salt and the Shell Lake Gypsum to member status, and combined them into the Lower Prairie Evaporite Formation. They also renamed the informal Quill member of Jordan (1968) the Quill Lake Marker Beds of the Shell Lake Member (Fig. 5).

The Whitkow Member is composed of a lower anhydrite and an upper salt. The anhydrite is only located adjacent to the buildups while the salt occupies the area between the buildups (Wardlaw and Reinson 1971). That part of the Prairie Evaporite Formation above the Shell Lake Member was named the Upper Prairie Evaporite Formation.

Reinson and Wardlaw (1972) defined the finely laminated, argillaceous and bituminous carbonate mudstone and associated anhydrite between Upper Winnipegosis buildups as the Ratner Member of the Upper Winnipegosis Formation of Jones (1965). The Ratner Member occurs in the subsurface from northeast of Saskatoon to North Dakota. Jones (1965) also noted these carbonates and considered them as equivalents to the much thicker carbonate mounds. The upper anhydritic parts he considered as part of the Prairie Evaporite Formation.

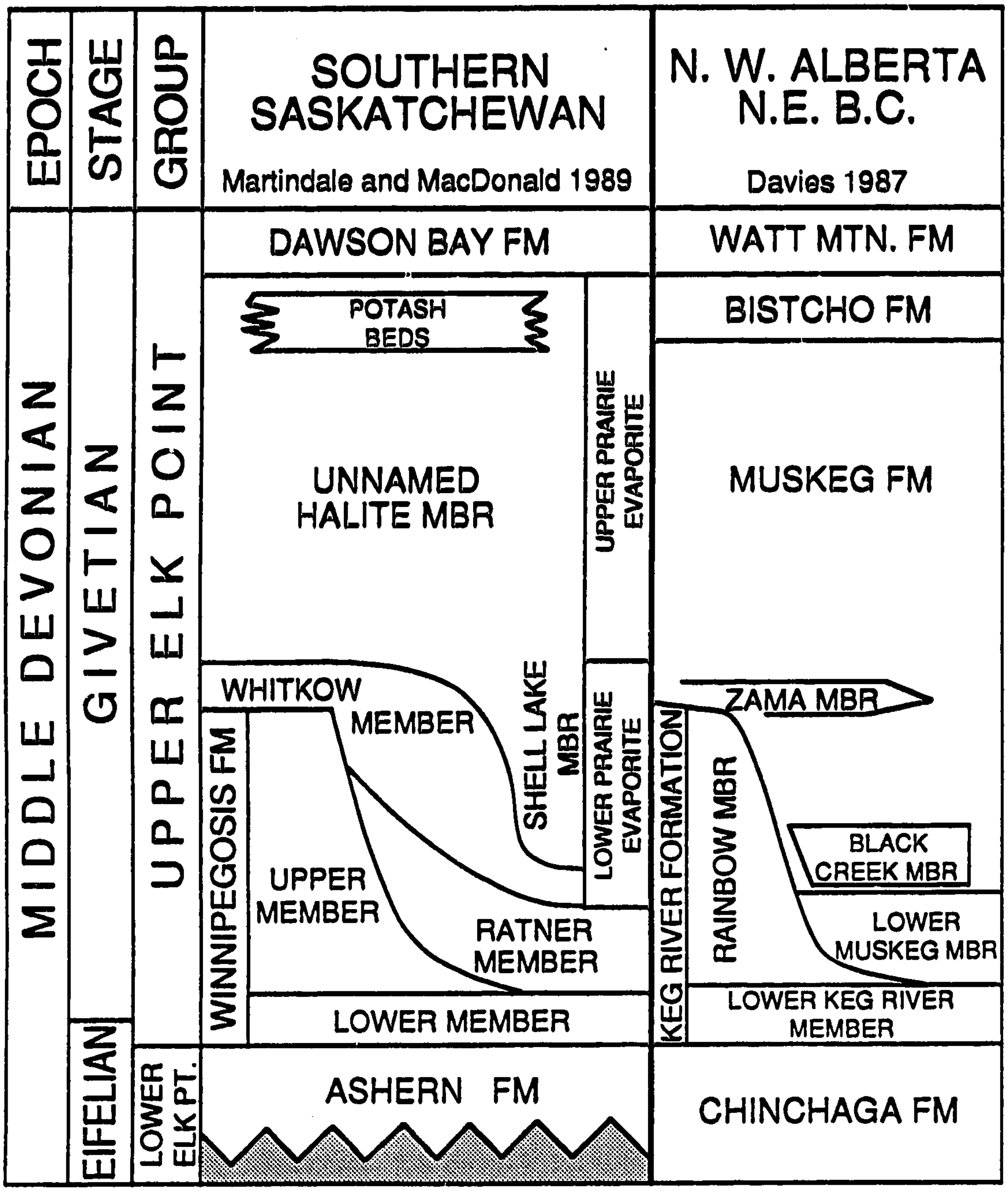


Fig. 6. Devonian stratigraphy in southeast Saskatchewan and northwest Alberta/ northeast British Columbia (modified from Martindale and MacDonald 1989 and Davies 1987).

Stratigraphy of the Ashern, Winnipegosis, and Prairie Evaporite formations

Ashern Formation

The Ashern Formation is composed almost entirely of argillaceous microcrystalline dolostone (Lobdell 1984). It blankets unconformably a brick red paleosol developed on a brecciated post-Silurian exposure surface (Rosenthal 1987, 1988). The Ashern Formation attains a maximum thickness of 55 m in northwestern North Dakota (Lobdell 1984).

In the Williston Basin portion of the Elk Point Basin, initial sedimentation in the Devonian is represented by the Ashern Formation (Fig. 6). A brief regression, as evidenced by the presence of a microbreccia (Pl. 1A) at the contact between the Ashern and Winnipegosis formations, ended deposition of the Ashern Formation (Rosenthal 1987; Perrin 1982). The Ashern Formation is time equivalent to the Contact Rapids Formation in central Alberta and to the Chinchaga Formation in northeastern British Columbia and northern Alberta. The deposition of the latter two formations began earlier than that of the Ashern Formation and they were not deposited on an erosional surface. This reflects the earlier submergence of the northeastern portion of the Elk Point Basin (Stearn *et al.* 1979, p. 233).

Winnipegosis Formation

With renewed transgression the Winnipegosis Formation was deposited during Givetian times. Jones (1965) divided the Winnipegosis Formation into the Lower Member, the Upper Member and the Ratner Member (Figs. 5, 6). The Winnipegosis Formation is laterally equivalent to the Keg River Formation in Alberta (Fig. 6).

Lower Member

The Lower Member, which paraconformably overlies the Ashern Formation, is composed of mottled crinoidal dolo and lime mudstones. Bioclasts include crinoids, brachiopods, bryozoans, and mollusks. In southeastern Saskatchewan the lower part of the Lower Member is generally limestone whereas the upper part of the member is dolostone. The basal limestone is up to 5 m thick, and the Lower Member has a total thickness of 8–18 m (Wardlaw and Reinson 1971).

Upper Member

The Upper Member, which conformably overlies the Lower Member, is composed of thick accumulations of packstones, grainstones, framestones and bindstones in organic buildups. In the Saskatchewan portion of the Williston Basin the Upper Member is always dolostone whereas in the southern part of the basin, in South Dakota, the Upper Member is commonly limestone. The Upper Member attains a maximum thickness of 96 m (Wardlaw and Reinson 1971).

In outcrop the boundary between the Upper and Lower members is placed at the lowest occurrence of argillaceous, bituminous or laminated marker beds (Norris *et al.* 1982). On subsurface logs the boundary is "picked" where the gamma ray response increases markedly. This response indicates the lower argillaceous content of the Upper Member. On some logs this "pick" is difficult to make. In core the boundary is easily seen as the Lower Member is much darker in color than the Upper Member (Pl. 1B).

Ratner Member

The Ratner Member is conformable with the Lower Member and grades into the overlying Prairie Evaporite Formation. Deposition of the Ratner Member was contemporaneous with deposition of the Upper Member buildups, with the Ratner Member forming as deeper basinal deposits. It is composed of bituminous laminated mudstones (laminites). In the northern part of the Elk Point Basin the Ratner Member is 12–17 m thick, but averages 4 m thick in the southern portion of the basin (Wardlaw and Reinson 1971).

The Prairie Evaporite Formation

The Prairie Evaporite Formation, laterally equivalent to the Muskeg Formation in Alberta, is divided into the Whitkow Member, the Shell Lake Member and an unnamed member (Figs. 5 , 6). Evaporite deposition was restricted to basinal areas.

The Whitkow Member

The lower part of the Whitkow Member is dominantly anhydrite which occurs as a halo around the Winnipegosis buildups. This halo appears thickest on the southeast side of the buildups, suggesting that brine circulation was from the northeast (Wardlaw and Reinson 1971). The upper part of the member is essentially pure salt. The Whitkow Member ranges in thickness from 0 m over Winnipegosis buildups to a maximum of 90 m in basinal areas (Wardlaw and Reinson 1971).

The Shell Lake Member

The Shell Lake Member is composed predominantly of anhydrite (Jordan 1967, 1968; Wardlaw and Reinson 1971; Reinson and Wardlaw 1972; Gendzwill 1978). It is absent over the Winnipegosis buildups but is up to 30 m thick in basinal areas (Reinson and Wardlaw 1972). A thin (up to 15 m) carbonate unit, the Quill Lake marker beds, commonly occurs in the Shell Lake Member.

The Unnamed Member

The upper unnamed member overlies the Whitkow and Shell Lake members and is dominantly halite with numerous laterally persistent sylvite beds. It attains a thickness of 100–120 m.

Depositional Environments of the Ashern, Winnipegosis and Prairie Evaporite formations

The Ashern Formation

The lack of diagnostic trace or body fossils in the Ashern Formation makes a paleoenvironmental interpretation difficult. Lobdell (1984) suggested that the Ashern Formation was deposited in a restricted embayment in the Elk Point Basin. The restriction probably resulted from the Meadow Lake Escarpment acting as a sill in central Saskatchewan. This interpretation, consistent with that of Perrin (1982), is followed here.

The Winnipegosis Formation

Perrin (1982), Perrin and Precht (1985), Precht (1986), and Perrin (1987) divided the deposition of the Winnipegosis Formation into three phases. Phase one represented transgression over an undifferentiated basin, resulting in deposition of shallow marine sediments throughout the basin. Phase two represented differentiation of the basin into a carbonate platform and restricted basin environments. On the shelf, lagoon, tidal flat, patch reef, and shallow marine environments were present, and in the basin were pinnacle reef and deep basin environments. During the third phase buildups were exposed when the sea level lowered.

The Prairie Evaporite Formation

After a slight eustatic sea-level lowering (Hallam 1984; Fig. 7) in the mid-Givetian the Elk Point Basin became barred by the Presqu'ile barrier reef in northwestern Alberta and the southern North West Territories (Fig. 2). Maiklem (1971) suggested that the sea level dropped as much as 30 m, and that evaporite deposition occurred in shallow pans.

Klingspor (1969) suggested that the evaporites in the Elk Point Basin were formed in deep water, being precipitated from stratified brines in the basinal areas, as described by

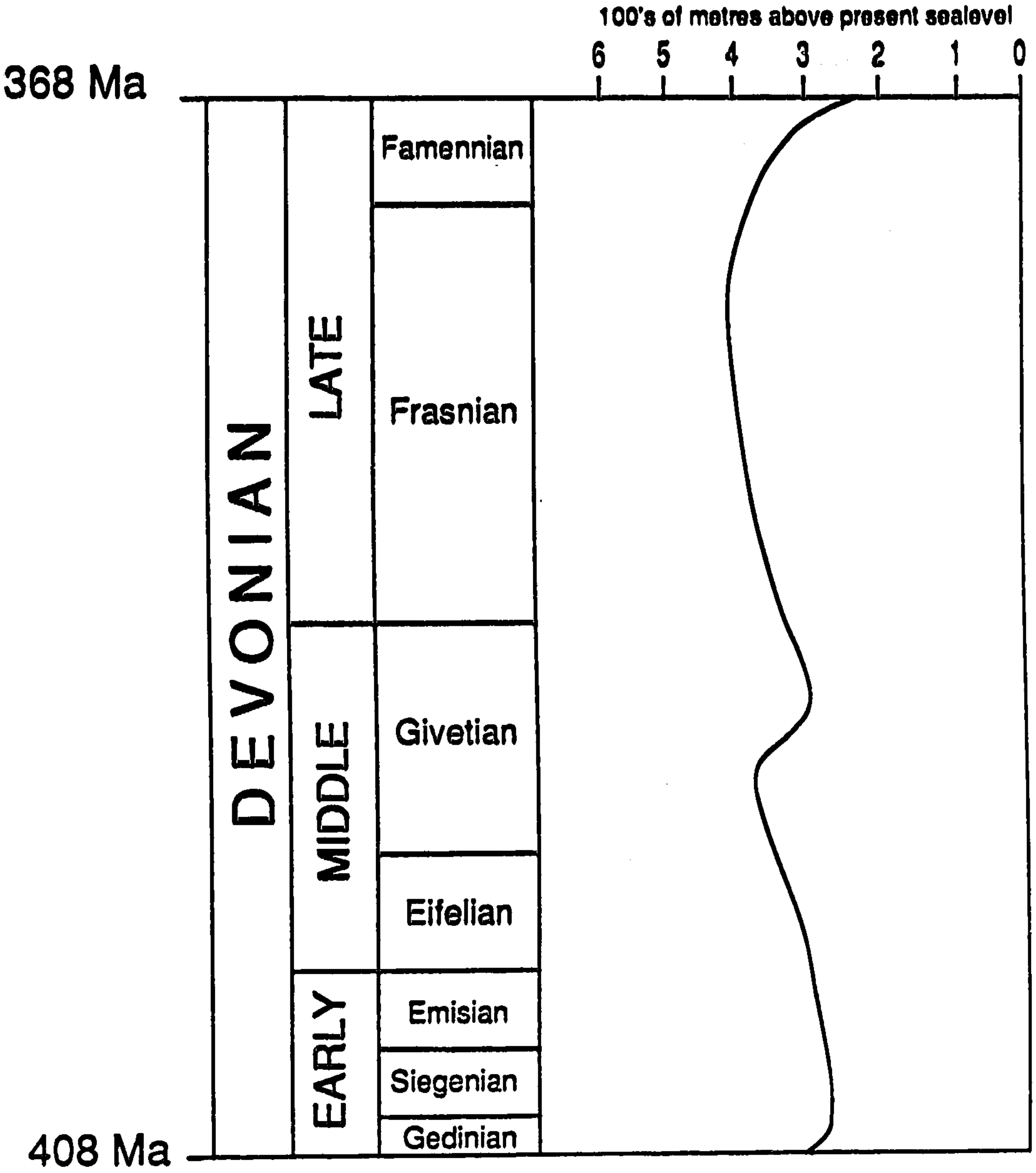


Fig. 7. Sealevel curve (modified from Hallam 1984).

Schmalz (1969). Water probably still entered the basin in significant quantities by seepage through the barrier reef system. Stratification of the brines resulted from evaporative concentration of waters due to restricted circulation after the basin was barred. The concentration and hence increased density caused the brines to sink, displacing less concentrated brines to shallower depths. The stratification permitted anhydrite and halite deposition in more restricted parts of the basin to be contemporaneous with carbonate deposition adjacent to the barrier.

It seems unlikely that the Prairie Evaporite Formation and Muskeg Formation evaporites were deposited on sabkhas and in brine pools, as suggested by Maiklem (1971), due to the great thicknesses of these formations. The deep water model would allow great thicknesses of evaporites to be built up in a relatively short (geologically) period of time over the entire length of the Elk Point Basin (1700 km).

Though orders of magnitude smaller, Lake MacLeod in Western Australia is a good modern analog to the Elk Point basin. The margins of the Lake MacLeod basin are at sea level, and the centre of the basin, the main brine sink, is 4.5–5 m below sea level (Logan 1987). The ocean is barred from Lake MacLeod by a ridge of porous eolianites. Water enters the basin by traveling 10–15 km through the barrier (Logan 1987). The distribution of evaporites in the Elk Point Basin is such that halite and sylvite dominate in the most southern portion of the basin (the Prairie Evaporite Formation). Farther north, in central and northern Alberta, Muskeg Formation anhydrites dominate. Directly behind the Presqu'ile Barrier Reef are very fine grained carbonates representing primary carbonates precipitated directly from seawater. The pattern of evaporite distribution indicates water more concentrated in salts occurred farther to the south in the more restricted parts of the basin. This is the same evaporite distribution seen in Lake MacLeod.

CHAPTER III — SEDIMENTOLOGY

Facies of the Winnipegosis Formation, southeast Saskatchewan

Introduction

In the Eifelian, prior to the formation of Winnipegosis buildups, the Elk Point Basin was a broad carbonate platform. After differentiation of the Elk Point Basin into distinct basin and shelf environments, buildups began to form in the basin and on the shelf. The buildups in this study formed in a basinal environment approximately 30–50 km northeast of the platform margin which was located in what is now North Dakota.

The Lower Member of the Winnipegosis Formation is composed of a bioturbated mudstone facies, which generally lacks bioclasts, and a crinoid/brachiopod mudstone to wackestone facies. These two facies represent deposition on the broad carbonate platform prior to differentiation of the Elk Point Basin into basin and shelf environments.

After differentiation of the Elk Point Basin, initial deposition on the Lower Winnipegosis platform produced thick sequences (35–50 m) with alternating beds of peloidal/bioclastic packstones and codiacean algal grainstones (A in Fig. 8). The packstone and grainstone facies was followed by a facies with abundant stromatolitic algal laminations and oncoids (B in Fig. 8). A coral/algal framework facies (C in Fig. 8) occurs above the algal laminated bindstone facies and the buildups are generally capped by a laminated dolostone facies (D in Fig. 8). Peloids are the most abundant allochems in the buildups, present in all facies but the laminated dolostone facies.

Lower Winnipegosis Formation

Bioturbated mudstone facies

This facies has a mudstone texture, with 5–10% bioclasts (dominantly crinoids and brachiopods), and can be composed of dolostone or limestone. It is mottled (Pl. 1C), probably as a result of bioturbation, and pyrite is a common accessory mineral. Poor preservation of the burrows precludes identification of specific ichnogenera. This facies

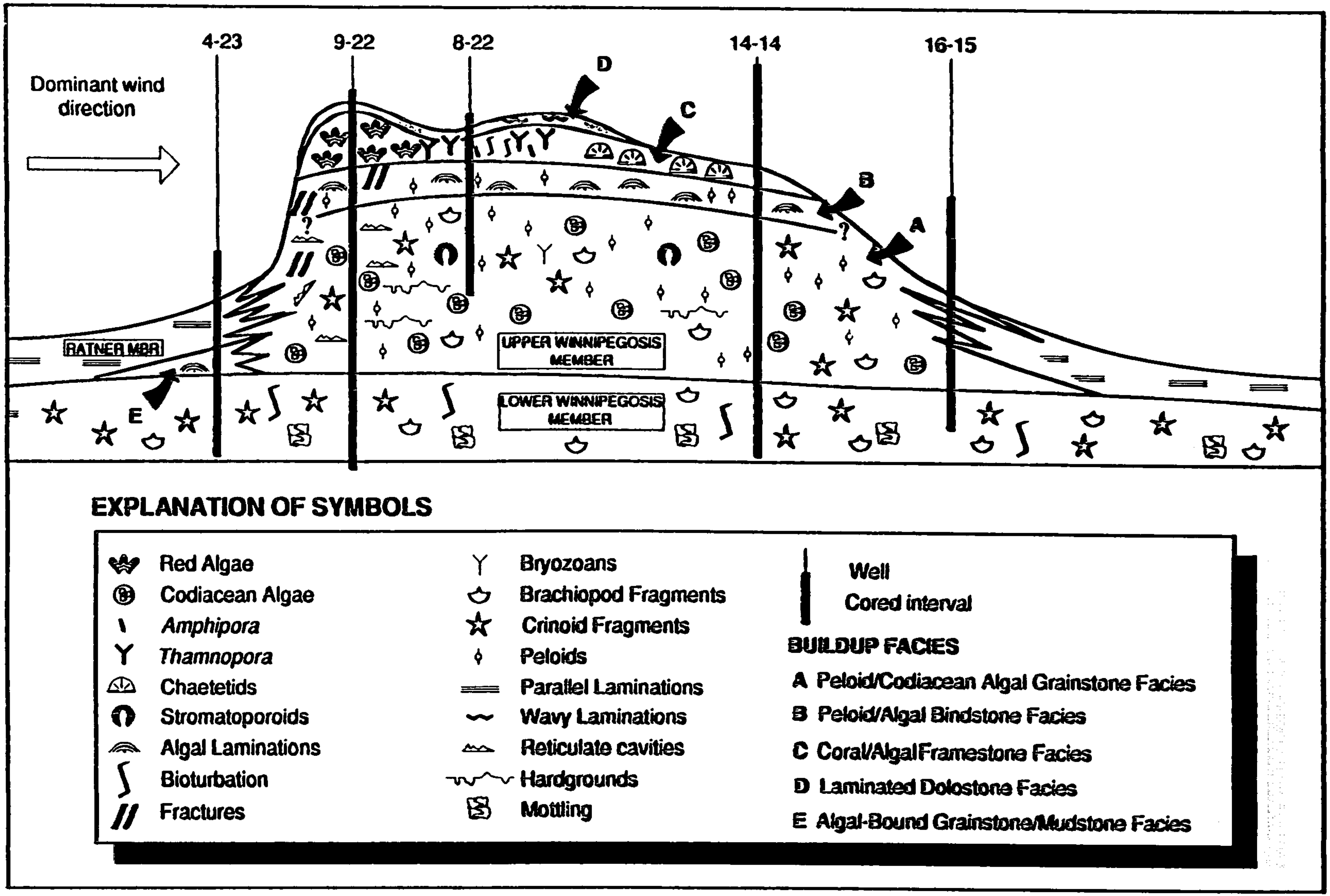


Fig. 8. Schematic cross-section through the Tableland buildup.

was deposited on top of the Ashern Formation and represents initial deposition on the Winnipegosis platform. Perrin (1982) suggested that deposition of the lower member represents a restricted subtidal environment during renewed transgression of the Elk Point Sea.

Crinoid/brachiopod mudstone to wackestone facies

The upper 4 m of the Lower Member is dominantly a crinoid and brachiopod mudstone to wackestone, with rare codiacean algae fragments and local bioturbation (Pl. 1B). This facies is dominantly dolostone, however, it is locally composed of limestone. It occurs above the bioturbated mudstone facies, and represents the last deposits on the Winnipegosis platform prior to buildup formation. The diversity of organisms in this facies suggests that it was deposited from normal marine water.

Ratner Member

Bituminous laminite facies

This facies (Fig. 8) is a dolostone with a mudstone texture. It is thinly laminated with abundant discontinuous bituminous laminations (Pl. 1D). Nodules of anhydrite, up to 1 cm long, are locally common in the upper 2–3 m of the facies (Pl. 2A), and bioclasts are absent throughout. The bituminous laminite facies occurs exclusively in the Ratner Member, and represents sediments deposited in the basin under conditions of restricted circulation. This facies overlies and is intercalated with flank deposits of the Upper Member.

Upper Member

Mottled mudstone facies

This facies is a dolostone with a mudstone texture (Pl. 2B). It has irregular mottling with laminated mudstone locally filling voids. No bioclasts are present. The sediments in this facies have been pervasively recrystallized, and few original textures can be identified. This facies is present within 2-3 m of the base of the buildups, and 20-40 cm thick. The mottling may be a result of bioturbation, and the lack of bioclasts suggests perhaps a stressed environment, or rapid deposition.

Peloidal/bioclastic packstone facies

Peloids (types I and II) form 75% or more of the allochems in this facies (A in Fig. 8). Bioclasts, including codiacean algae, brachiopods, ostracods, crinoids, gastropods, foraminifera and corals (*Thamnopora*) form the remainder of the allochems. The bioclasts are commonly unbroken. Recrystallization has obliterated many of the original textures. This facies contains no micrite other than that remaining in some peloids and micrite rims. The allochems are in a matrix formed of microcrystalline dolomite crystals, which probably represent recrystallized micrite. Bedding is generally absent.

Peloidal packstones are the most extensive and variable units in the Winnipegosis Formation. In one form or another peloidal and bioclastic packstones represent over 80% of the rocks in the buildups. They occur in all wells in this study and occur in roughly the same position in all three buildups.

In the 9-22 core, the mottled mudstone facies (Pl. 2B) is overlain by crinoid/peloid/bryozoan packstones and grainstones, containing abundant steeply dipping (25-30°) fibrous cement-lined cavities (Pl. 2C). The mottled mudstone facies and this portion of the peloid/bioclastic packstone facies are considered to represent foreslope deposits of the buildup, which were stabilized by synsedimentary marine cementation (Martindale and MacDonald 1989).

The diversity of organisms in this facies suggests that it formed in a normal marine environment with good water circulation, probably as a series of coalesced banks or shoals.

Codiacean algal grainstone facies

Interbedded with the peloidal packstone are beds composed almost exclusively of codiacean algal fragments (included in A in Fig. 8; Pls. 2D, 3A).

Litanaia Maslov is the dominant codiacean alga present in the Winnipegosis buildups examined in this study. Typically the fragments are composed of a cylindrical sheath (thallus), up to 5 mm in diameter, enclosing numerous (between 2 and 30) internal tubes (tubules), up to 250 µm in diameter (Pl. 3B). They were possibly composed of fine aragonite needles similar to modern codiacean algae, and their mechanical breakdown may have contributed a significant percentage of the micrite originally present in the Winnipegosis sediments.

Litanaia occurs as unabraded fragments up to 2.5 cm long and as dissociated tubules. Articulate fragments tend not to occur with other allochems and are commonly held in a matrix of 10–70 µm dolomite crystals. Porosity in this facies is generally poor but is locally excellent. Although there is little internal bedding, elongate algal fragments are locally imbricated. In two cores, 9-22 and 14-35, reticulate cavities are well developed in the codiacean algal grainstones. Where these cavities are sediment filled the codiacean algal grainstones have poor porosity, and where open the porosity is excellent.

Contacts between peloidal and codiacean algal grainstones, throughout the buildups, have dips averaging 20–30° but locally can be as high as 50°. Beds of codiacean algal grainstones and peloidal packstones are 2–40 cm thick. In the lower part of the grainstone facies, codiacean fragments are loosely packed and cemented by fibrous marine cements, resulting in the formation of an extensive network of shelter cavities. Filling of these shelter cavities locally resulted in severe reduction of the reservoir quality of this facies. In the upper part of the facies the shelter cavities are absent, and the codiacean fragments decrease in size and abundance.

The peloidal/bioclastic packstone facies and the interbedded codiacean algal grainstone facies, which form most of the reservoir in both the Tableland and 14-35 buildups are up to

40 m thick (Martindale and MacDonald 1989; Fig. 8). In the reservoirs, however, there is a marked lateral and vertical differentiation of facies. In the 8A-22 core, the packstone/wackestone facies consist of a homogeneous bed (23 m thick) of well-preserved peloids and codiacean algae with excellent porosity and permeability. In the 9-22 and 14-35 cores, however, the grainstone facies is thicker with more variable reservoir quality.

The deposition of this facies was intimately associated with that of the peloidal/bioclastic packstone/wackestone facies. Although the diversity of organisms in the codiacean algal grainstone facies is low, suggesting deposition in a stressed environment, modern sands forming in normal marine lagoons locally are composed almost exclusively of codiacean algal fragments (Flügel 1978, p. 334). In addition, recent work in the Caribbean, the Java Sea, and the Great Barrier Reef has revealed the occurrence of bioherms dominantly composed of fragments of the codiacean algae *Halimeda* (Hine *et al.* 1988; Roberts *et al.* 1988). Hine *et al.* (1988) described *Halimeda* bioherms from the Nicaraguan Rise in the southwest Caribbean Sea which have up to 140 m relief. The tops of these bioherms are in 40–50 m of water. Samples dredged from the bioherms in the Java Sea are dominated by *Halimeda* fragments in a lime mud matrix. The bioherms lack reef building corals, and boring by endolithic algae is extensive (Roberts *et al.* 1988).

These *Halimeda* bioherms appear to be a modern analog for the deposits of codiacean algal grainstone and peloid/bioclastic packstone facies in the Winnipegosis buildups. These facies were probably deposited from algal meadows on a series of coalesced shoals. The lack of a mud matrix suggests that there was sufficient current to prevent micrite deposition and the orientation of algal fragments suggests they were current oriented or deposited from grain-flows.

Algal laminated bindstone facies

This facies (B in Fig. 8) contains abundant peloids, brachiopods, ostracods, crinoids, and bryozoans, locally abundant oncoids, and rare corals (*Thamnopora*). This facies is characterized by an almost complete absence of codiacean algae and by the first appearance of chaetetids in the 14-35 core (Pl. 3C). The most distinctive features, however, are algal laminations. Laminations in both the bindstone and oncoids are composed of micritic and fine crystalline sucrosic dolomite. Porosity of this unit varies from 5% to almost 20%, with an average of 10–15%. The algal laminations are developed in a peloidal and bioclastic grainstone to wackestone. All peloids and bioclasts are highly altered and corroded by recrystallization, leaching, cementation, and dolomitization. This facies is well developed in the Tableland and 14-35 buildups and its thickness varies from 5–8 m. Except for scattered algal laminations and oncoids this facies is essentially absent from the 11-16 buildup. Also included in this facies are bioturbabted mudstones forming an extremely porous interval in the 8A-22 well (Pl. 4C; Martindale and MacDonald 1989).

The presence of the micrite and blue-green algal laminations suggest deposition in a protected quiet water area (Wilson 1975). Oncoids, however, indicate there was some water movement.

Coral/algal framestone facies

This facies (C in Fig. 8) is composed of *in situ* digitate red algae (*Solenopora;* Pl. 3D), *Thamnopora* (Pl. 4A) and chaetetids. The skeletons formed rigid frameworks with intervening shelter cavities that contain peloidal and bioclastic dolostones. Laminations, formed by blue–green algae (locally identifiable as *Sphaerocodium*), are common on the upper surfaces of the red algal colonies (Pl. 4B). Preservation of *Thamnopora* is generally in the form of micrite envelopes, and the microstructure has been replaced by microspar. There is good to excellent porosity between the crystals in the skeletons. In addition *Thamnopora* and chaetetid fragments display excellent intraparticle and moldic porosity. The skeletons of the red algae have been extensively leached and only locally is original microstructure structure preserved, by micritic outlines and rims (Pl. 4B). Porosity in this facies averages 10–15% but locally is up to 20%.

This facies is present in all buildups in this study. Red algae form the framework in the 11-16, 14-35 and the 9-22 (Tableland) cores. Red algae were important frame building algae in the Upper Devonian Swan Hills Judy Creek and Carson Creek North reef complexes in Alberta (Wray and Playford 1970). *Thamnopora* is the dominant frame-building organism in the 8A-22 core (Tableland). The top of the buildup in the 8A-22 core is 7 m lower in elevation than in the 9-22 well, and in a more restricted position on the buildup (Figs. 4, 8). The 14-14 well, drilled in an even lower position on the buildup and closer to the flank than the 8A-22 well, has chaetetids as the dominant frame-builder (Fig. 8). This facies rests conformably on the algal laminated bindstone facies and is 1–2 m thick.

A diverse fauna in the shelter cavities between colonies suggests that this facies formed in a normal marine environment, and the presence of *Solenopora* suggests a high energy area such as a reef flat (Wilson 1975). This facies represents deposition during the only time the Winnipegosis buildups could have been considered reefs.

Laminated dolostone facies

The laminated dolostone facies (D in Fig. 8) is thinly laminated and composed of microcrystalline dolomite crystals, and contains no recognizable allochems (Pls. 4D, 5A). The laminations are generally less than 1 mm thick, commonly with contorted and discontinuous organic laminations. Near the top of this facies, fractures, 1–5 cm wide, are filled with chaotically laminated mudstone (Pl. 5B).

This facies occurs above the coral/algal framestone facies, in the 14-35 and Tableland buildups. Although not present in the 14-14 Tableland well this is the uppermost facies in most of buildups. The 16-11 well was not cored above the framestone facies. The facies is generally less than 1 m thick.

The origin of this facies is difficult to determine. Examples from core are similar to cryptalgal fabrics illustrated by Flügel (1982, Fig. 3, p. 223) and thus may have formed as microbial mats. However, other examples from core appear similar to calcretes illustrated by Wright *et al.* (1988, Fig. 5, Fig. 9). Regardless of its mode of formation the lack of bioclastic and peloidal materials suggests that it formed in a stressed environment unable to support normal marine fauna. The stress was either increased salinity or subaerial exposure.

Facies model

Perrin (1982), Perrin and Precht (1985), Precht (1986), and Perrin (1987) divided the deposition of the Winnipegosis Formation into three phases. Phase one represented transgression over an undifferentiated basin. Differentiation of the basin and the formation of organic buildups occurred in the second phase, and during the third phase, shallowing of the sea subjected the buildups to evaporative conditions and vadose diagenesis. This tripartite subdivision of Winnipegosis deposition is also recognized in this study.

The bioclastic and bioturbated mudstone facies, representing the Lower Member, were deposited during a period of renewed transgression of the Elk Point Sea after emergence at the end of Ashern deposition. This represents deposition during Perrin's (1982) phase 1. During this time (Eifelian) the basin was a broad platform and experienced shallow marine deposition (Precht 1986). Precht (1986) and Kent (1984) suggested that the waters were poorly oxygenated and circulation was restricted since the rocks are highly bituminous and argillaceous. However, this interpretation is not followed here, because the high faunal diversity in these deposits suggests good circulation in an open marine environment (Heckel 1974). Deposits of this phase are similar throughout the basin and represent the same environment regardless of where they are located in the basin.

The organic buildups of the Upper Member represent deposition during the second phase of Perrin (1982). During this time (Givetian), the Elk Point Sea transgressed to its maximum extent, and the Elk Point Basin differentiated into two distinct regions: a "shallow" shelf, and a "deep" basin. (Figs. 7, 9; Perrin and Precht 1985). The bituminous laminites of the Ratner Member represent the basinal deposits. The basinal environments existed throughout most of Saskatchewan and the northern portion of North Dakota, while shelf environments were restricted to the margin of the basin, preserved in northeastern Montana, and parts of northwestern North Dakota (Fig. 7). Materials in this study were deposited in the basin approximately 45 km from the margin of the shelf. By the end of this phase shallowing of the sea had begun as a result of desiccation of the basin (Perrin and Precht 1985).

Wilson (1975) suggested that the formation of ancient carbonate buildups can be divided into five stages (Fig. 10). These stages are present in the buildups in this study. Stage one represents hydrodynamic accumulation of sediment on pre-existing topographic highs. Although the reason for the localization of Winnipegosis buildups is uncertain, they may have initiated on tectonically raised blocks. Stage two represents the establishment of baffling and binding organisms such as crinoids and algae. This stage is represented by the codiacean algal grainstone and peloid/bioclast packstone facies (Figs. 8, 10). Wilson's (1975) third phase represents stabilization of the buildup by surface encrustation. In the Winnipegosis buildups this phase is represented by the algal laminated bindstone facies (Figs. 8, 10). Stage four represents growth of a cap of frame-building and encrusting organisms. In the Winnipegosis buildups this phase is represented by the coral/algal framestone facies (Figs. 8, 10). Wilson's (1975) fifth phase is protection and stabilization of the buildups by early marine cementation. However, rather than being a distinct phase, cementation of the Winnipegosis buildups appears to have been contemporaneous throughout their deposition.

Buildups show about 50 m of relief in relationship to the basinal deposits, implying that at maximum transgression the Elk Point Sea was at least 50 m deep. This is well within the photic zone for modern reefs (Martindale 1976); however, factors such as amount of incident light, degree of hydrodynamic exposure, temperature, salinity and nutrient content of the water are not known. Thus, light availability cannot aid in

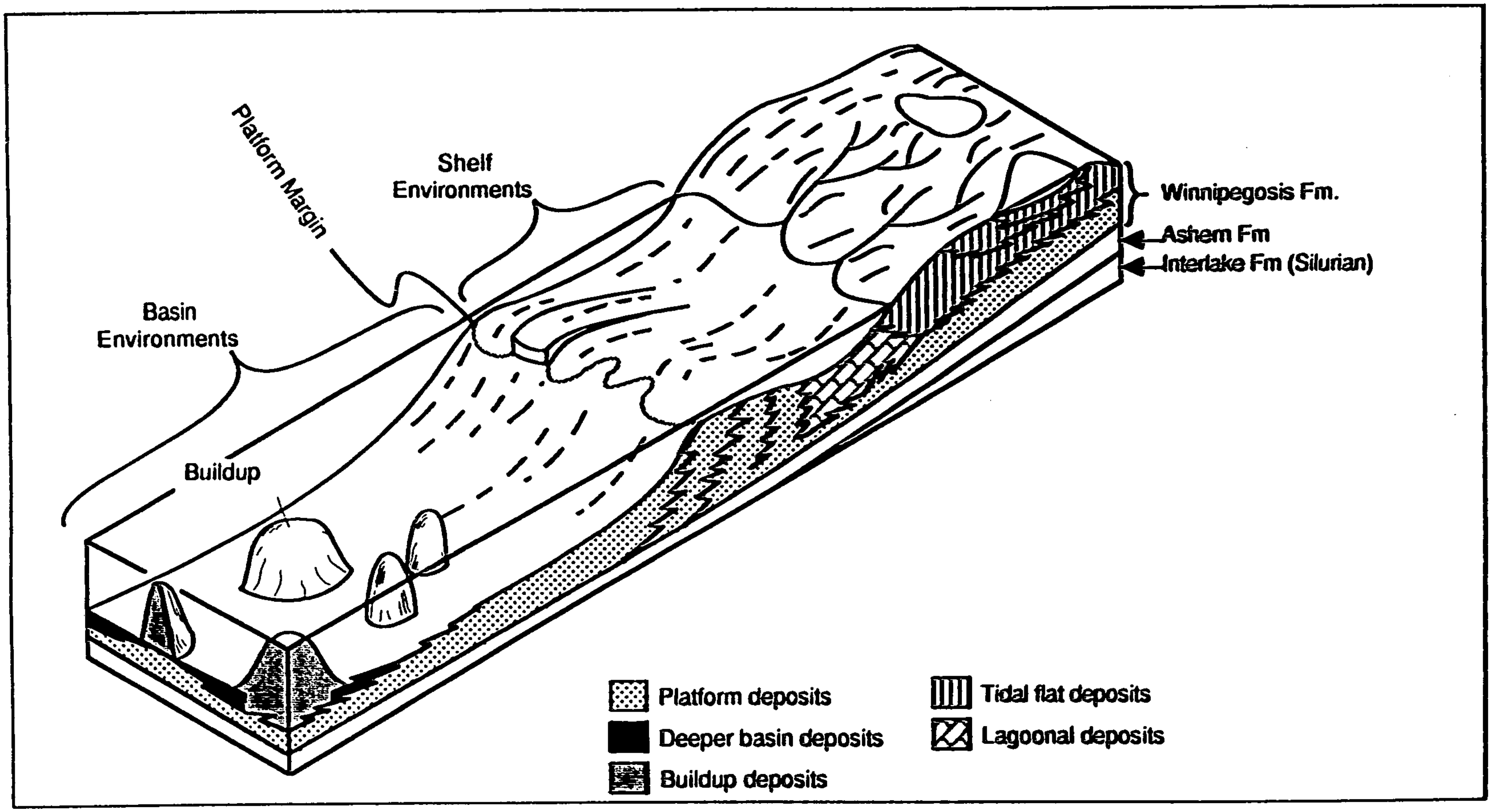


Fig. 9. Winnipegosis Formation depositional environments during the early Givetian, after the Elk Point Basin differenciated into distinct shelf and basin environments (modified from Perrin 1982).

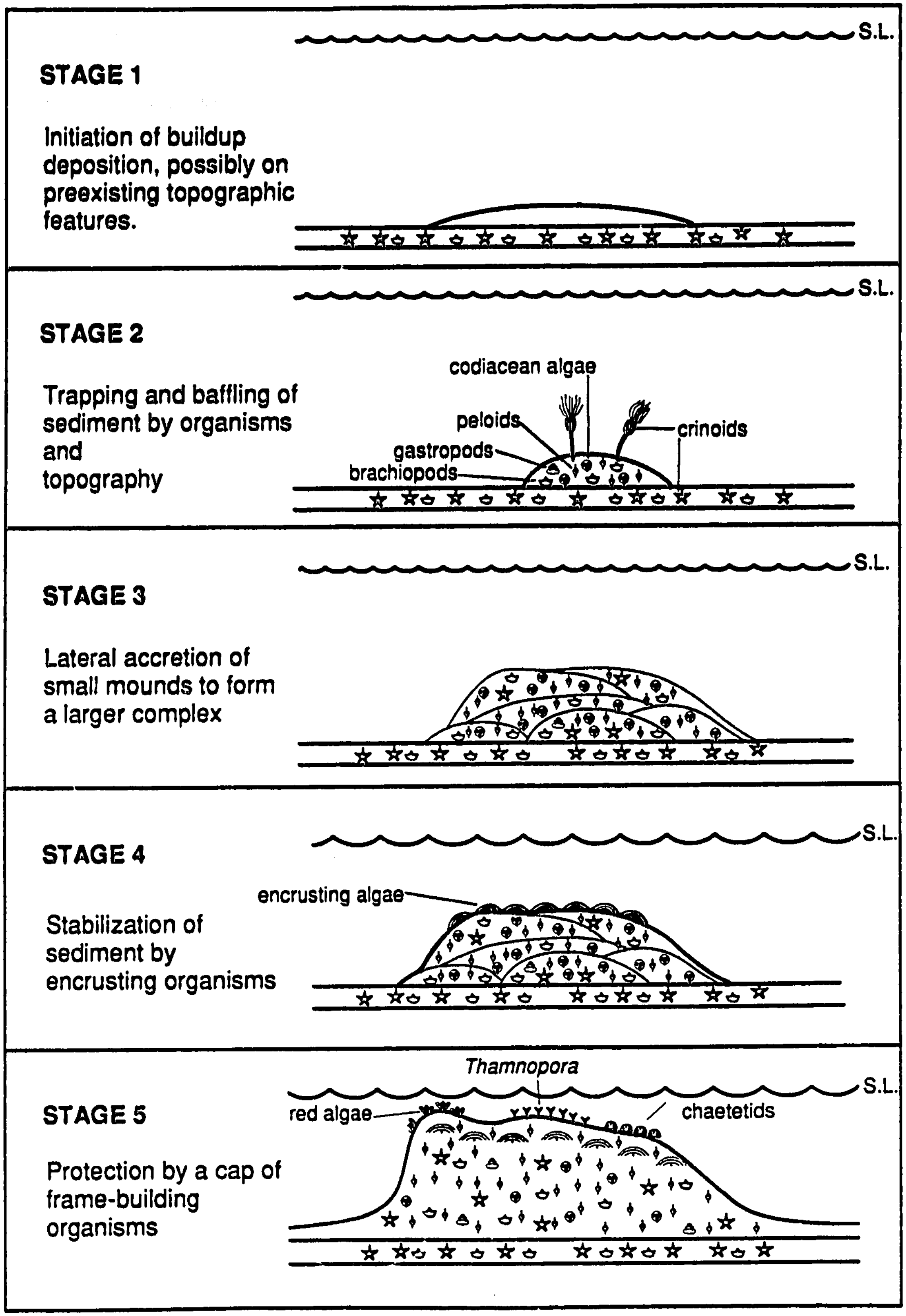


Fig. 10. Development of Winnipegosis buildups.

determining the depth to the tops of the buildups. The abundance of the peloid/bioclastic packstone facies and the abundance of micrite at time of deposition suggests that water energy was low and the depth was below fair weather wave base, or that the water was so shallow that effective wave action did not exist (Wilson 1975, p. 364). In the context of the Elk Point Basin it seems unlikely that the latter conditions existed.

The red alga, *Solenopora*, which locally dominates the coral/algal framestone facies, is similar to the modern alga *Lithophyllum*. This morphological similarity suggests growth in a shallow high energy, well-lit environment (Martindale 1976; Tracey *et al.* 1948; Ladd *et al.* 1950; Johnson 1961; Adey and Macintyre 1973) possibly at depths of less than 8 m (Martindale 1976). This suggests that sedimentation occurred at a greater rate than basin subsidence, and that the succession of facies in the buildups may represent a large scale shallowing upward sequence.

During the third phase of Winnipegosis deposition (Perrin 1982) sea level decreased and the tops of the buildups were exposed to shallow marine and/or subaerial conditions (Perrin 1982; Perrin and Precht 1985). These conditions are represented by the laminated dolostone facies. The absence of this facies from the 14-14 Tableland well, the structurally lowest core in the Tableland buildup, could be an indication that this portion of the buildup was not exposed, or that it was encased in evaporites prior to exposure. At the end of this phase of deposition, anhydrite and fine grained carbonates were deposited, eventually becoming mostly anhydrite. These deposits grade-up into massive anhydrite and halite of the Prairie Evaporite Formation.

CHAPTER IV — DIAGENESIS OF MATRIX AND ALLOCHEMS

Introduction

All allochems in the Winnipegosis Formation of the study area have been recrystallized and completely dolomitized. The poor preservation of original textures does not allow accurate reconstruction of original composition; therefore, assumptions regarding original textures are based on the neomorphic and dolomitization products.

Matrix and allochems display two types of cathodoluminescence. Coarsely crystalline material displays a dull orange luminescence, whereas areas dominated by microspar and micrite (i.e. peloids and micrite rims) correlate to areas of bright orange luminescence. This brighter luminescence, rather than by the trace element content, may be controlled by the finer crystal size of the dolomite or the presence of organic materials.

The patterns of fluorescence are similar to the patterns of cathodoluminescence, with most of the non-luminescent areas also being non-fluorescent. Areas of micrite and microspar (i.e. peloids and rims on allochems) fluoresce bright green.

Micrite envelopes

Except for crinoids, the allochems are outlined by micrite envelopes (Pl. 5C). and they are generally responsible for preserving the shape of bioclasts. The envelopes are composed of anhedral crystals of dolomite 2-4 μm across (Pl. 5D), and are between 5 and 20 μm thick. The poor preservation of bioclastic material in the Winnipegosis buildups makes it difficult to determine if the micrite envelopes formed constructively (*cf.* Kobluk and Risk 1977), destructively (*cf.* Bathurst 1975) or by inorganic precipitation (*cf.* Alexandersson 1972).

In modern sediments, inorganically precipitated micrite is most abundant in intraparticle porosity. In this study micrite envelopes are most abundant on the outer surfaces, but also occur in intraparticle pores in codiaceans, red algae, and *Thamnopora* fragments. Although the micrite envelopes on the outer surfaces of fragments probably did not originate through inorganic precipitation, those in internal pores may have.

Swinchatt (1969), from work on the Great Barrier Reef, suggested that abundant algal-bored grains indicates sedimentation in less than 40 m of water, and probably in less than 18 m. Swinchatt (1969) also noted that micritization of grains on the Bahamas-Florida platform normally occurs in water less than 12 m deep. By analogy this suggests that micritized grains and peloids in the Winnipegosis Formation probably formed in relatively shallow water.

Bioclasts

Preservation of Litanaia *fragments*

Preservation of *Litanaia* fragments is variable with internal tubules commonly not preserved. Fragments are also commonly disarticulated with only individual tubules being preserved. Well preserved fragments display thin (5–10 μm) micritic rims on the surface of the outer sheath and the interior of the tubules. Tubules are commonly filled with micrite or microspar dolomite and have a dark brown to black color (Pl. 3B). Between the outer sheath and the tubules is a matrix of 50–120 μm anhedral to subhedral crystals with a blocky mosaic texture.

Porosity between the coarse blocky mosaic dolomite crystals in the fragments is good to fair and is dominantly microvuggy and intercrystalline. Vugs are irregular in shape from 50–200 μm long and 25–70 μm wide. Late anhydrite cement commonly occurs in the pores. Generally there is no porosity between the microspar crystals in the tubules.

Coniglio and James (1985) suggested that peloids, in the Middle Cambrian to Middle Ordovician Cow Head Group, formed as a result of fragmentation of micrite and microspar filled tubules of the calcified alga *Girvanella*. In the Winnipegosis Formation, brecciation of dissociated micrite or microspar filled tubules of the calcified green alga *Litanaia* also appear to have made a significant contribution to peloid formation. Coniglio and James

(1985) suggested this method of peloid formation because the peloids commonly have sizes and characteristics similar to the algal tubules. This is also true for the peloids and codiacean algae tubules in the Winnipegosis buildups.

Preservation of Thamnopora

Thamnopora fragments are rare in the Winnipegosis buildups examined in this study, except in the 8A-22 core of the Tableland buildup, where it dominates the framestone facies. Fragments are 5–10 mm in diameter, and up to 10 cm long. Original skeletal microstructure is commonly preserved around the outside edges and internal pores, where it is represented by a fibrous texture which displays a sweeping extinction. Around the internal pores the fibrous microstructure extends into the coral skeleton for 75–125 µm (Pl. 5E). Parts of the coral skeleton not retaining original microstructure are composed of anhedral to euhedral microspar dolomite crystals (Pl. 5E).

Micrite envelopes and up to four cement generations occur in the intraparticle porosity of *Thamnopora* skeletons (Pl. 5E). Although a distinct succession of cements can be documented for most of the pores, the succession varies from pore to pore even though the pores may be close (50 µm) together. Micrite rims (10–25 µm thick) occur in all pores (Pl. 5E), and are similar to those formed on intraparticle porosity in recent corals from Grand Cayman, British West Indies. They may be inorganic precipitates as described by Alexandersson (1972) or destructive micrite envelopes similar to Mg-calcite micrite rims illustrated by James *et al.* (1976, Figs. 15*a*, *b*) from the Belize reefs. The first generation (phase I) of cement precipitated in most pores is a fibrous isopachous cement, 50–60 µm thick. This cement has a sweeping extinction and is in optical continuity with the coral's microstructure (Pl. 5E). Rarely there is an isopachous blocky cement precipitated on the syntaxial cement (phase II; Pl. 5E). The crystals (of phase II cement) are subhedral to euhedral and are 25–60 µm long. The isopachous rims are 50 µm thick and commonly display a sweeping extinction in optical continuity with the underlying fibrous cement. In the centre of the tubes there is commonly a coarse blocky cement (phase III; Pl. 5E). The crystals are euhedral to subhedral (30–110 µm on a side) and are randomly distributed. Locally this cement fills the tubes. The last phase of cement precipitated in *Thamnopora* skeletons is coarse (300–625 µm long and 50–250 µm wide) bladed anhydrite (phase IV). Generally this cement does not occlude porosity.

Thamnopora in the framestone facies in the 8A-22 Tableland core are commonly leached, providing excellent moldic porosity (Pl. 5A). Where skeletons are preserved the intrafossil porosity lack micrite rims and cement phase II; phase III cement is rare.

Preservation of crinoids

Crinoid fragments, 0.1–5 mm in diameter, are abraded and unabraded, with crinoid stems and calices locally still articulated. Commonly the centres of fragments have been replaced by sucrosic microspar (Pl. 6B), and rarely fragments have been completely replaced. Where dissolution has resulted in complete or near complete removal of the crinoid fragment coarse blocky euhedral to subhedral dolomite and coarse bladed anhydrite almost occlude the mold. Crinoid fragments are the only bioclasts which do not display micrite envelopes.

Syntaxial overgrowths are common on the crinoid fragments; however, they are always thin (generally less than 15 µm), except where crinoid fragments bordered shelter pores, where they are significantly thicker (up to 75 µm; Pl. 6B). Crinoid skeletons are formed of magnesium calcite with a lattice work of fine pores, giving fragments as much as 50% porosity. Commonly these pores are filled by syntaxial overgrowths, however, this has not been observed in the crinoids in this study. Rather the canals are preserved as irregular shaped inclusions generally less than 3 µm across. Folk and Siedlecka (1974) suggested a number of explanations for the lack of overgrowths in the internal pores in the crinoids from the Spirifer Limestone, Bear Island, Svalbard. As a crinoid fragment's mineralogy stabilizes by the loss of Mg $^{2+}$, the Mg^{2+}/Ca^{2+} ratio of the pore water in the crinoid fragment rises to values higher than that on the outside of the fragment. This high Mg^{2+} content may have poisoned the nucleation of low-magnesium calcite in the internal pores. Evamy and Shearman (1965, 1969) suggested that syntaxial overgrowths grow preferentially in the c-crystallographic direction and canals may not fill in since it would require growth in minimum growth direction of the crystal. Both of these possibilities may explain why the canals in the crinoid fragments in this study were not infilled with syntaxial cements.

Preservation of ostracods

Ostracods are common throughout all buildups but they are not generally abundant. Their shell material has been removed and their outline is only discernable due to the presence of a thin (<10 μm) micrite envelope. A fibrous cement occludes the shelter porosity in all the shells (Pl. 6C).

Preservation of brachiopods and gastropods

Although brachiopods are common in all facies, gastropods are rare. In most cases the shells have been leached and the molds are now lined or filled with fine dolomite crystals with a blocky mosaic texture. As all the brachiopod and mollusc shells have been leached and the molds filled with blocky calcite cement, this process probably occurred in a shallow burial environment. The outer surface of the shells are preserved as micrite rims, or they have encrustations of blue-green algal lamination (Pl. 6D), up to 0.5 mm thick. Commonly there is a geopetal bioclastic and peloidal sediment partially filling articulated brachiopod shells (Fig. 11; Pl. 6D). The geopetal sediment pre-dates, and is coeval with, a submarine isopachous fibrous cement (Pl. 6D), up to 750 μm thick. Rarely this fibrous cement can be recognized as being radiaxial. The fibrous cement is post-dated by a blocky isopachous cement, which forms rims up to 250 μm thick. This cement commonly displays a leached zone, with the resultant pore filled or partially filled with bladed anhydrite (Pl. 6D). The

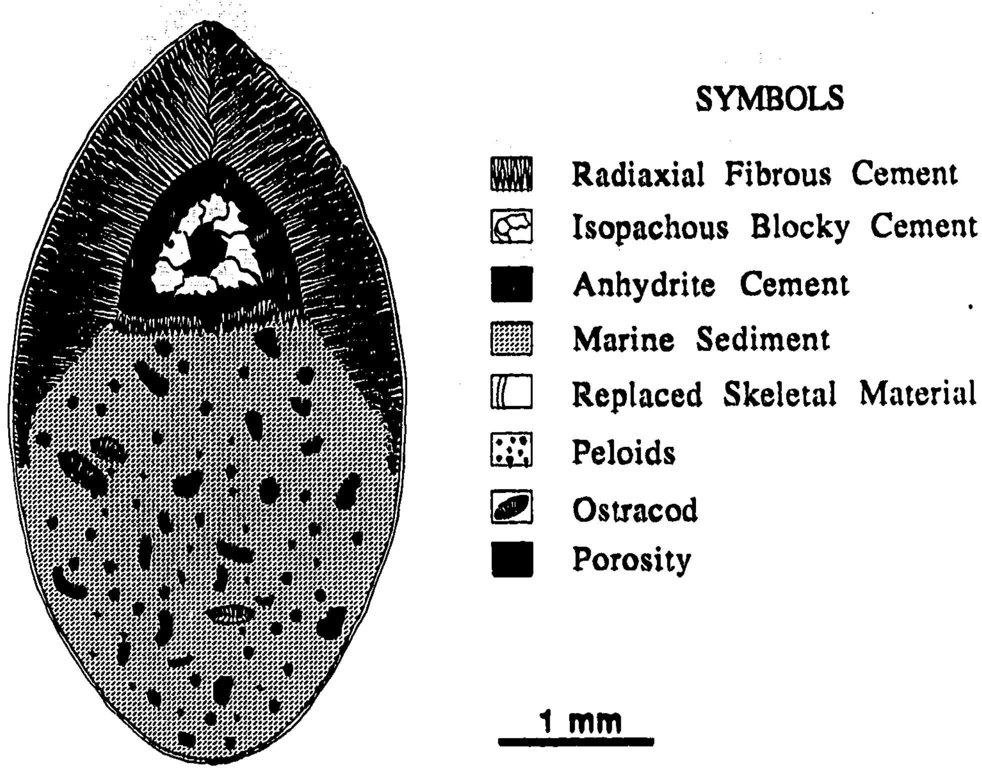


Fig. 11. Diagenetic fabrics in a brachiopod, from the coral/algal framestone facies.

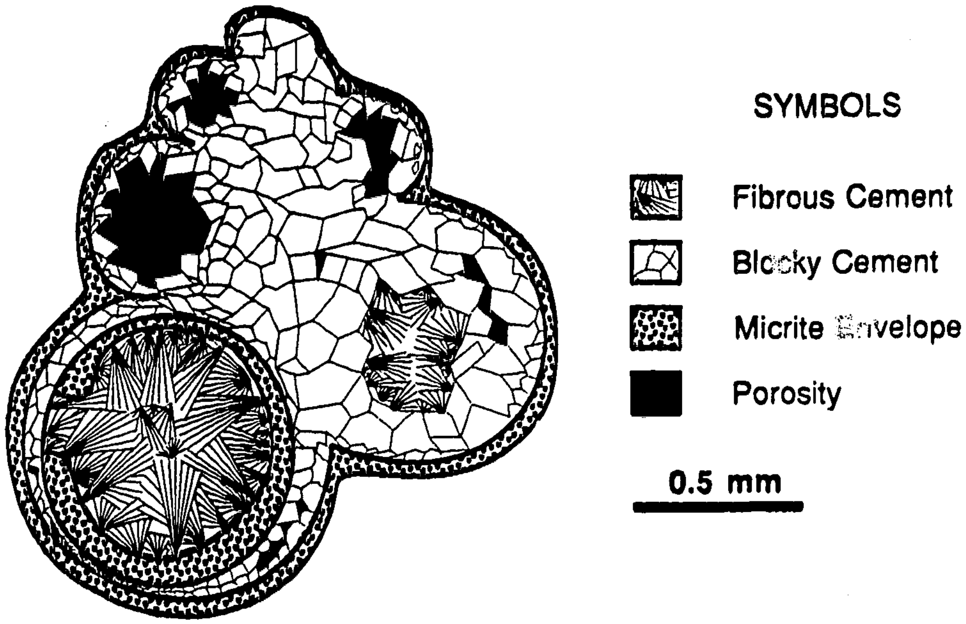


Fig. 12. Diagenetic fabrics in a gastropod from the coral/algal framestone facies.

blocky isopachous and anhydrite cements have not been observed in gastropods (Fig. 12; Pl. 6E).

Preservation of Solenopora

Commonly 75–80% (locally up to 100%) of the algal skeletons have been leached, and the resultant molds filled with a 70–200 µm pore–filling blocky mosaic cement (Pl. 6F). Portions of red algal skeletons not leached are commonly along the outside edge of the colonies with scattered patches distributed throughout the interior of the colonies (Pl. 4B). Blue green algal laminations commonly occur on the top surfaces of the colonies (Pl. 4B). Some of the algae in these encrustations are branching tubular filaments, which in a transverse section appears chain–like. This alga has been identified as *Sphaerocodium*, a stromatolitic algae commonly found in Devonian carbonates (Wray and Playford 1970).

Peloids

Type I peloids (Pl. 7A) display a mode of preservation similar to codiacean algal fragments. This suggests that type I peloids probably represent rounded skeletal fragments with micrite rims, or fragmented *Litanaia* tubules. During recrystallization and dolomitization the interiors of the fragments recrystallized to a blocky spar or were leached and replaced. Type II peloids (Pl. 7B), because they are homogeneous and composed of micrite or microspar crystals, may have originally been fecal pellets.

Preservation of the matrix

The matrix is composed of a blocky mosaic of anhedral, subhedral and euhedral microspar dolomite; however, some crystals are up to 100 µm long (Pl. 7A). This microspar matrix was proabably micrite which coarsened during aggrading neomorphism as described by Folk (1965), Flügel (1978), and Lasemi and Sandberg (1984). This was also suggested for the microspar matrix in Winnipegosis mounds in central Saskatchewan by Wilson (1985). Abundant inclusions (1-3 µm) in the crystals give them a dusty appearance. Locally there are areas with micritic outlines which could represent severely altered bioclast or molds filled by a coarse spar cement. Porosity in the matrix is highly variable, from 0–40%, and is dominantly intercrystalline and microvuggy.

The environmental conditions conducive to aggrading neomorphism of micrite were not understood by Folk (1965). Chafetz (1972), however, suggested that this phenomenon could result from surface weathering of carbonates. There is no evidence that the buildups were exposed to vadose conditions to the extent that all micrite in the buildups could be transformed to microspar. Machel (1986) described neomorphism of micrite to microspar in the Nisku reefs of Alberta, and suggested that this transformation occurred in diagenetic fluids in a shallow to intermediate burial environment. This also appears likely for the microspar in this study.

CHAPTER V — CEMENT FABRICS

Introduction

The term cement is used here to describe all passively precipitated, space-filling carbonate crystals (Bathurst 1975). Most cements have been recrystallized and dolomitized. Therefore, cement types are referred to in textural terms only, and original compositions and environments of precipitation are inferred from a comparison with modern analogs. Cement fabrics recognized in the Winnipegosis buildups in this study are diverse. Cement morphologies with a probable calcite (possibly aragonite) precursor include: fibrous isopachous (Tucker 1973; James and Ginsburg 1979; Longman 1980; James and Choquette 1983; Harris *et al.* 1985); radiaxial fibrous (Kendall and Tucker 1973; Tucker 1973; Bathurst 1975; Davies 1977; James *et al.* 1988); blocky isopachous (Halley *et al.* 1983; Wilson 1985); scalenohedral (Tucker 1973; Flügel 1978; Halley *et al.* 1983; Jones *et al.* 1984; Kerans 1985); and syntaxial (Evamy and Shearman 1965, 1969; Bathurst 1975; Walkden and Berry 1984; Kerans 1985; Kerans *et al.* 1986). These cements were precipitated early in the diagenesis of the buildups. Pore filling blocky mosaic cement was probably precipitated as an early dolomite cement (Folk and Siedlecka 1974). Limpid dolomite cement (Folk and Siedlecka 1974; Folk and Land 1975; Machel 1983), which occurs as syntaxial overgrowths on pre-existing blocky cement crystals, as well as quartz, and bladed anhydrite cement was precipitated late in the diagenesis of the buildups.

The early carbonate cements in this study all display a dull orange cathodoluminescence like that of the allochems and matrix. It is unlikely that the matrix, allochems, and all early cements had the same original trace element composition. This uniformity of luminescence could be a result of complete exclusion of quenching elements from the carbonates or more likely due to homogenization of trace element composition during recrystallization and/or dolomitization of buildups. The only carbonate cement which displays a luminescence different than the matrix and early cements is the late stage limpid dolomite cement.

The patterns of fluorescence are similar to the patterns of cathodoluminescence, with most non-luminescent areas also being non-fluorescent. Limpid dolomite cement is always non-fluorescent.

Cement types

Fibrous isopachous

This cement, forming isopachous rims 100–300 µm thick, is composed of elongate crystals with length/width ratios greater than 6:1. The crystals are oriented perpendicular to the substrate and the cement displays a sweeping extinction (Pls. 7C, 7D). Recrystallization has obliterated many of the original textures. Individual crystals are not sharply defined, because their edges are irregular and interpenetrant with adjacent crystals due to recrystallization. Commonly, the fibrous crystals have been recrystallized to mosaics of microspar with a relic sweeping extinction. Fibrous isopachous cement occurs in intraparticle (in articulated ostracods, Pl. 6C; corals, Pl. 5E; brachiopods) and interparticle porosity (Pls. 7C, 7D), occluding pores smaller than 0.5 mm. This cement, the first generation of cement precipitated in most primary porosity, occurs in all facies except the laminated dolostone facies.

The isopachous fibrous morphology suggests precipitation in a marine phreatic environment (Longman 1980, p. 465). From work on the Belize barrier reef, James and Ginsburg (1979) found that isopachous bladed Mg calcite (with sweeping extinction) is the most abundant cement in limestones from the lower part of the reef front, reef wall, and fore-reef. Harris *et al.* (1985) described isopachous fibrous aragonite occurring in crusts on shallow water carbonate platforms. These modern examples are similar to the fibrous cements in the Winnipegosis Formation. This similarity suggests that the fibrous isopachous cements in this study are of submarine origin (Fig. 13). Some examples of this

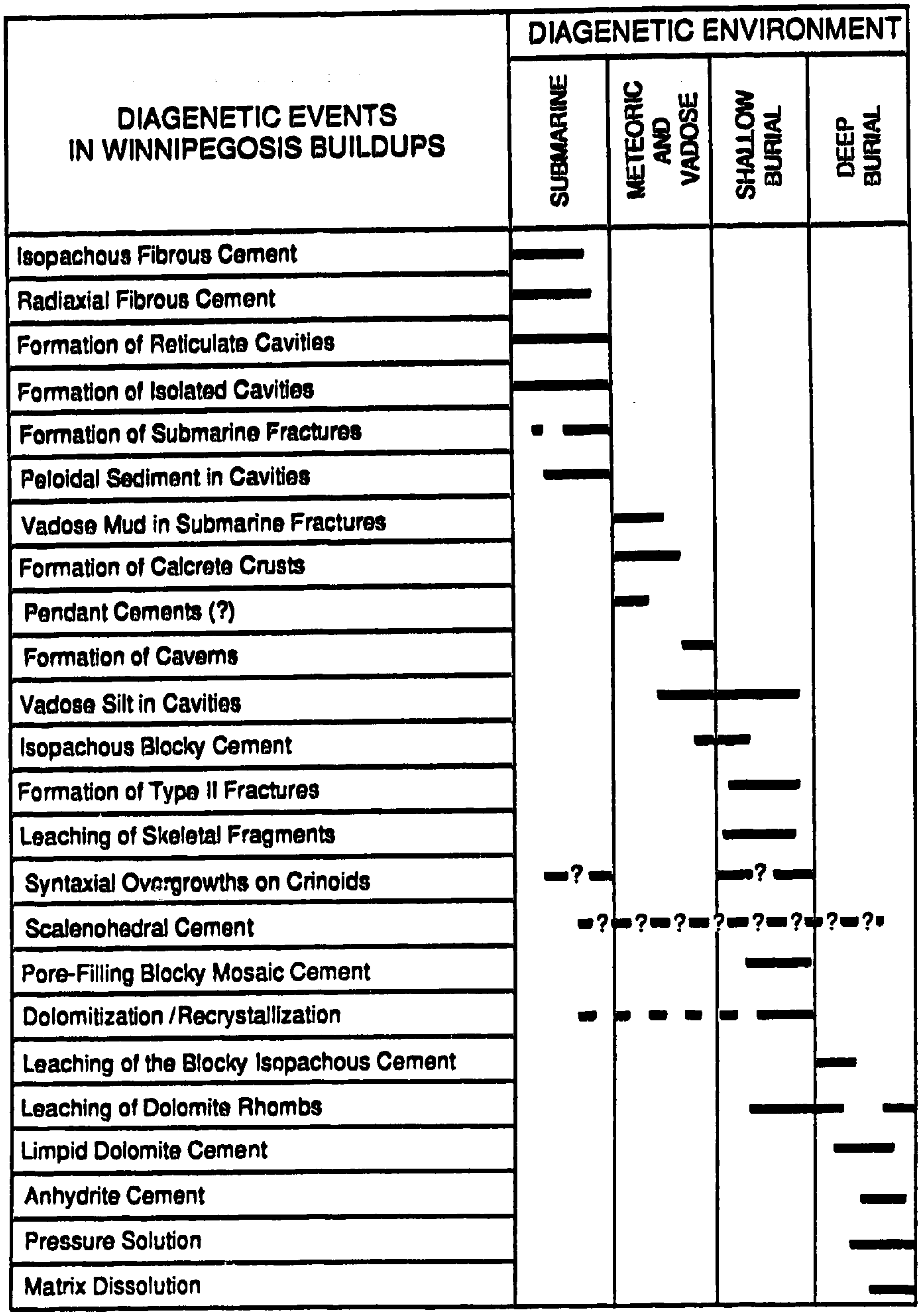


Fig. 13. Sequence of events in the diagenetic history of Winnipegosis buildups in southeast Saskatchewan.

type of cement may be recrystallization products of a radiaxial fibrous cement. Radiaxial and radial fibrous cements may be related to one another as end members of a spectrum, with the morphology of cement dependant upon the distance between nucleation sites on the substrate. If the distance is small, the number of sites is great and a botryoidal form is not produced. If the distance is great, the number of sites is small and botryoids are formed.

Radiaxial fibrous

Radiaxial fibrous cements are mosaics of fibrous crystals radiating from a common point on the substrate, forming botryoids of crystals 50–100 µm long and 30–50 µm wide (Pl. 8A). This cement is locally isopachous but also occurs as seemingly random mosaics filling pores less than 1–2 mm, and as patches in a micritic (now microspar) matrix. It occurs as isopachous crusts (50–500 µm thick) in brachiopods and cavities. It was precipitated contemporaneously and subsequent to internal sedimentation, but pre-dates the isopachous blocky cement. Radiaxial fibrous cements are not commonly recognized in this study, however, this may be due to lack of preservation.

Bathurst (1975) and Kendall and Tucker (1973) suggested that this type of mosaic represents a neomorphosed submarine cement with an original high magnesium calcite mineralogy. Davies (1977) and James *et al.* (1988) suggested that botryoidal calcite is neomorphic after submarine aragonite. Regardless of the original mineralogy this cement was probably precipitated in the submarine environment (Fig. 13). Where present it appears to be the first generation of cement.

Blocky isopachous

This cement is composed of coarse (100–225 µm) inclusion rich, blocky or equant anhedral to subhedral crystals with an overall sweeping extinction. It forms 100–200 µm thick isopachous rims which are generally one crystal thick (Pls. 6D, 8B, 8C). Abundant small (<5 µm) fluid inclusions give the crystals a dusty appearance. This cement lines partially sediment-filled shelter cavities and locally lines intraparticle porosity. It commonly overlies the radiaxial and radial fibrous cements; clearly post-dating them (Fig. 11). In the 9-22 Tableland core and the 14-35 core the basal portion of this cement commonly has been leached, with the resultant porosity partially or completely filled with a bladed anhydrite cement (Pls. 6D, 8B, 7C). This may be an indication that the earliest phase of the isopachous cement was chemically different from the remaining cement; it was leached when it was no longer in equilibrium with changing diagenetic fluids. This type of leaching is not so common in the 8A-22 and 14-14 Tableland cores. This type of cement dissolution has been described by Havard and Oldershaw (1976) from the Snipe Lake reef complex in the Upper Devonian Swan Hills Formation in central Alberta. Commonly differential dissolution occurs in zones of mixing between meteoric and marine waters (Back *et al.* 1986), however, in this study it appear to have occurred in a shallow to intermediate burial environment.

Blocky isopachous cement is commonly the first generation of cement lining porosity, and it occludes pores smaller than 0.4 mm. Crystal morphology suggests that this cement was originally calcite and its isopachous nature suggests that it was precipitated in a phreatic environment. Since locally it is the first generation of cement in many pores it must have formed early in the diagenetic history of these deposits. This type of cement is similar in appearance to early meteoric phreatic calcite cements illustrated by Halley *et al.* (1983); however, the distribution of the cement is not laterally or vertically restricted. It is unlikely that the blocky isopachous cements were precipitated in a meteoric environment because there is no evidence to suggest that the entire buildups were subjected to meteoric phreatic conditions. As it post-dates the fibrous isopachous and radiaxial cements it is interpreted to have been precipitated in a shallow burial environment (Fig. 13).

Pore-filling blocky mosaic

Pore filling blocky mosaic cement is composed of 100–175 µm, equant, anhedral to subhedral crystals. It fills or partly fills molds of red algae, brachiopods, and molluscs, and irregular pores of uncertain origin, in all facies (Pls. 6F, 8B). The pores and molds are 2 mm – 2 cm across. Commonly there is good intercrystalline and vuggy porosity (vugs up to 2 mm in diameter) in this cement. The blocky cement crystals generally have a dusty appearance, due to abundant small (<5 µm) two-phase fluid inclusions. Commonly the crystals display clear, inclusion-free (limpid) zones (Pl. 8C). Where the molds were only partially filled, fibrous and blocky isopachous cements never occur in the remaining porosity. However, blocky cement crystals adjacent to porosity have syntaxial overgrowths of limpid dolomite cement. Locally the remaining porosity was filled or partially filled with coarse bladed anhydrite (Pl. 6F). The formation of moldic porosity post-dates the isopachous cements and pre-dates precipitation of the limpid dolomite and anhydrite cements (Fig. 13).

The blocky crystals, when viewed with a scanning electron microscope display surfaces which are both corroded (Pl. 8D) and pristine (Pl. 8E). Pristine crystals have planar compromise boundaries and do not appear to have undergone extensive recrystallization. These pristine crystals may be limpid dolomite overgrowths on the original blocky crystals, whereas the corroded crystals may represent crystals without limpid dolomite overgrowths. Cathode luminescence of the limpid dolomite which occurs as zones in blocky crystals is identical to that of the dusty portions of the crystals, and is dull orange. This suggests that it was precipitated prior to recrystallization and/or dolomitization of the Winnipegosis buildups.

Folk and Siedlecka (1974) documented clear dolomite, with "dirty" cores, from the Carboniferous *Fusulina* Limestone and the Permian *Spirifer* Limestone formations on Bear Island, Svalbard, and Pleydell (1987) and Jones (1989a) reported similar dolomite from the Bluff Formation on Grand Cayman Island. Folk and Siedlecka (1974) proposed that "...an initial dolomite crystal formed under conditions of high salinity, and as time passed the water freshened and an overgrowth of limpid dolomite was formed on the dirtier nucleus." They proposed that this process could occur under conditions of shallow burial. The similarity between the cements observed by Folk and Siedlecka (1974) and the zoned, blocky cements in the Winnipegosis suggests that this cement was precipitated as dolomite, in a shallow burial environment (Fig. 13).

Though these inclusion free zones appear to be growth zones, fluorescence reveals that the zones commonly have irregular shapes and distributions within the crystals (Pl. 8F). This suggests that the inclusion free dolomite may have been precipitated in secondary porosity after partial dissolution of the dusty crystals. Zones paralleling cleavage and crystal faces may have filled porosity resulting from dissolution along cleavage planes.

Scalenohedral

Scalenohedral cement is composed of 125 µm long crystals with steep-sided terminations facing into primary porosity (Pl. 9A). This cement is light brown in color and has up to four growth zones marked by thin (5–10 µm) micritic bands. Individual micritic zones can be followed completely around the primary pores. Individual crystals commonly have undulose extinctions giving the cement an overall sweeping extinction.

Scalenohedral cement is rare in the Winnipegosis buildups, being present only in the 16-11 core. It occurs in sediment with an original wackestone to packstone texture and it appears to have lined primary porosity and encrusted grains. Subsequent to the precipitation of this cement encrusted grains were removed by dissolution, resulting in molds lined by the scalenohedral cement. Locally it has been precipitated on a fibrous isopachous cement, clearly post-dating it.

Scalenohedral cements form in meteoric phreatic (Halley *et al.* 1983, Fig. 46, p. 493; Flügel 1978), intertidal, subtidal (Flügel 1978) and shallow burial (Kerans 1985) environments. Scalenohedral cements in the Winnipegosis buildups are morphologically similar to fracture filling fibrous calcite cements illustrated by Tucker (1973, Fig. 9), cavity filling ferroan and non-ferroan calcites illustrated by Dickson (1966, Figs. *5A*, *7A*, *7B*) and cavity filling limpid dolomite cements illustrated by Jones *et al.* (1984, Figs. *4B*, *5D*, *6E*). The great variability in environments of precipitation of this type of cement and its limited distribution in the buildups in this study makes its difficult to determine its environment of precipitation (Fig. 13).

Syntaxial overgrowths on crinoids

Syntaxial cements occur as overgrowths on single-crystal substrates, such as crinoid fragments. Whereas the crinoid fragments contain abundant small canals preserved as dark inclusions, the overgrowths are clear and lack inclusions. Syntaxial overgrowths on crinoid fragments adjacent to shelter porosity have euhedral terminations and are generally thicker than on fragments in contact with a micrite matrix (Pl. 6B). Where in contact with the matrix the overgrowths stop abruptly. This suggests that the overgrowths are passive early cement fills of primary porosity as described by Walkden and Berry (1984), and that all overgrowths in this study were sites of original porosity. Overgrowths are common in the central canal of columnals as well as in fractures in the fragments; however, they are absent from the small (<3 µm) microstructure pores of the fragments. Where interior portions of the fragments were removed, syntaxial overgrowths, with euhedral terminations, partially fill the pores.

Since original shelter pores with overgrowths extending into them are still open and appear not tc have been affected by compaction, precipitation of overgrowths on crinoid fragments must have post-dated at least partial lithification of the micritic matrix. Since syntaxial overgrowths are rarely in contact or in association with other cements, it is difficult to determine their relationships. Syntaxial cements refilling dissolution porosity in crinoid fragments indicates that the cement post-dates at least one phase of leaching. Longman (1980) and Strasser and Davaud (1986) suggest that syntaxial overgrowths on crinoid fragments are characteristic of cementation in the meteoric phreatic zone. However, they occur throughout the buildups and there is no evidence to suggest exposure of the entire buildups to meteoric phreatic conditions, therefore the overgrowths were probably precipitated in either a submarine or shallow burial environment (Fig. 13).

Limpid dolomite

Limpid dolomite has a more stoichiometric chemistry and is more perfectly ordered than "average" dolomite. The crystals are water clear, since they lack imperfections, inclusions, growth steps, or other blemishes (Folk and Siedlecka 1974; Folk and Land 1975). When viewed with incident fluorescent light the limpid dolomite is nonfluorescent whereas dusty portions of the crystals fluoresce lime green (Pl. 8F). Limpid dolomite occurs in association with blocky dolomite crystals as syntaxial overgrowths (Pls. 8B, 9B) on blocky anhedral to subhedral crystals. These overgrowths generally have euhedral terminations, and locally have up to 3 brightly luminescent and nonluminescent zones when viewed under cathode luminescence. The remainder of the rock luminesces dull orange, suggesting that the limpid dolomite overgrowths were precipitated after recrystallization of the host rock. The distribution of this cement was controlled by the distribution of porosity. It fills smaller pores, but only lines larger pores.

The limpid dolomite cement was the last phase of carbonate cementation, and only pre-dated anhydrite precipitation. Although these overgrowths post-date recrystallization they may have been precipitated in a schizohaline environment, resulting from freshening water. However, unlike the zoned, pore-filling, blocky mosaic cement, it was probably precipitated in an intermediate to deep burial environment. Limpid dolomite precipitation in Nisku reefs in Alberta was also suggested to have occurred in an intermediate to deep burial environment (Machel 1983; Fig. 13).

Polyhedral crystal shape

The limpid dolomite crystals are polyhedral with a modified rhomb shape. Three types of modifications occur: 1) basal pinacoids (*c*, 0001), with the development of steep rhomb faces (*M*, 4041, and *f* 0221) to form triangular facets on all corners (Pl. 8E), 2) corners with more complex facets (*M*, 4041, and *v*, 2131; Pl. 9C), and 3) beveling of all corners (as in 1) and edges (*r* 1010) (Pl. 9D). EDAX confirmed that the crystals are composed of exclusively of magnesium and calcium, and the crystals do not appear to be recrystallized. This suggests that the morphology of these crystals is a primary feature and not a result of pseudomorphing after calcite.

Crystallographically, dolomite belongs to the rhombohedral subclass of the trigonal crystal class. Dolomite crystals are rhombohedral shaped, with two sets of related corners or coigns. The *c* axis of the rhombohedron cut through one set of coigns (crystallographically related corners), and the other six corners represent the second set of coigns. When one corner of a set is modified all others of that set must also be modified in order to maintain symmetry (Phillips 1971).

Maestre (1845), Tschermak (1881), Becke (1889), Goldschmidt (1916), Taylor (1937) and Wheeler (1939) described dolomite crystals with basal pinacoids from various deposits in Europe and North America. However, modern description of dolomite crystals which deviated from the normal six sided rhomb morphology are rare. This discussion is one of the first modern reports of polyhedral dolomite crystals.

One feature which many of these polyhedral dolomite crystals have in common is that the dolomite is limpid, and it is in intimate association with evaporite minerals. The Winnipegosis examples are no exception, because the Winnipegosis Formation is overlain by halite and anhydrite of the Prairie Evaporite Formation. Limpid dolomite occurs in pores which were later occluded or partially filled with anhydrite, and halite commonly occurs on the crystal faces. Naiman *et al.* (1983) discussed polyhedral limpid dolomite crystals from the Permian Upper Clear Fork and Glorieta formations in Texas, and suggested that a very high NaCl concentration in an otherwise dilute solution may have resulted in the formation of the bizarre dolomite crystal form as a result of some crystal poisoning effect.

Anhydrite

Coarsely crystalline, bladed anhydrite fills small solution vugs (< 2 cm in diameter), and commonly occurs above geopetal sediments in brachiopods. It fills or partially fills back-leached areas behind blocky isopachous cements (Pls. 7B, 8C), and occurs in intercrystalline porosity in blocky mosaic cements in fossil molds (Pls. 4B, 8D). It also fills or partially fills remaining shelter porosity (Pl. 6D), and occludes small (<2 cm across) solution vugs formed during deep burial. Since anhydrite is found throughout the buildups, post–dates all other cements, and it is not facies or porosity selective, it appears to be a late stage cement, precipitated in an intermediate to deep burial environment (Fig. 13).

Chert/quartz

Quartz is the least abundant cement in the buildups in this study, being found in only two samples. Chert cement occurs in intraparticle porosity in the codiacean algal grainstone facies in the 14-35 core, and isolated euhedral quartz crystals in the mudstone facies in the 9-22. The chert occurs in porosity which is usually filled with a blocky mosaic carbonate cement, and, therefore, must have pre–dated it, alternatively the blocky mosaic cement was replaced by the chert. The isolated quart crystals occurs as scattered crystals sitting on the blocky dolomite crystals, thus clearly post–dating the blocky carbonate cements. Due to the rareness of the chert and the quartz it is difficult to suggest the environment in which it was precipitated, and its timing is questionable.

Leaching

There have been a number of leaching events in the post depositional history of the Winnipegosis Formation. Evidence for dissolution can be observed in the partial or complete removal of bioclasts, resulting corroded bioclasts or moldic porosity, leaching of an early phase of blocky isopachous cements, partial dissolution of dolomite cements forming corroded crystals and hollow rhombs, and dissolution of matrix materials resulting in the formation of vuggy porosity.

Dissolution of bioclasts

Red alga, brachiopod, ostracod and mollusc fragments generally have been completely leached, with the molds being filled or lined with a blocky mosaic cement (Pls. 6E, 6F). Skeletal micro-structure which is preserved may reflect the early inversion of high magnesium calcite skeletal material to low magnesium calcite. Leached portions probably represent areas not inverted to low magnesium calcite. Leaching probably occurred during shallow burial because it appears to occur throughout the buildups, and submarine cements do not occur in the molds. Rather the molds were filled with blocky mosaic cement which was probably precipitated during shallow burial (Fig. 13).

The centres of crinoid fragments have commonly been leached, and rarely entire fragments have been dissolved. Where centers have been removed the void is commonly partially filled by syntaxial overgrowths, suggesting that dissolution occurred prior to precipitation of syntaxial overgrowths. Where whole fragments have been removed the void is filled or partly filled with anhydrite. This suggests that dissolution of crinoid fragments may have occurred at more than one time (i.e. early, prior to precipitation of the syntaxial overgrowths, and later, prior to anhydrite precipitation).

Cement dissolution

Also late in the diagenetic history, an early phase of the blocky isopachous cement was leached (Pl. 6D, 7C, 8B). The only cement which occurs in this dissolution porosity is bladed anhydrite, suggesting that leaching occurred after precipitation of all carbonate cement phases (Fig. 13).

Blocky crystals with and without limpid dolomite overgrowths display etching on crystal faces (Pl. 10A), and leaching along cleavage planes (Pls. 8C, 8D). Rarely, blocky crystals with limpid dolomite overgrowths display leached corners and faces (Pl. 10B), and rarely crystals have had their cores leached leaving only a rim of slightly corroded limpid dolomite (Pl. 10C). The hollow [illegible]nters are commonly filled or partly filled with a bladed anhydrite cement (Pls. 10C, 10D).

Hollow dolomite rhombs have been recorded from the Bluff Formation of Grand Cayman, British West Indies (Pleydell 1987, Jones 1989b), and in Paleozoic limestones on Bear Island (Folk and Siedlecka 1974). Folk and Siedlecka (1974) suggested that when water chemistry changed (freshened), the more soluble (less stable) "dirtier" cores were leached leaving rims of limpid dolomite. This appear to have occurred late in the diagenetic history, as only anhydrite cement (no carbonate cements) occurs in these hollow rhombs (Fig. 13).

Matrix dissolution

Vuggy porosity probably formed late in the burial history of the buildups. Some vugs have been partly filled with anhydrite but commonly they were not filled or lined with any cement. Because vugs are filled, partially filled, or completely empty, dissolution of the matrix appears to have occurred during and after precipitation of the late stage anhydrite cement, with the empty vugs having formed after anhydrite precipitation ended (Fig. 13).

Pressure solution

Chemical compaction, resulting in sutured grain contacts is rare. Where present it occurs exclusively in crinoid rich rocks. The abundance of micrite surrounding grains and the precipitation of early cements appears to have prevented the pervasive development of sutured grain contacts.

Generally chemical compaction is reflected in the development of sutured seam and micro (horse–tail) stylolites. Stylolites are present throughout the buildups except in the coral/algal framestone facies. In the laminated dolostone facies the stylolites are so abundant that a stylobedded fabric has formed. In the peloid/bioclastic packstones and peloid algal bindstone facies stylolites are sparse, with high amplitudes (upto 2 cm). The stylolites appear to have formed late in the diagenetic history of the buildups, post–dating cement precipitation, in a deep burial environment (Fig. 13).

CHAPTER VI — CAVITIES AND FRACTURES

Introduction

Winnipegosis buildups contain a variety of primary and solution modified cavities (MacDonald and Jones 1989). Cavities are divided into three types, herein referred to as reticulate cavity systems, isolated flat bottomed cavities, and caverns. Fracture systems are divided into types I and II.

Filled cavity and fracture systems in the Winnipegosis Formation buildups are important in several respects. Because cavity systems and fractures are abundant and have a variety of morphologies, it is important to explain their distribution and mode of formation. These filled cavities and fractures represent a major relic pore network, and their formation and later filling represents a major phase in the evolution of porosity in these carbonates.

Cavities are filled with peloidal marine sediment and vadose silt and mud, and they are commonly lined by isopachous fibrous and radiaxial fibrous cements.

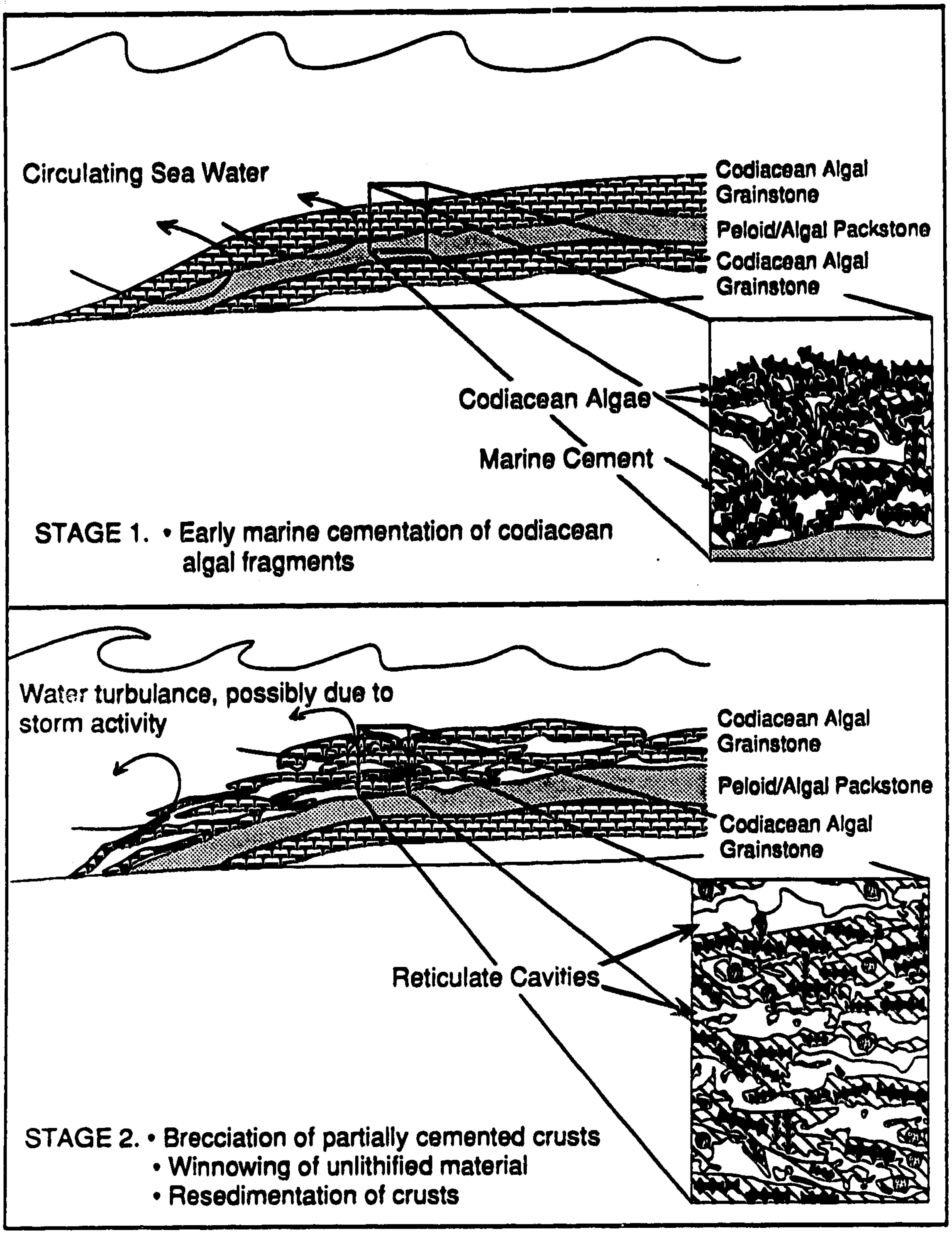
Cavity systems

Reticulate cavity systems

Reticulate cavities have flat bases and irregular roofs, although they are commonly irregular in shape (Pl. 11A). In all cases the cavities are filled with laminated and unlaminated white crystalline dolomite. Individual cavity systems extend laterally from less than 1 cm to widths greater than that of the core (10 cm). Heights of the cavities are highly variable (from millimetres to centimetres) as is their degree of interconnectedness. Locally there does not appear to be any evidence of binding or other stabilizing influences; however, locally there is some indication that cavity roofs were bridged by large codiacean algal fragments and the cavities are commonly lined by fibrous marine cements (Fig. 13). The bases of the reticulate cavities commonly parallel the bedding planes (up to 60°).

In the 14-35 buildup and the 9-22 well of the Tableland buildup, sediment filled reticulate cavities are common in the algal grainstones. In the 16-11 buildup and the 8A-22 well of the Tableland buildup the codiacean algal grainstones and reticulate cavities are virtually absent. The presence or absence of these cavity systems may be indicative of the part of the buildup from which the cores were taken. Bathurst (1980, 1982) and Kerans (1985) found that reticulate cavity systems and stromatactis are most common on the steep margins of buildups. This conforms with the location of the 9-22 core, which was drilled into the crest of the buildup, approximately 200 m from the steepest margin, on the windward side, of the buildup (Figs. 4, 8).

The formation of reticulate networks of cavities has been a point of much debate and speculation. These cavity systems display no evidence of being the products of dissolution or being formed by organisms. The occurrence of fibrous cement as linings in these cavities suggests that they formed in a marine environment, contemporaneous with deposition. Neumann *et al.* (1977) speculated that reticulate networks could be accounted for by the filling of excavations between crustose layers; a suggestion supported by Bathurst (1980, 1982) and followed herein. Beds of codiacean algal fragments appear to have been cemented, shortly after deposition, by the circulation of marine water through the beds. This early marine cementation resulted in the formation of a hard or firm crust (Fig. 14), probably akin to hardgrounds or other such cemented submarine surfaces. Reorientation (rotational or linear) or brecciation of these crusts could be accomplished with suitable water turbulence, bioturbation or gravitational slumping. With brecciation and reorientation of the crusts, unlithified sediment below the crusts was carried away allowing cavities to form beneath the crust's irregular lower surface (Fig. 14). Cementation brecciation and reorientation of successive crusts could allow complex systems of reticulate cavities to form. Interconnected cavities with a more irregular shape probably resulted from more pervasive cementation of the grainstones, forming thicker crusts resistant to reorientation and brecciation.



STAGE 1. • Early marine cementation of codiacean algal fragments

STAGE 2. • Brecciation of partially cemented crusts
- Winnowing of unlithified material
- Resedimentation of crusts

Fig. 14. Stages in the development of reticulate cavities.

In Winnipegosis buildups reticulate cavities appear gradational with the 'lacy vugs' of Logan and Semeniuk (1976). These 'lacy vugs' appear to have formed as a result of greater brecciation of the codiacean algal grainstone crusts.

Reticulate cavities are superficially similar to stromatactis described by Bathurst (1980, 1982). Bathurst (1980, 1982) defined stromatactis as reticulate cavity systems, embedded in a lithified carbonate mud, with smooth undulose bases and digitate roofs which are horizontally to subhorizontally disposed. Bathurst (1959) stated that the "... calcite spar which forms stromatactis is a cement fill of a cavity, commonly with internal sediment on the floor." The reticulate cavities in the Winnipegosis are slightly different from stromatactis described by Bathurst (1980, 1982), being formed in carbonates with an original grainstone texture and in most cases being entirely sediment filled. Locally fibrous cements are present in the materials surrounding the reticulate cavities as well as lining them.

Isolated cavities

These cavities generally have irregular shapes (Pl. 11B), and vary in size from greater than 10 cm wide (the width of the core) and 6 cm high to 2 cm wide and 2 cm high. These cavities are only formed in the peloid/bioclastic packstone and the algal/peloid bindstone facies. The roofs and walls of these cavities were commonly encrusted by algal laminations and lined by submarine cements. Generally an initial geopetal peloidal marine internal sediment is present on cavity floors, and can be several centimetres thick (Pl. 11B). The deposition of this sediment resulted in the remaining pore having flat horizontal to subhorizontal floors. The remaining porosity was then filled with laminated crystalline dolostone, and rarely with unlaminated crystalline dolostone.

They occur in all buildups, but are absent from the 8A-22 and 16-15 cores from the Tableland buildup, suggesting that they only occur on the steep windward margins of the buildups. Their formation appears to be related to early binding and cementation of the buildup margins (Fig. 13).

Caverns

Caverns are man-sized or larger pores of channel or vug shape (Choquette and Pray 1970). Forty metres from the top of the 14-35 core, the gamma ray log exhibits a marked increase, and the porosity logs exhibits a marked decrease. In core these log responses correlate to 2.5 m of laminated crystalline dolostone and black, pyritic, dolomitic shale (Pl. 11C), bounded sharply on the top and bottom by peloidal and bioclastic packstones. This interval is interpreted as being a sediment filled cavern. The black, pyritic, dolomitic shale occurs in the centre of the interval and is 40 cm thick. The dark color and abundant pyrite suggests that the environment in the cavern was reducing during its deposition. Though the lateral extent of this cavern is unknown, it may locally have a significant effect on the vertical permeability within the buildup (Martindale and MacDonald 1989).

The size of this feature suggests that it did not form contemporaneous with deposition. It more likely formed as a result of solution. Dissolution commonly occurs in the vadose zone where fresh undersaturated water percollates through the exposed carbonates (Fig. 13). Large caverns commonly form at the boundry between the vadose and phreatic zones (James and Choquette 1984).

Fracture systems

Introduction

In the Winnipegosis buildups examined in this study there are two types of fracture systems. Type I and type II fractures are distinguished by their size, morphology, filling, and distribution.

Type I fractures

Type I fractures, which are generally vertical to sub–vertical, are commonly greater than the width than the core, have jagged and fragmented edges (Pl. 11D). They are filled with laminated and unlaminated crystalline dolostone which commonly contains coarse clasts of wall rock (Pl. 11E), and rarely peloidal sediments.

Type I fractures, which only occur near the top of the buildups (within about 10 m), occur in all buildups in this study, and were formed in the peloidal packstone facies. In the Tableland buildup the 9-22 core displays type I fractures, whereas they are completely absent from the 8A-22, 16-15, 14-14 and 4-23 cores. The lack of well control precludes determination of the lateral extent or aerial distribution of the fracture systems in the Winnipegosis buildups. The 9-22 Tableland well is 200 m from the steepest margin and the windward side of the buildup, while the 8A-22 and 14-14 wells were drilled into a broad protected area in the lee of the crest (Fig. 8). Their proximity to the margin of the buildups suggests that the fractures may be related to early cementation and oversteepening of the margin, or they may have a tectonic origin (Fig. 13).

The type I fractures are interpreted as being neptunian dykes and sills. Playford (1984) described neptunian fracture systems from the Devonian reefs in the Canning Basin, West Australia and suggested that they formed most commonly along platform margins and decreased in abundance down the fore-reef slope and toward the back-reef. Playford (1984) suggested that fracture systems, in the Canning basin reefs, formed at an early stage in the lithification of the host sediment by syndepositional faulting.

Type II fractures

Type II fractures (Pl. 12A) are smaller than the type I fractures, being less than 1 cm wide and commonly being only millimetres in width. Types II fractures are similar to 'breccioid vein structures' described by Logan and Semeniuk (1976). Crystalline dolostone fills these fractures in the 9-22 and the 14-35 buildups. In the 16-11 core, the type II fractures are filled with brown crystalline dolostone.

These fracture systems are present in all buildups, but are restricted in distribution in the Tableland buildup, being present only in the 9-22 well. They occur as networks of thin veins which displace adjacent fragments of host rock only slightly. They appear to have formed as a result of compaction or water escaping through lithified or semi-lithified sediments. As deep and intermediate burial cements are excluded from these fractures they probably formed in a shallow burial environment (Fig. 13).

Cavity and fracture fills

Introduction

Cavities in the Winnipegosis buildups are filled with laminated and unlaminated crystalline dolostone, peloidal wackestone, and intraclastic mudstone. They are also commonly lined or filled by fibrous cement, pendant, and anhydrite cements.

Sediment fills

Crystalline dolostone

The most abundant cavity fill is white to light brown crystalline dolostone that contains no peloids or bioclasts (Pls. 11A, 11B, 11C), and locally up to 3–5% anhydrite. The dolomite crystals have a blocky mosaic texture, and fall into two crystal sizes, 20–50 μm and 75–150 μm. It has a uniform crystal size, with between 0–5% intercrystalline porosity.

Locally the crystalline dolostone is laminated (Pls. 11B, 11D), with laminations generally less than 1 mm thick and increasing in abundance toward the top of the cavities. The laminae are generally horizontal to subhorizontal but they also display steep dips (in excess of 60°) with the laminae at the top of the cavity commonly paralleling the cavity roof. In some cases the laminae are highly irregular in shape, possibly due to soft sediment deformation or water escape (Pl. 12B). Many cavity fills display a crude vertical color zonation; the lower portion being white whereas the upper portion is tan (Pl. 11A). Petrographically the white and tan dolostones are indistinguishable. The boundary between the two zones is generally highly irregular, commonly with steep dips. This particular feature could be a result of heterogeneous compaction.

Crystalline dolostone fills about 90% of the cavities and occurs throughout the buildups. It occurs in all types of cavities. The uniformity in filling suggests that all types of cavities were open at the same time or the source of the sediment was present during the formation and filling of all cavity types. The latter seems unlikely because the formation of this fill appears related to exposure of the buildups.

Crystalline dolostone may have originated as crystal silt as described by Dunham (1969). Crystal silt was suggested to be a by-product of vadose weathering, from the break down of pre-existing carbonate rocks (Dunham 1969).

Crystalline dolostone is similar to cavity and fracture fills described from the Devonian rocks in the Canning Basin West Australia (Kerans 1985; Playford 1984). This fill is also similar to a micritic cavity fill, called 'caymanite', found in the vugs, coral molds and fractures in Oligocene/Miocene age dolostones of the Bluff Formation, from Grand Cayman, British West Indies (Folk and McBride 1976; Collar 1985; Lockhart 1986; Jones and Smith 1988). These cavity fills also commonly display irregular bedding with dips up to 90°. The micrite (herein referred to as 'vadose micrite') is interpreted to have formed in stagnant swamps and ponds developed on the surface of subaerially exposed karst (Folk and McBride 1976; Jones 1989a). Later this vadose micrite filtered into the cavity and fracture systems below, carried by percolating meteoric and possibly marine water. (Folk and McBride 1976; Lockhart 1986; Jones and Smith 1988).

Whether the crystalline dolostone was originally composed of silt or mud sized particles, its origins appear to be related to exposure of the buildups to vadose conditions (Fig. 13). The model proposed for the formation and emplacement of the cavity-filling vadose micrite appears to explain the occurrence of crystalline dolostone in the cavity and fracture systems in the Winnipegosis buildups. Subsequent to deposition the sediment (micrite or silt) was recrystallized and dolomitized.

Intraclast mudstone

This sedimentary fill is light gray/brown, and composed of 75 to 100 μm anhedral dolomite crystals with a blocky mosaic texture. There are no bioclasts and only rare peloids. This fill is well laminated (Pl. 11D) and commonly contains fragments of wall rock (Pl. 11E).

Where laminated the laminae are composed of finer crystalline dolostone and/or organics. The laminae are locally disrupted by slumping or compactional deformation. The lack of peloids and bioclasts in this sediment fill suggests that it did not form in a normal unrestricted marine environment. This fill is restricted to the large neptunian fractures near the top of the buildups. It is similar to the crystalline dolostone (crystal silt or vadose micrite) described above, however, the laminations are much thicker, and darker in color, and the crystalline dolostone lacks intraclasts. Although this material appears originally to have been crystal silt or vadose micrite, the different textures may reflect a modified source area, different depositional condition, or it may simply be the courser material which could not filter into the deeper cavities.

Peloidal packstone

This sediment is similar to the peloidal packstone which represent 80% of the deposits in the buildups, except that bioclasts are generally absent. It partially fills flat bottomed cavities (Pl. 11B) with a layer that varies from millimetres to centimetres thick. As this cavity fill is the same as that sediment in which the flat-bottomed cavities were formed, this implies that cavity formation and filling occurred in a marine environment, contemporaneous with deposition of the buildups (Fig. 13).

Cavity linings and cements

Cements and linings are common in cavities, and the abundance of early marine cements suggests that the cavities formed sortly after deposition. Commonly the linings coat the entire surface of cavities and individual bioclasts, however, locally cavities display partial linings or coatings only on the upper surface of the cavity.

Fibrous cement linings

Locally, fibrous cements coat codiacean algal grains associated with reticulate and flat bottomed cavities as well as lining the cavities themselves. This lining occurs as isopachous rims up to 1 cm thick (Pl. 12C). The similarity of this cement to modern marine cements suggests that reticulate and flat bottomed cavities were open during submarine diagenesis. The lining of these cavities suggests that early marine cementation played an important role in the maintenance of the cavities and on a broader scale, stabilization of the buildups.

Laminated pendant structures

Ten metres from the top of the Tableland buildup in the 9-22 core two cavities contain finely laminated pendant structures hanging from the cavity roofs. These crusts are composed of a dark brown crystalline dolostone. Petrographically they are dominantly a blocky mosaic with no fibrous structure present. The laminations are very thin generally on the order of 100's of μm. It is difficult to tell if these structures are organic or inorganic due to poor preservation. On polished surfaces these structures are about 1 cm across and generally display a downward pointing "stalactite-like" structure (Pl. 12D), suggesting that they may be pendant cements. These structures also appear similar to "microstromatolites" illustrated by Jones and Kahle (1985), and could thus have an organic origin. Both pendant cements and microstromatolite have a vadose origin (Fig. 13) indicating that the buildups were exposed to vadose conditions. These pendant structures pre–date emplacement of the crystalline dolostone.

Anhydrite cements

The least abundant cavity fill is a coarse crystalline bladed anhydrite which appears to be a late stage cement. It occurs in all buildups and all cores, and fills <5% of the cavities.

Diagenetic Model

Marine cementation in modern reefs is commonly extensive in near surface portions of reef margins and slopes. This cementation greatly enhances the stability of reef margins allowing them to withstand wave action and maintain dips of up to 90° (Walls and Burrowes 1985). Submarine cements have been reported from ancient reefs in Australia, Europe, and Canada (Krebs and Mountjoy 1972; Schmidt *et al.* 1980; Mountjoy 1982; Schmidt *et al.* 1982; Machel 1983; Mountjoy and Krebs 1983; Frykman 1986; Kerans *et al.* 1986), and are abundant in the Winnipegosis Formation buildups. Cementation began in a marine environment with precipitation of radiaxial fibrous, and fibrous isopachous cements. The abundance of brecciated cemented crusts, which resulted in the formation of reticulate cavities, and the presence of flat–bottomed cavities with peloidal marine internal sediments, also attests to the importance of submarine cementation during buildup deposition. Submarine cementation, in conjunction with tectonism and or gravitational slumping near the end of buildup formation allowed the opening of neptunian fractures. These fractures where were partly filled while the buildups where still in a marine environment.

The abundance of micritic peloids, and the occurrences of micrite envelopes on most allochems suggests that boring by algae was also an important process in the marine environment. Inversion of high-magnesium calcite bioclasts to a more stable low-magnesium calcite mineralogy probably began in the marine environment, and resulted in the preservation of original skeletal microstructure in many fossil fragments.

As the Elk Point Sea began to shallow, the tops of the buildups were exposed to subaerial conditions. A freshwater lens and mixing zone probably did not form in these buildups, because the Elk Point Basin was a site of desiccation, and low rainfall at that time. In addition there are no meteoric cements to attest to the presence of a freshwater lens. The presence of a caliche (the laminated dolostone facies) capping all of the buildups in this study suggests that the buildups were exposed to vadose conditions, and in the 9-22 core there are rare occurrences of pendant cements. Vadose micrite or silt, formed due to erosion of the tops of the buildups, filtered into the open cavity and fracture systems, occluding much of the primary porosity.

When the Winnipegosis buildups entered a shallow burial environment blocky isopachous and pore filling blocky mosaic cements (and possibly syntaxial overgrowths on crinoids) where precipitated. Although these cements are similar to meteoric phreatic cements described by Halley *et al.* (1985) and Longman (1980), they are not laterally or vertically restricted in buildups. The lack of supporting evidence for a large freshwater lens precludes their being meteoric cements. It thus seems probable that they were precipitated in a shallow burial environment. From the presence of limpid zones in the blocky cement crystals, the diagenetic fluids in this environment appear to have been schizohaline, or had a highly variable salinity. The blocky isopachous cement most commonly occurs as linings in shelter pores in intra- and interparticle porosity. This environment was also the site of considerable secondary porosity formation, such as the formation of moldic porosity after the dissolution of unstable allochems. Pore filling blocky mosaic cement filled most of this moldic porosity; however, locally 30-50% of the moldic porosity remained open.

The timing of dolomitization is uncertain and a point of much debate. Perrin (1982) suggested that dolomitization began when the buildups entered the mixing zone. This is doubtful since the entire buildup and part of the platform is dolomitized, and there is no evidence for a mixing zone. Kendall (1988) suggested that dolomitization occurred when meteoric water, derived from an exposed recharge area to the east, entered and moved through the Lower Winnipegosis Member. Circulation of the dolomitizing water was produced by a hydraulic head generated through desiccation of the basin and maintained by continued evaporation. This theory seems unlikely since (a) the permeability of the Lower Winnipegosis Member is low and it would not transmit fluid well, and (b) the Lower Member is not entirely dolomitized. If dolomitizing fluids passed through the Lower Member it should have become completely dolomitized. Stanford and Jones (1988) and Stanford (1989) suggested that dolomitization did not begin until after evaporative conditions were established, and resulted from refluxing of saline brines through the buildups. This theory seems able to explain dolomitization of the formation and is followed here.

Precipitation of syntaxial limpid dolomite overgrowths on pre-existing blocky cement crystals occurred after dolomitization and/or recrystallization. Fluid chemistry changed during precipitation of this cement because some of the overgrowths are zoned, as revealed by cathodoluminescence. Precipitation of the limpid dolomite cement was followed by dissolution of the matrix, forming vugular porosity, and locally resulted in the leaching of the dusty cores around which limpid dolomite was precipitated. Vuggy porosity was not lined or filled by carbonate cements; however, much of the remaining porosity was filled or partially filled by bladed anhydrite cement. Anhydrite was the last phase of cement precipitation, and it and the limpid dolomite were precipitated in an intermediate or deep burial environment. Stylolite formation also occurred in a deep burial environment; however, their timing relative to cement precipitation is uncertain.

CHAPTER VII — CONCLUSIONS

1) The Winnipegosis reservoir at Tableland is heterogeneous, and to a large extent unrelated to original depositional facies. Reservoir quality is determined by the nature and extent of cement-lined and sediment-filled cavities and fractures, especially in the higher parts of the buildups and on the flanks.

2) Buildups probably formed on topographic highs, created by tectonic activity in the Elk Point Basin. There is no evidence in the Tableland area of organic shoaling on the platform which could have acted as a foundation for the buildups.

3) Buildups are composed of a number of coalesced grainstone shoals consisting of peloids, codiacean algae and to a lesser extent, crinoid debris. Shoals are capped by a organically-constructed framestone of red algae, branched corals and chaetetids.

4) Buildup formation was terminated by subaerial exposure. A thin calcrete, developed during this interval, caps the coral/algal framestone facies.

5) Fractures in the buildup, which were infilled by muds, may create significant permeability barriers.

6) Syndepositional cavity systems represented a major pore network in the buildups. Later filling caused a major decrease in the porosity of these carbonates. Due to the lack of porosity in the cavity filling material, portions of the buildups with abundant filled cavity and fracture systems tend to have highly variable reservoir quality.

7) Much of the primary porosity in the sediment was filled with cements precipitated in marine and shallow burial environments.

8) Cavity systems were filled early in the history of the buildups.

9) Cements precipitated late in the diagenetic history of the buildups had only a minor effect on reservoir quality of the buildups.

10) Stabilization of the sediments which compose the buildups was not a result of organic binding in about 90% of the buildups. Steep dips of beds, the steep sides of the

buildups, and the abundace of marine cements attests to the significance of submarine diagenesis in the development of the buildups.

11) Windward margins of the lower parts of the buildup were stabilized by marine cements which line interparticle porosity and cavities. Locally, cements significantly reduce porosity.

12) Diagenesis in the Winnipegosis Formation appears to be the reason for the very existence of the buildups.

REFERENCES

Adey, W. H., and Macintyre, I. G. 1973. Crustose coralline algae: a reevaluation in the geological sciences. Geological Society of America Bulletin, 84: 883–903.

Alexandersson, T. 1972. Intragranular growth of marine aragonite and Mg-calcite: evidence of precipitation from supersaturated seawater. Journal of Sedimentary Petrology, 42: 441–460.

Back, W., Hanshaw, B. B., Herman, J. S., and Van Driel, J. N. 1986. Differential dissolution of a Pleistocene reef in the ground–water mixing zone of coastal Yucatan, Mexico. Geology, 14: 137–140.

Baillie, A. D. 1951. Devonian geology of Lake Manitoba—Lake Winnipegosis area. Manitoba Mines Branch Publication, 49–2.

Baillie, A. D. 1953. Devonian system of the Williston Basin area. Manitoba Mines Branch Publication, 52–5.

Baillie, A. D. 1955. Devonian system of Williston Basin. American Association of Petroleum Geologists Bulletin, 39: 575–629.

Bathurst, R. G. C. 1959. The cavernous structure of some Mississippian stromatactis reefs in Lancashire, England. Journal of Geology, 67: 506–521.

Bathurst, R. G. C. 1975. Carbonate sediments and their diagenesis. Developments in Sedimentology 12, Elsevier, Amsterdam, The Netherlands.

Bathurst, R. G. C. 1980. Stromatactis—origin related to submarine-cemented crusts in Paleozoic mud mounds. Geology, 8: 131–134.

Bathurst, R. G. C. 1982. Genesis of stromatactis cavities between submarine crusts in Palaeozoic carbonate mud buildups. Journal of the Geological Society of London, 139: 165–181.

Becke, F. 1889. Ein Beitrag zur Kenntnis der Krystallformen des Dolomite. Tschermaks Mineralogische und Petrographische Mitteilungen, 10: 93–216.

Belyea, H. R. 1952. Notes on the Devonian system of the north—central plains of Alberta. Geological Survey of Canada, Paper 52-27.

Chafetz, H. S. 1972. Surface diagenesis of limestone. Journal of Sedimentary Petrology, 42: 325–329.

Choquette, P., and Pray, L. 1970. Geologic nomenclature and classification of porosity in sedimentary carbonates. American Association of Petroleum Geologists Bulletin, 54: 207–250

Collar, I. 1985. Origin of caymanite. Unpublished Undergraduate Thesis, University of Alberta, Edmonton, Alberta.

Coniglio, M., and James, N. P. 1985. Calcified algae as sediment contributors to early Paleozoic limestones: evidence from deep-water sediments of the Cow Head Group, Western Newfoundland. Journal of Sedimentary Petrology, 55: 746–754.

Davies, G. R. 1977. Former magnesian calcite and aragonite submarine cements in upper Paleozoic reefs of the Canadian Arctic: a summary. Geology, 5: 11–15.

Davies, G. R. 1987. Table of Formations of Alberta. AGAT Laboratories, Calgary Alberta.

Dickson, J. A. D. 1965. A modified staining technique for carbonates in thin section. Nature, 205: 587.

Dickson, J. A. D. 1966. Carbonate identification and genesis as revealed by staining. Journal of Sedimentary Petrology, 36: 491–505.

Dravis, J. J., and Yurewicz, D. A. 1985. Enhanced carbonate petrography using fluorescence microscopy. Journal of Sedimentary Petrology, 55: 795–804.

Dunham, R. J. 1962. Classification of carbonate rocks according to depositional texture. *In* Classification of Carbonate Rocks—A Symposium. *Edited by* W. E. Ham. American Association of Petroleum Geologists, Memoir 1, pp. 108–121.

Dunham, R. J. 1969. Early vadose silt in Townsend Mound (reef), New Mexico. *In* Depositional Environments in Carbonate Rocks. *Edited by* G. R. Friedman. Society of Economic Paleontologists and Mineralogists, Special Publication 14, pp. 139–181.

Embry, A. F., and Klovan, J. E. 1971. A Late Devonian reef tract on northeastern Banks Island, Northwest Territories. Bulletin of Canadian Petroleum Geology, 19: 730–781.

Evamy, B. D., and Shearman, D. J. 1965. The development of overgrowths from echinoderm fragments. Sedimentology, 5: 211–233.

Evamy, B. D., and Shearman, D. J. 1969. Early stages in development of overgrowths on echinoderm fragments in limestones. Sedimentology, 12: 317–322.

Fairchild, I. J. 1983. Chemical controls of cathodoluminescence of natural dolomites and calcites: new data and review. Sedimentology, 30: 579–583.

Flügel, E. 1982. Microfacies analysis of Limestones. Springer-Verlag, Berlin.

Folk, R. L. 1959. Practical petrographic classification of limestones. American Association of Petroleum Geologists Bulletin, 43: 1–38.

Folk, R. L. 1962. Spectral subdivision of limestone types. *In* Classification of Carbonate Rocks—A Symposium. *Edited by* W. E. Ham. American Association of Petroleum Geologists, Memoir 1, pp. 62–84.

Folk, R. L. 1965. Some aspects of recrystallization in ancient limestones. *In* Dolomitization and Limestone Diagenesis. *Edited by* L. C. Pray, and R. C. Murray Society of Economic Paleontologists and Mineralogists, Special Publication 13, pp. 13–48.

Folk, R. L., and Land, L. S. 1975. Mg/Ca ratio and salinity: two controls over crystallization of dolomite. American Association of Petroleum Geologists Bulletin, 59: 60–68.

Folk, R. L., and McBride, E. F. 1976. The Caballos Novaculite revisited – Pt. 1: origin of novaculite members. Journal of Sedimentary Petrology, 46: 486–496.

Folk, R. L., and Siedlecka, A. 1974. The "schizohaline" environment: its sedimentary and diagenetic fabrics as exemplified by Late Paleozoic rocks of Bear Island, Svalbard. Sedimentary Geology, 11: 1–15.

Fritz, M. 1988. Winnipegosis interest still strong. American Association of Petroleum Geologist Explorer, 9(9): 8–10.

Frykman, P. 1986. Diagenesis of Silurian bioherms in the Klinteberg Formation, Gotland Sweden. *In* Reef Diagenesis. *Edited by* J. H. Schroeder, and B. H. Purser. Springer-Verlag, Berlin, pp. 399–423.

Gendzwill, D. J. 1978. Winnipegosis mounds and Prairie Evaporite Formation of Saskatchewan—seismic study. American Association of Petroleum Geologists Bulletin, 62: 73–86.

Gerhard, L. C., Anderson, S. B., LeFever, J. A., and Carlson, C. G. 1982a. Geological development and origin of the Williston Basin. *In* Fourth International Williston Basin Symposium. *Edited by* J. E. Christopher and J. Kaldi. Saskatchewan Geological Society, Special Publication 6, p. 1.

Gerhard, L. C., Anderson, S. B., LeFever, J. A., and Carlson, C. G. 1982b. Geological development, origin, and energy mineral resources of the Williston Basin, North Dakota. American Association of Petroleum Geologists Bulletin, 66: 989–1020.

Goldschmidt, V. 1916. Atlas der Krystallformen. Heidelberg, Carl Winters University., v. III.

Grayston, L. D., Sherwin, D. F., and Allan, J. F. 1964. Middle Devonian. *In* Geological History of Western Canada. *Edited by* R. G. McCrossan, and R. P. Glaister. Alberta Society of Petroleum Geologists, pp. 49–59.

Grover, G., and Read, J. F. 1983. Paleoaquifer and deep burial related cements defined by regional cathodoluminescent patterns, Middle Ordovician carbonates, Virginia. American Association of Petroleum Geologists Bulletin, 67: 1275–1303.

Halabura, S. P. 1988. Pheasant project: a case study. American Association of Petroleum Geologists Bulletin, 72: 871.

Hallam, A. 1984. Pre-Quaternary sea-level changes. Annual Review of Earth and Planetary Sciences, 12: 205–243.

Halley, R. B., Harris, P. M., and Hine, A. C. 1983. Bank margin environment. *In* Carbonate Depositional Environments. *Edited by* P. A. Scholle, D. G. Bebout, and C. H. Moore. American Association of Petroleum Geologists, Memoir 33, pp. 463–506.

Harris, P. M., Kendall, G. St. C., and Lerche, I. 1985. Carbonate cementation—a brief review. *In* Carbonate Cements. *Edited by* N. Schneidermann and P. M. Harris. Society of Economic Paleontologists and Mineralogists, Special Publication 36, pp. 79–95.

Havard, C., and Oldershaw, A. 1976. Early diagenesis in back-reef sedimentary cycles, Snipe Lake reef complex, Alberta. Bulletin of Canadian Petroleum Geology, 24: 27–69.

Heckel, P. H. 1974. Carbonate buildups in the geologic record: a review. *In* Reefs in Time and Space. *Edited by* L. F. Laporte. Society of Economic Paleontologists and Mineralogists, Special Publication 18, pp. 90–155.

Hine, A. C., Hallock, P., Harris, M. W., Mullins, H. T., Belknap, D. F., and Jaap, W. C. 1988. *Halimeda* bioherms along an open seaway: Miskito Channel, Nicaraguan Rise, SW Caribbean Sea. Coral Reefs, 6: 173–178.

James, N. P., and Choquette, P. W. 1983. Diagenesis 6. Limestones—the sea floor diagenetic environment. Geoscience Canada, 10: 162–179.

James, N. P., and Choquette, P. W. 1984. Diagenesis 9—Limestones — the meteoric diagenetic environment. Geoscience Canada, 11: 161–194.

James, N. P., and Ginsburg, R. N. 1979. The seaward margin of Belize barrier and atoll reefs. International Association of Sedimentologists, Special Publication 3.

James, N. P., Ginsburg, R. N., Marszalek, D. S., and Choquette, P. W. 1976. Facies and fabric specificity of early subsea cements in shallow Belize (British Honduras) reefs. Journal of Sedimentary Petrology, 46: 523–544.

James, N. P., Wray, J. L., and Ginsburg, R. N. 1988. Calcification of encrusting aragonitic algae (Peyssonneliaceae): implications for the origin of late Paleozoic reefs and cements. Journal of Sedimentary Petrology, 58: 291–303.

Johnson, J. H. 1961. Limestone building algae and algal limestones. Colorado School of Mines, Boulder, Colorado.

Jones, B. 1989a. Porosity and permeability development in the carbonate succession of Grand Cayman, British West Indies. *In* The Development of Porosity in Carbonate Reservoirs. *Compiled by* G. R. Bloy, M. G. Hadley, and B. V. Curtis. Canadian Society of Petroleum Geologists Continuing Education Short Course Notes, Section 3.

Jones, B. 1989b. The role of micro-organisms in phytokarst development on dolostones and limestones, Grand Cayman, British West Indies. Canadian Journal of Earth Sciences, In press.

Jones, B., and Kahle, C. F. 1985. Lichen and algae: agents of biodiagenesis in karst breccia from Grand Cayman Island. Bulletin of Canadian Petroleum Geology, 33: 446–461.

Jones, B., and Smith, D. 1988. Open and filled karst features on the Cayman Islands: implications for the recognition of paleokarst. Canadian Journal of Earth Sciences, 25: 1277–1291.

Jones, B., Lockhart, E. B., and Squair, C. 1984. Phreatic and vadose cements in the Tertiary Bluff Formation of Grand Cayman Island, British West Indies. Bulletin of Canadian Petroleum Geology, 32: 382–397.

Jones, L. 1965. The Middle Devonian Winnipegosis Formation of Saskatchewan. Saskatchewan Department of Mineral Resources, Report 98.

Jordan, S. P. 1967. Saskatchewan reef trend looks big. Oilweek, January 16, pp. 10–12.

Jordan, S. P. 1968. Will Zama be duplicated at Quill Lake, Saskatchewan. Oilweek, February 26, pp. 10–12.

Kendall, A. C. 1988. Regional dolomitization in cratonic basins—the evaporite connection. Annual meeting of the Geological Association of Canada/Mineralogical Association of Canada, p. 4.

Kendall, A. C., and Tucker, M. E. 1973. Radiaxial fibrous calcite: a replacement after acicular carbonate. Sedimentology, 20: 365–389.

Kent, D. M. 1984. Carbonate and associated rocks of the Williston Basin, their origin, diagenesis, and economic potential. Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, Short Course Notes, Denver, Colorado, 1984.

Kerans, C. 1985. Petrology of Devonian and Carboniferous carbonates of the Canning and Bonaparte basins, Results of research for WAMPRI projects 1 and 50. Western Australian Mining and Petroleum Research Institute, Report 12.

Kerans, C., Hurley, N. F., and Playford, P. E. 1986. Marine diagenesis in Devonian reef complexes of the Canning Basin, Western Australia. *In* Reef Diagenesis. *Edited by* J. H. Schroeder and B. H. Purser. Springer-Verlag, Berlin, pp. 357–380.

Kindle, E. M. 1914. The Silurian and Devonian section of western Manitoba. Geological Survey of Canada, Summary Report, 1912: 247-261.

Klingspor, A. M. 1969. Middle Devonian Muskeg Evaporites of Western Canada. American Association of Petroleum Geologists Bulletin, 53: 927–948.

Kobluk, D. R., and Risk, M. J. 1977. Calcification of exposed filaments of endolithic algae, micrite envelope formation and sediment production. Journal of Sedimentary Petrology, 47: 517–528.

Krebs, W., and Mountjoy, E. W. 1972. Comparison of Central European and Western Canadian Devonian reef complexes. 24th International Geological Congress, Montreal, Section 6, pp. 294–309.

Ladd, H. S., Tracey, J. I., Wells, J. W., and Emery, K. O. 1950. Organic growth and sedimentation on an atoll. Journal of Geology, 58: 410–425.

Lasemi, Z., and Sandberg, P. A. 1984. Transformation of aragonite-dominated lime muds to microcrystalline limestones. Geology, 12: 420–423.

Law, J. 1955. Geology of northwestern Alberta and adjacent areas. American Association of Petroleum Geologists Bulletin, 39: 1927–1974.

Lobdell, F. K. 1984. Age and depositional history of the Middle Devonian Ashern Formation in the Williston Basin, Saskatchewan and North Dakota. *In* Oil and Gas in

Saskatchewan. *Edited by* J. A. Lorsong and M. A. Wilson. Saskatchewan Geological Society, Special Publication 7, pp. 5–12.

Lockhart, E. B. 1986. Nature and genesis of caymanite in the Oligocene-Miocene Bluff Formation of Grand Cayman Island, British West Indies. Unpublished M.Sc. thesis, University of Alberta, Edmonton, Alberta.

Logan, B. W. 1987. The MacLeod evaporite basin Western Australia. American Association of Petroleum Geologists, Memoir 44.

Logan, B. W., and Semeniuk, V. 1976. Dynamic metamorphism processes and products in Devonian carbonate rocks, Canning Basin, Western Australia. Geological Society of Australia, Special Publication 6.

Longman, M. W. 1980. Carbonate diagenetic textures from near-surface diagenetic environments. American Association of Petroleum Geologists Bulletin, **64**: 461–487.

Lowenstam, H. A. 1950. Niagaran reefs of the Great Lakes area. Journal of Geology, **69**: 517–533.

MacDonald, R. W., and Jones, B. 1989. Cavity and Fracture Systems in the Winnipegosis Formation (Givetian) Buildups, Southeastern Saskatchewan. Exploration Update'89, Canadian Society of Petroleum Geologists/Canadian Society of Exploration Geophysicists Joint Convention, June 12–14, 1989, Calgary Alberta, Programs and Abstracts, p. 105.

Machel, H. G. 1983. Facies and diagenesis of some Nisku buildups and associated strata Upper Devonian, Alberta, Canada. *In* Carbonate Buildups - a core workshop. *Edited by* P. M. Harris. Society of Economic Paleontologists and Mineralogists Core Workshop 4, pp. 144–181.

Machel, H. G. 1985. Cathodoluminescence in calcite and dolomite and its chemical interpretation. Geoscience Canada, **12**: 139–147.

Machel, H. G. 1986. Limestone diagenesis of Upper Devonian Nisku carbonates in the subsurface of central Alberta. Canadian Journal of Earth Sciences, **23**: 1804–1822.

Machel, H. G. 1987. Cathodoluminescence activation and zonation in carbonate rocks: an experimental approach. Geologie en Mijnbouw, **66**: 67–74.

Maestre, A. 1845. Description Geognostica y Mineradel Distrito de Cataluña Aragon. Anales de Minas (Madrid), **3**: 193–278.

Maiklem, W. R. 1971. Evaporative drawdown - a mechanism for water-level lowering and diagenesis in the Elk Point Basin. Bulletin of Canadian Petroleum Geology, **19**: 487–503.

Martindale, W. 1976. Calcareous encrusting organisms of the Recent and Pleistocene reefs of Barbados, West Indies. Ph.D thesis, University of Edinburgh, United Kingdom.

Martindale, W. and MacDonald, R. W. 1989. Sedimentology and diagenesis of the Winnipegosis Fm. Tableland area, S. E. Saskatchewan. *In* The Development of Porosity in Carbonate Reservoirs, *Compiled by* G. R. Bloy, M. G. Hadley, and B. V.

Curtis. Canadian Society of Petroleum Geologists Continuing Education Short Course Notes, Section 7.

Martindale, W., and Orr, N. E. 1988a. Middle Devonian Winnipegosis reefs of the Tableland area S.E. Saskatchewan. Canadian Society of Petroleum Geologists Reservoir, 15: 1–2.

Martindale, W., and Orr, N. E. 1988b. Middle Devonian Winnipegosis reefs of the Tableland area southeast Saskatchewan. American Association of Petroleum Geologists Bulletin, 72: 876–877

McGehee, J. R. 1949. Pre-Waterways Paleozoic stratigraphy of Alberta plains. American Association of Petroleum Geologists Bulletin, 33: 603–613.

Meyers, W. J. 1974. Carbonate cement stratigraphy of the Lake Valley Formation (Mississippian) Sacramento Mountains, New Mexico. Journal of Sedimentary Petrology, 44: 837–861.

Mountjoy, E. W. 1982. Winnifred Pass mud mounds, Upper Devonian, Alberta: cavity types and diagenesis. Department of Geological Sciences, McGill University, Montreal. DSS Contract No. 145B–1–0601

Mountjoy, E. W., and Krebs, W. 1983. Diagenesis of Devonian reefs and buildups, Western Canada and Europe—a comparison. Zeitschrift der Deutsche geologische Gesellschaft, 134: 5–60

Naiman, E. R., Bein, A., and Folk, R. L. 1983. Complex polyhedral crystals of limpid dolomite associated with halite, Permian Upper Clear Fork and Glorieta Formations, Texas. Journal of Sedimentary Petrology, 53: 549–555.

Neumann, A. C., Kofoed, J. W., and Keller, G. H. 1977. Lithoherms in the Straits of Florida. Geology, 5: 4–10.

Nickel, E. 1978. The present status of cathode luminescence as a tool in sedimentology. Minerals Science Engineering Journal, 10: 763–786.

Norris, A. W., Uyeno, T. T., and McCabe, H. R. 1982. Devonian rocks of the Lake Winnipegosis-Lake Manitoba outcrop belt, Manitoba. Geological Survey of Canada, Memoir 392.

Perrin, N. A. 1982. Environments of deposition and diagenesis of the Winnipegosis Formation (Middle Devonian), Williston Basin, North Dakota. *In* Fourth International Williston Basin Symposium. *Edited by* J. E. Christopher and J. Kaldi. Saskatchewan Geological Society, Special Publication 6, pp. 51–66.

Perrin, N. A. 1987. Depositional environments and diagenesis, Winnipegosis Formation (Middle Devonian), Williston Basin, North Dakota. Ph.D. thesis, University of North Dakota, Grand Forks, North Dakota.

Perrin, N. A., and Precht, W. F. 1985. Depositional environments, paleoecology and diagenesis of selected Winnipegosis Formation (Middle Devonian) reef cores, Williston Basin, North Dakota. *In* Rocky Mountain Carbonate Reservoirs. *Edited by* M. W. Longman, K. W. Shanley, R. F. Lindsay and D. E. Eby. Society of Economic Paleontologists and Mineralogists, Core Workshop 7, pp. 125–182.

Peterson, J. A., and MacCary, L. M. 1987. Regional stratigraphic and general petroleum geology of the U.S. portion of the Williston Basin and adjacent areas. *In* Williston Basin: anatomy of a cratonic oil province. *Edited by* M. W. Longman. Rocky Mountain Association of Geologists, pp. 9–45.

Phillips, F. C. 1971. An introduction to crystallography. Halsted Press, New York.

Pierson, B. J. 1981. The control of cathodoluminescence in dolomite by iron and manganese. Sedimentology, 28: 601–610.

Playford, P. E. 1984. Platform-margin and marginal-slope relationships in Devonian reef complexes of the Canning Basin. *In* The Canning Basin W.A. *Edited by* P. G. Purcell. Proceedings of the Geological Society of Australia/Petroleum Exploration Society Australia Symposium, pp. 189–214.

Pleydell, S. M. 1987. Aspects of diagenesis and ichnology in the Oligocene-Miocene Bluff Formation of Grand Cayman Island, British West Indies. Unpublished M.Sc. thesis, University of Alberta, Edmonton, Alberta.

Precht, W. F. 1986. Reservoir development and hydrocarbon potential of Winnipegosis (Middle Devonian) pinnacle reefs, southern Elk Point Basin, North Dakota. Carbonates and Evaporites, 1: 83–99.

Reinson, G. E., and Wardlaw, N. C. 1972. Nomenclature and stratigraphic relationships, Winnipegosis and Prairie Evaporite Formations, Central Saskatchewan. Bulletin of Canadian Petroleum Geology, 20: 301–320.

Roberts, H. H., Aharon, P., and Phipps, C. V. 1988. Morphology and sedimentology of *Halimeda* bioherms from the eastern Java Sea (Indonesia). Coral Reefs, 6: 161–172.

Rosenthal, L. R. 1987. The Winnipegosis Formation of the northeastern margin of the Williston Basin. *In* The Fifth International Williston Basin Symposium. *Edited by* C. J. Carlson and J. E. Christopher. Saskatchewan Geological Society, Special Publication 9, pp. 37–46.

Rosenthal, L. R. 1988. The Winnipegosis Formation (Middle Devonian) of the northeastern margin of the Williston Basin, Canada. *In* Devonian of the World, Volume II: Sedimentation. *Edited by* N. J. McMillan, A. F. Embry, and D. J. Glass. Proceedings of the Second International Symposium on the Devonian System, Canadian Society of Petroleum Geologists, pp. 463–475.

Schmalz, R. F. 1969. Deep-water evaporite deposition: a genetic model. American Association of Petroleum Geologists Bulletin, 53: 798–823.

Schmidt, V., McDonald, D. A., and McIlreath, I. A. 1980. Growth and diagenesis of Middle Devonian Keg River cementation reefs, Rainbow Field, Alberta. *In* Carbonate Reservoir Rocks. *Edited by* R. B. Halley, and R. G. Loucks. Society of Economic Paleontologists and Mineralogists Core Workshop 1, pp. 43–63.

Schmidt, V., McIlreath, I. A., and Budwill, A. E. 1982. Origin and diagenesis of Middle Devonian pinnacle reefs encased in evaporites, "A" and "E" pools, Rainbow field, Alberta. *In* Carbonate Petroleum Reservoirs. *Edited by* P. O. Roehl and P. W. Choquette. Springer-Verlag, Berlin, pp.143–159.

Sherwin, D. F. 1962. Lower Elk Point section in east-central Alberta. Journal of the Alberta Society of Petroleum Geologists, 10: 185–191.

Stanford, R. L. 1989. Sedimentology and diagenesis of the Winnipegosis Formation, southeastern Saskatchewan. Unpublished M.Sc. thesis, University of Alberta, Edmonton, Alberta.

Stanford, R. L., and Jones, B. 1988. Diagenetic history of Givertian Winnipegosis Formation in Southeastern Saskatchewan. American Association of Petroleum Geologists Bulletin, 72: 882.

Stearn, C. W., Carroll, R. L., and Clark, T. H. 1979. Geological evolution of North America, third edition. John Wiley and Sons, New York.

Strasser, A, and Davaud, E. 1986. Formation of Holocene Limestone sequences by progradation cementation, and erosion: two examples from the Bahamas. Journal of Sedimentary Petrology, 56: 422–428.

Swinchatt, J. P. 1969. Algal boring: a possible depth indicator in carbonate rocks and sediments. Geological Society of America Bulletin, 80: 1391–1396.

Taylor, R. E. 1937. Water-insoluble residues from the rock-salt of Louisiana salt plugs. American Association of Petroleum Geologists Bulletin, 21: 1268–1310.

Ten Have, T., and Heijnen, W. 1985. Cathodoluminescence activation and zonation in carbonate rocks: and experimental approach. Geologie en Mijnbouw, 64: 297–310.

Thomas, G. E. 1974. Lineament-block tectonics; Williston—Blood Creek Basin. American Association of Petroleum Geologists Bulletin, 58: 1305–1322.

Tracey, J. I., Ladd, H. S., and Hoffmeister, J. E. 1948. Reefs of Bikini, Marshall Is. Geological Society of America Bulletin, 59: 861–878

Tschermak, G. 1881. Isomorphie der Rhomboedrischen Carbonate. Tschermaks Mineralogische und Petrographische Mitteilungen, 4: 99–121.

Tucker, M. E. 1973. Sedimentolgy and diagenesis of Devonian pelagic limestones (Cephalopodenkalk) and associated sediments of Rhenohercynian Geosyncline, West Germany. Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen, 142: 320–350.

Tyrrell, J. B. 1892. Report on northwestern Manitoba and portions of the adjacent District of Assiniboia and Saskatchewan. Geological Survey of Canada, Annual Report 1891, Part E, pp. 1–240.

Van Hees, H. 1956. Elk Point Group; notes on a sub-surface cross section extending from east-central Alberta through Saskatchewan to western Manitoba. Journal of Alberta Society of Petroleum Geologists, 4: 29–39.

Walkden, G. M., and Berry, J. R. 1984. Syntaxial overgrowths in muddy crinoidal limestones: cathodoluminescence sheds new light on an old problem. Sedimentology, 31: 251–267.

Walls, R. A., and Burrowes, G. 1985. The role of cementation in the diagenetic history of Devonian reefs, Western Canada. *In* Carbonate Cements. *Edited by* N. Schneidermann and P. M. Harris. Society of Economic Paleontologists and Mineralogists, Special Publication 36, pp. 185–220.

Wardlaw, N. C., and Reinson, G. E. 1971. Carbonate and evaporite deposition and diagenesis, Middle Devonian Winnipegosis and Prairie Evaporite formations of south-central Saskatchewan. American Association of Petroleum Geologists Bulletin, 55: 1759–1786.

Warne, S. St. J. 1962. A quick field or laboratory staining scheme for the differentiation of the major carbonate minerals. Journal of Sedimentary Petrology, 32: 29–38.

Wheeler, V. C. 1939. New Mexico locality. The Mineralogist (Portland, Oregon), 7: 385.

Williams, G. K. 1984. Some musings on the Devonian Elk Point Basin, western Canada. Bulletin of Canadian Petroleum Geology, 32: 216–232.

Wilson, J. L. 1975. Carbonate facies in Geologic History. Springer-Verlag, Berlin.

Wilson, N. L. 1985. A study of the Upper Winnipegosis mounds in south-central Saskatchewan. M.Sc. thesis, University of Saskatchewan, Saskatoon, Saskatchewan.

Wray, J. L., and Playford, P. E. 1970. Some occurrences of Devonian reef-building algae in Alberta. Bulletin of Canadian Petroleum Geology, 18: 544–555.

Wright, V. P., Platt, N. H., and Wimbledon, W. A. 1988. Biogenic laminar calcretes: evidence of calcified root-mat horizons in paleosols. Sedimentology, 35: 603–620.

PHOTOGRAPHIC PLATES