DOLOMITE AND DOLOMITIZATION IN THE MIDDLE DEVONIAN WINNIPEGOSIS FORMATION, NORTH DAKOTA

By

Eli Kostelnyk

A Thesis

Submitted to the Faculty of Graduate Studies

in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Geological Sciences

University of Manitoba

Winnipeg, Manitoba

0-612-32156-8

DOLOMITE AND DOLOMITIZATION IN THE MIDDLE DEVONIAN WINNIPEGOSIS FORMATION, NORTH DAKOTA

BY

ELI KOSTELNYK

A Thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

Table of Contents

LIST OF FIGURES

LIST OF TABLES

List of Photographs

ABSTRACT

The Middle Devonian Winnipegosis Formation in North Dakota is composed of limestones, dolomitized limestones and dolostones. The Lower Winnipegosis Member was deposited basin-wide as a relatively uniform shallow marine ramp under normal, open marine conditions. The Upper Winnipegosis Member represents two distinct depositional environments: (1) a central deep basin with scattered pinnacle reefs and the coevally deposited deep-marine sediments of the Ratner Member and (2) peripheral carbonate shelf deposits. Evaporite deposits of the Prairie Formation eventually filled the basin and completely buried the Winnipegosis Formation.

Six different dolomite types, five anhydrite types, dedolomitization, a late diagenetic calcite and a ferroan dolomite event were identified to have formed over three diagenetic stages. The synsedimentary diagenetic stage includes Idio-Ep dolomite and anhydrite type 1 forming in supratidal patterned dolostones. Most of the mosaic dolomite types (Idio-E, Idio-S, Xeno-S and Xeno-A) formed in the early diagenetic stage by seepage reflux and to a smaller extent by mixed-water dolomitization. The late diagenetic stage includes the formation of ISO dolomite, saddle dolomite, dedolomitization, a late diagenetic calcite and a ferroan dolomite event in a deep burial setting.

Results from $\delta^{18}O$ and $\delta^{13}C$ analyses of dolomite in the Lower Winnipegosis Member indicate that Middle Devonian sea water was an important component of the

dolomitizing fluids in the Lower Winnipegosis Member. Geochemical and petrographic data of dolomites from the Upper Winnipegosis and Ratner members indicate that dolomite has been recrystallized. A narrow range of $\delta^{18}O_{dol}$ values, uniform luminescence and generally higher concentrations of Fe and Mn in rims of crystals than in cores indicate that dolomite recrystallization occurred late in the diagenetic history of the Winnipegosis Formation, after or at the same time as the ferroan dolomite event.

ACKNOWLEDGMENTS

I am indebted to my thesis advisor, Dr. Nancy Chow who has shown much patience and understanding throughout this project. I thank her for her guidance, support and encouragement during the course of this study.

My thanks to Imperial Oil for their funding contributions toward this project. Many thanks to Julie LeFever and the Wilson M. Laird Core and Sample Library, Grand Forks, North Dakota for all their assistance. Many thanks to Marva Short for pulling me through some tough times and to Wascana Energy Inc. and Mobil Oil Canada for their support and encouragement during this study. Professors Bill Last and Ian Ferguson gave academic as well as moral support - thanks guys. The editing comments of Drs. Bill Last and Brian Stimpson were also greatly appreciated.

Brad Spence and Hani Khaladi helped prepare samples for thin sections. Irene Berta prepared thin sections. Lisa Sack prepared samples for XRD. Mark Cooper, Wayne Blonski and Bill Buhay provided their much needed knowledge of geochemistry.

I am forever indebted to Joshua and Jordan for their patience. I apologize for their frustrations - always waiting for Dad to come home.

CHAPTER 1: INTRODUCTION

1.1 PROLOGUE

The Middle Devonian Winnipegosis Formation is an extensively dolomitized reef-bearing carbonate sequence of the Elk Point Group in the intracratonic Elk Point Basin (Fig. 1.1). The southeastern portion of this Basin is more generally known as the Williston Basin. Discovery of prolific hydrocarbons in pinnacle reefs of the Winnipegosis Formation in the Tableland area of Saskatchewan and more recently in the Temple Field, North Dakota has generated interest in the petroleum industry for more detailed studies of the Formation. Since then, there have been many studies of these dolomitized carbonates. Dolomitization of carbonates has been linked to an increase (as well as a decrease) in reservoir quality (porosity and permeability). In the exploration for hydrocarbons in carbonates, it is important to be able to predict where the better porosity and permeability is within the target unit. There are many dolomitization models and variations of those models that have been proposed for various modern and ancient sedimentary deposits around the world. This study considers the dolomitization of the Winnipegosis Formation in the subsurface of North Dakota.

1.2 OBJECTIVES

This study evaluates the products and processes of dolomitization in the Winnipegosis Formation in North Dakota. In order to accomplish this, the following objectives were established: (1) lithofacies identification and depositional interpretation in order to provide a depositional framework for the examination of diagenetic features; (2) identification of diagenetic features and interpretation of the overall paragenetic sequence; (3) identification, description and interpretation of different types of dolomite; (4) development or refinement of dolomitization models for the Winnipegosis Formation; and (5) reconstruction of a dolomitization history for the Winnipegosis Formation.

1.3 Study Area

The area of study is located in the subsurface of the northwestern corner of North Dakota (Fig. 1.2). The study area lies between Township 148N (United States Standard Land Office Grid System) and the Canada-United States border, and Range 74WPM (PM = Primary Meridian) and the Montana-North Dakota state boundary. The area includes the following North Dakota counties: Bottineau, Burke, Divide, Dunn, McHenry, McKenzie, Mountrail, Renville, Ward and Williams.

1.4 Methods

Forty-nine core totaling approximately 2.5 km in length were logged at the Wilson M. Laird core and sample library at the North Dakota Geological Survey's (NDGS) University Station in Grand Forks, North Dakota. The core were described, photographed and sampled for thin section analyses. Gamma ray, caliper, resistivity, and porosity logs from the 49 cored drill holes were examined to assist in the delineation of lithology and formation correlation. Specific core are referred to in the text by their NDGS catalogue number (refer to Appendix B for details on core). 250 thin sections were made at the University of Manitoba. Thin sections were stained with Alizarin Red-S to distinguish between calcite and dolomite, and potassium ferricyanide for distinction between ferroan and non-ferroan carbonates. Porosity was determined by visually estimating the sizes and amount of pore spaces as a percentage of the total area in thin section. Standard transmitted light petrography was done using a Nikon Optiphot-Pol microscope with a UFX-IIA photomicrographic attachment. Fluorescence observations were done using the Nikon microscope with an epi-fluorescence attachment EF-D with a high-pressure mercury lamp. The blue violet (BV) barrier filter proved to be the most useful for this study and was used exclusively to examine all thin sections. The Nikon setup allowed for concurrent use of transmitted light and epi-fluorescent microscopy. Selected thin sections were polished and examined using a Nikon Optiphot microscope with a Technosyn cold cathode luminescence (CL) unit (model 8200 MKII). These petrographic techniques were complemented by mineralogical analysis of selected samples using a Philips PW x-ray diffractometer and elemental (Ca, Mg, Fe, Mn, Zn, Sr, Na) analysis using a Cameca SX-50 electron microprobe. Selected powder samples, collected using a Foredom (#30) hand-held drill and binocular microscope, were sent to the Environmental Isotope Laboratory at the University of Waterloo for carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) stable isotope analysis. Details of operating conditions for these various techniques are given in Appendix F.

1.5 TERMINOLOGY

Geologic terms can be slightly confusing and even misleading. This section defines the usage of certain terms used in this study. Petrographic terminology for this study is based on Dunham's (1962) classification of carbonate rocks as modified by Embry and Klovan (1971). A "dolo" prefix is used in this study where the carbonate rock is dolostone (e.g. stromatoporoid doloboundstone - a stromatoporoid boundstone that is between approximately 75 - 100% dolomite).

Bank - an isolated platform surrounded by deep ocean water and cut off from terrigenous clastic sediments (James and Kendall, 1992).

Buildup - a non-genetic term used to describe a laterally restricted body of carbonate rock which differs in composition and internal fabric from the surrounding and overlying deposits and display topographic relief above equivalent, typically thinner, strata (Heckel, 1974).

Dedolomitization - a term originally used by Morlot (1847) for the replacement of dolomite by calcite during diagenesis or chemical weathering (from Bates and Jackson, 1980).

Dolomitic limestone -previous definitions include a limestone in which the mineral dolomite is conspicuous, but calcite is more abundant (Pettijohn, 1957) and a limestone that has been incompletely dolomitized (Chilingar et al., 1979). In this study the name 'dolomitic limestone' was given to a rock unit if a drop of cold dilute (10%)

hydrochloric acid (HCL) did not produce effervescence immediately but produced effervescence before roughly 5 seconds (approximately between 10-75% dolomite).

Dolostone - carbonate rock largely composed of the mineral dolomite (Shrock, 1948). In this study the name 'dolostone' was given to a rock unit if a drop of cold dilute (10%) hydrochloric acid did not produce effervescence after roughly 5 seconds (approximately 75-100% dolomite).

Mound - a buildup lacking large skeletal metazoans, which formed through organic accumulation rather than purely mechanical accumulation (Wilson, 1975).

Patterned carbonate - A diagenetic feature in very fine to finely crystalline carbonate rocks consisting of light and dark colored areas varying in shape, complexity and intensity of development (Dixon, 1976).

Patterned dolostone - A light brown to buff colored dolomudstone characterized by ovoid to irregular-shaped patches of anhydrite that vary in complexity and intensity of development.

Platform - a carbonate platform is a large edifice formed by the accumulation of sediment in an area of subsidence (James and Kendall, 1992). Most such structures have a flat top, possess steep sides and can be several kilometers thick and extend over many hundreds of square kilometers.

Ramp - a carbonate ramp is a shelf that slopes gently basinward at angles of less than 1 degree (James and Kendall, 1992).

Reef - a massive or layered buildup which formed through organic accumulation and was potentially wave-resistant, being stabilized syndepositionally by organic framework and/or submarine cementation (James, 1987).

Shelf - a carbonate shelf is a platform tied to an adjacent continental land mass (James and Kendall, 1992).

Stenohaline - Said of a marine organism that tolerates only a narrow range of salinity (Bates and Jackson, 1980).

1.6 Geologic Setting

1.6.1 Middle Devonian Elk Point Basin

During early Middle Devonian time the seas transgressed southeastward from northwestern Alberta into the Williston Basin (Meijer-Drees, 1994). Transgressive deposits of the Ashern Formation are overlain by the regressive deposits of the Winnipegosis and Prairie Formations which represent a depositional cycle and formed a distinct sedimentary package in the Williston Basin portion of the Elk Point Basin referred to as the Middle Devonian Elk Point Group (Meijer-Drees, 1994; Fig. 1.3). The Elk Point Basin is bounded by the Presqu'ile Barrier to the northwest; the Peace River Arch, West Alberta Ridge, Southern Alberta Arch-Bearpaw Anticline, the Swift Current Platform and the central Montana and Sweetgrass arches to the west; the Black Hills Uplift to the southwest; the Sioux or Transcontinental arch to the southeast; and the Precambrian Shield to the east and northeast (Fig. 1.4). Middle Devonian carbonate rocks of the Elk Point Group are exposed in outcrops along a northwest-trending, roughly linear belt in the Lake Winnipegosis-Lake Manitoba region of southwestern Manitoba. Rocks of the Elk Point group also outcrop in Alberta, Saskatchewan and the Northwest Territories. Surface exposures of Middle Devonian carbonates can be traced in the subsurface from the Northwest Territories through Alberta, Saskatchewan, Manitoba, Montana and into North Dakota.

Deposition of the Elk Point Group occurred in Eifelian to Givetian time, during which an overall rise in eustatic sea level occurred (Grayston et al., 1964; Vail et al., 1977; Johnson et al., 1985). During the Early Devonian the Meadow Lake Escarpment, a local uplift (Fig. 1.4), acted as a barrier to the southeastward transgressing epicontinental sea (Grayston et al., 1964). Once this barrier was breached the sea transgressed over the eroded Silurian Interlake Group in the southern portions of the Elk Point Basin. Transgressing Eifelian seas advanced southeastward depositing the Lower Keg River and the Upper Chinchaga members in northwestern Alberta (Grayston et al., 1964; Johnson et al., 1985) and the now dolomitized, argillaceous lime muds of the Ashern Formation (Johnson and Lescinsky, 1986).

The Ashern-Winnipegosis contact is generally conformable and represents the continued or renewed transgression associated with a change from restricted to open marine conditions (Perrin, 1987). After a brief erosional hiatus lime muds were deposited forming the carbonate ramp deposits of the Lower Member of the Winnipegosis Formation. Transgression continued as the Elk Point Basin, southeast of the Meadow

Lake Escarpment, differentiated into separate depositional environments of what is now the Upper Member of the Winnipegosis Formation (Perrin, 1987). A relative drop in sea level subsequently restricted the inflow of normal marine water into the Elk Point Basin due to the emergence of a barrier located near the northern end of the Elk Point Basin in northern Alberta. This barrier is a major Middle Devonian reef sill, the Presqu'ile Barrier Complex (Edie, 1959; Mckennit, 1961; Meijer-Drees, 1994). The restricted marine waters of the Elk Point Basin became concentrated, through evaporative drawdown processes (Maiklem, 1971), to the point of evaporite precipitation, resulting in the accumulation of thick basin-wide evaporite deposits of the Prairie and Muskeg Formations. Renewed transgression in middle to late Givetian time (Meijer-Drees, 1994) and subsequent carbonate deposition marked the end of one depositional cycle (Elk Point Group) and the beginning of another depositional cycle - the Manitoba Group (Edie, 1958, 1959).

1.6.2 Formation Descriptions: Elk Point Group

In North Dakota the Elk Point Group consists of, in ascending order, argillaceous dolostones of the Ashern Formation, variably dolomitized limestones of the Winnipegosis Formation and salts of the Prairie Formation. The general stratigraphy of the Elk Point Group in North Dakota is outlined in Fig. 1.3. Stratigraphic equivalents of the Middle Devonian Winnipegosis Formation in the Elk Point Basin are: the Winnipegosis Formation in west-central Saskatchewan (Sherwin, 1962), the Keg River Formation in northern and central Alberta (Law, 1955a, 1955b; Sherwin, 1962), and the Pine Point Formation and the Presqu'ile Formation in northern Alberta (Morrow, 1973).

1.6.2.1 Ashern Formation

Baillie (1951, 1953a) proposed the term 'Ashern Formation' for the poorly bedded argillaceous dolostone and the brownish-red to brick-red, slightly silty, dolomitic shale in the Lake Winnipegosis-Lake Manitoba outcrop belt. In North Dakota, Lobdell (1984) informally subdivided the Ashern Formation into a lower red member and an upper grey member. Both Ashern members are argillaceous, microcrystalline dolostones with minor amounts of quartz silt. The Ashern Formation constitutes the basal part of the Devonian succession in the Elk Point Basin of Manitoba, Saskatchewan and North Dakota. It unconformably overlies the dolostones of the Silurian Interlake Formation and underlies the Lower Member of the Winnipegosis Formation.

The Ashern Formation may represent the reworking of a residual soil formed during Late Silurian to Early Devonian time (Norris et al., 1982). The upper 'dark gray member' of the Ashern Formation was interpreted to have been deposited in a restricted lagoon or embayment under hypersaline, reducing conditions (Perrin, 1987). The spatial distribution of the Ashern Formation is irregular and may represent an infilling of topographic lows of the eroded Silurian surface (McCabe and Bannatyne, 1970). McKennit (1961) and Perrin (1981) concurred that the Ashern Formation represents a residual lateritic clay reworked by a Middle Devonian transgressing sea in a progressively reducing environment. However, Rosenthal (1987) postulated that the Ashern Formation may be a non-marine depositional event unrelated to the Elk Point transgression.

1.6.2.2 Elm Point Formation (Manitoba)

The name Elm Point Limestone was introduced by Kindle (1914) for Manitoba limestone outcrops underlying the Winnipegosis Formation and overlying the Ashern Formation near the north end of Lake Manitoba. Baillie (1951) referred to this limestone as the Elm Point Formation. The Elm Point Formation is identified only in Manitoba and is typically a medium yellowish-brown, variably mottled, very fine-grained limestone. The Elm Point Formation is essentially equivalent to the Lower Member of the Winnipegosis Formation of North Dakota (Norris et al., 1982).

1.6.2.3 Winnipegosis Formation

Lower Winnipegosis Member

The Lower Member of the Winnipegosis Formation disconformably overlies the Ashern Formation in North Dakota, Montana, Saskatchewan and is depositionally equivalent to the Elm Point Formation of Manitoba (Baillie, 1953a, 1953b, 1955, 1956). In North Dakota the Lower Winnipegosis Member is considered a carbonate ramp deposit generally consisting of mottled and laminated, variably dolomitized limestones. Perrin (1987) refers to the Lower Winnipegosis Member as a transitional subtidal facies between the Ashern Formation and the Upper Winnipegosis Member. The mottled texture, characteristic of the Lower Winnipegosis Member, has been ascribed to preferential dolomitization of burrow structures (e.g. Kendall, 1976; Perrin, 1987; Chow and Longstaffe, 1995). The presence of local topographic features in the upper surface of the carbonate ramp provided a foundation for the deposition of the organic buildups of the Upper Winnipegosis Member in North Dakota (Ehrets and Kissling, 1987) and Saskatchewan (Martindale and MacDonald, 1989).

UPPER WINNIPEGOSIS MEMBER

Baillie (1951, 1953a) first proposed the name and described the Winnipegosis Formation in the Manitoba outcrop belt as consisting of two rock types. The first is a massive to thick bedded dolostone constituting the bioherm facies. The second rock type is described as saccharoidal thinly bedded, dolostone of the interbioherm areas which constitutes the 'normal' facies of the Formation (see Ratner Member below). Differentiation of the Elk Point Basin into distinct shallow shelf and deep basin regimes (Fig. 1.2) during deposition of the Upper Winnipegosis Member enabled the development of reefs along the platform margin and allowed for sustained vertical growth of pinnacle reefs in the subsiding basin (Perrin, 1981, 1982a, 1982b, 1987; Perrin and Precht, 1985, Meijer-Drees, 1994). The deep basin succession in North Dakota is a sequence of either: (1) thick mound or reef carbonate complexes of the Upper Winnipegosis Member or (2) thin bituminous, laminated, inter-reef carbonates of the Ratner Member (see Ratner Member below; LeFever et al., 1991). With continued regression of the Devonian sea the platform margins and pinnacle reefs became at least partially exposed as shallow water sediments were deposited around the emergent reefs (Perrin, 1981, 1982a, 1982b, 1987; Perrin and Precht, 1985; Ehrets and Kissling, 1987). The basin was eventually filled by the evaporites of the overlying Prairie Formation, possibly over a period of only a few thousand years (Wardlaw and Shwerdtner, 1966).

The reef carbonate complex of the western platform margin is host to the hydrocarbon producing Temple Field (northeastern Williams County) which sparked considerable interest in exploration of the Winnipegosis Formation. Consequently, oil-charged pinnacle reefs were discovered basinward from the platform margin in North Dakota (Ehrets and Kissling, 1987) and Saskatchewan (Martindale and MacDonald, 1989).

RATNER MEMBER

Wardlaw and Reinson (1971) proposed the name Ratner Member (based on the subsurface in Saskatchewan) for the finely laminated carbonate mudstone and enterolithic anhydrite containing bituminous partings and organic-rich layers of the interbioherm area. There is no consensus as to which formation the Ratner Member belongs. Some studies place the Ratner Member in the Prairie Formation (e.g. southern Saskatchewan - Kendall, 1973,1976; North Dakota and Manitoba - LeFever et al., 1991) ,whereas other studies place the Ratner Member in the Winnipegosis Formation (e.g. North Dakota - Perrin, 1987; Saskatchewan - Stanford, 1989, and Martindale and MacDonald, 1989;

Manitoba - Teare, 1990). In this study, the Ratner Member is considered as part of the Winnipegosis Formation.

1.6.2.4 Prairie Formation

Baillie (1953a) named the salt and anhydrite beds overlying the Winnipegosis Formation and underlying the Dawson Bay Formation as the Prairie Evaporite Formation. It has also been called the Prairie Formation and the Prairie Evaporite (Perrin, 1981, 1982a, 1982b, 1987; Perrin and Precht, 1985; Ehrets and Kissling, 1987; Martindale and MacDonald, 1989). The name Prairie Formation is used in this study. As halite filled the inter-reef areas to the top of the Winnipegosis pinnacle reefs (lower Prairie Formation) coastal sabkhas developed on the emergent pinnacle reefs, as well as on the adjacent subaerially exposed shelf areas (Perrin, 1987). Potash deposits representing very shallow brine depths and very high salinities cap this thick halite deposit. The Prairie Formation consists of four such potash-capped halite sequences (Oglesby, 1987).

The contact between the Winnipegosis and Prairie formations varies from place to place within the basin (McKennit, 1961; Norris et al., 1982; Perrin, 1987). In the subsurface of North Dakota, dolostone generally underlies a relatively thin layer of anhydrite that is overlain by a thick sequence of halite. Perrin (1987) placed the Winnipegosis-Prairie contact above the anhydrite and below the halite. In areas where interbedded dolostone and anhydrite were found above thin salt beds, Perrin (1987) established the contact at the top of this 'mixed' sequence and below the thick salt. This study uses the contact above the 'mixed' evaporite sequence as defined by Perrin (1987). In the Manitoba outcrop belt, where salt is not present, the bottom of the shaly Mafeking Member (second redbed) of the Dawson Bay Formation overlies the Winnipegosis Formation (Fig. 1.3: McKennit, 1961, Norris et al., 1982). Norris et al. (1982) noted thin beds of limestone-shale breccias at the top of the Winnipegosis Formation in the outcrop belt which they termed 'transitional beds'. In some Manitoba drill core some breccia clasts resemble dolostones of the Winnipegosis Formation and others resemble the overlying Mafeking Member. Norris et al. (1982) interpreted these mixed breccias to represent dissolution and collapse of evaporites originally interbedded with the carbonates of the Winnipegosis Formation, and indicated that the contact lies somewhere within this breccia. Similar brecciated transitional beds were noted in some areas of North Dakota. In this study, the Winnipegosis-Prairie contact is placed at the base of the brecciated zone because it represents the base of the now-dissolved salts, as well as the 'mixed' evaporites defined by Perrin (1987).

Following evaporite deposition and complete withdrawal of the Devonian sea, erosion of the upper part of the Prairie Formation occurred. The second "redbed" of the Dawson Bay Formation, unconformably overlying the Prairie Formation, has been interpreted to be either the result of this erosion or the first depositional event of the Dawson Bay Formation in a coastal sabkha during renewed transgression of Devonian seas in the Elk Point Basin (Perrin, 1987).

1.7 Previous Studies

The presence of Devonian rocks in the Western Canada Sedimentary Basin was first recognized by Billings (1859) based on the evidence of fossils collected from Snake Island on Lake Winnipegosis near the town of Winnipegosis and Manitoba Island on Lake Manitoba by Hind (1859). The first detailed description of Middle Devonian carbonate outcrop in Manitoba was provided by Tyrrell (1893) who included them in the Winnipegosan Formation. Whiteaves (1891, 1892) identified and described much of the fauna collected by Tyrrell and pointed out the relationship between Devonian fauna in Manitoba and those in Europe based on the occurrence of the brachiopod *Stringocephalus burtini*. Baillie (1953b) subsequently changed the name of the unit to the Winnipegosis Formation to avoid any connotation of time. Kindle (1914) recognized a thinly bedded limestone underlying the Winnipegosis Formation in Manitoba which he called the Elm Point Formation. Wallace (1915, 1925) discussed the lithology and fossils of both the Winnipegosis and Elm Point formations from the Manitoba outcrop. Kerr (1949) provided a description of wells, drilled through the Paleozoic, in Manitoba, Saskatchewan and North Dakota. Van Hees (1956) constructed subsurface cross section from Alberta, through Saskatchewan and into Manitoba. McKennit (1961) discussed economic potential in the Winnipegosis Formation in Manitoba.

The single most important work on the Winnipegosis Formation was probably that of Baillie (1951) who recognized and described "bioherm and interbioherm" facies of the Winnipegosis Formation in the Manitoba outcrop belt. Baillie (1953a, 1953b, 1955,

1956) related the Elm Point, Winnipegosis and Ashern Formations of the Manitoba outcrop belt to the subsurface of Manitoba, Saskatchewan, North Dakota and Montana. He named the Prairie Evaporite Formation and correlated the Winnipegosis Formation across Manitoba, eastern Alberta and western Saskatchewan (Fig. 1.4). McGehee (1949, 1952) described the Middle Devonian Elk Point Formation in eastern Alberta and correlated the Formation to the subsurface of Saskatchewan, southwestern Manitoba and North Dakota. Belyea (1952) raised the Elk Point Formation to group status, and Law (1955a, 1955b) subsequently introduced new formation names for the Devonian subsurface equivalents in Alberta: Chinchaga, Keg River, Muskeg and Watt Mountain. Van Hees (1958) discussed the regional significance of the Meadow Lake Escarpment in relation to the Lower Paleozoic stratigraphy in Saskatchewan. McCabe (1967,1972) discussed the tectonic framework of the basin. Norris and Uyeno (1971) described conodonts in the Devonian outcrop belt of Manitoba.

In more recent work, McCabe and Barchyn (1982) interpreted the Elm Point Formation to be a platform facies deposit. Norris et al. (1982) gave a detailed description of Devonian outcrop in the Lake Manitoba-Lake Winnipegosis outcrop belt of Manitoba. Rosenthal (1987) compiled a series of observations from Winnipegosis Formation outcrops and drill core in Manitoba and proposed a depositional/diagenetic model with implications for subsurface hydrocarbon exploration. Teare (1990) identified six dolomitized facies within Winnipegosis reef complexes in the Dawson Bay area of

Manitoba and described three dolomite types in twenty phases of diagenesis interpreted to have occurred in four principal diagenetic environments.

Sandberg and Hammond (1958) extended Baillie's (1953a, 1953b, 1955) Manitoba nomenclature, with minor revisions, to the subsurface of the Williston Basin in the United States. They shortened the name Prairie Evaporite Formation to Prairie Formation and considered the Ashern Formation as basal Winnipegosis, contrary to Andrichuk (1952) who separated out the Ashern Formation in Montana and North Dakota. Sandberg (1961) recognized that, during Middle Devonian time, the sedimentary depocenter had shifted in the Williston Basin from North Dakota to Saskatchewan. He attributed this to downwarping of the basin and the intermittent uplift of structural features along the western margin of the basin. Carlson and Anderson (1965) correlated Sloss sequences (Sloss, 1963) into the United States portion of the Williston Basin. They also considered the Ashern Formation to be basal Winnipegosis and the beginning of the Kaskaskia sequence. Sandberg (1961) and Sandberg and Mapel (1967) divided the subsurface Winnipegosis Formation of North Dakota into basin and margin facies. Kinard and Cronoble (1969) identified restricted lagoon and shoal environments in the Middle Devonian subsurface of North Dakota and Montana. Perrin (1981, 1982a, 1982b, 1987) summarized depositional environments, reef lithofacies, major diagenetic features and porosity patterns of the Winnipegosis Formation in North Dakota. Precht (1986) discussed the petroleum potential of the Winnipegosis Formation in North Dakota. Heck and Burke (1991) compiled seven wireline-log cross-sections through North Dakota, and into surrounding states and provinces to establish the character and distribution of Devonian strata in North Dakota.

Studies of the Winnipegosis Formation in Saskatchewan have been numerous and are mostly related to the economic potash deposits of the Prairie Formation (e.g. Powley, 1951; Lane, 1959; Yont, 1960, 1962; Sherwin, 1962; Jones, 1964, 1965a, 1965b, 1966; Streeton, 1971; Kendall, 1973, 1976 and 1979; Baar, 1974; Fuzesy, 1975, 1976, 1980; Gendzwill, 1978a, 1978b; Wilson, 1984). Walker (1956, 1957) described diagenetic features in the Winnipegosis Formation in western Saskatchewan. Edie (1959) suggested the presence of atoll reefs for the Winnipegosis Formation in central Saskatchewan. Stanford (1989) recognized two dolomite types in three diagenetic phases in the Winnipegosis Formation in southeastern Saskatchewan. Martindale and MacDonald (1989) examined Upper Winnipegosis buildups in the Tableland area of Saskatchewan and related buildup sedimentology and diagenesis to hydrocarbon reservoir quality and heterogeneity. MacDonald (1989) concentrated on primary and solution modified cavities and calcite cements in Upper Winnipegosis buildups in the Tableland area of Saskatchewan.

The Winnipegosis Formation has been part of many regional studies. Fuller and Porter (1962) introduced a cross section of the Elk Point Basin from North Dakota to central Alberta illustrating shifting depocenters. Grayston et al. (1964) composed an illustrated geologic history of the Paleozoic in western Canada. More recently, Mossop and Shetson (1994) compiled an Atlas of the Western Canadian Sedimentary Basin.

Schmidt (1971) and Schmidt et al. (1980) examined early diagenetic carbonate cementation of Elk Point Basin reefs. Krebs and Mountjoy (1972) related Devonian reef complexes in Canada to those in western Europe. Heckel and Witzke (1979) related the Western Canada Sedimentary Basin Devonian carbonates to the Devonian world paleogeography. Wilson (1984) gave a summary of depositional environments in the Elk Point Basin. A review of the Winnipegosis Formation literature (Kent, 1984) and history of hydrocarbon exploration (Hriskovitch, 1970) were also completed. A correlation of Paleozoic strata from Manitoba and North Dakota was compiled by LeFever et al. (1991). Meijer-Drees (1994) summarized the depositional history and stratigraphy of the Elk Point Group within the Interior Plains of Western Canada.

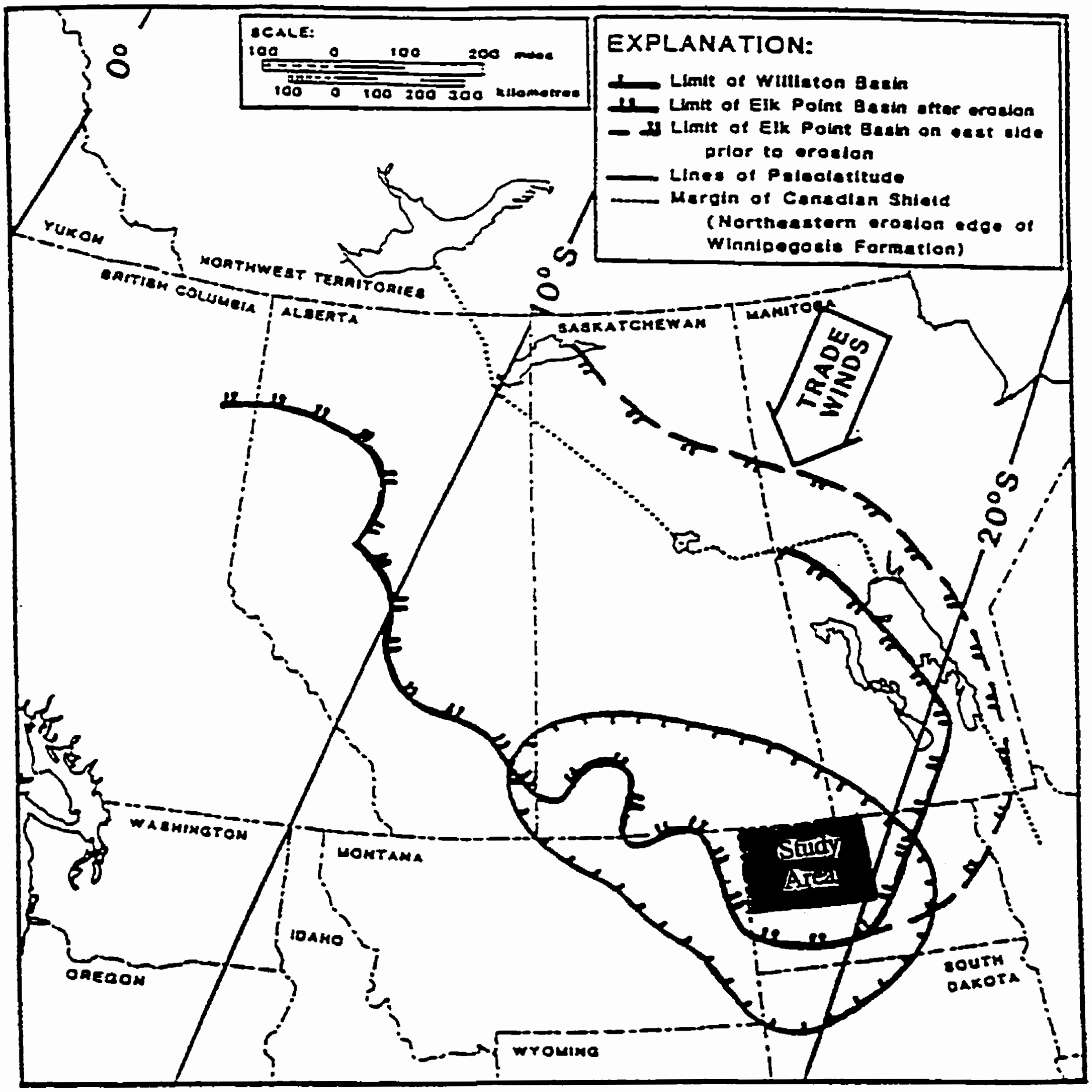


Fig. 1.1. Location of the Williston Basin (Grayston, et al., 1974; Worsley and Fuzesy, 1978), paleolatitudinal lines and trade wind directions (Heckel and Witzke, 1979) for the Middle Devonian, and postulated pre-erosional eastern limit of the Elk Point Basin (Maiklem, 1971). This figure also shows the post-erosional limit of the Elk Point Basin [Modified from Perrin, 1987].

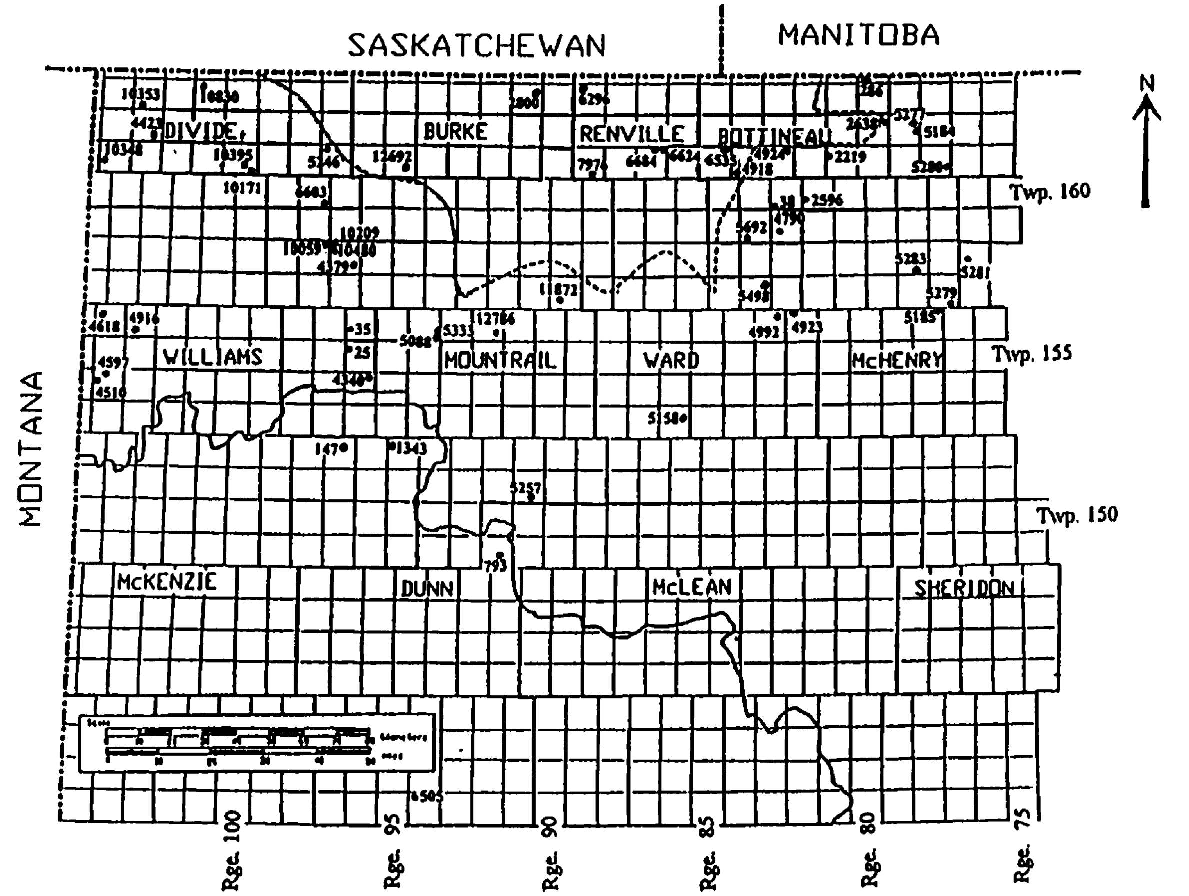


Fig. 1.2. Location of study area: Township 148 north to the Canada - United States border and Range 74 west of the Primary Meridian to the North Dakota - Montana border. Dots, and corresponding numbers, represent well locations and the corresponding NDGS well catalogue number. Dashed line represents differentiated basin (north of line) and shelf setting (south of line) during deposition of the Upper Winnipegosis Member (modified from Ehrets and Kissling, 1987).

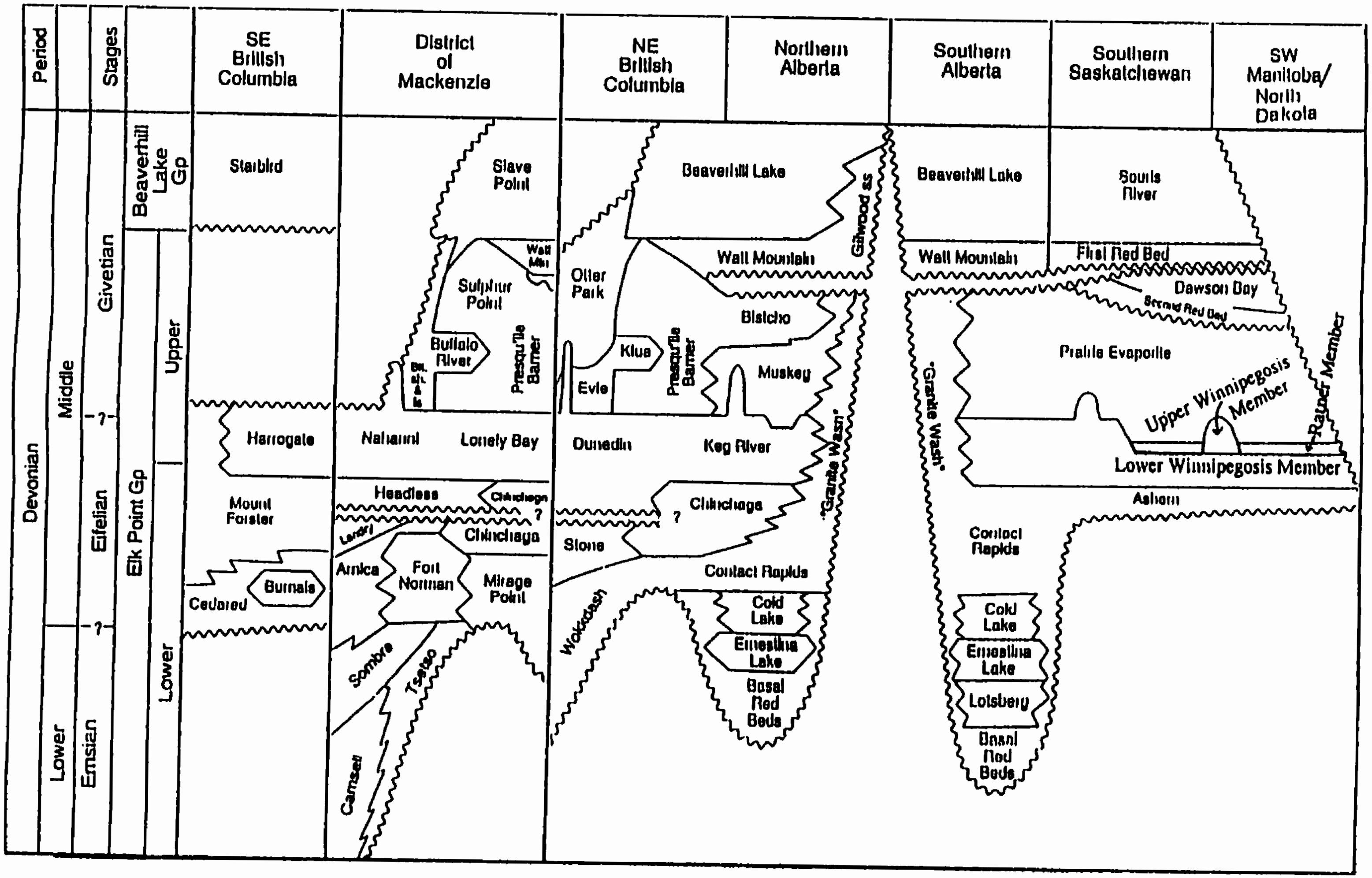


Fig. 1.3. Middle Devonian stratigraphic correlation in the Elk Point Basin (after Meijer-Drees, 1994).

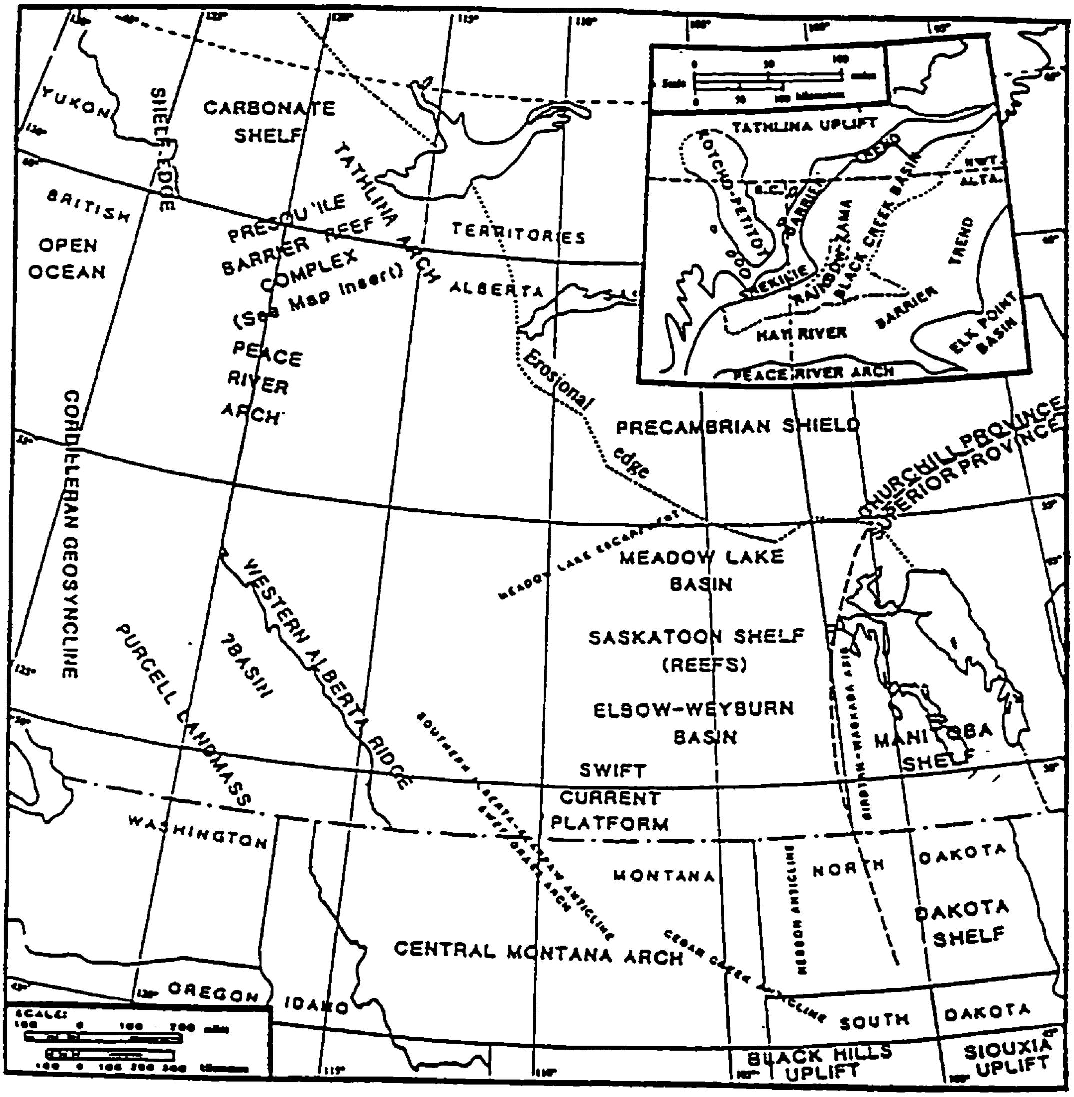


Fig. 1.4. Structural features bounding the Elk Point Basin (from Perrin, 1987).

CHAPTER 2: DEPOSITIONAL FRAMEWORK

2.1 INTRODUCTION

The Winnipegosis Formation in North Dakota is divided into three members: the Lower Winnipegosis Member, the Upper Winnipegosis Member and the Ratner Member (Fig. 1.3; McGehee, 1949, 1952; Baillie, 1951; Sandberg and Hammond, 1958; Reinson and Wardlaw, 1972). The Lower Member is a carbonate ramp deposit which overlies the Ashern Formation throughout the study area. The Lower Winnipegosis Member consists of a crinoid-brachiopod wackestone lithofacies and is 10-80 m in thickness. The Upper Winnipegosis Member consists of carbonate shelf deposits, which occur around the perimeter of the basin interior, and pinnacle reefs in the basin interior. Shelf deposits of the Upper Member are 5-25 m in thickness and are interpreted to be composed of seven lithofacies: 1) fossiliferous wackestone, 2) coral-stromatoporoid doloboundstone, 3) microbial bindstone, 4) fossiliferous packstone and boundstone, 5) patterned dolostone, 6) peloidal packstone and 7) mudstone. Pinnacle reefs are generally less than 30 m in thickness and consist of three lithofacies: fossiliferous wackestone, coral-stromatoporoid doloboundstone and microbial bindstone. The laminated mudstone lithofacies comprising the Ratner Member accumulated in the basin interior between pinnacle reefs.

Upper Winnipegosis Member and Ratner Member lithofacies do not occur throughout the study area. Therefore, four geographic zones that represent the distribution of lithofacies have been established (Fig. 2.1, 2.2): 1) the central geographic zone which contains the Ratner Member and the pinnacle reefs of the Upper Winnipegosis Member, 2) the southern geographic zone defined by mudstone and patterned dolostone lithofacies of the Upper Winnipegosis Member shelf deposits, 3) the eastern geographic zone characterized by a shelf-margin reef complex and 4) the western geographic zone which lacks a shelf-margin reef complex but contains patch reefs.

2.2 Lower Winnipegosis Member: Crinoid-Brachiopod Wackestone Lithofacies

2.2.1 Description

The Lower Winnipegosis Member is dominated by a single lithofacies, the crinoid-brachiopod wackestone lithofacies that is grey to grey-brown, undolomitized limestone to dolostone. Massive mudstones, 0-20 m in thickness, occur at the base of the Lower Winnipegosis Member and are overlain in turn by laminated mudstones and wackestones up to 15 m thick (e.g. NDGS #10830), mottled to massive mudstones and wackestones 10-70 m thick and rarely fossiliferous packstones 0-5 m thick. Patterned dolostone rarely caps the Lower Winnipegosis Member. The mottled lithologies are the most common in this lithofacies (e.g. NDGS #5088, 5333) occurring in all geographic zones of the study area. Mottles are generally surrounded by stylolites or microstylolite swarms containing scattered dolomite crystals.

Crinoid ossicles are generally more abundant than brachiopods and dominate the massive to laminated mudstones and wackestones. In most core samples brachiopod valves are fragmented and aligned nearly parallel to bedding. Other minor skeletal constituents include thamnoporid corals, alveolitid and favositid corals, massive and tabular stromatoporoids and codiacean algae in the uppermost few metres. Trilobite fragments are present sporadically throughout the Lower Winnipegosis Member.

Dolomite content varies both vertically and laterally in the Lower Winnipegosis Member. The most common occurrence of dolomite is in 2-10 cm size, dark brown, porous dolostone patches which have sharp boundaries with the adjacent limestone. However, some dolostone patches grade into the surrounding limestone over distances of a few centimetres. Dolomite abundance generally increases only slightly up-section, however, dolostone predominates near the western boundary of the eastern geographic zone (e.g. NDGS# 5257, 5158, 4924, 38). Minor massive dolomudstone zones occur at or near the lower and upper contacts of the Lower Winnipegosis Member.

2.2.2 INTERPRETATION

The abundance of crinoid ossicles and brachiopod valves and the presence of stromatoporoids, corals and trilobites in predominantly mudstones and wackestones indicate that the Lower Winnipegosis Member represents open-water conditions with normal marine salinity (cf. Heckel, 1972; Wilson, 1975). The abundance of carbonate mud and laminations suggests that deposition occurred in a low energy environment. The mottled texture of the crinoid-brachiopod wackestone lithofacies is interpreted to be due primarily to bioturbation, an interpretation consistent with that proposed by Perrin (1982a, 1982b, 1987).

Isopach maps of the Lower Member indicate an absence of significant local thickness variations, however, a general increase in thickness toward the central geographic zone was noted (Perrin, 1982b; Ehrets and Kissling, 1987), suggesting that the Lower Member is a ramp deposit. Textures and structures typical of storm activities are lacking in this facies suggesting that deposition of the Lower Winnipegosis Member was probably predominantly below storm wave base.

2.3 Upper Winnipegosis Member

2.3.1 Fossiliferous Wackestone Lithofacies

2.3.1.1 Description

The fossiliferous wackestone lithofacies is generally a dark grey, partly dolomitized limestone. Mottled wackestones are most commonly found at the base of the Upper Winnipegosis Member and are generally overlain by massive or variegated wackestones. Thin beds of packstone to grainstone, a few centimetres in thickness, are common near the top of this lithofacies. The fossiliferous wackestone lithofacies is found directly above the Lower Winnipegosis Member in all geographic zones (Fig. 2.2).

The most common skeletal components of this lithofacies are, in order of decreasing abundance: crinoid ossicles, brachiopod valves, codiacean algae, tabular and bulbous stromatoporoids and thamnoporid corals. Minor skeletal components include favositid and alveolitid corals and gastropods. Crinoid ossicles and brachiopod valves decrease in abundance toward the top of this lithofacies where they become subordinate to corals and stromatoporoids. Most bulbous stromatoporoids and massive corals are whole but most tabular stromatoporoids and digitate corals are fragmented. Generally, thamnoporid corals give way up-section to tabular and then bulbous stromatoporoids. Codiacean most commonly occur in the eastern geographic zone (e.g. NDGS# 4918).

The fossiliferous wackestone lithofacies varies from predominantly dolostone in the eastern geographic zone to mostly dolomitic limestone in the central and southern geographic zones to mostly limestone in the western geographic zone. Where the underlying few meters of the Lower Winnipegosis Member is dolostone the entire fossiliferous wackestone lithofacies is also dolostone (e.g. NDGS# 793). Where the underlying Lower Winnipegosis Member is limestone, the basal meter or so of the fossiliferous wackestone lithofacies is limestone and grades upward into dolomitic limestones (e.g. NDGS# 4924, 4918) or dolostones (e.g. NDGS# 10480, 4918).

Porosity within this facies varies from <2-15% in the limestones to 5-20% in the dolomitic limestones and dolostones. Porosity generally increases up-section from <2% to 15-20%.

2.3.1.2 Interpretation

The massive or variegated wackestone textures found in the lower sections of this lithofacies and the presence of large quantities of mud indicate that the energy of the depositional environment was sufficiently low to allow mud deposition and to prevent winnowing of the mud. The abundance of filter feeders such as brachiopods also suggests relatively clear waters (cf. Heckel, 1972), probably below fair-weather wave base. The sporadic packstone to grainstone layers near the top of this lithofacies may represent short-lived high energy events, such as storms, which suggests deposition above storm wave base. The fossil succession, from crinoids and brachiopods at the base of this lithofacies to corals and stromatoporoids near the top of this lithofacies also suggests an increase in energy. The fossiliferous wackestone lithofacies is interpreted to have been deposited in normal marine conditions, probably very near the storm wave base.

2.3.2 Coral-Stromatoporoid Doloboundstone Lithofacies

2.3.2.1 Description

The coral-stromatoporoid doloboundstone lithofacies only occurs directly above the fossiliferous wackestone lithofacies in the central geographic zone (Fig. 2.2). The thickness of this lithofacies can be as much as 70 m (NDGS# 6535) with an approximate area of 65 hectares (0.7 km^2; Perrin and Precht, 1985). The basal 3-7 m of this lithofacies generally consists of 20-40 cm thick crinoid and/or brachiopod dolowackestones and dolopackstones interbedded with massive, discontinuously laminated and mottled mudstones. Crinoids and brachiopods within the interbedded areas are generally abundant near the base of this lithofacies and decrease up-section. Codiacean algae are observed near the base of the lithofacies in only one location (NDGS# 12786). These interbedded facies give way to coral-stromatoporoid doloboundstones and/or stromatoporoid doloboundstones which dominate most of this lithofacies. The coral-stromatoporoid doloboundstone lithofacies contains minor amounts of late diagenetic calcite (see Chapter 3) and anhydrite (see Chapter 3) near the top of this lithofacies.

The most common skeletal components are massive and bulbous stromatoporoids and thamnoporid corals. Alveolitid, favositid and rugose corals are minor constituents. Most of the less fragile skeletal components appear to be in growth position. Corals usually decrease in abundance up-section while stromatoporoids increase. Stromatoporoid forms are generally tabular near the base of this lithofacies and bulbous or massive up-section.

Dolostone showing a distinct "clotted" fabric (PHOTO 2.1) is found sporadically within the uppermost 10-15 m of the coral-stromatoporoid doloboundstone lithofacies (NDGS# 12786, # 7976, # 6624). The clotted areas generally span the width of the core and are generally less than 8 to 10 cm thick. The dark gray "clots", 1-5 mm in size, have an irregular distribution pattern and are enclosed in a brown dolomudstone matrix. Encrusting lamellar stromatoporoids are found at the outer margin of a few of these clotted areas (PHOTO 2.2).

Porosity within this lithofacies can vary dramatically over short vertical distances from nearly 0% in dolomudstones to as much as 30% to 35% in dolowackestones or doloboundstones. The clotted areas can have markedly different porosities. Porosity is either absent or approximately 10% fenestral porosity.

2.3.2.2 INTERPRETATION

The observed skeletal components, as well as the suggested lateral extent of this lithofacies, suggests that the stromatoporoid-coral doloboundstone lithofacies represents pinnacle reefs that developed under normal open marine conditions. Perrin (1982a, 1982b), Perrin and Precht (1985), Fischer and Burke (1987), and others have also interpreted this lithofacies as pinnacle reefs.

The clotted fabric near the top of the lithofacies is interpreted to be part of thrombolitic structures. This fabric is similar to that described by Aitken (1967), Radke (1980), Kennard (1981), and Kennard and James (1986). Aitken (1967) first described thrombolites as cryptalgal structures related to stromatolites, but lacking laminations and characterised by a macroscopic clotted fabric. Thrombolites in this study are completely dolomitized and the original microscopic textures, as well as any trace of microbes which may have been responsible for the macroscopic clotted texture, have been obliterated. This study suggests that the clotted fabric is part of a coherent, and possibly rigid, microbial structure which may have contributed to the of the isolated pinnacle reefs. The occurrence of the thrombolites adjacent to massive and bulbous forms of stromatoporoids and rugose corals indicates that these structures developed in subtidal and probably highly agitated waters. Walter and Heys (1985) suggested that clotted textures are formed by bioturbation of laminated stromatolites. In this study lamellar stromatoporoids are found encrusting the thrombolites suggesting that the clotted textures did not result from bioturbation of laminated stromatolites. Perrin (1982b, 1987)) referred to this texture in her pinnacle reefs as reef sediments in the form of peloidal muds. Aitken (1967), Pratt and James (1982) and Walter and Heys (1985) agree that thrombolites develop mostly in the subtidal zone, at and below the lowest low tide level in either low or high turbulent energy. Kennard (1981) suggested that thrombolites developed in agitated and less highly saline waters than stromatolites.

The lower section of this lithofacies, where thamnoporid corals are abundant and tabular stromatoporoids are common, represents the stabilization and colonization stage of buildup development (cf. Perrin and Precht, 1985; Martindale and MacDonald, 1989). The upper sections of this facies, where the thrombolites are observed and where massive corals and stromatoporoids are common to abundant, represent the diversification stage of buildup growth.

2.3.3 Microbial Bindstone Lithofacies

2.3.3.1 Description

The microbial bindstone lithofacies is a light to dark brown and dark grey dolomudstone, generally only a few tens of centimetres thick, and contains crenulated laminae. Allochems are scarce and include peloids and very rare globular stromatoporoid fragments. Desiccation cracks are present near the top of this lithofacies (PHOTO 2.3). In the central geographic zone the microbial bindstone lithofacies overlies the coral-stromatoporoid doloboundstone lithofacies (Fig. 2.3). The microbial bindstone lithofacies in the eastern and western geographic zones mostly overlies the fossiliferous packstone and boundstone lithofacies (see section 2.3.4) and rarely overlies the patterned dolostone (section 2.3.5) or fossiliferous wackestone lithofacies (Fig. 2.3).

Fenestral porosity within this lithofacies is typically 5-10%, and rarely 15-20%, but can be negligible in the presence of anhydrite or halite.

2.3.3.2 INTERPRETATION

The occurrence of the crenulated laminae with fenestral porosity and desiccation cracks suggests a high intertidal to supratidal depositional environment. The microbial bindstone lithofacies is interpreted to have formed as microbial mats or stromatolites in shelf areas, as well as on the pinnacle reefs. The microbial bindstone lithofacies of this study is similar to the algal (cyanobacterial) lithofacies of Perrin (1987) which she described as algal mats forming in tidal-flat conditions.

2.3.4 Fossiliferous Packstone and Boundstone Lithofacies

2.3.4.1 Description

The lithology of the fossiliferous packstone and boundstone lithofacies is highly variable depending on geographic location. In general this lithofacies contains a mottled wackestone at the base grading upward into, and sometimes overlain by, a mottled packstone. However, boundstones, mudstones, floatstones and less commonly grainstones are found sporadically in variable thickness throughout this lithofacies. The fossiliferous packstone and boundstone lithofacies generally overlies the fossiliferous wackestone lithofacies and is overlain by the microbial bindstone lithofacies (Fig. 2.3). This lithofacies only occurs on the carbonate shelf in the eastern and western geographic zones and is dominated by dolostone. Limestones are found only in the extreme east and northernmost parts of the eastern and western geographic zones.

Skeletal material is common in this lithofacies. Some stromatoporoids are fragmented and others are in situ. Stromatoporoid forms generally change from tabular near the base to massive and/or globular near the top of the lithofacies. Brachiopod fragments, crinoid ossicles and thamnoporid coral fragments are present in varied amounts throughout this lithofacies. Alveolitid and favositid corals, which do not appear to be in-situ, are commonly present in the middle to basal sections. Minor allochems throughout this lithofacies are *Amphipora*, peloids and codiacean algae.

The fossiliferous packstone and boundstone lithofacies is similar to the interbedded dolowackestone, dolopackstone and dolomudstones of the basal section of the coral-stromatoporoid doloboundstone lithofacies.

Porosity is generally negligible in the lower sections of the mottled wackestones but can be as high as 15 - 20% in the in the upper sections of the fossiliferous packstone and boundstone lithofacies.

2.3.4.2 INTERPRETATION

The abundance of stromatoporoid boundstones and the presence of a variety of in situ stromatoporoids and corals, common brachiopods and crinoids, suggest that this facies represents deposition under normal marine conditions. Such a diverse stenohaline fauna is indicative of a subtidal marine environment (Laporte, 1967, Heckel, 1972). The high variability in fabric and lithology of this lithofacies suggests a variability in depositional energy conditions. The similarities of this lithofacies to the basal section of the coral-stromatoporoid doloboundstone suggests that the 2 lithofacies were deposited under similar environmental conditions. The fossiliferous packstone and boundstone lithofacies is interpreted to have been deposited in an open marine environment as shelf margin reefs in the eastern geographic zone and patch reefs in the shelf interior in the eastern and western geographic zones. Perrin and Precht (1985), Precht (1986) and Perrin (1987) interpret their coral, stromatoporoid packstone lithofacies as shelf margin reefs and patch reefs in the Winnipegosis Formation.

2.3.5 Patterned Dolostone Lithofacies

2.3.5.1 Description

The patterned dolostone lithofacies in this study is composed of light brown to buff colored dolomudstones which are characterized by ovoid to irregular-shaped patches, 0.5-3 mm in diameter, of dark grey crystalline anhydrite that impart a distinctive 'patterned' fabric to this lithofacies (PHOTO 2.4). This lithofacies is also distinguished by a paucity of allochems. Patterned dolostones are always found near the top of the Upper Winnipegosis Member usually below but occasionally above the microbial bindstone lithofacies (Fig. 2.3). Patterned dolostones have been found only on the shelf areas near the outer boundaries of the study area.

Dixon (1976) coined the term "patterned carbonates" for a diagenetic feature in very fine to finely crystalline carbonates that he described as light and dark colored areas in patterns of varying degrees of shape, complexity and intensity of development. Dixon (1976) recognized this feature in various Mesozoic and Paleozoic carbonate strata in the Arctic islands, Alberta and the Northwest Territories. The similarities between the patterned dolostones of this study and Dixon's (1976) are: 1) the fabric developed in very fine to fine crystalline dolostones, 2) a paucity of allochems, 3) an association with stromatolite beds, and 4) an association with evaporite minerals.

2.3.5.2 Interpretation

The paucity of skeletal allochems suggests harsh environmental conditions comparable to the supratidal zone of the Persian Gulf or Andros Island in the Bahamas (Dixon, 1976). The lack of primary sedimentary structures, the paucity of allochems and consistent very fine to fine crystalline grain size in these patterned dolostones suggest that this lithofacies was a gelatinous, soupy slurry of carbonate muds in what may have been similar to the Holocene sea marginal ponds within the sabkha setting described by Friedman (1980).

The color differences in the patterned dolostone is due to the presence of varying concentrations of anhydrite crystals (anhydrite type 1; see Chapter 3). If oxidizing conditions prevailed, anhydrite or gypsum might be expected to be formed as an early diagenetic mineral (cf. Logan, 1987). The dark coloration in Dixon's (1976) patterned carbonate was attributed to varying concentrations of very finely crystalline pyrite crystals. The pyrite was interpreted to have formed as a product of early diagenesis due to chemical reactions in a sulphate-rich, reducing environment.

The patterned dolostone, in this study, is interpreted to have been deposited as a carbonate mud in an arid supratidal shelf setting at or near the end of Winnipegosis time.

2.3.6 PELOIDAL PACKSTONE LITHOFACIES

2.3.6.1 DESCRIPTION

The peloidal packstone lithofacies is generally less than 1 m in thickness and consists of grey-brown to dark brown peloidal dolopackstones and dolograinstones. This lithofacies is not laterally continuous and most commonly occurs in the shelf areas of the eastern geographic zone with rare occurrences in the shelf areas of the southern and western geographic (Fig. 2.3). The peloidal packstone lithofacies grades laterally into the fossiliferous packstone and boundstone lithofacies or the fossiliferous wackestone lithofacies toward the shelf margin.

Peloids are abundant and are generally fine to medium grained. Fragments of bulbous and tabular stromatoporoids are common. Brachiopod valves, crinoid ossicles, *Amphipora* and codiacean algae occur in the shelf areas but are collectively minor components. Anhydrite is always present in this facies either as 2-10 cm thick lenses or as pore-filling cement.

Porosity in this lithofacies ranges from <5 - 30% depending on the anhydrite content. The most common porosity types are interparticle, vuggy and microvuggy; moldic porosity is minor.

2.3.6.2 Interpretation

The abundance of peloids in the peloidal packstone lithofacies and the association with the fossiliferous packstone and boundstone lithofacies suggest that the peloidal packstone lithofacies was derived from the reworking of the fossiliferous packstone and boundstone lithofacies as reef talus (cf. Coniglio, 1986). The general grain size of allochems and the presence of *Amphipora* and codiacean algae suggest a moderate energy environment of deposition such as a back reef. This lithofacies is interpreted to be deposited in an open marine setting probably above fair-weather wave base in an energy environment sufficient to transport reefal debris.

2.3.7 Mudstone Lithofacies

2.3.7.1 Description

The mudstone lithofacies is light to medium brown and consists of laminated, massive and rare mottled dolomudstones (e.g. NDGS# 2638) and dolomitic mudstones (e.g. NDGS# 5257). Rare lime mudstones occur at the base of this lithofacies and only where the underlying Lower Winnipegosis Member is limestone. This lithofacies occurs throughout the interior shelves below the patterned dolostone and microbial bindstone lithofacies (Fig. 2.3). The mudstone lithofacies always occurs landward of the peloidal packstone lithofacies. Anhydrite layers, up to 30 cm thick, and anhydrite lenses, 5-15 cm thick, are common near the top of this lithofacies. Allochems are rare in the mudstone lithofacies and include crinoids, brachiopods, coral and stromatoporoid fragments, *Amphipora* and codiacean algae.

Porosity is generally secondary and includes intercrystalline, microvuggy and moldic but it is commonly filled with anhydrite and/or halite. In the absence of anhydrite and halite, porosity can locally reach up to 20%.

2.3.7.2 INTERPRETATION

The abundance of mud in this lithofacies and the paucity of allochems suggest deposition in a relatively low energy conditions in a restricted marine environment. The presence of the anhydrite layers and lenses at the top of the mudstone lithofacies suggests a hypersaline environment of deposition. This lithofacies is interpreted as being deposited in a relatively low energy, hypersaline environment on the shelf interior (cf. Perrin, 1987; Stanford, 1989).

2.4 RATNER MEMBER: LAMINATED MUDSTONE LITHOFACIES

2.4.1 DESCRIPTION

The laminated mudstone lithofacies consists of brown and/or grey limestone, anhydritic dolostone and dolostone. The base of this lithofacies is commonly lime mudstone (when underlain by limestone of the Lower Winnipegosis Member) and grades upward through dolomudstone to anhydritic dolostone. Skeletal allochems are absent. The laminae are typically less than 2-4 mm in thickness and are commonly bounded by microstylolites or low-amplitude stylolites. Organic matter and/or clays are commonly concentrated along these dissolution seams. Layers of nodular anhydrite, up to approximately 80 cm thick, are common near the top of this lithofacies. Halite is common in pore spaces and fractures. This lithofacies occurs only in the inter-reef areas above the Lower Winnipegosis Member (Fig. 2.3). The laminated mudstones appear to intertongue with the fossiliferous wackestone and coral-stromatoporoid doloboundstone lithofacies of the Upper Winnipegosis Member.

Intercrystalline porosity in the laminated mudstone lithofacies can be as high as 25-30% in the dolomudstone laminations to less than 5% in the lime mudstone laminations.

2.4.2 INTERPRETATION

The paucity of fossils, the lack of evidence for subaerial exposure (such as desiccation cracks) and the regularly laminated structure of the laminated mudstone lithofacies suggests a deep basin depositional environment. Intertonguing of the laminated mudstone lithofacies with the fossiliferous wackestone lithofacies and coral-stromatoporoid doloboundstone lithofacies of the Upper Winnipegosis Member also suggests inter-reef deposition for the laminated mudstone lithofacies. The textures and sedimentary structures of the anhydrite found interbedded with and overlying the laminated mudstone lithofacies suggest an increasingly restricted, hypersaline, deep basinal depositional environment (cf. Davies and Ludlam, 1971; Maiklem, 1971; Schreiber et. al, 1982; Kendall, 1984).

2.5 Synthesis of Depositional History

The Lower Winnipegosis Member is a carbonate ramp deposit found everywhere in the study area and consists of a crinoid-brachiopod wackestone lithofacies. The Lower Winnipegosis Member was deposited basin-wide as a relatively uniform, shallow marine ramp, at first, under supratidal conditions in some areas (Perrin, 1987), but mostly under normal, subtidal marine conditions (cf. Grayston et al., 1964; Barss et al., 1968,1970; Bebout and Maiklem, 1973; Norris et al., 1982; Perrin, 1987; Meijer-Drees, 1994). At the end of Lower Winnipegosis deposition, the crinoid-brachiopod wackestone lithofacies had little topographic relief in Saskatchewan (Wardlaw and Reinson, 1971), North Dakota and Montana (Perrin, 1987) and most likely throughout the rest of the basin.

Near the end of Lower Winnipegosis deposition a rapid rise in sea level within the Elk Point Basin resulted in a tranquil deep-water ramp (cf. McIlreath and James, 1984). Eventually the basin became so deep that normal ramp deposition essentially ceased. This starved basin condition is thought to have formed in the Elk Point Basin where water depths exceeded at least 75 m (Wardlaw and Reinson, 1971). At this time the Elk Point Basin was differentiated into shallow shelves (eastern, western and southern geographic zones) and a central deep basin with isolated pinnacle reefs (central geographic zone). There have been numerous explanations proposed for this change in the paleobathymetry (e.g. Williams, 1984; Johnson et al. 1985; Perrin, 1987; Kirkby and Tinker, 1992; Chow et al., 1995). The most likely explanation appears to be a eustatic pulse that involved initial, rapid, deepening followed by continued deepening at a lesser rate (Johnson et al., 1985). Water depths throughout the basin were no longer uniform due to a change in paleobathymetry which allowed for the development of shelf margin reefs (eastern geographic zone), patch reefs (eastern and western geographic zones) and the pinnacle reefs (central geographic zone) of the Upper Winnipegosis Member. According to Perrin (1987), the depth of the basin in North Dakota was 91 m when growth of the pinnacle reefs ceased.

The Upper Winnipegosis Member is composed of reefal and non-reefal lithofacies. Reefal lithofacies include the fossiliferous wackestone lithofacies, the coral-stromatoporoid doloboundstone lithofacies and the microbial bindstone lithofacies. Non-reefal lithofacies include the fossiliferous wackestone lithofacies, the microbial bindstone lithofacies, the fossiliferous packstone and boundstone lithofacies, the patterned dolostone lithofacies, the peloidal packstone lithofacies and the mudstone lithofacies.

The fossiliferous wackestone lithofacies accumulated above the crinoid-brachiopod wackestone lithofacies of the Lower Winnipegosis Member to form local bathymetric highs (cf. Perrin, 1987). Localized, high density faunal communities may have colonized these highs, producing and/or baffling large volumes of sediment. The fossiliferous wackestone lithofacies then developed enough synoptic relief to sustain a faunal community in which organic framework biota flourished. The coral-stromatoporoid doloboundstone lithofacies is the result of a faunal succession to organic framework biota and represents the rigid infrastructure of the Upper Winnipegosis Member pinnacle reefs. The laminated mudstone lithofacies of the Ratner Member represents coeval deposition in the inter-reef basinal area within the differentiated basin. The microbial bindstone lithofacies represents the final stages of deposition in an intertidal setting near the top of the pinnacle reefs as the Middle Devonian seas regressed due to evaporative drawdown (cf. Maiklem, 1971; Perrin, 1987).

The fossiliferous packstone and boundstone lithofacies represents shelf margin reefs or patch reefs. The mudstone lithofacies was deposited on the shelf behind the shelf margin reefs in a back reef setting. The peloidal packstone lithofacies is generally found in close proximity to patch reefs in the eastern and western geographic zones and may represent the final shallowest water deposition or reef detritus in a moderate to high energy environment. The patterned dolostone lithofacies is difficult to interpret unequivocally but its deposition is similar to Holocene sea marginal ponds in the Red Sea area (cf. Friedman, 1980) and is interpreted to have been deposited in a supratidal setting at or near the end of Winnipegosis time. The microbial bindstone lithofacies above and landward of the shelf reefs represents intertidal deposition in the form of microbial mats and is an indication of a relative sea level fall.

With continued regression in the Elk Point Basin, increasingly evaporitic sediments accumulated in the inter-reef areas of the deep basin. The Presqu'ile barrier reef complex to the northwest served as a sill to separate the Elk Point Basin from the open ocean (Morrow, 1973). Williams (1984) suggests that there may have been other such barriers within the Elk Point Basin that were not preserved in the rock record. When the barriers effectively separated the Elk Point Basin from the open ocean, the basin became increasingly evaporitic and water depth decreased due to evaporative drawdown (Maiklem, 1971). Sea level dropped sufficiently to expose the top of the build-ups (cf. Shearman and Fuller, 1969a; Fuller and Porter, 1969a, 1969b; Wardlaw and Reinson, 1969b; Norris et al., 1982; Perrin, 1987). The laminated mudstone lithofacies of the Ratner Member represents deposition in the inter-reef areas of an increasingly saline, deep basinal, probably anoxic environment. Further salinity increase in the basin resulted in precipitation of gypsum (anhydrite) crystals in the upper waters which then settled to the sea floor. As salinity further increased halite and then sylvite precipitated in various cycles (Oglesby, 1987) forming the Prairie Formation.

Cessation of reef growth may have been due to a rapid fall in sea level (McCammis and Griffith, 1967, 1968, 1975), an increase in salinity (Langton and Chin, 1968a, 1968b, 1975) or other factors such as climate or water circulation and turbidity (Mountjoy, 1980).

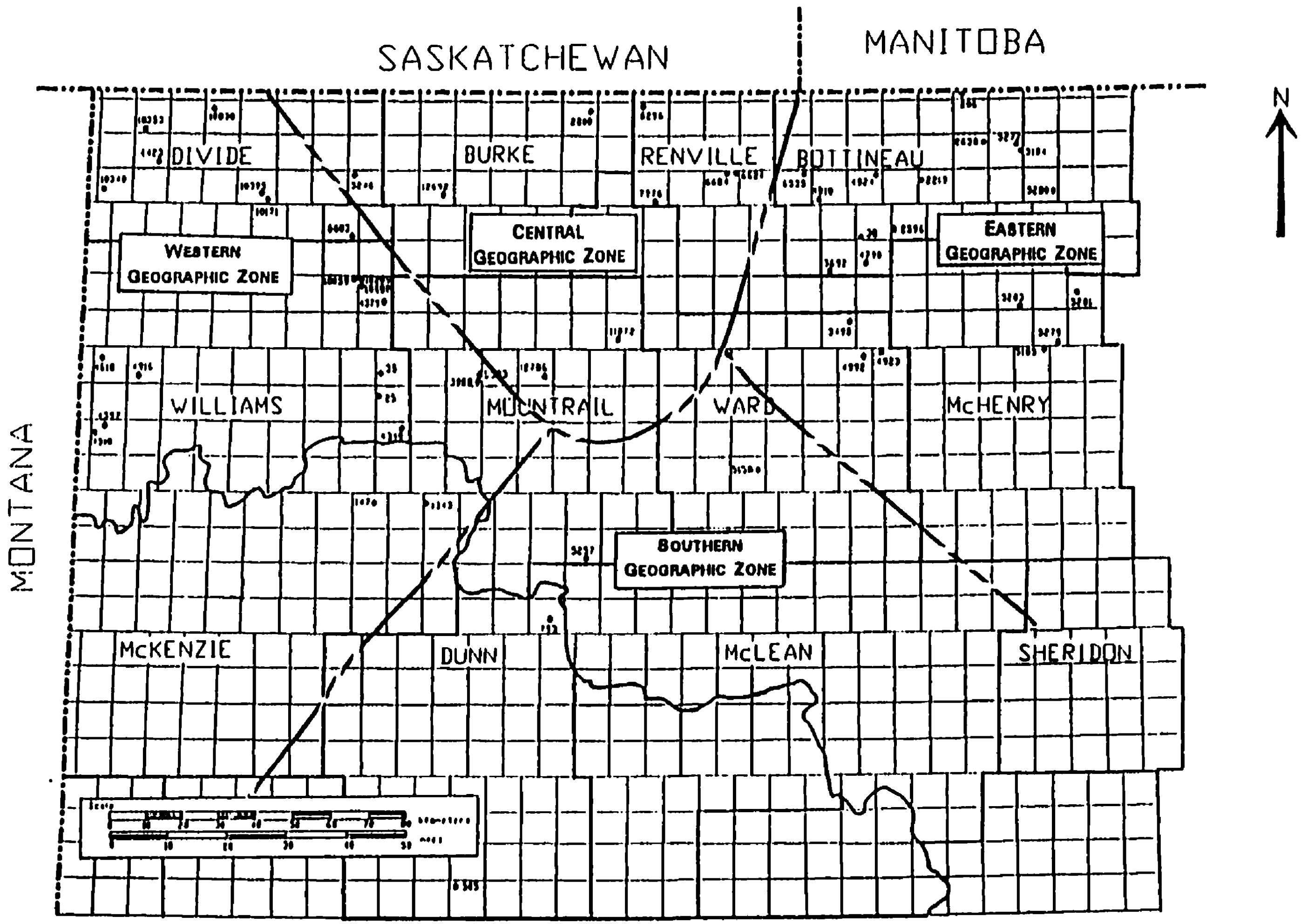


Fig. 2.1. Location of geographic zones within the study area

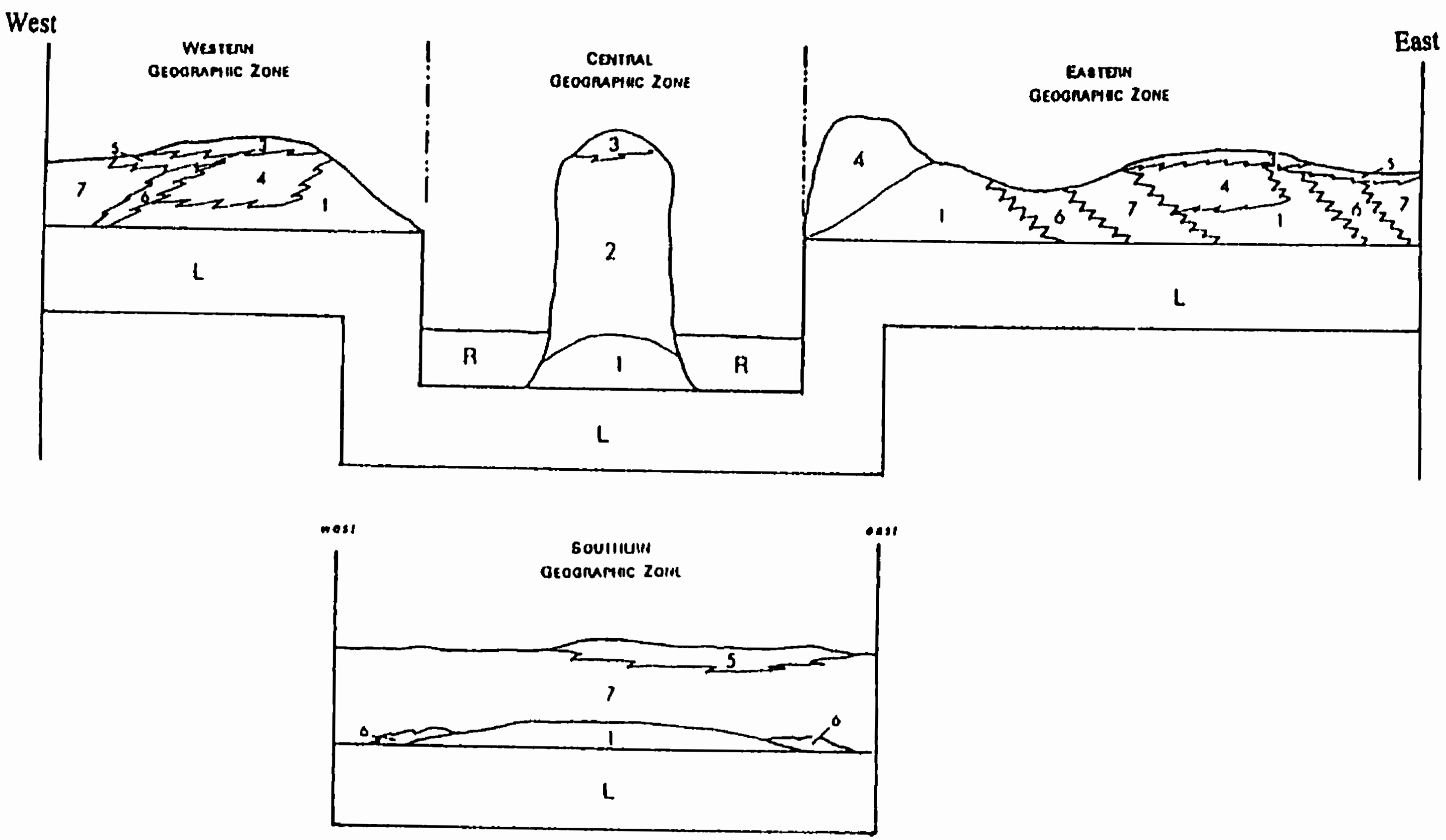


Fig. 2.2. Schematic of lithofacies distribution in the geographic zones. No scale implied. (L = Lower Winnipegosis Member, R = Ratner Member, 1 = Fossiliferous wackestone, 2 = Coral-stromatoporoid boundstone, 3 = Microbial bindstone, 4 = Fossiliferous packstone and boundstone, 5 = Patterned dolostone, 6 = Peloidal packstone, 7 = Mudstone).

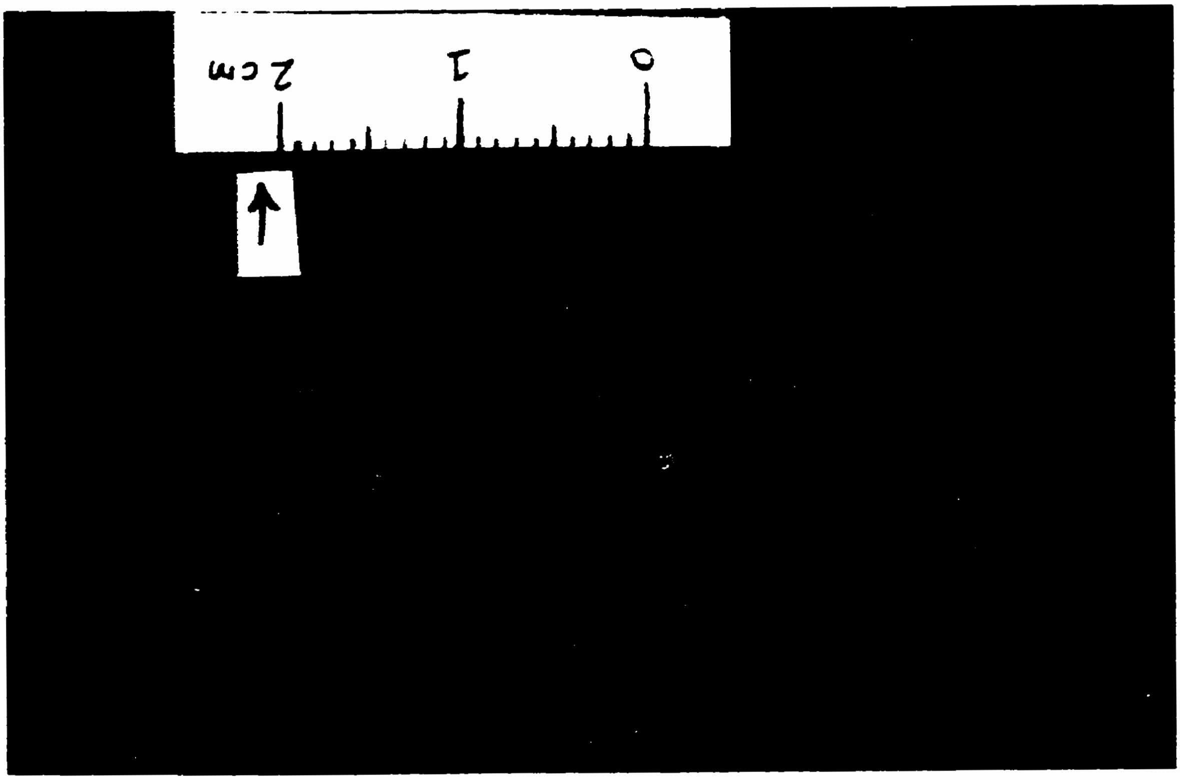


PHOTO 2.1. Core photograph of clotted fabric interpreted to be part of thrombolitic structure. From the coral-stromatoporoid doloboundstone lithofacies of an Upper Winnipegosis Member pinnacle reef in the central geographic zone. NDGS# 6624, depth = 7208 ft. (Scale is in cm; arrow indicates "up" direction).

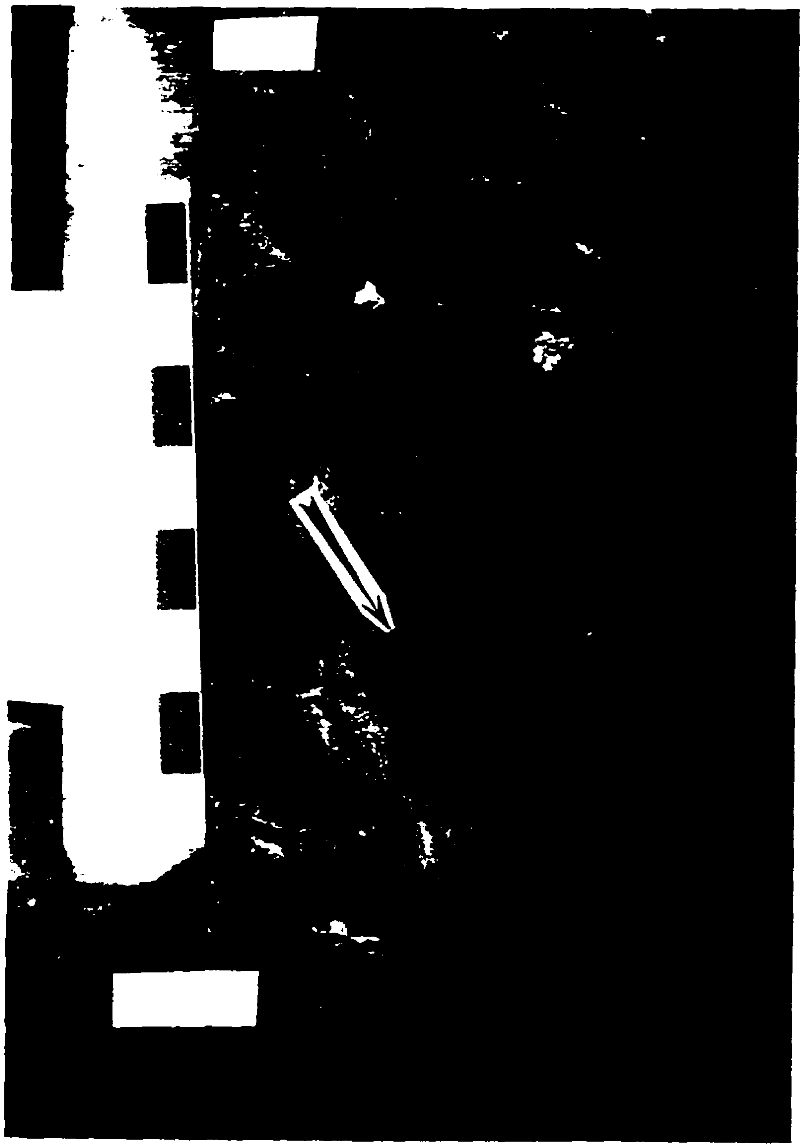


PHOTO 2.2. Core photograph of clotted fabric interpreted to be part of thrombolitic structure with encrusting lamellar stromatoporoid (arrow). From the coral-stromatoporoid doloboundstone lithofacies of an Upper Winnipegosis Member pinnacle reef in the central geographic zone. NDGS# 7976, depth = 8362 ft.. (Scale is in cm).

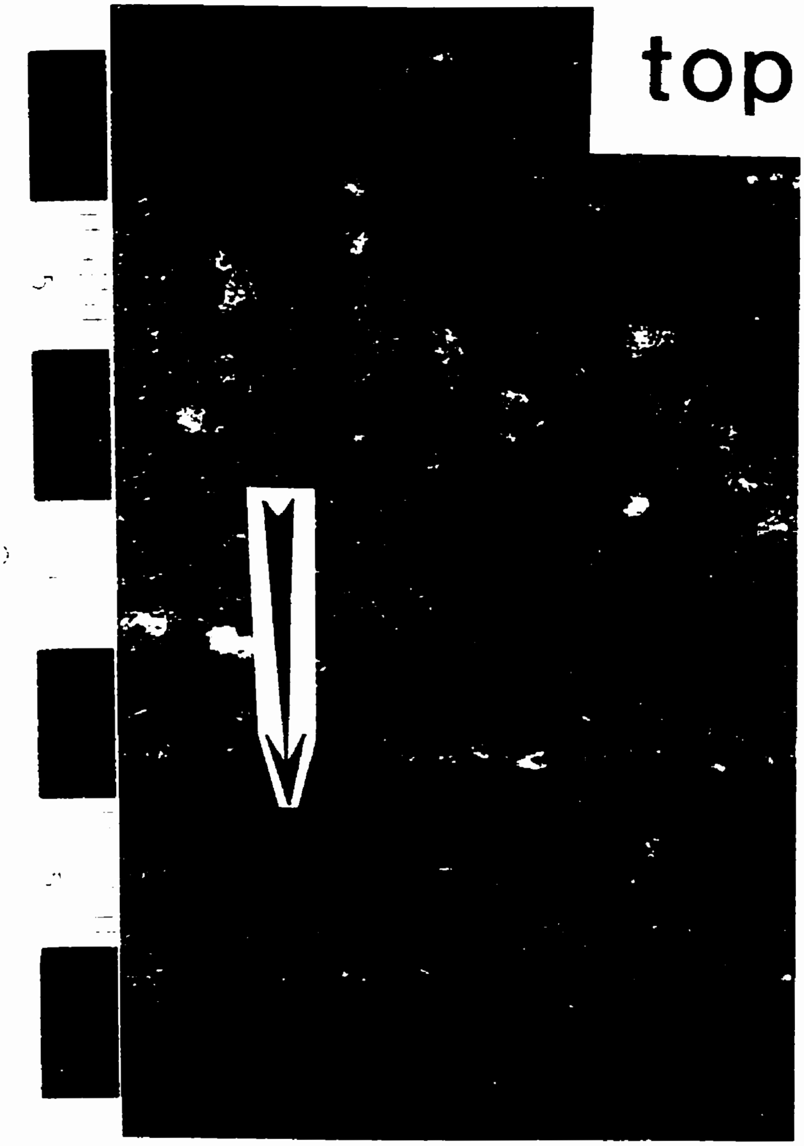


PHOTO 2.3. Core photograph of desiccation crack (arrow) in the Upper Winnipegosis Member microbial bindstone lithofacies from the shelf interioir of the western geographic zone. NDGS# 10395, depth = 10388 ft. (Scale is in cm).

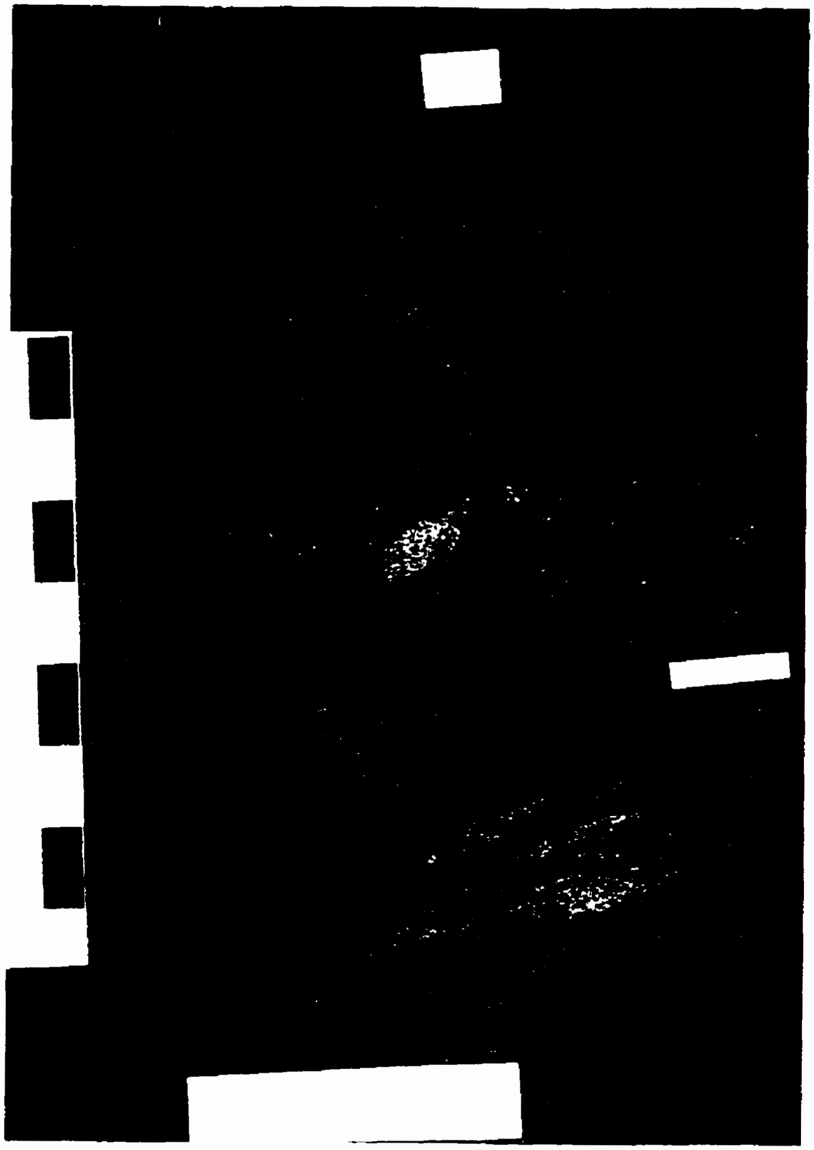


PHOTO 2.4. Core photograph of patterned dolostone lithofacies from the Upper Winnipegosis Member shelf interior of the eastern geographic zone. NDGS# 5283, depth = 5242 ft. (Scale is in cm).

CHAPTER 3: PETROGRAPHY

3.1 INTRODUCTION

Six different dolomite types are recognized in the Winnipegosis Formation and classified according to crystal boundary shape using a modified version of the classification of Gregg and Sibley (1984). A summary of the characteristics of each dolomite type is shown in Table 3.1.

This classification is descriptive but carries genetic implications because size distribution is controlled by both nucleation and growth kinetics, and crystal boundary shape may be affected by growth kinetics (Sibley and Gregg, 1987). Crystal growth of idiotopic (or planar) dolomite crystal mosaics is considered to occur at low dolomite supersaturation states and/or low temperatures. Above some temperature (critical roughening temperature - CRT) xenotopic (or non-planar) dolomite crystal mosaics may form. A CRT for dolomite has been estimated to lie between 50 and 100°C.

In this study, classification of dolostone (and dolomitic limestone) textures is based on transmitted light microscopy, aided by analyses using epi-fluorescence and cathodoluminescence. This classification forms the framework for electron microprobe and stable isotope analyses. The relative abundance of the various dolomite types has been estimated based on standard petrographic analysis. The apparent maximum dimensions of dolomite crystals were measured and described using Folk's (1962) size scale for authigenic carbonates.

Authigenic minerals associated with the six different dolomite types in this study are: anhydrite (section 3.4.1), dedolomite (section 3.4.2) and late diagenetic calcite (section 3.4.3). The textural relationships between the authigenic minerals and the dolomite in this study are critical in delimiting the paragenetic sequence for dolomite in the Winnipegosis Formation.

3.2 Dolomite Distribution

The distribution of dolomite in the Winnipegosis Formation varies vertically and laterally within the study area (Fig. 3.1). Dolomite tends to increase in abundance up section so that dolomitic limestone and limestone predominate near the base of the formation and dolostone is predominant near the top of the formation. Dolomite content is most abundant in the central geographic zone and decreases with distance from the central geographic zone in the eastern, western and southern geographic zones.

3.2.1 Central Geographic Zone

The Lower Winnipegosis Member is generally limestone where it is overlain by limestones in the Ratner Member, and dolostone or dolomitic limestone where it is overlain by dolostones in the Ratner or Upper Winnipegosis members (Fig. 3.1).

The lithofacies comprising the pinnacle reefs of the Upper Winnipegosis Member are pervasively dolomitized (e.g. NDGS# 6624, 12786) except for the fossiliferous wackestone lithofacies at the base of these reefs (e.g. NDGS# 7976) which is usually limestone.

The Ratner Member is predominantly dolostone, but lime mudstone, up to 19 m in thickness, is found at the base of the Ratner Member (e.g. NDGS# 2800, 6296, 6684, 12692). Dedolomite is found sporadically through the pervasively dolomitized area of the Ratner Member only. Anhydrite is always present as beds, layers or isolated crystals near or at the top of the Ratner Member.

3.2.2 SOUTHERN GEOGRAPHIC ZONE

The Lower Winnipegosis Member is predominantly limestone, but contains variable amounts of isolated dolomite rhombs and sporadic occurrences of dolostone (e.g. NDGS# 5257). Where the Upper Winnipegosis Member is completely dolostone the uppermost portion of the Lower Winnipegosis Member is also dolostone and grades downward through dolomitic limestone into limestone (e.g. NDGS# 5158).

The top of the Upper Winnipegosis Member is always dolostone (e.g. NDGS# 5158) and the remainder of the unit consists of a mixture of dolostone, dolomitic limestone and limestone lithologies (e.g. NDGS# 5257).

3.2.3 Western Geographic Zone

The Lower Winnipegosis Member is predominantly limestone except for a thin layer of dolostone near its base (e.g. NDGS# 5088). Dolostone is rarely present at the top of the Lower Winnipegosis Member. The contact between the Lower Winnipegosis and Upper Winnipegosis members generally occurs where the limestone lithologies of the Lower Winnipegosis Member abruptly become dolostone lithologies (if present) of the Upper Winnipegosis Member (e.g. NDGS# 4510, 4597, 5333, 5088).

The Upper Winnipegosis Member contains variable amounts of dolomite. In the extreme north-west of the study area the Upper Winnipegosis Member is virtually all dolostone (e.g. NDGS# 10830, 10348, 10353). In all other areas of the western geographic zone the lithology of the Upper Winnipegosis Member is quite variable.

3.2.4 Eastern Geographic Zone

Based on two cores (NDGS# 38 and 6535) in the eastern geographic zone, the Lower Winnipegosis Member appears to be limestone where it is overlain by Upper Winnipegosis Member limestones, and to be dolostone where it is overlain by Upper Winnipegosis Member dolostones.

The Upper Winnipegosis Member in the eastern geographic zone is almost all dolostone. Limestone occur only in the eastern most areas of this geographic zone (e.g. NDGS# 5279, 5280, 5281, and 5283).

3.3 Dolomite Types

In this study, six petrographic types of dolomite are recognized in the Winnipegosis Formation based on crystal boundary shape (cf. Greg and Sibley, 1984; Sibley and Greg, 1987). Figure 3.2 shows a diagrammatic representation of the six dolomite types which include: 1) idiotopic euhedral (Idio-E) and idiotopic euhedral, sub-type P (Idio-Ep), 2) idiotopic subhedral (Idio-S), 3) xenotopic subhedral (Xeno-S), 4) xenotopic anhedral (Xeno-A), 5) isolated dolomite crystals (ISO) and 6) saddle dolomite. The following petrographic features were also examined to further characterize the different dolomite types: 1) crystal size using Folk's (1962) classification; 2) qualitative determination of iron content using potassium ferricyanide-stained thin sections; 3) presence of mineral or fluid inclusions; 4) presence of zoning in crystals; 5) epi-fluorescence (epi-FL) color. Cathodoluminescence (CL) microscopy was of limited use, as the dolomites generally show bright to moderate-red luminescence with little variation in hue and intensity within and between thin section samples. A summary of the petrographic characteristics of dolomites in this study are shown in Table 3.1. Table 3.2 shows the relationship of dolomite type to the lithofacies.

3.3.1 Idiotopic Euhedral (IDIO-E and Idio-Ep) Dolomite

3.3.1.1 Petrography

The Idio-E dolomite type occurs as crystal-supported mosaics in which greater than 50% of the dolomite crystals are euhedral in form (Fig. 3.2; PHOTO 3.1). The Idio-Ep dolomite type is similar in crystal shape and mosaic characteristics to the Idio-E dolomite but is separated as a sub-type of Idio-E because of its finer crystal size and its occurrence only in the patterned dolostone lithofacies.

Idio-E dolomite crystals are generally light brown under plane-polarized transmitted light. Crystal sizes range from 8-500 μm, with an average size of approximately 50 μm (finely crystalline). Idio-Ep dolomite mosaics are consistently aphanocrystalline. Idio-E dolomite is generally non-ferroan but crystals that are adjacent to open pore spaces or cement-filled pore spaces may have a ferroan outer rim. Inclusions are almost always present within Idio-E dolomite crystals and consist of calcite, very fine dolomite rhombs or opaques (iron sulphides?). Within individual crystals, inclusions are either randomly distributed or preferentially concentrated along cleavage traces. There are only rare occurrences of crystals that have an inclusion-rich core and an inclusion-free ferroan or non-ferroan outer rim (PHOTO 3.2).

Approximately one-third of the Idio-E samples contain crystals that show zoning under epi-fluorescence microscopy. These zoned crystals show variable fluorescence patterns which include: a) uniform blue-fluorescing cores with uniform orange-fluorescing rims; b) uniform blue-fluorescing cores with concentrically zoned orange-fluorescing rims; and c) orange-fluorescing cores with blue-fluorescing rims. Unzoned samples display a uniform, blue to blue-green fluorescence. Idio-Ep samples do not fluoresce.

Intercrystalline porosity is most common within the Idio-E mosaics and high porosity (approximately 10-20%) is generally associated with coarser crystal sizes. Porosity is decreased by the local presence of cements of anhydrite, halite and, to a lesser degree, calcite. Porosity within the Idio-Ep mosaics is totally occluded by micrite.

3.3.1.2 Occurrence

The Idio-E dolomite is the most commonly observed dolomite type in the study area. Idio-E dolomite is found in all geographic zones within the study area but most commonly occurs in the Upper Winnipegosis Member and least commonly in the Lower Winnipegosis Member. Idio-E dolomite is not specific to any single lithofacies, with the exception of the Idio-Ep sub-type, which only occurs in the patterned dolostone lithofacies. The Idio-E dolomite is the dominant dolomite type in pervasive dolostones of the Upper Winnipegosis Member and the laminated mudstone lithofacies of the Ratner Member. Idio-E dolomite is a minor component in some limestones, occurring: (1) as a selective replacement of allochems in the coral-stromatoporoid doloboundstone lithofacies and the fossiliferous packstone and boundstone lithofacies in the Upper Winnipegosis Member; (2) adjacent to and within pressure dissolution seams in the crinoid-brachiopod wackestone lithofacies of the Lower Winnipegosis Member and in the mudstone lithofacies of the Upper Winnipegosis Member and (3) as irregular patches and stringers within anhydrite beds near the top of the Upper Winnipegosis Member.

3.3.2 Idiotopic Subhedral (IDIO-S) Dolomite

3.3.2.1 Petrography

The Idio-S dolomite type was assigned to those dolomite crystal mosaics containing 25-50% euhedral crystals (Fig. 3.2; PHOTO 3.3). Subhedral crystal forms are predominant in the remainder of the crystal mosaic. Crystals comprising the Idio-S mosaics range in size from 5 - 800 μm, averaging approximately 60 μm (finely crystalline). Idio-S dolomite crystals contain moderate to abundant inclusions of calcite and minor amounts of aphanocrystalline dolomite and opaques. The most common identifiable relict allochems replaced by the Idio-S dolomite are crinoid ossicles which are easily recognized by their relatively large crystal size and unit extinction.

Approximately one-half of the Idio-S dolomite samples examined exhibit zoning. Under plane-polarized light, most zoned crystals display cloudy cores with clear rims. Rare ferroan rims occur in crystals that are adjacent to pore spaces. Epi-FL only highlights this zoning and does not reveal any other zoning. Fluorescence colors of the Idio-S dolomite are dull blue, dull green and rarely orange.

Porosity is relatively poor (less than 3 - 5%) within Idio-S dolomite mosaics and usually occurs as secondary vugs to microvugs, moldic and rare microfractures.

3.3.2.2 Occurrence

The Idio-S dolomite type is found in all geographic zones within the study area but is almost exclusively found in the Upper Winnipegosis Member. This dolomite has been found in lithofacies of the shelf margin reefs and all lithofacies seaward of the shelf margin reefs. The Idio-S dolomite type was found in the Lower Winnipegosis Member at only two locations (NDGS# 4934 and 6535) subjacent to the shelf margin of the Upper Winnipegosis Member.

Idio-S dolomite commonly replaces anhydrite at or near the top of the Upper Winnipegosis Member. Where Idio-E dolomite is present, Idio-S is subordinate and occurs in the matrix or in patches. Idio-S dolomite also fills moldic porosity in the fossiliferous wackestone lithofacies, coral-stromatoporoid doloboundstone lithofacies and the fossiliferous packstone and boundstone lithofacies. Idio-S dolomite occasionally contains larger isolated euhedral dolomite rhombs (ISO dolomite, as discussed later).

3.3.3 Xenotopic Subhedral (XENO-S) Dolomite

3.3.3.1 Petrography

This dolomite type occurs as crystal mosaics in which greater than 50% of the dolomite crystals are subhedral and up to 25% are euhedral in form (Fig. 3.2). Anhedral crystal forms make up the remainder of the crystal mosaic. In some samples it was difficult to determine whether the dolomite type is Idio-S or Xeno-S. The main criterion used to distinguish between these two dolomite types is the amount of anhedral crystals within the dolomite mosaic. Where the amount of anhedral crystals was greater than euhedral crystals the sample was deemed to be Xeno-S. Xeno-S dolomite rhombs range from 2 - 250 μm with an average size of about 20 μm (finely crystalline). Xeno-S dolomite crystals generally contain moderate to abundant inclusions which include calcite, dolomite, opaques (sulphides?) and rare anhydrite. Within individual crystals, inclusions are generally randomly distributed and inclusion patterns reflecting relict allochems are rare. Zoned Xeno-S crystals are rare; only the outer rims of a few crystals adjacent to pore spaces are ferroan. Epi-FL does not reveal any other zoning and shows only uniform, dull blue, green, and rare orange fluorescing dolomite crystals.

Porosity associated with this dolomite is generally poor to very poor. Microvugs are the most common type of porosity and possible moldic porosity is extremely rare.

3.3.3.2 Occurrence

Xeno-S dolomite is of minor abundance compared with other dolomite crystal mosaics examined in the study area. Xeno-S dolomite was found mainly in mudstone lithofacies in all geographic zones and in the coral-stromatoporoid doloboundstone lithofacies in the central geographic zone of the Upper Winnipegosis Member (Table 3.2). Xeno-S dolomite also occurs in the matrix of the fossiliferous packstone and boundstone lithofacies; within the anhydrite near the top of the Upper Winnipegosis Member; and replacing allochems in the crinoid-brachiopod wackestone lithofacies, the coral-stromatoporoid doloboundstone lithofacies, and the peloidal packstone lithofacies. Xeno-S dolomite only rarely occurs as the dominant dolomite type in the pervasively dolomitized lithofacies. Macroscopic textures of allochems are generally partially preserved and microscopic features are not preserved. Where Xeno-S dolomite is present, Idio-S or Xeno-A dolomite (see following sections) is found in close proximity.

3.3.4 Xenotopic Anhedral (Xeno-A) Dolomite

3.3.4.1 Petrography

This dolomite type occurs as crystal mosaics in which greater than 50% of the dolomite crystals are anhedral in form; the remainder is dominated by subhedral dolomite crystals (Fig. 3.2; PHOTO 3.4). Xeno-A dolomite crystals range from 1-160 μm but average between approximately 1-50 μm (cryptocrystalline to aphanocrystalline). This dolomite is typically non-ferroan; ferroan zones or entirely ferroan crystals are extremely rare. The finely crystalline to medium crystalline Xeno-A dolomite crystals display minor inclusions, and no zoning was apparent under epi-FL. Fluorescence colors within the Xeno-A dolomite are dull green, dull blue, bright blue and rarely orange. Xeno-S dolomite appears to grade into Xeno-A dolomite within the same core and even within the same thin section (discussed later).

Porosity is generally not observed within the Xeno-A dolomites, and only rarely reaches about 2% as microvugs.

3.3.4.2 Occurrence

Overall, Xeno-A dolomite is minor in occurrence compared with other dolomite crystal mosaics examined in the study area. This dolomite type occurs in all geographic zones in the Lower Winnipegosis, Upper Winnipegosis and Ratner members. This dolomite appears not to be lithofacies selective. Xeno-A dolomite is commonly found within Idio-E, Idio-S and Xeno-S dolomite types. Patches of Xeno-A dolomite are found in the fossiliferous wackestone lithofacies, the coral-stromatoporoid doloboundstone lithofacies, the fossiliferous packstone and boundstone lithofacies and the mudstone lithofacies, as well as in the anhydrite near the top of the Upper Winnipegosis Member. These irregular shaped patches, as large as 5 cm, generally overprint the lithofacies fabric. Replacement of allochems by Xeno-A dolomite is common in the crinoid-brachiopod wackestone lithofacies of the Lower Winnipegosis Member and also occurs in the coral-stromatoporoid doloboundstone lithofacies and the peloidal packstone lithofacies of the Upper Winnipegosis Member. Xeno-A dolomite is found at the base of the Lower Winnipegosis Member at one location; it is also found within the Ashern Formation at the same location (NDGS # 35).

3.3.5 Saddle Dolomite

3.3.5.1 Petrography

Saddle or baroque dolomite crystals are characterized by curvilinear crystal margins and cleavage traces, as well as undulatory extinction (cf. Radke and Mathis, 1980; Fig. 3.2; PHOTO 3.5a and 3.5b). Saddle dolomite crystals range in size from 0.02-3.1 mm, averaging between 1-2 mm (medium crystalline to coarse crystalline). Individual saddle dolomite crystals are generally euhedral in form and rarely subhedral. Almost all saddle dolomite crystals contain minor to moderate amounts of opaque or calcite inclusions. Approximately one-half of all saddle dolomite crystals examined were ferroan and minor occurrences had outer ferroan rims. CL and epi-FL microscopy did not reveal any other zoning within the saddle dolomite. Under Epi-FL saddle dolomite is a uniform dull green or dull blue color and does not show any zoning.

3.3.5.2 Occurrence

Saddle dolomite is of relatively minor abundance compared to all the other dolomite types examined in the study area. This dolomite is most abundant in the central geographic zone but also occurs in the other three geographic zones. This dolomite rarely forms crystal mosaics and is usually found as isolated crystals throughout the Winnipegosis Formation and throughout the study area. Saddle dolomite also occurs in groups of generally less than 10 crystals most commonly in the coral-stromatoporoid doloboundstone lithofacies of the central geographic zone. Saddle dolomite is commonly found as a cement lining small fractures, or moderately sized intercrystalline and moldic porosity (pores greater than about 3 to 5 mm) within Idio-E, Idio-S, Xeno-S and Xeno-A dolomites mosaics. Saddle dolomite is found in the crinoid-brachiopod wackestone lithofacies of the Lower Winnipegosis Member; in the coral-stromatoporoid doloboundstone lithofacies, the fossiliferous wackestone lithofacies and the mudstone lithofacies of the Upper Winnipegosis Member; and in the laminated mudstone lithofacies of the Ratner Member.

3.3.6 Isolated (ISO) Dolomite Crystals

3.3.6.1 Petrography

This dolomite type occurs as isolated single crystals or in small clusters, usually in a limestone but also in dolostones and dolomitic limestones (Fig. 3.2; PHOTO 3.6a and 3.6b). Saddle dolomite is excluded from this dolomite type because of its unique characteristics. Where single crystals of dolomite appear to be much larger than the surrounding dolomite crystals, these larger crystals are included in the ISO dolomite type. Atypical, isolated dolomite crystals in dolostones or limestones are also included in the ISO dolomite type (e.g. a single, euhedral dolomite crystal within a Xeno-A dolomite mosaic). Crystal forms within this dolomite type are, from most to least abundant, euhedral, subhedral and anhedral.

Crystal size of the ISO dolomite type varies from 2-150 μm averaging about 15-20 μm (very finely crystalline to finely crystalline). Euhedral ISO dolomite crystals are typically larger than subhedral and anhedral ISO dolomite crystals. Inclusions can be seen in ISO dolomite crystals but their composition could not be determined due to their very small size. Inclusion patterns are generally random and rarely follow cleavage traces. Ferroan ISO dolomite crystals are rare. Epi-FL colors in finely crystalline ISO dolomites are mostly dull blue-green and dull blue, with minor occurrences of bright blue-white, bright orange cores with dull blue rims (PHOTO 3.6b) and inclusions. Epi-

FL zoning in finer ISO dolomite crystals could not be adequately resolved due to interfering fluorescence from adjacent crystals.

3.3.6.2 Occurrence

ISO dolomite is slightly more abundant than the saddle dolomite but is still a minor dolomite type. ISO dolomite crystals are found throughout the study area and are most abundant in the crinoid-brachiopod wackestone lithofacies of the Lower Winnipegosis Member. Isolated dolomite crystals are found within the Lower Winnipegosis Member: (1) as dispersed crystals within the limestone matrix, (2) adjacent to and within pressure dissolution seams, (3) in intercrystalline and moldic porosity and (4) within allochems. Euhedral ISO dolomite crystals are also found dispersed throughout the Upper Winnipegosis and Ratner members. They commonly occur adjacent to stylolites, where they usually cut across the stylolites and rarely are truncated by the stylolites. This dolomite type is also found associated with the anhydrite at or near the top of the Upper Winnipegosis Member, within void-filling anhydrite, and as inclusions within isolated anhydrite crystals.

3.4 Other Authigenic Minerals

Anhydrite, dedolomite and late diagenetic calcite are associated with the dolomite types described in the previous sections. The textural relationship between the anhydrite, the late diagenetic calcite and the six different dolomite types is essential in determining the timing of dolomitization. In this study, there are 5 anhydrite types described in the following section. Dedolomitization is defined as the process of replacing dolomite by calcite during diagenesis and dedolomite is the product (Bates and Jackson, 1980).

3.4.1 Anhydrite

In the Winnipegosis Formation anhydrite generally increases in abundance up-section. In the Lower Winnipegosis Member, anhydrite is generally rare and sporadic, whereas in the Upper Winnipegosis Member and the Ratner Member anhydrite is common. Five types of anhydrite have been recognized and described based on mode of occurrence.

Anhydrite type 1 consists of ovoid to irregular shaped patches, 0.5-5 mm in size, of anhydrite crystals within the patterned dolostone lithofacies of the Upper Winnipegosis Member (PHOTO 2.5). Anhydrite crystals are prismatic and generally between 100-500 μm long but can be as small as 2 μm and as large as 1 mm. The crystals are oriented either randomly or roughly parallel to the patch boundary. Rare ISO dolomite occurs within these anhydrite patches.

Anhydrite type 2 is nodular anhydrite (PHOTO 3.7) that is found near the top of the Winnpegosis Formation in the central, eastern and western geographic zones. Where it occurs it overlies dolostones of the Upper Winnipegosis Member.

Anhydrite nodules are irregular in shape with their longest axis generally oriented parallel to bedding. Nodules range in size from 2 - >10 cm long and approximately 0.5 - 8 cm wide. Individual nodules are white to gray-white, slightly discolored around their edges and usually separated by brown or black dolomitic muds. Crystals comprising the nodular anhydrite vary in size from 5 mm long and 2 mm wide to 50 μm long and 2 μm wide, but small crystals (approximately 2 mm long and 50 μm wide) are most common. Generally the anhydrite crystals are acicular to prismatic in shape and occur in small clusters that are randomly oriented within the nodules. Inclusions are rarely seen in medium to coarse crystalline anhydrite crystals and are mostly ISO dolomite crystals with rare calcite. Small patches (2 - 10 mm in size) and stringers of Idio-E dolomite and Idio-S dolomite that cut across and replace the anhydrite are common within and between anhydrite nodules.

Anhydrite type 3 is laminated anhydrite overlying dolostones of the Ratner Member in the central geographic zone (PHOTO 3.8). The laminae are irregular to undulatory but generally horizontal. Individual laminae are never more than 2 cm thick. The anhydrite crystals within the laminated anhydrite are generally acicular to prismatic and can reach lengths of up to 2 mm and widths of up to 50 μm. This anhydrite contains abundant dark gray to black lenses and stringers of clay and/or organic material within and between the anhydrite laminations. Idio-E dolomite is commonly found within and adjacent to the clay/organic lenses or stringers. Small patches of dolomite, which are generally a mixture of Idio-E, Idio-S, Xeno-S and Xeno-A dolomite types, cut across the anhydrite.

Anhydrite type 4 occurs as large (10-40 mm in size), irregular-shaped anhydrite patches and as fracture-fill. The anhydrite patches most commonly occur in the coral-stromatoporoid doloboundstone lithofacies, fossiliferous packstone and boundstone lithofacies, fossiliferous wackestone lithofacies and the peloidal packstone lithofacies of the Upper Winnipegosis Member, and are rare in the Lower Winnipegosis Member. Anhydrite-filled fractures (2 -5 mm wide) are common in all lithofacies at or near the top of the Winnipegosis Formation and are found sporadically throughout the Lower Winnipegosis Member. Anhydrite-filled fractures are often found leading from the anhydrite patches within the mudstone lithofacies and argillaceous areas of the fossiliferous wackestone lithofacies and the fossiliferous packstone and boundstone lithofacies.

Large patches of anhydrite commonly contain prismatic crystals (< 1 mm long) of anhydrite in a nearly random orientation, but may also have crystals up to 20 mm long and 10 mm wide. ISO dolomite inclusions within the larger anhydrite crystals are rare. Anhydrite crystals occurring in fractures are generally 0.5-2 mm long. The walls of most anhydrite-filled fractures and the outer boundaries of anhydrite patches contain a thin, partial lining of euhedral ISO dolomite crystals, up to 20 μm in size, that is a few crystals thick. Euhedral ISO dolomite crystals and rare calcite are found within and between anhydrite crystals.

Anhydrite type 5 consists of isolated anhydrite crystals which are acicular to prismatic and typically between 1.5 - 25 mm long (PHOTO 3.7). Isolated anhydrite crystals are found in all lithofacies of the Upper Winnipegosis, Lower Winnipegosis, and Ratner members in all geographic zones. Isolated anhydrite crystals have been found: (1) as cement within individual corallites and brachiopods within the crinoid - brachiopod wackestone of the Lower Winnipegosis Member, (2) replacing stromatoporoid and coral microstructures in the coral-stromatoporoid doloboundstone lithofacies and the fossiliferous packstone and boundstone lithofacies of the Upper Winnipegosis Member, (3) replacing the fabric of the crinoid-brachiopod wackestone lithofacies of the Lower Winnipegosis Member, the mudstone lithofacies of the Upper Winnipegosis Member, and the laminated mudstone lithofacies of the Ratner Member, and (4) replacing Idio-S and Xeno-S dolomites within the coral-stromatoporoid doloboundstone lithofacies and fossiliferous packstone and boundstone lithofacies of the Upper Winnipegosis Member, as well as displacing the laminated mudstones of the Ratner Member. Anhydrite type 5 crystals seem to be either nearly horizontally or vertically aligned and in some cases radiate from a central point to form "pseudo-rosettes". Both calcite inclusions and dolomite inclusions are commonly found within these isolated anhydrite crystals.

Anhydrite type 5 is found replacing and displacing Winnipegosis sediments and is interpreted to have started forming after sediment deposition but before lithification. With continued sediment compaction and continued dissolution of early deposited anhydrite, anhydrite type 5 may have continued forming after lithification of Winnipegosis sediments.

3.4.2 DEDOLOMITE

In the Winnipegosis Formation dedolomite occurs preferentially in finely to very finely crystalline dolomite crystals, as follows: (1) at margins of euhedral dolomite crystals, resulting in serrated edges and small embayments of calcite in the dolomite; (2) small, irregular-shaped patches of calcite fully within dolomite crystals (PHOTO 3.9); (3) along dolomite crystal zone boundaries; and (4) nearly complete replacement of the dolomite crystal by calcite. Dedolomite occurs in the western and central geographic zones in: (1) ISO dolomite of the Upper Winnipegosis and Lower Winnipegosis members, (2) Idio-E dolomite within the Ratner Member only, and (3) the Idio-S, Xeno-S and Xeno-A dolomites of the Upper Winnipegosis and Ratner Members. The most common occurrence of dedolomite is in the ISO dolomite type.

3.4.3 LATE DIAGENETIC CALCITE

Late diagenetic calcite cement is coarse to medium crystalline and commonly non-ferroan and poikilotopic. This calcite contains irregular-shaped ISO dolomite inclusions, 20 μm in size, dedolomite, minor anhedral and truncated anhydrite crystals, fragments of the host rock and rare opaques. This calcite cement occurs in the Idio-E, Idio-S, Xeno-S and Xeno-A dolomite types occluding: (1) late fractures that truncate all fabric that are present sporadically throughout the Winnipegosis Formation, (2) molds of halite hopper crystals found near the top of the Lower Winnipegosis Member, (3) intercrystalline or intergranular porosity in limestones of the Lower Winnipegosis Member, (4) moldic and intercrystalline porosity in dolomitic and dolostone lithofacies in the shelf areas of the Upper Winnipegosis Member (PHOTO 3.3 and PHOTO 3.4), (5) intraskeletal porosity within the coral-stromatoporoid doloboundstone lithofacies of the Upper Winnipegosis Member and (6) intercrystalline porosity near the top of the Ratner Member.

3.5 PARAGENETIC SEQUENCE

The paragenetic sequence for dolomites in the Winnipegosis Formation in the study area can be divided into three stages: synsedimentary, early diagenetic, and late diagenetic (Fig. 3.3). In this study, the synsedimentary stage includes those diagenetic processes occurring at the time of sediment deposition and/or very shortly after deposition. The early diagenetic stage includes those processes associated with early or shallow burial of the sediment prior to significant compaction. The late diagenetic stage involves diagenesis in a deep burial environment.

3.5.1 Synsedimentary Diagenetic Stage

The synsedimentary diagenetic stage includes formation of: (1) Idio-Ep dolomite, (2) anhydrite type 1, (3) anhydrite type 2, and (4) anhydrite type 3.

The Idio-Ep dolomite sub-type is facies selective, occurring only in the patterned dolostone lithofacies of the Upper Winnipegosis Member that is interpreted to be of sabkha origin. This dolomite is interpreted to be syndepositional based on similarities with modern sabkha dolomites (e.g. Wells, 1962; Curtis et al., 1963; Illing et al., 1965; Kinsman, 1966; Butler 1969, 1970; Patterson and Kinsman, 1982). MacKenzie (1981) showed that in the Persian Gulf sabkha dolomites euhedral anhydrite crystals encrust euhedral dolomite rhombs and dolomite rhombs encrust aragonite crystals with no obvious evidence of replacement. Anhydrite type 1, which occurs only within the patterned dolostone lithofacies, is considered to have formed essentially coevally with the Idio-Ep dolomite.

The mode of occurrence of anhydrite types 2 and 3 (nodular, laminated) and their association with the microbial bindstone lithofacies support a synsedimentary origin under hypersaline depositional conditions (cf. Perrin, 1987). Nodular and laminated anhydrites have also been documented and interpreted as synsedimentary in studies of modern evaporites and other ancient examples (cf. Schreiber et al., 1973; Kendall, 1992).

3.5.2 Early Diagenetic Stage

The early diagenetic stage includes formation of: (1) Idio-E dolomite, (2) Idio-S dolomite, (3) Xeno-S dolomite, (4) anhydrite type 5 and (5) Xeno-A dolomite.

Idio-E dolomite is the most common dolomite type found in all pervasively dolomitized lithofacies throughout the Winnipegosis Formation. Idio-E dolomite is associated with synsedimentary to later diagenetic features suggesting that the process involved in creating this dolomite type was widespread and long-lived. Some Idio-E dolomite is interpreted to have started forming syndepositionally within the laminated mudstone lithofacies of the Ratner Member and in the microbial bindstone lithofacies of the Upper Winnipegosis Member. This interpretation is based on the occurrence of Idio-E dolomite within anhydrite type 2 and 3 deposited at or near the top of the Upper Winnipegosis Member. Some Idio-E dolomite also replaced anhydrite type 2 indicating that Idio-E dolomite formation continued after the deposition of anhydrite type 2. This is also substantiated by the cross cutting nature of dolomite patches (Idio-E and others) within the laminated anhydrite. Most Idio-E dolomite associated with pressure dissolution seams in the Lower Winnipegosis Member and in the lower sections of the Upper Winnipegosis Member is interpreted to have been concentrated, due to their

differential rate of crystal growth, (3) partial crystal growth inhibitors such as low concentration of clays and/or organics, (4) density or homogeneity of dolomite nucleation sites, (5) temperature at which dolomite mosaics form, (6) chemistry of dolomitizing fluids, i.e. degree of dolomite supersaturation, and (7) mineral growth kinetics.

Anhydrite type 5 occurs in all lithofacies and is interpreted to be replacive and displacive; therefore, the replacive anhydrite type 5 started to precipitate shortly after deposition, prior to sediment lithification, and the replacive anhydrite type 5 continued to form in compacted Winnipegosis sediments into the late diagenetic stage. However, Anhydrite type 5 is mainly early diagenetic.

Xeno-A dolomite is commonly found as the matrix for, or as irregular shaped patches within, Idio-E, Idio-S and Xeno-S dolomite types. The Xeno-A dolomite sometimes appears to grade into, but generally appears to replace existing dolomite and is considered to have formed after the Idio-E, Idio-S and Xeno-S dolomite. Xeno-A dolomite formed before the saddle dolomite, dedolomite and late diagenetic calcite.

3.5.3 Late Diagenetic Stage

The late diagenetic stage includes formation of: (1) ISO dolomite, (2) anhydrite type 4, (3) dedolomite, (4) late diagenetic calcite, (5) saddle dolomite and (6) ferroan dolomite.

ISO dolomite is dispersed throughout every lithofacies, limestone and dolostone, of the Winnipegosis Formation and in all geographic zones. ISO dolomite inclusions have been found within the individual anhydrite type 5 crystals which indicates that the ISO dolomite formed before or at the same time as anhydrite type 5. ISO dolomite is also found in synsedimentary anhydrite types 2 and 3, but is most common adjacent to pressure dissolution seams throughout the Winnipegosis Formation. Pressure dissolution seams may form at burial depths as shallow as 3 m (Wanless, 1979) to 10 m (Meyers and Hill, 1983), but they are generally a deep-burial phenomena (Choquette and James, 1986). Some ISO dolomite crystals are truncated by the dissolution seams and others appear to truncate the seams, indicating that the bulk of the ISO dolomite formed concomitantly with pressure dissolution in the deep burial environment during the late diagenetic stage. Euhedral ISO dolomite crystals also appear as thin layers of cement within pores and lining fractures filled with Anhydrite type 4.

Anhydrite type 4 is found as fracture fill and porosity fill within the Winnipegosis Formation. Fractures cut across the existing fabric in the Upper Winnipegosis and Lower Winnipegosis members. Anhydrite type 4 formed after the ISO dolomite. Anhydrite type 4 may be the product of remobilization of pre-existing anhydrite (possibly anhydrite types 2 and 3) and precipitation within fractures and large pore spaces within the Winnipegosis Formation.

Dedolomite is found as partial or complete calcite replacement of dolomite crystals comprising all dolomite types in this study, except for saddle dolomite. Dedolomitization can only occur when the diagenetic fluids involved are undersaturated with respect to dolomite and supersaturated with respect to calcite (cf. Evamy, 1967; Sibley, 1982; Holail et al., 1988). Dedolomitization in the Winnipegosis Formation is interpreted to have formed after the formation of all dolomite types, except saddle dolomite and the ferroan dolomite.

Calcite cement occurs within intercrystalline pore spaces in Idio-E, Idio-S, Xeno-S and Xeno-A dolomite types and within halite crystal molds in the crinoid-brachiopod wackestone lithofacies of the Lower Winnipegosis Member. This evidence indicates that this calcite cement was late diagenetic, forming after the Idio-E, Idio-S, Xeno-S and Xeno-A dolomite types. This diagenetic calcite is petrographically similar to other deep burial cements described by Choquette and James (1986). Although there is no unequivocal evidence, it is speculated that the late diagenetic calcite cementation and the dedolomite were coeval.

Saddle dolomite is found mostly as cement in pores or fractures cutting across Idio-E, Idio-S, Xeno-S and Xeno-A dolomite mosaics. Saddle dolomite is interpreted to have formed after the Idio-E, Idio-S, Xeno-S and Xeno-A dolomite types. Since partially or fully calcitized saddle dolomite crystals have not been found the saddle dolomite is assumed to have formed later than the dedolomite.

The last dolomite event appears to be the precipitation of ferroan dolomite as rims in dolomite crystals comprising the Idio-E, Idio-S, Xeno-S, ISO, and saddle dolomite types. Some of the late calcite cement is rarely ferroan and may have formed, in part, at the same time as the ferroan dolomite. Almost all of the ferroan rims were observed in crystals situated in or very close to pores. The most likely explanation for the emplacement of the ferroan dolomite is an entirely separate dolomitizing event that precipitated ferroan dolomite in the form of overgrowths on existing dolomite crystals and as localized ferroan Xeno-A dolomite.

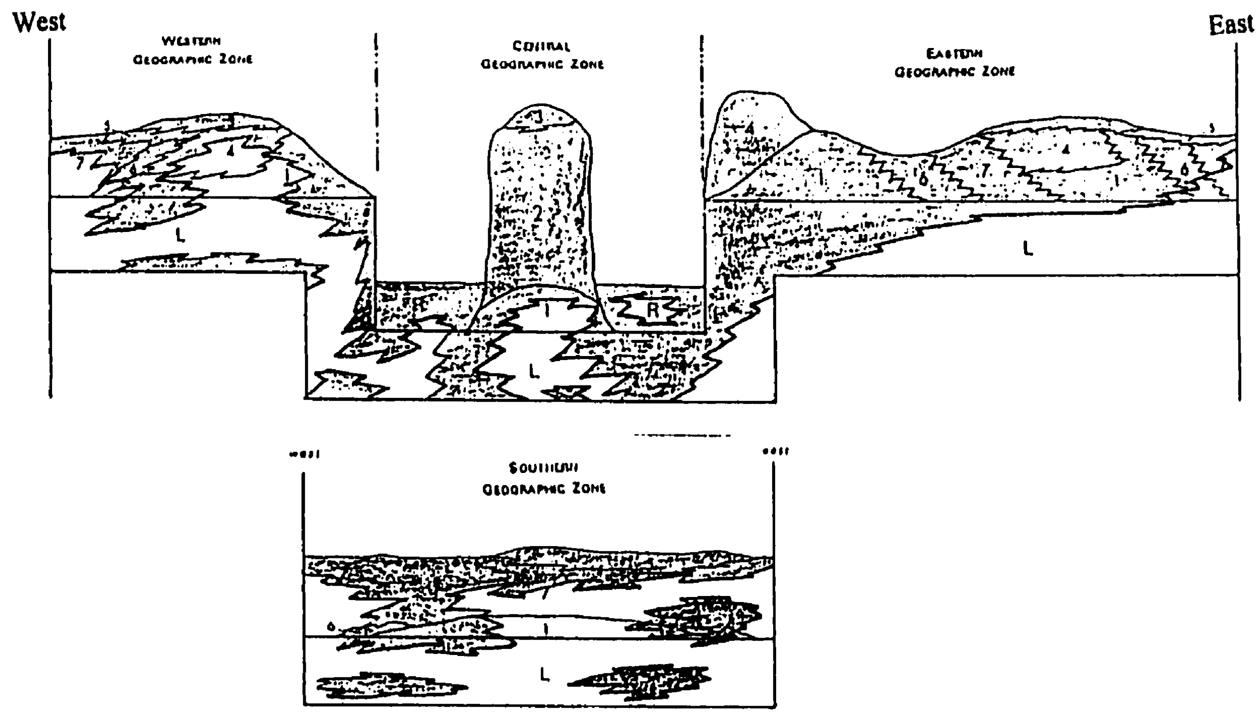


Fig. 3.1. Schematic of dolomite distribution (shaded areas) within the various lithofacies and geographic zones. No scale implied. (L = Lower Winnipegosis Member, R = Ratner Member, 1 = Fossiliferous wackestone, 2 = Coral-stromatoporoid boundstone, 3 = Microbial bindstone, 4 = Fossiliferous packstone and boundstone, 5 = Patterned dolostone, 6 = Peloidal packstone, 7 = Mudstone).

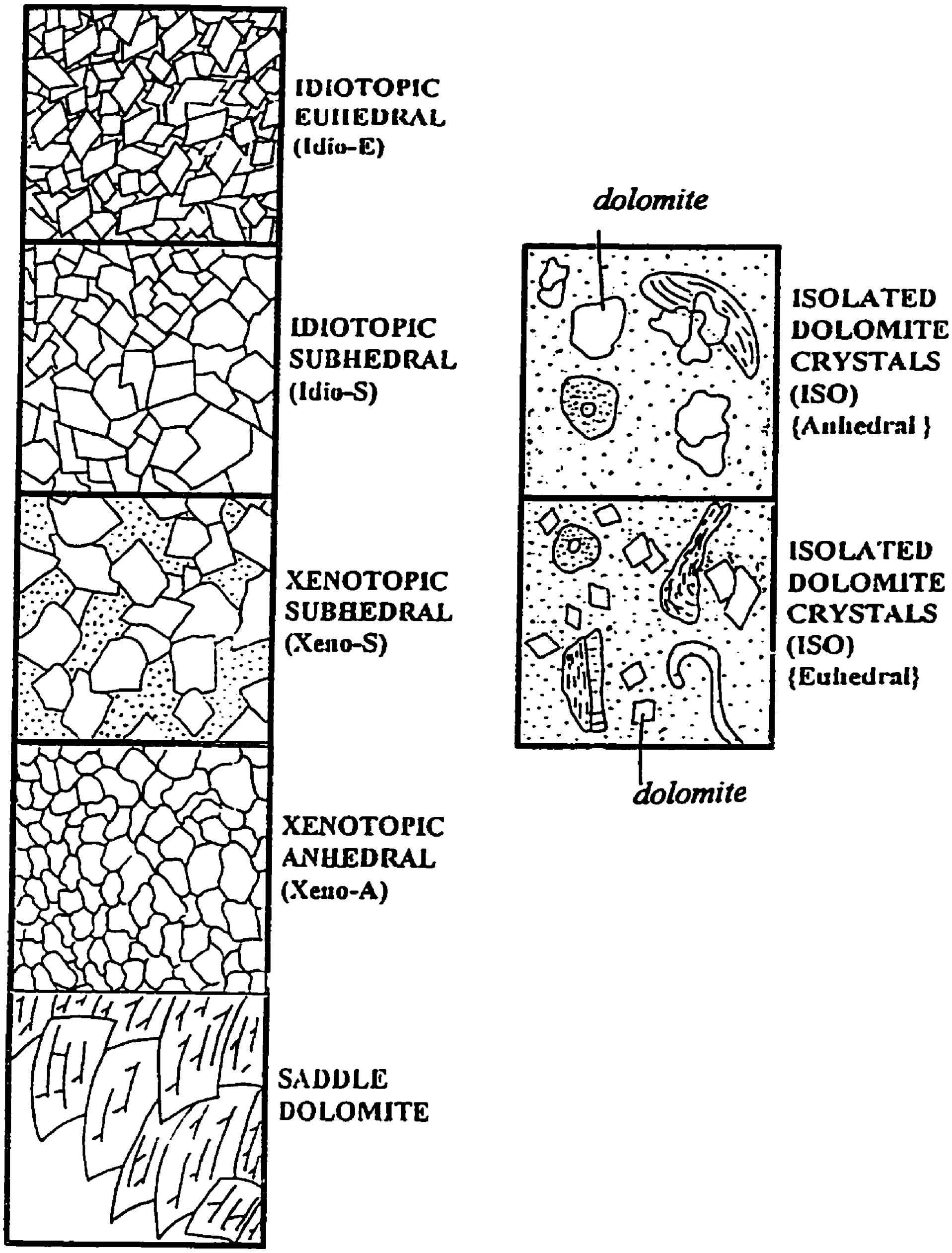


Fig. 3.2. Diagrammatic representation of dolomite textural classification used in this study.

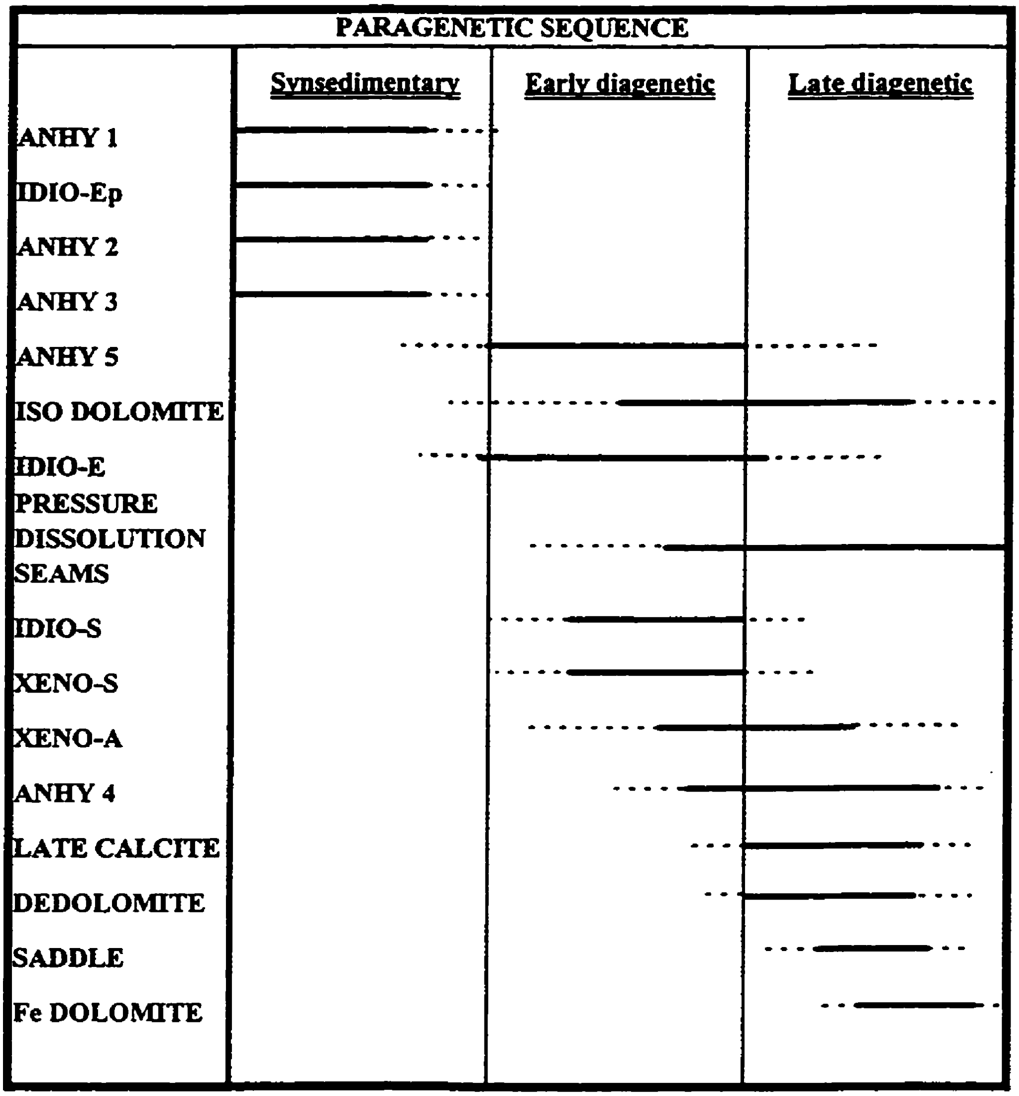


Fig. 3.3. Diagrammatic representation of the paragenetic sequence for dolomite and related diagenetic phases in the Winnipegosis Formation. Solid lines indicate most likely timing of emplacement. Dashed lines indicate possible extensions of timing.

Table 3.1. Summary of the petrography of the dolomite types.

Dolomite Type	Crystal size (µm)	Iron content (Stained samples)	Opaque Inclusions	Zoning	C.L. Color	Epi-Fl. Color (B-V filter)
Idio-E	8 to 500 avg. 50	Rare. Outer rims on non-ferroan crystals adjacent to pores.	Moderate in most samples, otherwise rare to none.	crystals in samples are zoned. Epi-Fl. Cloudy centres, clear rims.	Uniform, bright to moderate red with extremely little variation.	Orange or blue, **or** orange cores with blue rims.
Idio-S	5 to 800 avg. 60	Rare. Outer rims on non-ferroan crystals adjacent to pores.	Moderate to abundant in all samples.	About ½ are zoned. Mostly cloudy core and clear or ferroan rims.	Uniform, bright to moderate red with extremely little variation.	Mostly dull blue to dull green and rarely orange.
Xeno-S	2 to 250 avg. 20	Rare. Rims on crystals adjacent to pores.	Moderate to abundant in all samples.	Rare. Ferroan rims.	Uniform, bright to mod. red with very little variation.	Mostly dull green or dull blue with rare orange.
Xeno-A	1 to 160 avg. 100	Rare.	Crystals are generally too small to detect inclusions. Minor in coarser crystals.	No zoning detected.	Uniform, moderate to dull red.	Mostly dull blue, minor bright blue and dull green. Rare orange.
Saddle Dolomite	20 to 3100 avg. 1000 to 2000.	Approx. 60% are ferroan and 15% have ferroan rims.	Minor to moderate in all samples.	Ferroan rims only.	Uniform, dull red.	Either uniform dull blue or uniform dull green.
ISO	2 to 150 but usually 10 to 20.	Rare. Generally entire thin section i ferroan.	Generally too small to detect inclusions. Minor in coarser crystals.	Rare ferroan rims.	Uniform red with no differentiation of calcite matrix and dolomite crystals.	Mostly dull blue or dull green. Minor bright blue and orange

Table 3.2. Occurrence of dolomite types based on core and petrographic observations (C = common, M = moderate, R = rare).

Dolomite Type	LOWER WINNIPEGOSIS MEMBER	UPPER WINNIPEGOSIS MEMBER							RATNER MEMBER
	Crinoid brachiopo wackestone	Fossiliferous wackestones	Coral - stromatoporoid boundstone	Microbial bindstone	Fossiliferous packstone and boundstone	Patterned dolostone	Peloidal packstone	Mudstone	Laminated mudstone
IDIO-E	Pervasive -R Patches -M Anhydrite -R	Pervasive -C Patches -M	Pervasive -C Patches -M Matrix -M Allochems -R	Pervasive -C	Pervasive -C Patches -M Matrix -M Allochems -M	Pervasive -C Patches -R	Pervasive -C	Pervasive -C Patches -M Stylolites -M	Pervasive -C Patches -R Stylolites -C
IDIO-S		Pervasive -M Patches -M Matrix -R	Pervasive -M Matrix -M Patches -C Allochems -M Cement -R	Pervasive -M Allochems -R	Pervasive -M Cement -M			Pervasive -C Patches -C Matrix -R	Patches -C
XENO-S	Allochems -R Patches -M		Pervasive -M Allochems -M		Matrix -M		Allochems -C	Pervasive -M Anhydrite -M	
XENO-A	Pervasive -R Allochems -M	Matrix -R Patches -C	Pervasive R Allochems -R Matrix -R Patches -C		Matrix -R Patches -C		Pervasive -M Allochems -M	Pervasive -M Anhydrite -M Matrix -M Patches -C	
SADDLE DOLOMIT	Cement -C Dispersed -M Patches -R Stylolites -R	Cement -C Dispersed -M Stylolites -R	Cement -C					Cement -C Patches -R	Cement -C Dispersed -M
ISO	Stylolites -C Dispersed -M Allochems -M Cement -R	Stylolites -C Dispersed -M Cement -R	Dispersed -C	Cement -C Dispersed -C	Dispersed -C Allochems -M Stylolites -M Cement -R	Dispersed -C	Dispersed -C	Dispersed -C Patches -M Allochems -M Cement -R	Dispersed -C Stylolites -C

Table 3.3. Summary of the petrography of the anhydrite types.

Anhydrite type	Occurrence	Description
1	• Only in Patterned dolostone lithofacies	• 0.5-5mm ovoid to irregular shaped patches • prismatic crystals, avg. 100-500 µm long
2	• nodular anhydrite	• irregular shaped nodules, 2-10cm long, 0.5-8cm wide • acicular to prismatic crystal, avg. 2mm long and 50µm wide
3	• laminated anhydrite	• irregular to undulatory laminae (<2cm thick) parallel to bedding • contains organic matter between laminae • acicular to prismatic crystals, <2mm long and 50µm wide
4	• mostly in Upper Winnipegosis Member • rare in Lower Winnipegosis Member	• irregular shaped patches (10-40mm across) and • fracture-fill (2-5mm wide) • prismatic crystals, avg. 1mm long, can be up to 20mm long
5	• Upper Winnipegosis Member • Lower Winnipegosis Member • Ratner Member	• acicular to prismatic, isolated crystals • crystals 1.5-25mm long

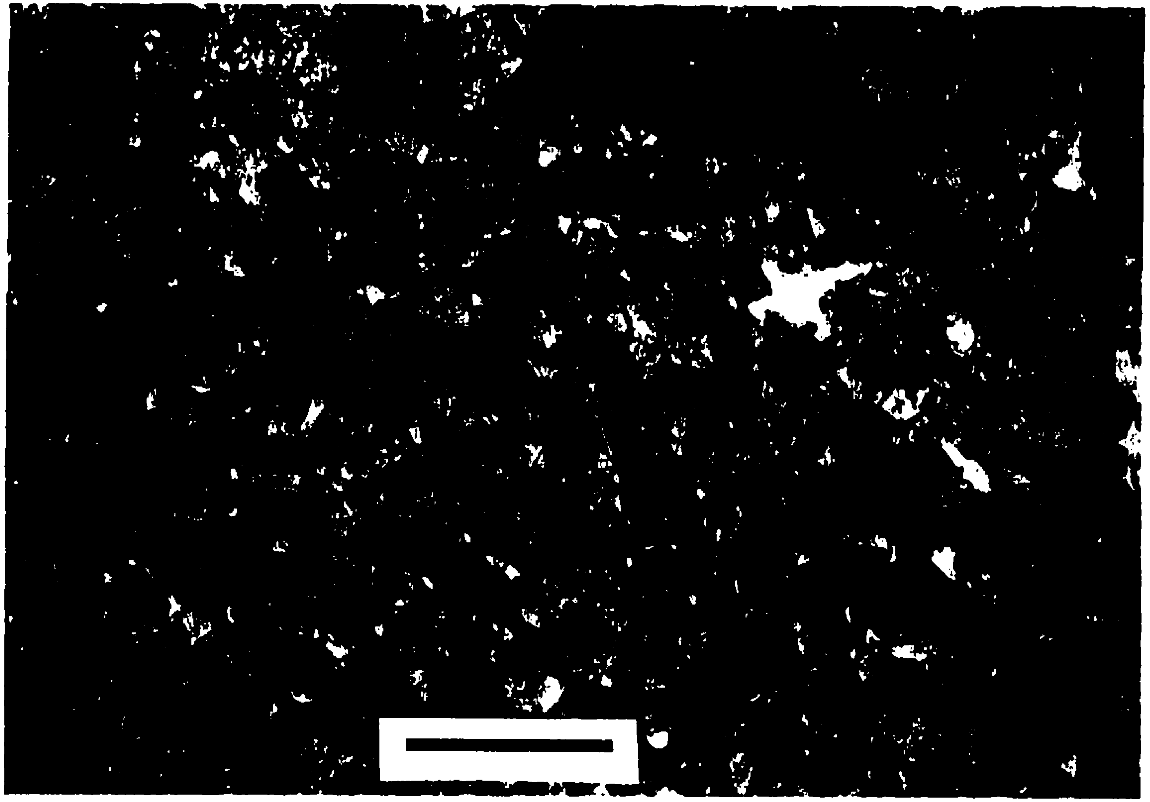


PHOTO 3.1. Photomicrograph of Idio-E dolomite from the Ratner Member laminated mudstone lithofacies in the central geographic zone. NDGS# 2800, depth = 8305 ft. Plane polarized light. (Scale bar is 100 μm).

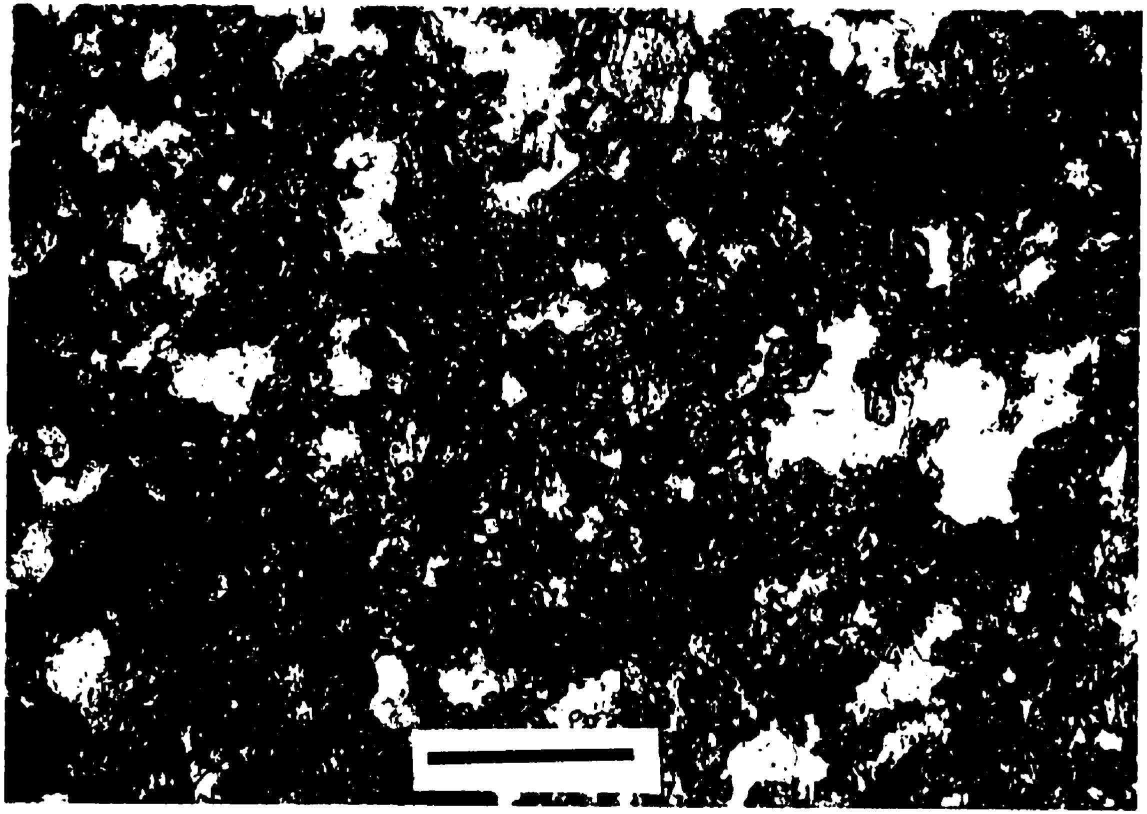


PHOTO 3.2. Photomicrograph of Idio-E dolomite from Upper Winnipegosis Member shelf mudstone lithofacies from the southern geographic zone. NDGS# 5158, depth = 8835 ft. Plane polarized light. (Scale bar is 100 μm).

PHOTO 3.3. Photomicrograph of Idio-S dolomite and vuggy porosity filled with late diagenetic calcite cement (stained red in photomicrograph). Photograph from the Upper Winnipegosis Member mudstone lithofacies in the western geographic zone. NDGS# 4340, depth = 11506 ft. Plane polarized light. (Scale bar is 50 μm).

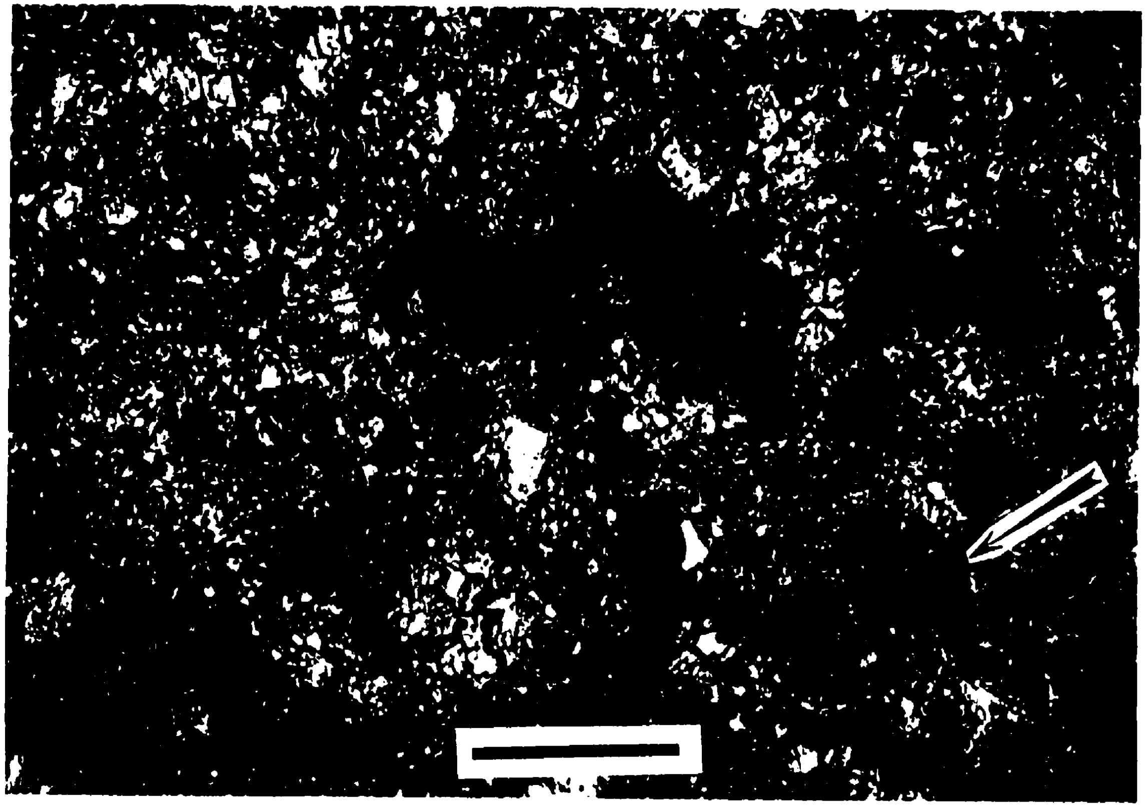


PHOTO 3.4. Photomicrograph of Xeno-A dolomite (arrow) and calcite filled vuggy and moldic porosity (stained red in photomicrograph). Xeno-A dolomite appears to have corroded the margins of the larger dolomite crystal. Photograph from the Upper Winnipegosis Member microbial bindstone lithofacies in the western geographic zone.
NDGS# 4597, depth = 11918 ft. Plane polarized light. (Scale bar is 100 μm).

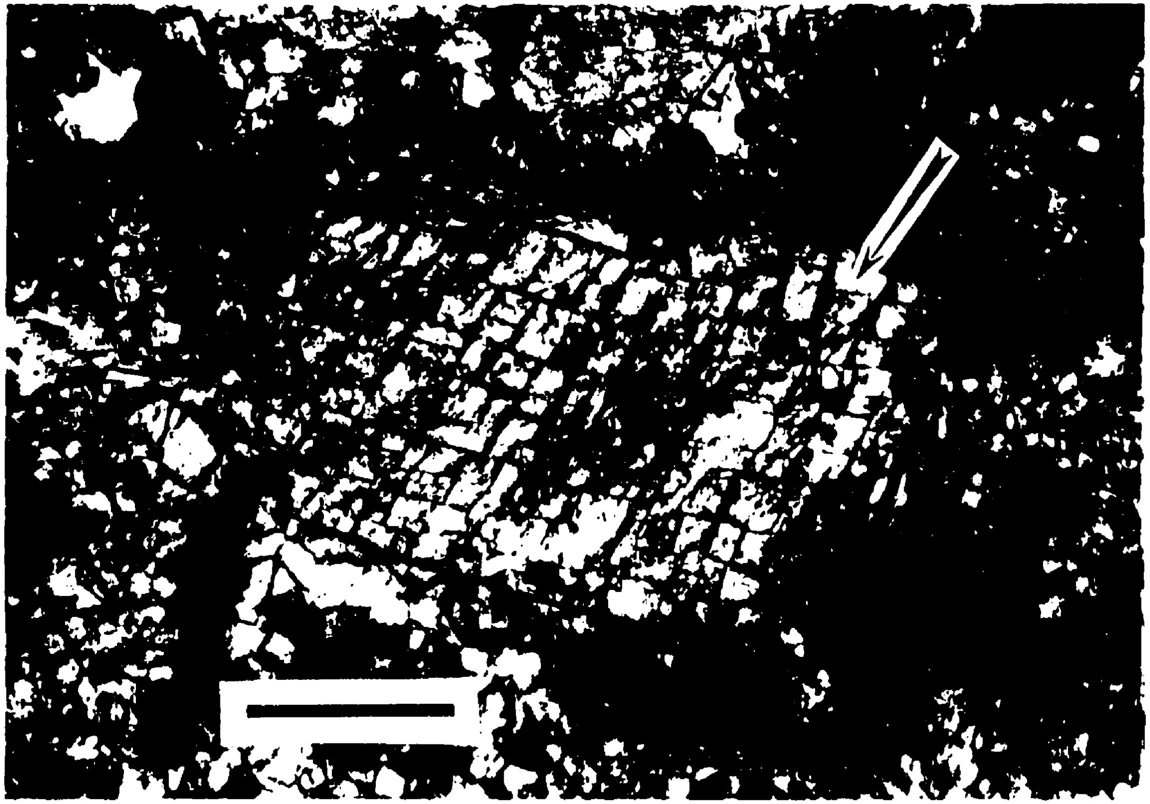


PHOTO 3.5a. Photomicrograph of saddle dolomite (arrow) surrounded by late diagenetic calcite cement (stained red in photomicrograph) in a matrix of mostly Xeno-A dolomite and minor Idio-E dolomite. Photograph from the Ratner Member laminated mudstone lithofacies in the central geographic zone. Plane polarized light. NDGS# 2800, depth – 8314 ft. (Scale bar is 100 μm).

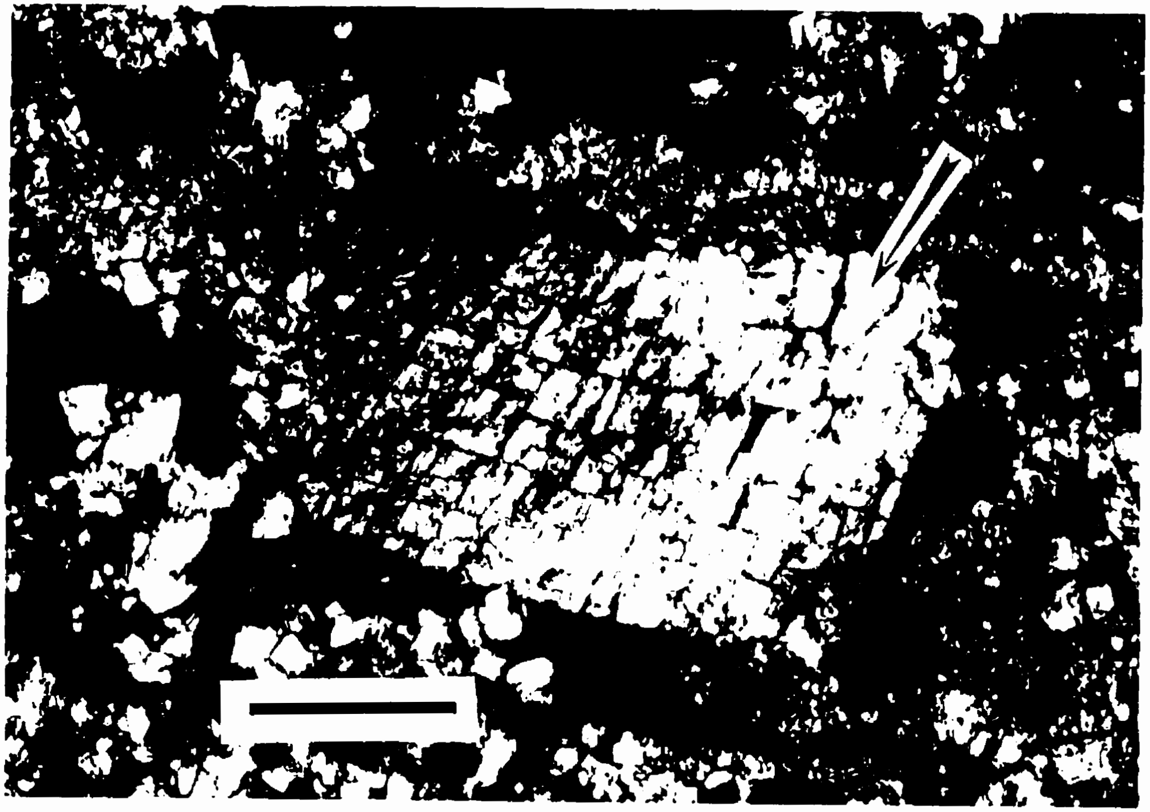


PHOTO 3.5b. Photomicrograph of saddle dolomite (arrow) surrounded by late diagenetic calcite cement (dark zones in photomicrograph) in a matrix of mostly Xeno-A dolomite and minor Idio-E dolomite. Photograph from the Ratner Member laminated mudstone lithofacies in the central geographic zone. Same photomicrograph as PHOTO 3.5a with crossed nicols. NDGS# 2800, depth = 8314 ft. (Scale bar is 100 μm).

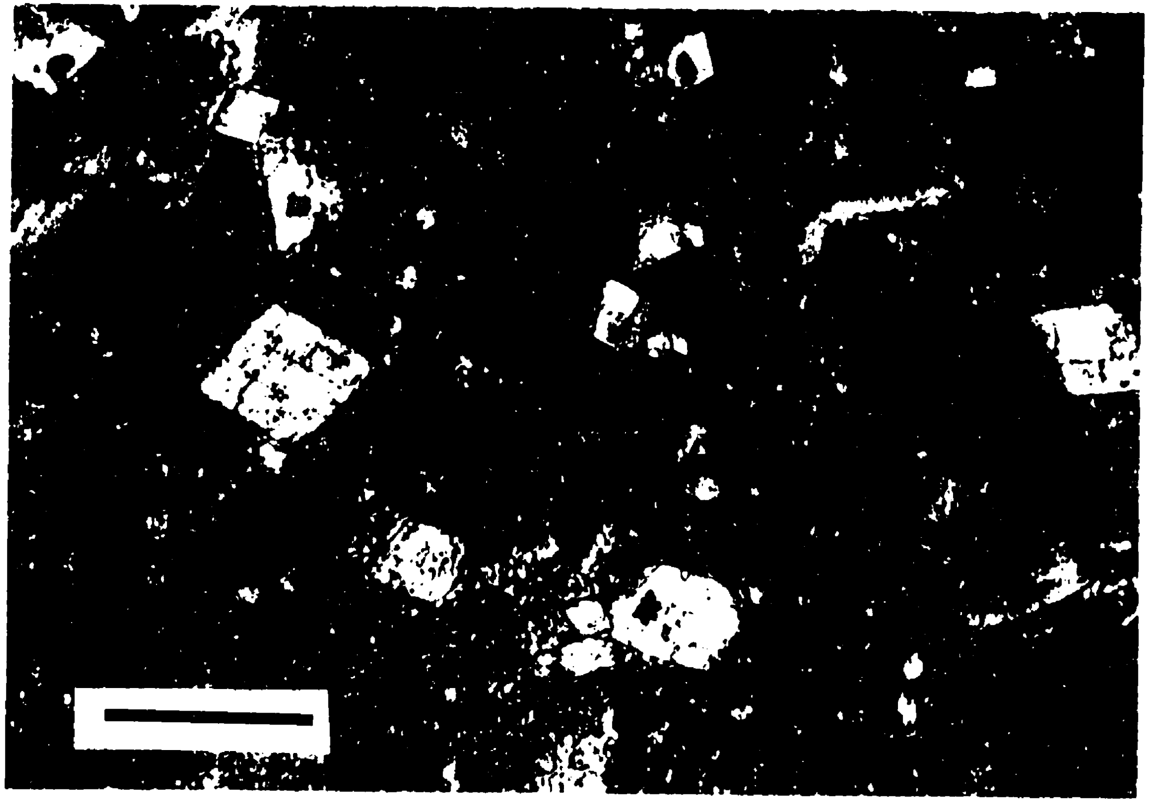


PHOTO 3.6a. Photomicrograph of ISO dolomite in a limestone matrix(stained red in photomicrograph) in the Upper Winnipegosis Member mudstone lithofacies in the southern geographic zone. Plane polarized light.
NDGS# 5257, depth = 11166 ft. (Scale bar is 100 μm).

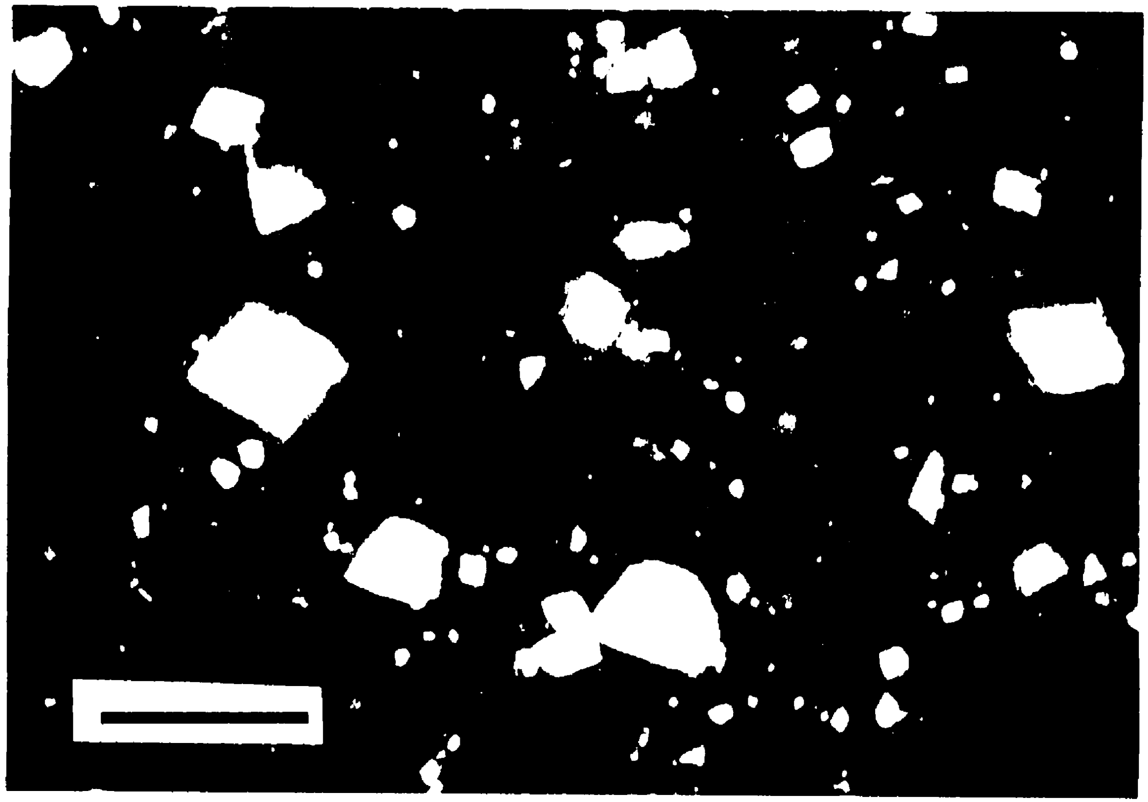


PHOTO 3.6b. Photomicrograph of ISO dolomite under epi-fluorescence in a limestone matrix in the Upper Winnipegosis Member mudstone lithofacies in the southern geographic zone. Colors are actually more orange than appear in the photomicrograph. NDGS# 5257, depth = 11166ft. (Scale bar is 100 μm).

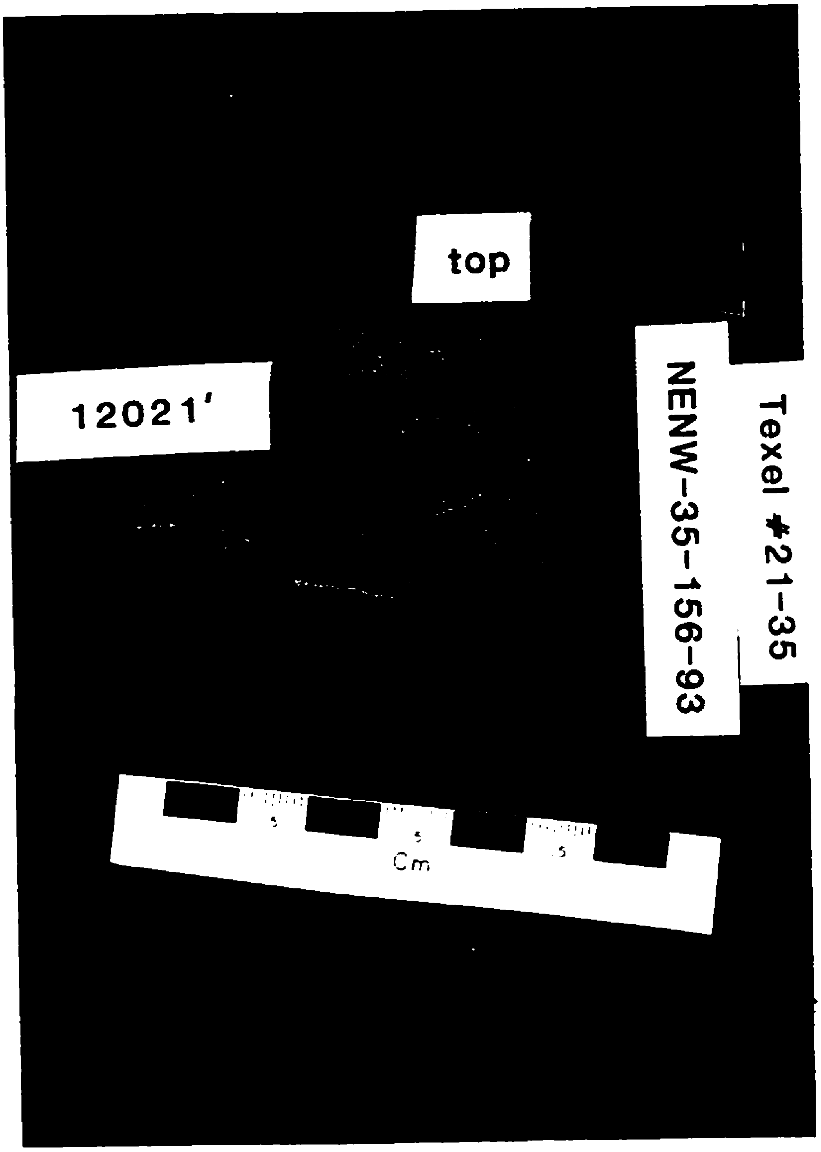


PHOTO 3.7. Core photograph of anhydrite type 2 (nodular anhydrite: upper half of core) and anhydrite type 5 (isolated anhydrite crystals: lower half of core) from the top of the Upper Winnipegosis Member mudstone lithofacies in the western geographic zone. NDGS# 5088, depth = 12021 ft. (Scale is in cm).

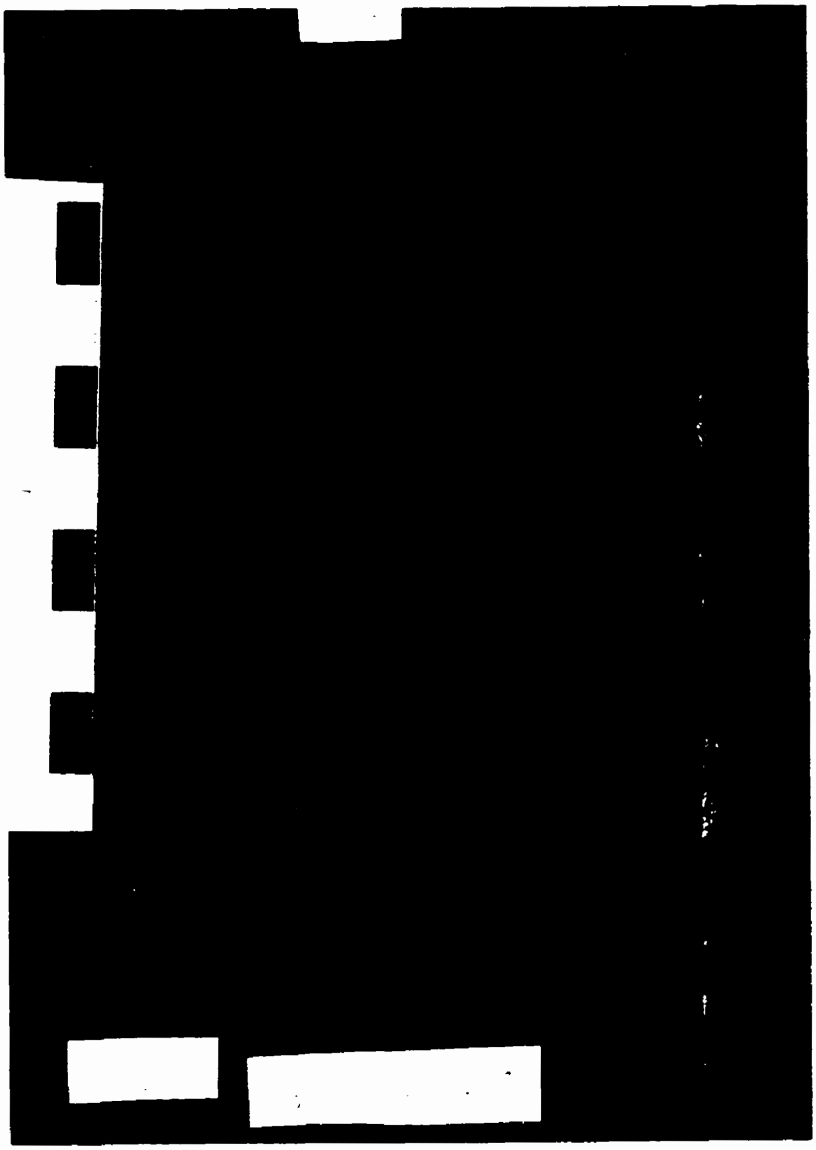


PHOTO 3.8. Core photograph of anhydrite type 3 (laminated anhydrite) at the top of the Ratner Member laminated mudstone lithofacies in the central geographic zone. NDGS# 2800, depth = 8289 ft. (Scale is in cm).

PHOTO 3.9. Photomicrograph of an ISO dolomite crystal partially replaced by dedolomite along cleavage traces and at the crystal edge in the Upper Winnipegosis mudstone lithofacies of the western geographic zone. Plane polarized light. NDGS# 4597, depth = 11920 ft. (Scale bar is 50 μm).

CHAPTER 4: DOLOMITE GEOCHEMISTRY

4.1 INTRODUCTION

Inorganic geochemical techniques can be used to help in the interpretation of the origin of dolomite. The study of carbon and oxygen stable isotopes enables estimates of the temperature of dolomite precipitation (e.g. Amthor et al., 1993); depth (burial) of dolomite formation (e.g.. Allan and Matthews, 1982; Amthor et al., 1993; Saller and Yaremko, 1994); the influence of hypersaline, meteoric or marine waters in the dolomitizing fluids (e.g. Lohmann, 1985; Given and Lohmann, 1985; Gill et al., 1995); and the influence of organic matter (e.g. Hudson, 1977). Trace and minor element analyses can also aid in the determination of the chemistry of the fluids involved in dolomitization (e.g. Popp et al., 1983). The objectives of this chapter are to present the geochemical data available for the Winnipegosis Formation and integrate them with petrographic and core observations to delimit factors involved in dolomitization.

4.2 SUMMARY OF TRACE AND MINOR ELEMENT ANALYSES

A total of 56 samples representative of the six dolomite types, described in Chapter 3, were chosen for trace and minor element analysis using a Cameca electron microprobe (refer to methodology in Chapter 1 and Appendix E). The results of these analyses are shown in Appendix D. Most of the Na, Mn, Zn and Sr values obtained for the dolomite samples are below the detection limits of the Cameca electron microprobe (Na = 0.02 wt %; Mn = 0.03 wt %; Zn = 0.09 wt %; Sr = 0.095 wt %; R. Chapman, pers. comm., 1996). Most of the samples contain Fe (0.03 to 2.88 weight %), but no Fe concentration trends between dolomite types or within any one dolomite type could be identified. In general Fe concentrations seem to be slightly higher in the rims (or near the outside edges) than in the cores of dolomite crystals. This was also observed in thin sections stained with potassium ferricyanide and rarely under cathodoluminescence. Similarly, Mn concentrations above detection limits occur only in the rims of dolomite crystals (0.03 to 0.06 wt %) and are not dolomite-type specific.

4.2.1 Interpretation of Trace and Minor Elements

It is difficult to interpret trace element contents of ancient dolomites quantitatively due to a number of factors, including uncertainty of appropriate distribution coefficients (cf. Land, 1980; Mattes and Mountjoy, 1980; Veizer, 1983; Hardie, 1987), although general statements may be made. The slightly higher Fe concentrations in the rims of dolomite crystals and the occurrence of significant Mn concentrations only in the rims of dolomite crystals suggest that: (1) the chemistry of the dolomitizing fluids evolved such that Fe^{+2} and Mn^{+2} became available or (2) a separate and later dolomitizing fluid, with higher concentrations of Fe and Mn caused the precipitation of dolomite crystals or Fe^{+2} and Mn^{+2}-rich overgrowths on existing dolomite crystals.). A major phase of alteration and stabilization may be indicated by high Fe^{+2} and Mn^{+2} contents in the dolomites (Al-Aasam and Lu, 1996).

4.3 Summary of Stable Isotope Analyses

The results of the $\delta^{18}O$ and $\delta^{13}C$ stable isotope analyses of 30 Winnipegosis dolomite samples are summarized in Table 4.1 and plotted in Figures 4.1 and 4.2 according to dolomite type. All results of isotopic measurements are reported in per mil (‰) PDB values in Appendix D. Refer to the methodology section in Chapter 1 and Appendix E for a summary of the analytical methods. The range of $\delta^{18}O$ values is from -6.80‰ to -2.62‰ and the range of $\delta^{13}C$ values is from +0.77‰ to +2.84‰ for all the dolomite types.

4.3.1 Lower Winnipegosis Member

Three samples from the Lower Winnipegosis Member provided the following results: $\delta^{18}O$ -3.05‰ and $\delta^{13}C$ +2.56‰ for Xeno-S dolomite, $\delta^{18}O$ -2.20‰ and $\delta^{13}C$ +2.35‰ for Idio-E dolomite, and $\delta^{18}O$ -8.22‰ and $\delta^{13}C$ -0.55‰ for saddle dolomite. The mean values of $\delta^{18}O$ and $\delta^{13}C$, excluding saddle dolomite, are -2.26‰ and +2.46‰ respectively. The Lower Winnipegosis Member samples have the most positive $\delta^{18}O$ values of all Winnipegosis Formation dolomite samples analysed.

4.3.2 UPPER WINNIPEGOSIS AND RATNER MEMBERS

Twenty four stable isotope samples of the Upper Winnipegosis Member have $\delta^{18}O$ and $\delta^{13}C$ values that range from -8.37‰ to -4.80‰ (mean -5.9‰) and -0.02‰ to +3.38‰ (mean -1.7‰) respectively. The mean $\delta^{18}O$ and $\delta^{13}C$ values of the various dolomite types within the Upper Winnipegosis Member are: Idio-E, $\delta^{18}O$ -5.26‰ and $\delta^{13}C$ +1.93‰; Idio-S, $\delta^{18}O$ -6.80‰ and $\delta^{13}C$ +1.68‰; Xeno-S, $\delta^{18}O$ -5.75‰ and $\delta^{13}C$ +2.54‰; Xeno-A, $\delta^{18}O$ -6.83‰ and $\delta^{13}C$ +0.77‰; saddle, $\delta^{18}O$ -7.25‰ and $\delta^{13}C$ +0.67‰; allochems = $\delta^{18}O$ -5.99‰ and $\delta^{13}C$ +2.07‰. In the Ratner Member, only the Idio-E dolomite type was analyzed for $\delta^{18}O$ and $\delta^{13}C$ and the mean values were -6.68‰ and +2.84‰ respectively.

4.4 INTERPRETATION OF STABLE ISOTOPES

4.4.1 $\delta^{13}C$

The range of $\delta^{13}C_{dol}$ values of -0.10 to +3.38‰ (excluding saddle dolomite) for the Winnipegosis Formation is relatively narrow. This range is similar to that of the shallow burial dolomites of the Elm Point Formation in Manitoba (-0.2 to +1.8‰; Chow and Longstaffe, 1995) and that of all the dolomites of the Rainbow buildups of the Keg River Formation in northwestern Alberta (+1.5 to +2.8‰; Qing and Mountjoy, 1989).

The narrow range of $\delta^{13}C_{dol}$ of the Winnipegosis Formation suggests that: 1) organic carbon was not involved in dolomitization, 2) the influence of meteoric waters on dolomitization was minimal and 3) a major phase of alteration and stabilization of these dolomites may have occurred. Organic carbon is, in general, greatly depleted in ^{13}C and any dolomites precipitated in pore-fluid environments in which the supply of organic carbon is high will have light $\delta^{13}C$ values (c.f. Hudson, 1977; Veizer, 1983; Allan and Wiggins, 1993). Carbonates influenced by meteoric diagenesis show a wide variability in $\delta^{13}C$ values due to a wide spectrum of ^{13}C sources (cf. Allan and Matthews, 1982; Veizer, 1983; Given and Lohmann, 1985; Qing and Mountjoy, 1989

4.4.2 $\delta^{18}O$

MIDDLE DEVONIAN MARINE CARBONATE SIGNATURE

Biogenic calcite in the Winnipegosis Formation in the study area was not analysed for carbon and oxygen stable isotopes. However, Teare (1990) examined well-preserved brachiopods of the Winnipegosis Formation in the Dawson Bay area of Lake Winnipegosis in Manitoba. He interpreted their mean $\delta^{18}O$ value (-4.3‰) to be an estimate of the typical marine $\delta^{18}O$ signature for primary biogenic calcite precipitated in equilibrium with Middle Devonian marine waters. Chow and Longstaffe (1995) obtained $\delta^{18}O$ values of -4.2 to -3.7‰ for non-luminescent brachiopods from the Elm Point Formation in central Manitoba. These values are compatible with $\delta^{18}O$ values obtained for other Middle and Upper Devonian marine carbonates: -3.7‰ for unaltered brachiopods from several Devonian carbonates throughout North America (Popp et al., 1986); and -5.1‰ for submarine cements of the Keg River Formation in central Alberta (Qing and Mountjoy ,1989).

Popp et al. (1986) suggested that Middle Devonian sea water was either warmer by approximately 10°C or depleted in ^{18}O by approximately 2 to 3‰ SMOW relative to modern sea water. The mean $\delta^{18}O$ value of -2.5‰ SMOW for Middle Devonian sea water is used in this study.

LOWER WINNIPEGOSIS MEMBER

The $\delta^{18}O_{dol}$ values from the Lower Winnipegosis Member (Xeno-S -3.05‰ and Idio-E -2.92‰) are in agreement with the shallow burial dolomites of the wackestone-packstone lithofacies in the Elm Point Formation of Manitoba ($\delta^{18}O$ = -2.1 to +0.5‰; Chow and Longstaffe, 1995) and the fine crystalline dolomite in the back-barrier facies (Muskeg Formation) of the Presqu'ile barrier ($\delta^{18}O$ = -3.8 to -1.5‰; Qing and Mountjoy, 1990). The $\delta^{18}O_{dol}$ values of this study are similar to the range expected for dolomite precipitation from Middle Devonian seawater. Therefore, the dolomite of the Lower Winnipegosis Member is interpreted to have formed from Middle Devonian marine waters.

A mean Middle Devonian marine $\delta^{18}O$ water value of -2.5‰ SMOW is used here as an estimate to model the temperature of dolomitization using equation (1) from

Friedman and O'Neil (1977). The Lower Winnipegosis Member $\delta^{18}O_{dol}$ values (-3.05 and -2.92‰) were converted to ‰ SMOW by using equation (2) from Friedman and O'Neil (1977).

$$\underset{\text{(Calculated)}}{[3.2 \times 10^{6}\, T(K)^{-2}]} - 1.5 = \underset{\text{(measured)}}{\delta^{18}O_{dol}\ \text{SMOW}} - \underset{\text{(estimated)}}{\delta^{18}O_{water}\ \text{SMOW}} \qquad (1)$$

$$\delta^{18}O\ \text{SMOW} = 1.03086 \times \delta^{18}O\ \text{PDB} + 30.86 \qquad (2)$$

The temperature for Idio-S and Idio-E dolomite precipitation in the Lower Winnipegosis Member is estimated to be between 40 and 45°C. Using an estimate for a mean surface temperature of 30°C and a geothermal gradient of 33°C/km, the mean estimated temperatures correspond to burial depths of about >300 m. If mean surface temperatures approached the higher value of 40°C, as implied by Popp et al. (1986) and recorded for modern day Persian Gulf waters, the calculated temperatures indicate that dolomitization may have started as shallow as 70 m.

Upper Winnipegosis and Ratner Members

All $\delta^{18}O$ values for dolomites of the Upper Winnipegosis and Ratner members plot in a cluster between -8.37‰ and -4.80‰. These values are lower than those estimated for Middle Devonian marine dolomites and are more typical of dolomites formed in a burial environment (cf. Mattes and Mountjoy, 1980). The $\delta^{18}O$ values may be explained by the following scenarios: (1) originally a single stage of dolomite formation during burial diagenesis with either (a) preservation of the primary geochemical signature, or (b) later re-equilibration of the dolomite at higher temperatures and/or with lighter $\delta^{18}O$ pore fluids at deeper burial depths (c.f. Land, 1980, 1985; Mazullo, 1992); and (2) several stages of dolomitization followed by later dolomite alteration and stabilization (recrystallization) resulting in the re-setting of $\delta^{18}O$ of the different dolomite types (e.g. Zenger and Dunham, 1988). Petrographic and stratigraphic evidence suggest that there was more than one original dolomite type. For example, the patterned dolostone (Idio-Ep dolomite) is interpreted to have formed syndepositionally in a sabkha setting, and saddle dolomite is interpreted to have originated during burial. This evidence precludes the first scenario. The second scenario, involving dolomite recrystallization, is considered to be most likely. Dolomite recrystallization will be discussed in Chapter 5.

4.5 Geochemistry Summary

1. The $\delta^{13}C_{dol}$ values for the Lower Winnipegosis (+2.35 to +2.56‰), the Upper Winnipegosis (-0.02 to +3.38‰) and Ratner (+2.56 to +3.13‰) members suggest that organic carbon was not involved in dolomitization of the Winnipegosis Formation.

The narrow range of enriched $^{13}C_{dol}$ in the Upper Winnipegosis (-0.02 to +3.38‰) and Ratner (+2.56 to +3.13‰) members suggests that meteoric water probably did not greatly influence the isotopic compositions of the dolomitizing fluids.

2. Primary biogenic calcite precipitated in equilibrium with Middle Devonian marine waters is estimated to have a $\delta^{18}O$ value of -4.3‰ PDB (Teare, 1990). Popp et al. (1986) suggested that Middle Devonian sea water was either warmer by approximately 10°C or depleted in ^{18}O by approximately 2 to 3‰ SMOW relative to modern sea water. The mean $\delta^{18}O$ value of -2.5‰ SMOW for Middle Devonian sea water is used in this study.

3. $\delta^{18}O_{dol}$ values for the Lower Winnipegosis Member (-3.05 to -2.92‰) suggest that Middle Devonian seawater was an important component of the dolomitizing fluids. The estimated isotopic temperature of dolomite formation (40 to 45°C) supports a shallow burial (approximately 70 m) origin for the dolomites of the Lower Winnipegosis member.

4. The relatively depleted $^{18}O_{dol}$ of the Upper Winnipegosis (-8.37 to -4.80‰) and Ratner (-7.03 to -6.34‰) members suggest that any influence from Middle Devonian seawater in the dolomitization of the Upper Winnipegosis and Ratner members have been overprinted and are now obscure. Geochemical and petrographic evidence suggests that recrystallization of dolomites may have occurred in some portions of the Upper Winnipegosis Member in the study area

5. The slightly higher Fe concentrations in the rims of dolomite crystals along with an indication of Mn only in the rims of dolomite crystals suggests a separate dolomitizing event that precipitated ferroan dolomite in the form of overgrowths on existing dolomite crystals.

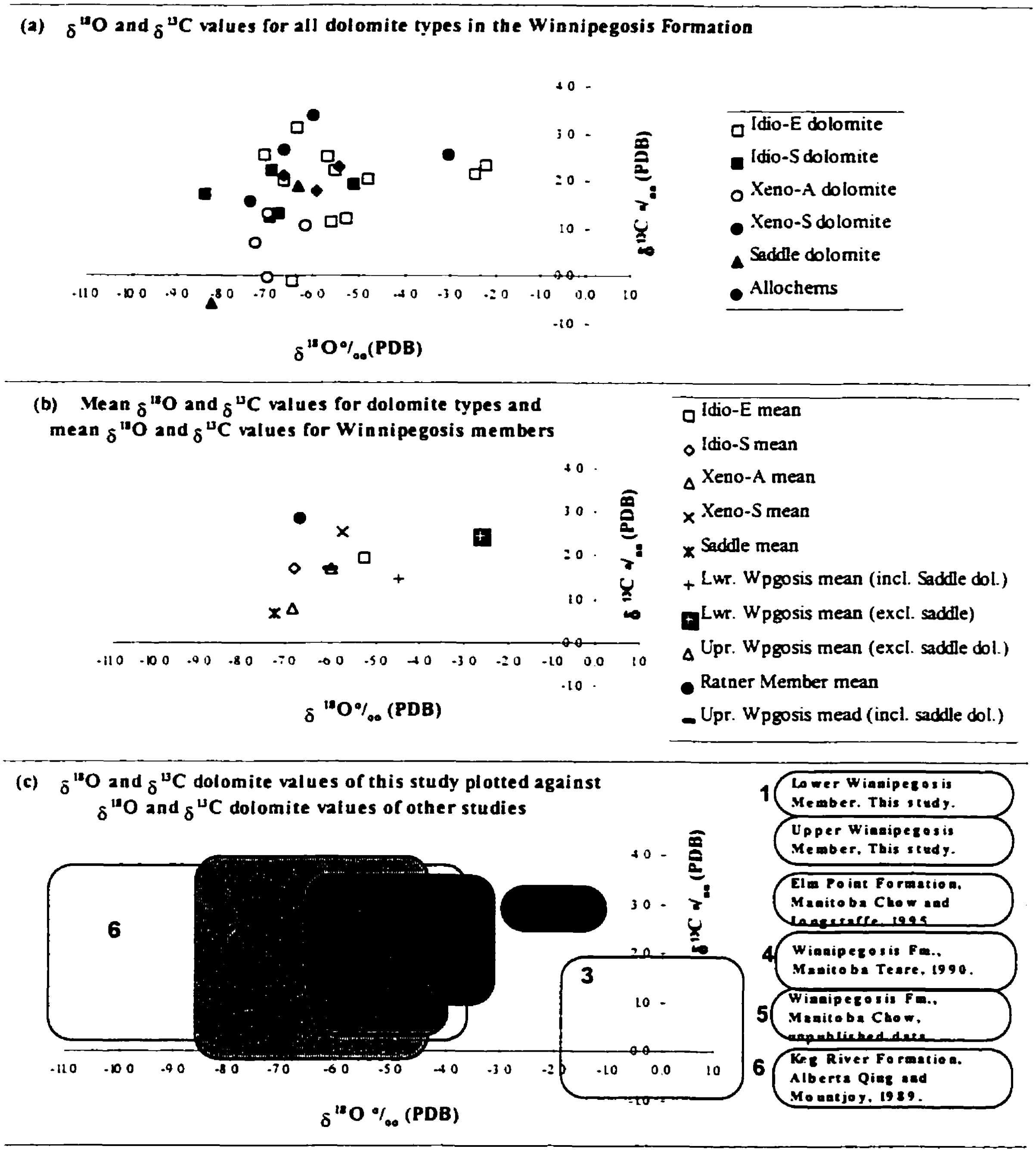


Fig. 4.1. Carbon and oxygen stable isotope plots for dolomite in the Winnipegosis Formation. (a) $\delta^{18}O_{dol}$ and $\delta^{13}C_{dol}$ values for all samples analysed, (b) Mean $\delta^{18}O_{dol}$ and $\delta^{13}C_{dol}$ for each dolomite type, (c) data from other Middle and Upper Devonian studies (see text for explanation).

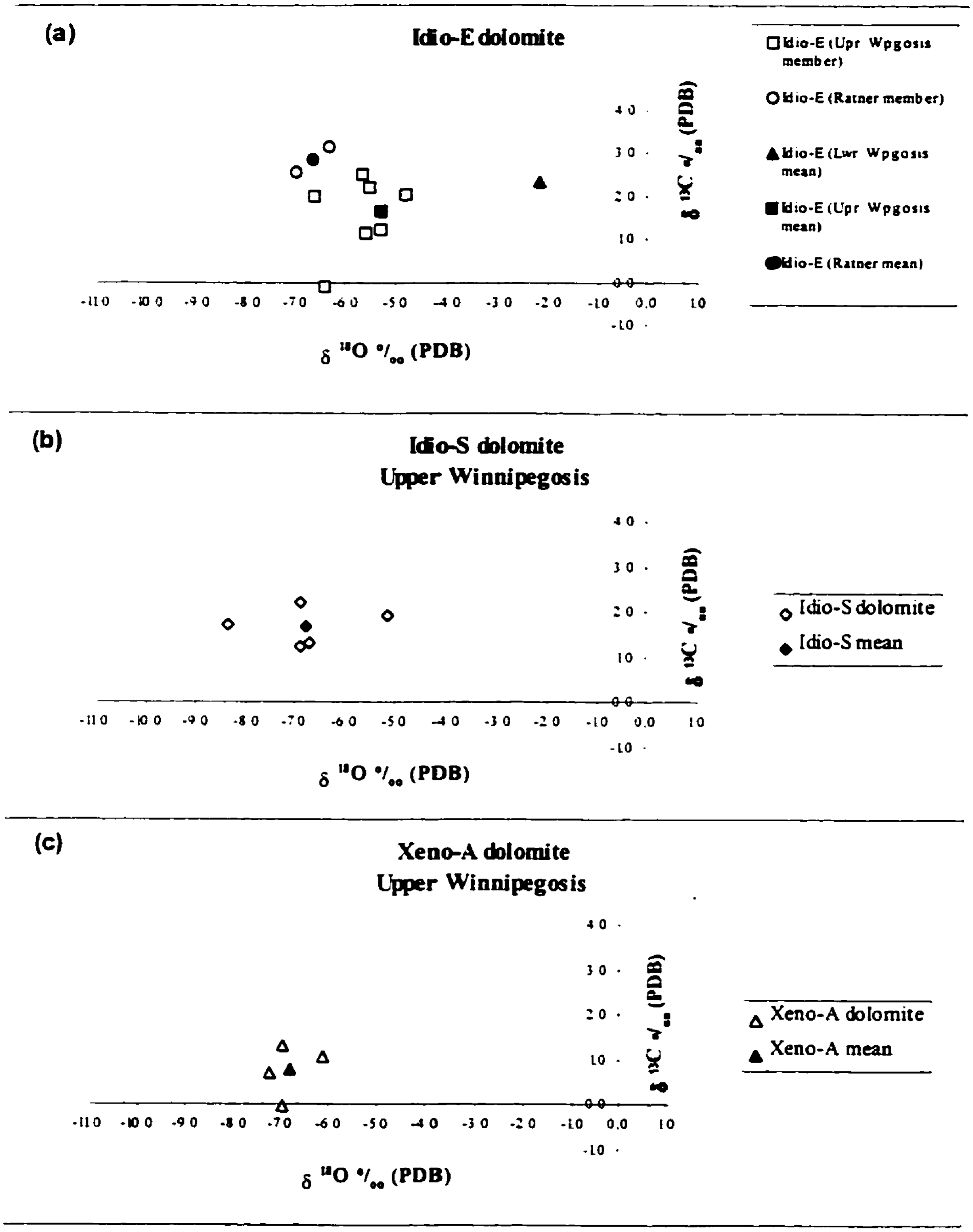
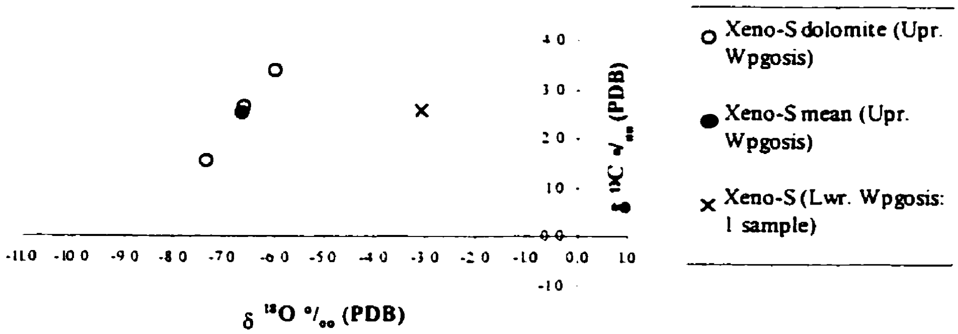


Fig. 4.2. $\delta^{18}O_{dol}$ and $\delta^{13}C_{dol}$ plots for each of the dolomite types in the Winnipegosis Formation. (a) Idio-E in the Upper Winnipegosis and Ratner members, (b) Idio-S, (c) Xeno-A, (d) Xeno-S, (e) saddle dolomite, (f) dolomitized allochems (crinoids and brachiopods) in the Upper Winnipegosis Member.

Fig. 4.2 (Cont.).

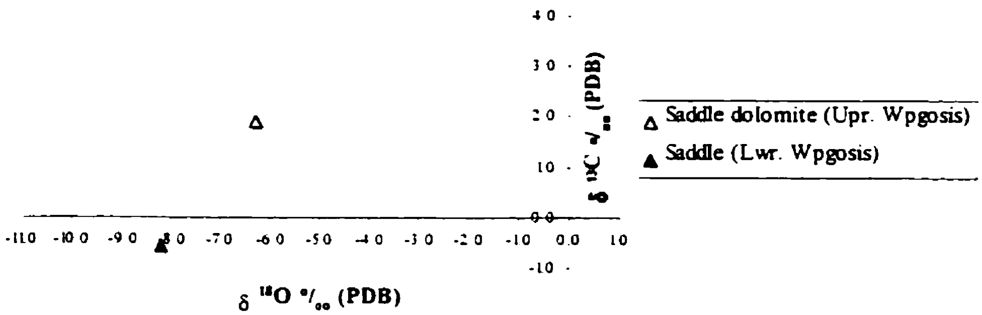
(d)

Xeno-S dolomite



(e)

Saddle dolomite



(f)

Dolomitized Allochems
Upper Winnipegosis

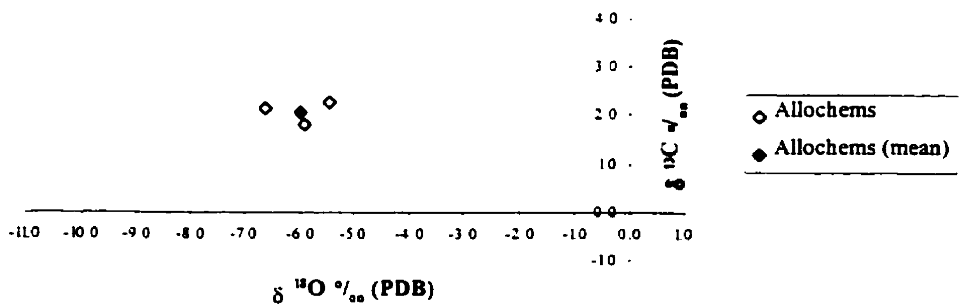


Table 4.1. Summary of stable isotope data (σ = standard deviation).

dolomite type	Overall Winnipegosis Fm.				Lower Wpgosis Member				Upper. Wpgosis Member				Ratner Member			
	$\delta^{18}O$ (PDB)	σ $\delta^{18}O$	$\delta^{13}C$ (PDB)	σ $\delta^{13}C$	$\delta^{18}O$ (PDB)	σ $\delta^{18}O$	$\delta^{13}C$ (PDB)	σ $\delta^{13}C$	$\delta^{18}O$ (PDB)	σ $\delta^{18}O$	$\delta^{13}C$ (PDB)	σ $\delta^{13}C$	$\delta^{18}O$ (PDB)	σ $\delta^{18}O$	$\delta^{13}C$ (PDB)	σ $\delta^{13}C$
Idio-E	-5.26	1.52	1.93	0.84	-2.20	0.00	2.35	0.00	-5.28	1.20	1.65	0.80	-6.68	0.34	2.84	0.29
Idio-S	-6.80	1.03	1.68	0.36	-	-	-	-	-6.80	1.03	1.68	0.36	-	-	-	-
Xeno-A	-6.82	0.42	0.77	0.51	-	-	-	-	-6.82	0.42	0.77	0.51	-	-	-	-
Xeno-S	-5.75	1.63	2.54	0.65	-3.05	0.00	2.56	0.00	-6.65	0.55	2.53	0.75	-	-	-	-
Saddle	-7.25	0.97	0.67	1.22	-8.22	0.00	-0.55	0.00	-6.28	0.00	1.88	0.00	-	-	-	-
Allochem	-5.99	0.48	2.07	0.20	-	-	-	-	-5.99	0.48	2.07	0.20	-	-	-	-
Average (including saddle dolomite)	-5.91	1.53	1.76	0.89	-4.49	2.66	1.45	1.42	-6.02	1.28	1.71	0.78	-6.68	0.34	2.84	0.29
Average (excluding saddle dolomite)	-5.82	1.52	1.48	0.73	-2.62	0.42	2.46	0.11	-6.01	1.31	1.70	0.79	-6.68	0.34	2.84	0.29

CHAPTER 5: DOLOMITIZATION MODELS AND DOLOMITE RECRYSTALLIZATION

5.1 Introduction

In this chapter stratigraphy, petrography, and facies analysis are combined to aid in the interpretation of dolomitization mechanisms in the Winnipegosis Formation of North Dakota. The isotopic geochemistry in this study is of little use because of dolomite recrystallization in the Upper Winnipegosis and Ratner Members in the study area.

5.2 Dolomitization Models

5.2.1 Supratidal Dolomitization

As previously discussed, the patterned dolostone in the Upper Winnipegosis Member is interpreted to have been deposited in the supratidal setting and the Idio-Ep dolomite comprising this lithofacies is interpreted to be synsedimentary. The patterned dolostones in this study are similar to the patterned carbonates of Dixon (1976). All of Dixon's (1976) examples of 'patterned carbonates' are restricted to fine-grained carbonate rocks having mostly a supratidal origin. The patterned dolostones of this study are also similar to sabkha sediments found in arid tidal flats of the Holocene of the Persian Gulf (Wells, 1962; Curtis et al., 1963). Hardie (1987) summarized the sabkha model of dolomitization based on these arid tidal flats where seawater below the sabkha surface is progressively concentrated through evaporation. Continued evaporation causes the seawater below the surface of the sabkha to rise up through the capillary zone. The precipitation of aragonite and gypsum results in a Mg-rich hypersaline brine which is interpreted to be the dolomitizing fluid. This process is called evaporative pumping (cf. Hsü and Siegenthaler, 1969; Hsü and Schneider, 1973). Idio-Ep dolomite and anhydrite type 1 in the Upper Winnipegosis Member are interpreted to be products of evaporative pumping.

5.2.2 Reflux dolomitization

Near the end of Winnipegosis time a relative sea level drop exposed the Presqu'ile barrier complex and restricted the inflow of normal marine waters into the Elk Point Basin. Concentration of marine waters through evaporation resulted in evaporative drawdown of at least 30 m (Maiklem, 1971) which caused the buildups in the basin to become islands and also caused the precipitation of evaporite deposits.

In a restricted evaporite basin salinities in the upper waters could have increased to the point of gypsum/anhydrite precipitation (Friedman, 1972). As the gypsum/anhydrite sank to lower levels in the water column the Mg/Ca ratio would have increased the level of dolomite saturation (Friedman, 1980; Land, 1982; Logan, 1987). The dolomitization reaction occurred after much gypsum (anhydrite) had precipitated, sulphate had been removed and the Mg/Ca ratio approached 9.0 (Morrow, 1978) or higher. The accumulation of any thick evaporite deposit would have required the formation of a bottom seal which restricted the downward outflow of basin waters (Sonnenfeld, 1984). For example, Logan (1987) postulated that significant thickness of evaporites did not begin to accumulate in the Quaternary MacLeod Basin, Australia until after the formation of a basin-lining anhydrite aquiclude.

For the Winnipegosis Formation, it is suggested here that anhydrite type 2 (nodular anhydrite) near the top of the Upper Winnipegosis Member and anhydrite type 3 (laminated anhydrite) near the top of the Ratner Member formed at least a partial barrier (bottom seal) to the downward flow of hypersaline brines. This bottom seal probably did not form throughout the study area at the same time. Anhydrite would have first accumulated in the deep basinal inter-reef areas above the Ratner Member. The dense dolomitizing brines may not have effectively flowed through the anhydrite seal but rather could have pooled above the anhydrite seal until the seal could be breached either by simply spilling over the lateral edge of the basin seal or through fractures or some other physical conduit. Evidence of this pooling of dolomitizing fluids may be the thin dolomudstone layers/lenses associated with the anhydrite at or near the top of the Ratner Member and below the first thick accumulation of halite in the Prairie Formation (e.g. NDGS# 4340, 5333). The most likely spill points would have been in shallow water depths above the zone of anhydrite accumulation in areas that were bathymetrically high such as pinnacle reefs or shelf margins. Once the dolomitizing brines breached the anhydrite (spill points) it seeped downward and dolomitized the carbonates of the

Winnipegosis Formation . This process of dolomitization was originally called seepage refluxion (Adam and Rhodes, 1960).

Since diagenetic reactions require movement of fluids to transport reactants and products involved in the diagenetic reactions, rocks with low permeability are less susceptible to diagenesis (Sperber et al., 1984). The Lower Winnipegosis Member generally has low porosity and low permeability and would, therefore, be less susceptible to diagenesis by regionally developed fluid flow patterns. The general distribution of dolomite in the Winnipegosis Formation in this study (Fig. 3.1) indicates that the most likely pathway of the dolomitizing brines would be: (1) down through the porous pinnacle reef lithofacies of the Upper Winnipegosis Member until the Lower Winnipegosis Member was encountered, then laterally through the Ratner Member and (2) down through the shelf lithofacies of the Upper Winnipegosis Member, above the zone of anhydrite accumulation (the bottom seal), then into the top of Lower Winnipegosis Member downward toward the basin and possibly into the Ratner Member.

Idio-E dolomite is the most abundant dolomite type in pervasively dolomitized lithofacies and is most likely to have formed at low dolomite supersaturation states and/or below the critical roughening temperature (CRT of <50 to $100^{\circ}C$; Sibley and Gregg, 1987). The crystal growth theory of Jackson (1958a, 1958b) predicts that at low temperature and/or low supersaturation atoms are added to crystal faces layer by layer with dislocations or surface kinks acting as nucleation sites. The result is smooth faceted crystal surface and euhedral crystal mosaics. Above the critical saturation and/or critical roughening temperature (Gregg and Sibley, 1984), atoms are randomly added to the crystal surface resulting in a rough crystal surface with non-faceted crystal growth and anhedral crystal mosaics. The first fluids passing over the spill points and into the Winnipegosis Formation were most likely the upper, less dense, less supersaturated (with respect to dolomite) fluids in the restricted basin which resulted in the formation of Idio-E dolomite. With continued evaporation and anhydrite deposition the more dense, more dolomite supersaturated brine would accumulate at the base of the water column. Once this brine breached the spill points and seeped into the Winnipegosis Formation Idio-S, Xeno-S and Xeno-A dolomite may have formed. Growth space restrictions, kinetic controls and anhydrite as a dolomite inhibitor may also be factors in the formation of Xeno-S and Idio-S dolomite over Idio-E dolomite (Greg and Sibley, 1984, 1986; Sibley and Gregg, 1987; Hardie, 1987).

The $\delta^{18}O$ values obtained for the Winnipegosis Formation dolomites do not agree with a reflux origin for dolomite. Typically, dolomites formed from hypersaline waters are enriched in ^{18}O (e.g. McKenzie, 1981; Botz and van der Borch, 1984; Allen and Wiggins, 1993). Anderson and Arthur (1983) suggested that when salt concentrations become high through evaporation, $\delta^{18}O$ values of the residual brine initially increase then decrease. Sofer and Gat (1972, 1975) modelled the evaporation of brines and showed that this unusual isotopic behaviour is due to the effect of dissolved salts on the thermodynamic activities of the isotopic water species. However, in this study the clustered light oxygen isotope values are interpreted to be mainly the result of dolomite recrystallization.

5.2.3 Mixed water dolomitization

Near the end of Winnipegosis time a relative sea level drop would have subaerially exposed the shelf margins and pinnacle reefs in the Elk Point Basin and a laterally limited meteoric-phreatic zone would have formed (Perrin, 1992). The transition between the meteoric-phreatic zone and the marine-phreatic zone would have been a zone of mixed water. The "Dorag" or mixed water model of dolomitization (Badiozamani, 1973) has been postulated for dolomitization in recent sediments (e.g. Gill et al., 1995), Holocene and Pleistocene sediments (e.g. Allan and Matthews, 1982) as well as more ancient rocks (e.g. Randazzo et al., 1983). Mixed water dolomitization does not occur syndepositionally, but rather early in the burial history after some compaction but while porosity remains high (Choquette and Steinen, 1980).

The meteoric-phreatic and the marine-phreatic zones typically have different chemical properties. The meteoric-phreatic zone has low salinity and a low Mg content, the marine-phreatic zone typically has high salinity and a high Mg content and the mixed-zone has lowered salinity (relative to seawater) and increased Mg content (relative to meteoric water) which promotes dolomitization (cf. Land, 1973; Morrow, 1982a, 1982b; Perrin 1987). The lowering of salinity in this mixed-zone causes slow precipitation, a lowering of the sulphate concentration (Folk and Land, 1975; Kastner, 1984) and a high carbonate ion concentration (Lippman, 1973; Morrow, 1982) which promote precipitation of dolomite. Badiozamani (1973) showed that dolomitization could occur in a mixed-water zone having a compositional range of between 5 and 30% seawater. Dolomite saturation levels of the mixed-water are presumed to be low and the temperature of the dolomitization process is assumed to be similar to surface temperatures because meteoric waters are involved. However, there is some controversy over the validity of the mixed water model for dolomitization. Some concerns include the validity of the geochemical foundations of the model (e.g. Carpenter, 1976; Machel and Mountjoy, 1986; Hardie, 1987) and only a few Holocene examples of mixed water dolomites that have been confirmed (e.g. Land, 1973; Humphry, 1988).

Some Idio-E dolomite mosaics may have formed in mixed waters (see discussion of crystal growth theory in section 5.2.2). The hypersaline brines in the lower part of the water column of the deeper basin (discussed in section 5.2.2) may not have formed early enough to interfere with the mixed-water dolomitization of subaerially exposed outer margins of the shelf and basinal buildups. Alternatively, reflux dolomitization may have occurred in the lower part of the water column concurrently with, and unaffected by, the mixed water dolomitization. As the various evaporite cycles filled the basin (Oglesby, 1987) their associated hypersaline brines may have contributed to further dolomitization of topographically higher (subaerially exposed) portions of the Winnipegosis Formation in the Elk Point Basin.

Carbonate sediments that are dolomitized in mixed solutions of meteoric water and normal sea water are characterised by depleted ^{18}O and relatively light and often variable $\delta^{13}C$ values (cf. Land, 1973; Given and Lohmann, 1986). Although the $\delta^{18}O$ values for the dolomites of the Upper Winnipegosis Member and the Ratner Member are depleted by 2 to 2.4‰ compared to the $\delta^{18}O$ for Middle Devonian marine biogenic calcite (-4.3‰) the $\delta^{18}O$ values in this study are interpreted to be mainly the result of dolomite recrystallization.

5.2.4 Burial Dolomitization

Burial dolomitization seems to have played only a small role in the dolomitization of the Winnipegosis Formation. Most of the dolomite in this study has been related to supratidal, reflux and mixed-water dolomitization. However, there are some dolomite occurrences that are interpreted to have formed from hydrothermal fluids (saddle dolomite) and along pressure dissolution seams (some ISO dolomite).

Saddle dolomite is found in all geographic zones of the study area and in all members of the Winnipegosis Formation, occurring mainly as isolated crystals, and as cement lining small fractures and intercrystalline and moldic porosity. The formation of this dolomite requires slow crystallization (Folk and Land, 1975) at temperatures of 60 - 150°C with depths of burial from 1500-4500 m (Radke and Mathis, 1980). Harris et al. (1981) mapped heat gradients in North Dakota and did not find abnormally high heat flows. Gerhard et al. (1982) suggested that from a basin analysis point of view a source of heat may be the Yellowstone area and that major faults may have acted (are acting?) as conduits for heat flow into the Williston Basin. Majorowicz et al. (1988) also pointed out the occurrence of north-south, trending anomalous basement structural features coincident with the North American Central Plains electrical conductivity anomaly, a magnetotelluric electrical anomaly, a heat flow anomaly and a zone of enhanced maturation of organic matter.

In the Lower and Upper Winnipegosis members ISO dolomite is found in close association with pressure dissolution seams. ISO dolomite is also found dispersed throughout the various lithofacies. Some ISO crystals are truncated by pressure dissolution seams and others overgrow pressure dissolution seams, indicating that these crystals formed approximately coevally with pressure dissolution. Pressure dissolution seams may form at burial depths as shallow as 3 m (Wanless, 1979), but they are generally a deep-burial phenomena (Choquette and James, 1986). Some ISO dolomite crystals appear to have formed in the synsedimentary and early diagenetic stages but there is a lack of sufficient evidence to interpret the dolomitization mechanism

5.3 Dolomite Recrystallization

Stratigraphy, facies analysis and petrographic evidence suggest that more than one dolomitization mechanism has occurred in the Upper Winnipegosis Member. However, geochemical data do not support these interpretations.

The relatively narrow range of $\delta^{18}O_{dol}$ values for the variety of dolomite types in the Upper Winnipegosis and Ratner Members suggests that these dolomites were subjected to an event (or events) that erased their primary $\delta^{18}O_{dol}$ values. If increasing temperature in the burial environment was the major influence on $\delta^{18}O$ values, then dolomites in the Upper Winnipegosis, Ratner and Lower Winnipegosis members should have been affected similarly (cf. Qing and Mountjoy, 1992; Amthor et al., 1993; Mountjoy and Amthor, 1994). The mean $\delta^{18}O_{dol}$ for the Upper Winnipegosis and Ratner Members is approximately 4‰ lighter than the mean $\delta^{18}O_{dol}$ for the Lower Winnipegosis Member that is interpreted to reflect an origin from Middle Devonian seawater. On the other hand, saddle dolomite, being indicative of elevated temperatures (Radke and Mathis, 1980), is found in all geographic zones and within all 3 members suggesting that similar temperatures affected each of the members of the Winnipegosis Formation in the study area. This 4‰ difference in $\delta^{18}O_{dol}$ values between the Upper Winnipegosis and Ratner members and the Lower Winnipegosis Member suggests that the dolomites of the Upper Winnipegosis and Ratner Members have been recrystallized. The Lower Winnipegosis Member may have not been affected by dolomite recrystallization because: (1) there was originally not an abundance of dolomite in the Lower Winnpegosis Member, and/or (2) the Lower Winnipegosis Member has very poor porosity and permeability and the fluids involved in recrystallization tended to affect only the more porous and permeable Upper Winnipegosis and Ratner members. Other studies have also demonstrated that dolomite recrystallization may not occur at a formation-wide scale (e.g. Zenger and Dunham, 1988; Gao and Land, 1991; Gregg and Shelton, 1990; Amthor and Friedman, 1992; Malone et al., 1994).

The uniform red cathodoluminescence of the various types of dolomite supports the occurrence of a recrystallization event. The uniform red cathodoluminescence of the dolomite indicates no significant variations in the relative concentrations of activators (mainly Mn^{+2}) and quenchers (mainly Fe^{+2}; Machel et al., 1991). In this study, Fe and Mn content is generally greater in rims of crystals than in cores. Enrichment of Fe^{+2} and Mn^{+2} in dolomite has been attributed to recrystalization (cf. Banner et al., 1988; Gao, 1990; Montenez and read, 1992). Fe^{+2} and Mn^{+2} tend to be enriched in later diagenetic dolomites compared to its earlier dolomites (Land, 1980; Mattes and Mountjoy, 1980; Veizer, 1983). However, if the pore fluids involved in recrystallization are depleted in Fe^{+2} and Mn^{+2} the recrystallized dolomite would not be enriched in these cations (Malone et al., 1994).

Since all the dolomite types in this study have a relatively narrow $\delta^{18}O$ range in value, and uniform luminescence, and generally higher Fe^{+2} and Mn^{+2} in rims of crystals than in cores it is interpreted that the recrystallization of dolomite occurred after, or at the same time as, the ferroan dolomite.

5.4 Recommendations for future work

Geochemical data obtained in this study has been of limited use in deciphering dolomitization mechanisms for Winnipegosis Formation dolomites. The following is an outline of additional analytical work that might help to further refine interpretations made in this study.

Homogenization temperatures from fluid inclusion studies of the various dolomite types recognized in this study can be used to interpret temperatures of dolomite formation in the Winnipegosis Formation. Fluid inclusion analysis can also be useful in estimating the salinity of the fluids involved in dolomitization (e.g. Veizer et al., 1977; Mattes and Mountjoy, 1980; Zenger and Dunham, 1988).

$^{87}Sr/^{86}Sr$ radiogenic isotopic analyses of the various dolomite types in this study could be used to assess the role of Middle Devonian seawater in dolomitization. Other studies (e.g. Teare, 1990; Mountjoy and Halim-Dihardja, 1991; Mountjoy et al., 1992) have compared $^{87}Sr/^{86}Sr$ values for Devonian dolomites to the Sr seawater curve of Burke et al. (1982) and interpreted that some dolomitizing fluids were derived from Middle Devonian seawater.

X-ray diffraction (XRD) data from dolomites can be useful in providing a more detailed knowledge of crystal structure (cation ordering or lattice spacing) and geochemistry (Mg^{+2}, Ca^{+2}, Fe^{+2}), and they can be used to distinguish between different types of dolomite. The mineral dolomite, $Ca(CO_3)_2$, is commonly not stoichiometric, but has an excess of Ca^{+2}, up to Ca_{58} Mg_{42}, or less commonly an excess of Mg^{+2}, up to Ca_{48} Mg_{52} (Hardy and Tucker, 1988). Stoichiometric evaluation of the various dolomite types in this study will help refine the interpreted dolomitization mechanisms. For example, the relatively high Mg/Ca ratios of solutions in evaporitic setting (e.g. reflux and sabkha models) induces the formation of nearly stoichiometric dolomite, whereas lower Mg/Ca ratios in non-evaporite settings (e.g. mixed-water models) result in the precipitation of more calcium-rich dolomite (Morrow, 1988).

Scanning electron microscopy (SEM) can be useful in examining crystal to crystal relationships in a dolomite crystal mosaic (e.g. Gregg and Sibley, 1984). Solution pits on the surface of dolomite crystals can be interpreted to be the result of a dissolution event related to dolomite recrystallization (e.g. Durocher and Al-Aasm, 1997).

CHAPTER 6: SUMMARY

1. The Middle Devonian Winnipegosis Formation accumulated during Eifelian to Givetian time. Initial transgression of Middle Devonian seas into the North Dakota portion of the Elk Point Basin is represented by deposition of the underlying Ashern Formation. Following a minor regressive pulse, the carbonate sediments of the Winnipegosis Formation accumulated during renewed transgression and subsequent restriction of the basin. Basin restriction is represented by the thick evaporite accumulations of the overlying Prairie Formation.
2. The Lower Winnipegosis Member accumulated as a relatively uniform carbonate ramp under normal, subtidal marine conditions and consists of a single lithofacies, the crinoid-brachiopod wackestone lithofacies.
3. The Upper Winnipegosis Member represents carbonate accumulations in a basin that was differentiated into shallow shelves (eastern, western and southern geographic zones) and a central deep basin with isolated pinnacle reefs (central geographic zone). A total of seven lithofacies have been identified in the Upper Winnipegosis Member. The fossiliferous wackestone lithofacies accumulated on the relatively deep carbonate ramp and provided enough synoptic relief in the basin area for the coral-stromatoporoid doloboundstone lithofacies to accumulate in the form of pinnacle reefs. The fossiliferous packstone and boundstone lithofacies developed on the shelf margin and shelf interior in the form of shelf margin reefs and patch reefs. The peloidal

packstone lithofacies represents reef detritus and the mudstone lithofacies was deposited in the quieter waters of the shelf interior. The patterned dolostone lithofacies accumulated in a supratidal setting on the shelf interior near the end of Winnipegosis time. The microbial bindstone lithofacies represents intertidal deposition of microbial mats and accumulated on the pinnacle reefs and on the shelf areas.

4. The laminated mudstone lithofacies of the Ratner Member represents deposition in the inter-reef areas of an increasingly saline, deep basinal, probably anoxic environment. Further salinity increase in the basin is represented by accumulations of gypsum (anhydrite) above the basinal Ratner Member and above the shelf deposits of the Upper Winnipegosis Member.
5. Six different dolomite types, five anhydrite types, dedolomite and a late diagenetic calcite were identified to have formed over three diagenetic stages in the Winnipegosis Formation.
6. The synsedimentary diagenetic stage of the Winnipegosis Formation was influenced by the depositional environment. Idio-Ep dolomite sub-type and anhydrite type 1 are facies selective, occurring only in the supratidal patterned dolostone lithofacies of the Upper Winnipegosis Member. Idio-E dolomite started forming in the laminated mudstone lithofacies of the Ratner Member during the early diagenetic stage by reflux dolomitization.

7. The early diagenetic stage bridges the transition from the synsedimentary diagenetic stage to the late diagenetic stage related to burial. Idio-E dolomite formed in the shelf areas by mixed-water dolomitization. The bulk of the Idio-E dolomite formed by reflux dolomitization above the spill points of the restricted hypersaline basin: (1) hypersaline brines moved downward through the Upper Winnipegosis pinnacle reefs into the Ratner Member, and (2) seeped downward into the shelf margins of the Upper Winnipegosis Member and basinward along the top of the Lower Winnipegosis Member, possibly into the Ratner Member. Idio-S and Xeno-S dolomite probably formed coevally, but after the onset of Idio-E dolomite. The more dolomite-supersaturated brines followed the original hypersaline brines over the spill points and into the Winnipegosis Formation forming the Idio-S and Xeno-S dolomite.
8. The late diagenetic stage occurred during progressive burial of the Winnipegosis Formation. ISO dolomite is associated with pressure dissolution seams formed in a deep burial environment. Dedolomitization and late diagenetic calcite cement may have formed coevally, post-dating all mosaic dolomite types and pre-dating saddle dolomite. Saddle dolomite formed mostly as cement in the deep burial environment.

9. The $\delta^{18}O_{dol}$ values of the Upper Winnipegosis (-5.9‰) and Ratner (-6.68‰) members are typical of dolomites formed in a burial environment. However, uniform cathodoluminescence and generally higher Mn and Fe concentrations in rims of crystals indicate that the dolomite in the Upper Winnipegosis and Ratner members has been recrystallized. Dolomite in the Lower Winnipegosis Member does not seem to be recrystallized. Dolomite recrystallization in the Upper Winnipegosis and Ratner members may have occurred along with or after the ferroan dolomite event late in the diagenetic history of the Winnipegosis Formation.

REFERENCES

Adams, J.E. and Rhodes, M.L., 1960, Dolomitization by seepage refluxion: American Association of Petroleum Geologists Bulletin 44, p. 1912-1920.

Aitken, J. D., 1967, Classification and environmental significance of cryptalgal limestones and dolomites, with illustrations from the Cambrian and Ordovician of southwestern Alberta: Journal of Sedimentary Petrology, v. 37, p. 1163-1178.

Al-Aasm, I.S., Taylor, B.E., and South, B., 1990, Stable isotope analysis of multiple carbonate samples using selective acid extraction: Chemical Geology, v. 80, p. 119-125.

Al-Aasm, I.S. and Lu, Z., 1996, Neomorphism of early formed dolomite: Petrographic and chemical evidence from Mississippian Pekisko Formation: [abs.] Geological Association of Canada - Mineralogical Association of Canada Joint Annual Meeting, Program with abstracts, v. 21, Winnipeg 1996.

Allan, J.R. and Matthews, R.K., 1982, Isotope signatures associated with early meteoric diagenesis: Sedimentology, vol. 29, p. 797-817.

Allan, J.R. and Wiggins, W.D., 1993, Dolomite reservoirs: Geochemical techniques for evaluating origin and distribution: American Association of Petroleum Geologists Continuing Education Course notes #36, Tulsa, 129pp.

Amthor, J.E. and Friedman, G.M., 1992, Early- to late- diagenetic dolomitization of platform carbonates: Lower Ordovician Ellenburger Group, Permian Basin, west Texas: Journal of Sedimentary Petrology, v. 62, p. 131-144.

Amthor, J.E., Mountjoy, E.W. and Machel, H.G., 1993, Subsurface dolomites in Upper Devonian Leduc Formation buildups, central part of Rimbey-Meadowbrook reef trend, Alberta, Canada: Bulletin of Canadian Petroleum Geology, v. 41, P.164-185.

Anderson, T.F. and Arthur, M.A., 1983, Stable isotopes of oxygen and carbon and their application to sedimentologic and paleoenvironmental problems: *in* Stable Isotopes in Sedimentary Geology; Society of Economic Paleontologists and Mineralogists Short Course, p. 1-1 to 1-151.

Andrichuk, J., 1952, Devonian of the Northern Rocky Mountain and Great Plains area: *in* Sonnenberg, F. P., (ed.), Billings Geological Society Guidebook: Third annual field convention, Black Hills-Williston Basin. p. 57-63.

Baar, C.A., 1974, Geological problems in Saskatchewan potash mining due to peculiar conditions during deposition of potash beds: *in* Coogan, A.H., ed. 4th Symposium on salt, v. 1, general geology of salt and other evaporites: Cleveland, Ohio, Northern Ohio Geological Society, p. 101-118.

Badiozamani, K., 1973, The dorag dolomitization model - application to the Middle Ordovician of Wisconsin: Journal of Sedimentary Petrology, v. 43, p. 965-984.

Baillie, A.D., 1951, Devonian geology of Lake Manitoba-Lake Winnipegosis area, Manitoba: Manitoba Department of Mines and Mineral Resources, Mines Branch Publication 49-2, 72p.

Baillie, A.D., 1953a, Devonian names and correlations in Williston Basin area: American Association of Petroleum Geologists Bulletin, v. 37, p. 444-447.

Baillie, A.D., 1953b, Devonian system of Williston Basin area, Manitoba: Manitoba Department of Mines and Mineral Resources, Mines Branch Publication 52-5, 105p.

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

Baillie, A.D., 1956, Devonian system of Williston Basin area; in three parts: Canadian Oil and Gas Industries, v. 9, no. 9, p. 65-75, no. 10, p. 56-66, no. 11, p. 120-127.

Banner, J.L., Hanson, G.N. and Meyers, W.J., 1988, Water-rock interaction history of regionally extensive dolomite of the Burlington-Keokuk Formation (Mississippian): isotopic evidence: *in* Shukla, V. and Baker, P. (eds.) Sedimentology and geochemistry of dolostones. Special publication number 43, Society of Economic Paleontologists and Mineralogists, p. 97-114.

Barss, D.L., Copland, A.B., and Ritchie, W.D., 1968, Geology of Middle Devonian reefs, Rainbow area, Alberta, Canada: [abs] American Association of Petroleum Geologists Bulletin, v. 52, p.519.

Barss, D.L., Copland, A.B. and Ritchie, W.D., 1970, Geology of Middle Devonian Reefs, Rainbow area, Alberta, Canada: *in* Halbouty, M.T., (ed.), Geology of giant petroleum fields: American Association of Petroleum Geologists Memoir 14, p. 14-49.

Bates, R.L., and Jackson, J.A., (eds.),1980, Glossary of Geology, 2nd edition: American Geological Institute, Falls Church, Virginia.

Bebout, D.G. and Maiklem, W.R., 1973, Ancient anhydrite facies and environments, Middle Devonian Elk Point Basin, Alberta: Bulletin of Canadian Petroleum Geology, v. 21, p. 287-343.

Belyea, H.R., 1952, Notes on the Devonian system of the north central plains of Alberta: Canada Geological Survey Paper 52-27, 66p.

Billings, E., 1859, On some of the Silurian and Devonian fossils collected by Professor Henry Y. Hind on the Assiniboine and Saskatchewan exploring expedition: *in* H. Y. Hind, Northwest Territories reports-Assiniboine and Saskatchewan exploring expedition, p. 186, 187, John Lovell, Toronto.

Botz, R. and van der Borch, C.C., 1984, Stable isotope studies of carbonate sediments from the area, South Australia: Sedimentology, v. 31, p. 837-849.

Braithwaite, C.J.R., 1991, Dolomite, a review of origins, geometry and textures: Transactions of the Royal Society of Edinburgh: Earth Science, v. 82, p. 99-112

Burke, W.H., Dentson, R.E., Hetherington, E.A., Koepnick, R.B., Nelson, H.F., and Otto, J.B., 1982, Variation of seawater $^{87}Sr/^{86}Sr$ throughout Phanerozoic time: Geology, v. 10, p. 516-519.

Butler, G.P., 1969, Modern evaporite deposition and geochemistry of co-existing brines, the sabkha, Trucial Coast, Arabian Gulf: Journal of Sedimentary Petrology, v. 39, p. 79-80.

Butler, G.P., 1970, Holocene gypsum and anhydrite of the Abu Dhabi sabkha, Trucial Coast: an alternative explanation of origin: 3rd Symposium on Salt, Northern Ohio Geological Society, Cleveland, Ohio, p. 120-152.

Carlson, C. G. and Anderson, S. B., 1965, Sedimentary and tectonic history of the North Dakota part of the Williston Basin: American Association of Petroleum Geologists Bulletin, v. 49, p. 1833-1846.

Carpenter, A.B., 1976, Dorag dolomitization model by K. Badiozamani - a discussion: Journal of Sedimentary Petrology, v. 46, p. 258-261.

Chilingar, G.V, Zenger, D.H., Bissel, H.J. and Wolk, K.H., 1979, Dolomites and dolomitization: *in* Larsen, G. and Chilingar, G.V. (eds.), Diagenesis in sediments and sedimentary rocks. Amsterdam, Elsevier, Developments in sedimentology 25A, p. 423-525.

Choquette, P.W. and James, N.P., 1986. Diagenesis #12. Diagenesis in limestones - The deep burial environment: Geoscience Canada, v. 14, p. 3-35.

Choquette, P.W. and Steinen, R.P., 1980, Mississippian non-supratidal, Ste. Genevieve limestone, Illinois Basin: evidence for mixed water dolomitization: *in* Zenger, D.H., Dunham, J.B., and Ethington, R.L. (eds.), Concepts and models of dolomitization. Society of Economic Paleontologists and Mineralogists Special Publication 28, p. 163-196.

Chow, N. and Longstaffe, F.J., 1995, Dolomites of the Middle Devonian Elm Point Formation, southern Manitoba: intrinsic controls on early dolomitization: Bulletin of Canadian Petroleum Geology, v. 43, p. 214-225.

Chow, N, Wendte, J. and Stasiuk, L.D., 1995, Productivity versus preservation controls on two organic-rich carbonate facies in the Devonian of Alberta: sedimentological and organic petrological evidence: Bulletin of Canadian Petroleum Geology, v. 43, p. 433-460.

Coniglio, M., 1986, Stable isotopic and elemental relationships of ancient shallow-marine slope carbonates, Cambro-Ordovician Cow Head Group: Journal of Sedimentary Petrology, v. 56, p.455-463.

Curtis, R., Evans, G., Kinsman, D.J.J., and Shearman, D.J., 1963, Association of dolomite and anhydrite in the recent sediments of the Persian Gulf: Nature, v. 197, p. 679-680.

Davies, G.R., and Ludlam, S.D., 1971, A basinal model for Middle Devonian "laminites", Elk Point Basin of western Canada: [abs] Geological Society of America Abstracts, v. 3, p. 376.

Dixon, J., 1976, Patterned carbonate – a diagenetic feature: Bulletin of Canadian Petroleum Geology, v. 24, p.450-456.

Dunham, R.J., 1962, Classification of carbonate rocks according to depositional texture: in Ham, W.E. (ed.), Classification of carbonate rocks: American Association of Petroleum Geologists Memoir 1, p. 108-121.

Durocher, S. and Al-Aasm, I.S., 1997, Dolomitization and neomorphism of Mississippian (Visean) Upper Debolt Formation, Blueberry Field, northeastern British Columbia: Geologic, petrologic and chemical evidence: American Association of Petroleum geologists Bulletin, v. 81. p. 954-977.

Edie, R.W., 1958, Middle Devonian Elk Point Group and Dawson Bay Formation, central Saskatchewan: [abs] *in* 2nd International Williston Basin Symposium, Regina, Saskatchewan, North Dakota Geological Society and Saskatchewan Geological Society, p. 129.

Edie, R.W., 1959, Middle Devonian sedimentation and oil possibilities, central Saskatchewan, Canada: American Association of Petroleum Geologists Bulletin, v. 43, p. 1026-1057.

Ehrets, J.R. and Kissling, D.L., 1987, Winnipegosis platform margin and pinnacle reef reservoirs, northwestern North Dakota: *in* Fischer, D.W., (ed.), Fifth International Williston Basin Symposium Core Workshop Volume, Grand Forks, North Dakota, p. 1-32.

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

Evamy, B.D., 1967, Dedolomitization and the development of rhombohedral pores in limestones: Journal of Sedimentary Petrology, v. 37, p. 1204-1215.

Fischer, D.W. and Burke, R.B., 1987, A synoptic overview of Winnipegosis Pinnacle reefs in North Dakota.: North Dakota Geological Survey, Miscellaneous series 68, 15p.

Folk, R.L., 1962, Spectral subdivision of limestone types: *in* Ham, W.E. (ed.) Classification of Carbonate Rocks, Memoirs of the American Association of Petroleum Geologists 1, p. 62-84.

Folk, R.L., 1980, Petrology of Sedimentary Rocks: Hemphill Publishing, Austin, Texas.

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

Friedman, G.M., 1965, Terminology of crystallization textures and fabrics in sedimentary rocks: Journal of Sedimentary Petrology, v. 35, p.643-655.

Friedman, G.M., 1972, Significance of Red Sea in problem of evaporites and basinal limestones: American Association of Petroleum Geologists Bulletin, v. 56, p. 1072-1086.

Friedman, G.M., 1980, Dolomite is an evaporite mineral: evidence from the rock record and from sea-marginal ponds of the Red Sea: *in* Zenger, D.H., Dunham, J.B., and Ethington, R.L., (eds.), Concepts and models of dolomitization: Society of Economic Paleontologists and Mineralogists Special Publication no. 28, p. 69-80.

Friedman, G.M. and O'Neil, J.R., 1977, Compilation of stable isotope fractionation factors of geochemical interest: *in* Fleischer, M. (ed.), Data of Geochemistry, United States Geological Survey Professional Paper 440K, 12p.

Fuller, J.G.C.M. and Porter, J.W., 1962, Profile and stratigraphic cross sections of Devonian strata in the northern Great Plains between central Alberta and eastern North Dakota: *in* Billings Geological Society Guidebook, 13th annual field conference, 1962: Billings, Montana, Billings Geological Society, p. 42-46.

Fuller, J.G.C.M., and Porter, J.W., 1969a, Evaporites and Carbonates; two Devonian basins of western Canada: Bulletin of Petroleum Geology, v. 17, p. 182-193.

Fuller, J.G.C.M. and Porter, J.W., 1969b, Evaporite Formations with petroleum reservoirs in Devonian and Mississippian of Alberta, Saskatchewan and North Dakota: American Association of Petroleum Geologists Bulletin, v. 53, p. 909-926.

Fuzesy, L.M., 1975, Future oil seen for rare Williston pay: Oil and Gas Journal, v. 73, p. 188-198.

Fuzesy, L.M., 1976, Geology and hydrocarbon potential of the Winnipegosis Formation in southeastern Saskatchewan: *in* Christopher, J.E. and MacDonald, Robert, (eds.), Summary of Investigations, 1975: Saskatchewan Geological Survey, Department of Mineral Resources, p. 66-70.

Fuzesy, L.M., 1980, Geology of the Deadwood (Cambrian), Meadow Lake and Winnipegosis (Devonian) Formations in west-central Saskatchewan: Saskatchewan Mineral Resources Report 210, 64p.

Gao, G., 1990, Geochemical and isotopic constraints on the diagenetic history of a massive stratal, late Cambrian (Royer) dolomite, Lower Arbuckle Group, Slick Hills, SW Oklahoma, USA: origin and modification: Geochemica et Cosmica Acta, v. 54, p. 1979-1990.

Gao, G. and Land, L.S., 1991, Early Ordovician Cool Creek dolomite, middle Arbuckle Group, Slick Hills, SW Oklahoma, U.S.A.: origin and modification: Journal of Sedimentary Petrology, v. 61, p. 161-173.

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

Gendzwill, D.J., 1978b, Winnipegosis mounds and Prairie Evaporite Formation of Saskatchewan -- seismic study: *in* Williston Basin Symposium, 24th annual conference, Billings, Montana, 1978: Billings, Montana Geological Society, p. 121-130.

Gerhard, L.C., Anderson, S.B., Lefever, J.A. and Carlson, C.G., 1982, Geological development, origin and Energy mineral resources of Williston Basin, North Dakota: American Association of Petroleum Geologists Bulletin, v. 66, p. 989,1020.

Gill, I.P, Moore, C.H. and Aharon, P., 1995, Evaporitic mixed water dolomitization on St. Croix, United States Virgin Islands: Journal of Sedimentary Research, v. A65, p. 591-604.

Given, R.K. and Lohmann, K.C., 1985, Isotopic evidence for early meteoric diagenesis of the reef facies, Permian reef complex of west Texas and New Mexico: Journal of Sedimentary Petrology, Vol. 56, p. 183-193.

Given, R.K. and Lohmann, K.C., 1986, Isotopic evidence for the early meteoric diagenesis of the reef facies, Permian reef complex of west Texas and New Mexico: Journal of Sedimentary Petrology, v. 56, p. 183-193.

Grayston, L.D., Sherwin, D.F. and Allen, J.F., 1964, Middle Devonian: *in* McCrossan, R.G. and Glaister, R.P., (eds.), Geological history of Western Canada: Calgary, Alberta Society of Petroleum Geologists, p. 49-59.

Gregg, J.M. and Sibley, D.F., 1984. Epigenetic dolomitization and the origin of Xenotopic dolomite texture: Journal of Sedimentary Petrology, v. 54, p.908-931.

Gregg, J.M. and Sibley, D.F., 1986, Epigenetic dolomitization and the origin of Xenotopic dolomite texture - Reply: Journal of Sedimentary Petrology, v. 56, p. 735-736.

Gregg, J.M., and Shelton, K,L., 1990, Dolomitization and dolomite neomorphism in the back reef facies of the Bonneterre and Davis Formation (Cambrian), southeastern Missouri: Journal of Sedimentary Petrology, v. 60, p. 549-562.

Hardie, L.A., 1987, Dolomitization: A critical view of some current views: Journal of Sedimentary Petrology, v. 57, p. 166-183.

Hardy, R. and Tucker, M., 1988, X-ray powder diffraction of sediments: *in* Tucker, M., (ed), Techniques in Sedimentology, Blackwell Scientific Publications, Oxford, p. 191-228.

Harris, K.L., 1981, An evaluation of hydrothermal resources of North Dakota; phase II final technical report: University of North Dakota Engineering Experiment Station Bull. 81-05-EES-02.

Heck, T. J. and Burke, R. B., 1991, Devonian stratigraphy of North Dakota from wireline-log sections: *in* Bluemle, J. P., 1991. Report of investigation no. 90 North Dakota Geological Survey.

Heckel, P.H., 1972, Recognition of ancient shallow marine environments: *in* Rigby, J.K. and Hamblin, W.K., (eds.), Recognition of ancient sedimentary environments; Society of Economic Paleontologists and Mineralogists Special Publication 16, p. 226-268.

Heckel, P. H., 1974, Carbonate buildups in geologic record: a review: *in* Laporte, L. F. (ed.), Reefs in time and space; Society of Economic Paleontologists and Mineralogists Special Publications 18, p. 90-155.

Heckel, P.H. and Witzke, B.J., 1979, Devonian world paleogeography determined from distribution of carbonates and related lithic paleoclimatic indicators: *in* House, M.R., Scrutton, C.T. and Bassett, M.C. (eds.), The Devonian System: Special Papers in Paleontology 23, Paleontological Association, London, p. 99-123.

Hind, H.Y., 1859, Northwest Territories Reports - Assiniboine and Saskatchewan exploring expeditions: John Lovell, Toronto

Holail, H., Lohmann, K.C. and Sanderson, I., 1988, Dolomitization and dedolomitization of Upper Cretaceous carbonates: Bahariya Oasis, Egypt: *in* Shukla, V. and Baker, P.A. (eds.), Sedimentology and geochemistry of dolostones; Society of Economic Paleontologists and Mineralogists Special Publication No. 43, p. 191-207.

Hriskovitch, M.E., 1970, Middle Devonian reef production, Rainbow area, Alberta, Canada: American Association of Petroleum Geologists Bulletin, v. 54, p. 2260-2281.

Hudson, J.D., 1977, Stable isotopes and limestone lithification: Journal of the Geological Society of London, v. 133, p.637-660.

Humphrey, J.D., 1988, Late Pleistocene mixing zone dolomitization, southeastern Barbados, West Indies: Sedimentology, v. 35, p. 327-348.

Hsü, K.J. and Siegenthaler, C., 1969, Preliminary experiments on hydrodynamics movement induced by evaporation and their bearing in the dolomite problem: Sedimentology, v. 12, p. 11-25.

Hsü, K.J. and Schneider, J.F., 1973, Progress report on dolomitization-hydrology of Abu Dhabi sabkhas, Arabian Gulf: *in* Purser, B.H. (ed.), The Persian Gulf, New York, Springer - Verlag, p. 409-422.

Illing, L.V., Wells, A.J., and Taylor, J.C.M., 1965, Penecontemporaneous dolomite in the Persian Gulf: Society of Economic Paleontologists and Mineralogists Special Publication no. 13, p. 89-111.

Jackson, K.A., 1958a, Mechanisms of growth: *in* Liquid metals and solidification. Cleveland, American Society of Metals, p. 174-186.

Jackson, K.A., 1958b, Interface structure: *in* Doremus, R.M., Roberts, B.W. and Turnbull, D. (eds.), Growth and Perfection of Crystals, New York, John Wiley and Sons, p. 319-323.

James, N. P., 1987, Structure and Stratigraphy of modern and ancient reefs: *in* Principles and concepts for exploration and exploitation of reefs in Western Canada Sedimentary Basin. Canadian Reef Inventory Project, Short Course. Calgary: Canadian Society of Petroleum Geologists, 70 p.

James, N. P. and Kendall, A. C., 1992, Introduction to Carbonate and Evaporite Facies Models: *in* Walker, R. P. and James, N. P. (eds.), Facies Models: response to sea level change: Geological Association of Canada. p. 265-275.

Johnson, J.G., Klapper, G., and Sandberg, C.A., 1985, Devonian eustatic fluctuations in Euramerica: Geological Society of America Bulletin, v. 96, p. 567-587.

Johnson, M.E., and Lescinsky, H.L., 1986, Depositional dynamics of cyclic carbonates from the Interlake group (Lower Silurian) of the Williston Basin: Palaios, v. 1, p. 111-121.

Jones, H.L., 1964, The stratigraphy of the Middle Devonian Winnipegosis Formation in Saskatchewan: *in* International Williston Basin Symposium, 3rd, Regina, Saskatchewan, 1964: Billings, Montana, Billings Geological Society, p. 73-91.

Jones, H.L., 1965a Sedimentation and economic prospects of Middle Devonian Winnipegosis Formation of Saskatchewan:[abs] American Association of Petroleum Geologists Bulletin, v. 49, p. 1570.

Jones, H.L., 1965b, The Middle Devonian Winnipegosis Formation of Saskatchewan: Saskatchewan Mineral Resources Report 98, 101p.

Jones, H.L., 1966, Some aspects of sedimentation and paleoecology of Middle Devonian Winnipegosis Formation of Saskatchewan, Canada: [abs] American Association of Petroleum Geologists Bulletin, v. 50, p. 619-620.

Kastner, M., 1984, Control of dolomite formation: Nature, v. 311, p. 410-411.

Kendall, A.C., 1973, Laminated ("varvitic") carbonates and anhydrites from Ordovician and Devonian of Saskatchewan: [abs] American Association of Petroleum Geologists Bulletin, v. 57, p. 958-959.

Kendall, A.C., 1976, The Ashern, Winnipegosis, and lower Prairie Evaporite Formations of the commercial potash areas: *in* Christopher, J.E. and MacDonald, Robert, (eds.), Summary of Investigations, 1975 by Saskatchewan Geological Survey: Saskatchewan Department of Mineral Resources Miscellaneous Report, p. 61-65.

Kendall, A.C., 1979, Carbonate-evaporite relationships in Middle Devonian Saskatchewan: [abs] American Association of Petroleum Geologists Bulletin, v. 62, p. 530-531.

Kendall, A.C., 1984, Evaporites: *in* Walker, R.G., (ed.), Facies Models (2nd edition): Geological Association of Canada Reprint Series 1, p. 259-296.

Kendall, A.C., 1992, Evaporites: *in* Walker, R.G. and James, N.P. (eds.), Facies Models: response to sea level change, Geological Association of Canada, p. 375-409.

Kennard, J., 1981, The Arranthrunga Formation: Upper Cambrian eperic carbonates in the Georgia Basin, Central Australia: Bulletin of the Bureau of Mineral Resources, Geology and Geophysics, Australia 211:61p.

Kennard, J.M., and James, N.P., 1986, Thrombolites and Stromatolites: Two distinct types of microbial structures: Palaios, v.1, p. 492-503.

Kent, D.M., 1984, Carbonate and associated rocks of the Williston Basin, their origin, diagenesis and economic potential: Society of Economic Paleontologists, Rocky Mountain Section, Short Course Notes, Denver, Colorado, 1984, 137p.

Kerr, L.B., 1949, The stratigraphy of Manitoba with reference to oil and natural gas possibilities: Manitoba Mines Branch Publication 49-1.

Kinard, J.C. and Cronoble, W.R., 1969, The Winnipegosis Formation in northeast Montana: *in* Eastern Montana Symposium: Montana Geological Society, 20th annual conference, Billings, Montana, 1969, p. 33-44.

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

Kinsman, D.J.J., 1966, Gypsum and anhydrite of Recent age, Trucial Coast, Persian Gulf.: 2nd Symposium on salt, v. 1, Northern Ohio Geological Society, Cleveland ,Ohio, p. 302-326.

Kirkby, K.C. and Tinker, S.W., 1992, The Keg River/Winnipegosis petroleum system in northeast Alberta: [abs] American Association of Petroleum Geologists Annual Convention, Calgary, Official program, p. 66.

Krebs, W. and Mountjoy, E.W., 1972, Comparison of central Europe and western Canadian Devonian reef complexes: *in* Stratigraphy and Sedimentology, Section 6: International Geological Congress, 24th, Montreal, 1972, Proceedings, p. 294-309.

Land, L.S., 1973, Holocene meteoric dolomitization of Pleistocene limestones, North Jamaica: Sedimentology, v. 20, p. 411-424.

Land, L.S., 1980, The isotopic and trace element geochemistry of dolomite: the state of the art: *in* Zenger, D.H., Dunham, J.B. and Ethington, R.L., (eds.), Concepts and models of dolomitization; Society of Economic Paleontologists and Mineralogists Special Publication, v. 28, p. 87-110.

Land, L.S., 1982, Dolomitization: American Association of Petroleum Geologists Educational Short Course Notes Number 24, 20p.

Land, L.S., 1985, The origin of massive dolomite: Journal of Geological Education, v. 33, p. 112-125.

Lane, D.M., 1959, Dawson Bay Formation in the Quill Lakes-Qu'Appelle area, Saskatchewan: Saskatchewan Mineral Resources Report 38, 49p.

Langton, J.R. and Chin, G.E., 1968a, Rainbow member facies and related reservoir properties, Rainbow Lake, Alberta: Bulletin of Canadian Petroleum Geology, v. 16, p. 104-143.

Langton, J.R. and Chin, G.E., 1968b, Rainbow member facies and related reservoir properties, Rainbow Lake, Alberta: American Association of Petroleum Geologists Bulletin, v. 52, p. 1925-1955.

Langton, J.R. and Chin, G.E., 1975, Rainbow member facies and related reservoir properties, Rainbow Lake, Alberta: *in* Davies, G.R., (ed.), Devonian reef complexes of Canada, v. 1, Rainbow, Swan Hills: Canadian Society of Petroleum Geologists Reprint series 1, p. 35-74.

Laporte, L.F., 1967, Carbonate deposition near mean sea-level and resultant facies mosaic: Manlius Formation (Lower Devonian) of New York State: American association of Petroleum Geologists Bulletin, v. 51, p. 73-101.

Law, James, 1955a, Rock units of northwestern Alberta: Journal of the Alberta Society of Petroleum Geology, v. 3, p. 81-83.

Law, James, 1955b Geology of northwestern Alberta and adjacent areas: American Association of Petroleum Geologists Bulletin, v. 39, p. 1927-1978.

LeFever, J. A., Martiniuk, C. D. and Anderson, S. B., 1991, Correlation cross-sections along the United States-Canada International Border North Dakota-Manitoba.

Lippman, F., 1973, Sedimentary carbonate minerals: Springer Verlag, New York. p. 228.

Lobdell, F. K., 1984, Age and depositional history of the Middle Devonian Ashern Formation in the Williston Basin, Saskatchewan and North Dakota: *in* Lorsong, J. A., and Wilson, M. A., (eds.), Oil and gas in Saskatchewan: Regina, Saskatchewan Geological Society Special Publication 7, p. 5-12.

Logan, B.W., 1987, The McLeod evaporite basin, Western Australia: Tulsa, The American Association of Petroleum Geologists, Memoir 44, 140 pp.

Lohmann, K.C., 1985, Covariant Carbon and Oxygen isotopic trends in calcified marine cements: Estimation of marine isotopic signatures: Journal of Sedimentary Petrology, v.

MacDonald, R.W., 1989, Diagenesis of Winnipegosis Buildups (Givetian) Tableland area, southeastern Saskatchewan: Unpublished M.Sc. thesis, University of Alberta.

Machel, H.G., Mason, R.A., Mariano, A.N. and Mucci, A., 1991, Causes and emission of luminescence in calcite and dolomite: *in* Barker, C.E. and Kopp, O.C. (eds.), Luminescence microscopy and spectroscopy: qualitative and quantitative applications. Short course no. 25, Society of Economic Paleontologists and Mineralogists, Dallas, p. 9-25.

Machel, H.G. and Mountjoy, E.W., 1986, Chemistry and environments of dolomitization - a reappraisal: Earth Science Reviews, v. 23, p. 175-222.

MacKenzie, J.A., 1981, Holocene dolomitization of calcium carbonate sediments from the coastal sabkhas of Abu Dhabi, U.A.E: A stable isotope study; Journal of Geology, v. 89, p. 185-198.

MacKenzie, J.A., Hsü, K.J. and Schneider, J.F., 1980, Movement of subsurface water under the sabkha, Abu Dhabi UAE, and its relationship to evaporative dolomite genesis: Society of Economic Paleontologists and Mineralogists Special Publication no. 28, p. 11-30.

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

Majorowicz, J.A., Jones, F.W. and Osadetz, K.G., 1988, Heat flow environment of the electrical conductivity anomalies in the Williston Basin, and occurrences of hydrocarbons: Bulletin of Canadian Petroleum Geology, v. 36, p. 86-90.

Malone, M.J., Baker, P.A. and Burns, S.J., 1994, Recrystallization of dolomite: evidence from the Monterey Formation (Miocene), California: Sedimentology, v. 41, p. 1223-1239.

Martindale, W., and Orr, N. E., 1987, Middle Devonian Winnipegosis reefs of the Tableland area of Southern Saskatchewan: [abs] *in* Marchant, T. (ed.), Second International Symposium on the Devonian System, Program and Abstracts: Calgary, Alberta, Canadian Society of Petroleum Geologists, p. 156.

Mattes, P.W. and Mountjoy, E.W., 1980, Burial dolomitization of the Upper Devonian Myette Buildup, Jasper National Park, Alberta: *in* Zenger, D.H., Dunham, J.B. and Effington, R.L. (eds.), Concepts and models of dolomitization, Society of Economic Paleontologists and Mineralogists Special Publication, p. 259-297.

Mazzullo, S.J., 1992, Geochemical and neomorphic alteration of dolomite: A review: Carbonates and Evaporites, v. 7, p. 21-37.

McCabe, H.R., 1967, Tectonic framework of Paleozoic formations in Manitoba: Canadian Institute of Mining and Metallurgy Bulletin, v. 54, p. 765-774.

McCabe, H.R., 1972, Stratigraphy of Manitoba, and introduction and review: Geological Association of Canada Special Paper 9, p. 167-187.

McCabe, H.R. and Bannatyne, B.B 1970, Mines Branch core-hole program for stratigraphy and industrial minerals: Manitoba Mines Branch, Summary of Geological Fieldwork 1970, Geological Paper 4/70, p. 40-41.

McCabe, H.R. and Barchyn, D., 1982, Paleozoic stratigraphy of southeastern Manitoba, Field trip guidebook, trip 10: Winnipeg, Canada, May, 1982: Geological Association of Canada and Mineralogical Association of Canada, 48p.

McCammis, J.G. and Griffith, L.S., 1967, Middle Devonian facies relations, Zama area, Alberta: Bulletin of Canadian Petroleum Geology, v. 15, p. 434-467.

McCammis, J.G. and Griffith, L.S., 1968, Middle Devonian facies relations, Zama area, Alberta: American Association of Petroleum Geologists Bulletin, v. 52, p. 1899-1924.

McCammis, J.G. and Griffith, L.S., 1975, Middle Devonian facies relations, Zama area, Alberta: *in* Davies, G.R., (ed.), Devonian reef complexes of Canada, v. 1, Rainbow, Swan Hills: Canadian Society of Petroleum Geologists Reprint Series 1, p. 1-34.

McCrea, J.M., 1950, On the isotopic chemistry of carbonates and paleotemperature scale: Journal of Chemical Physics, v. 18, p. 849-857.

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

McGehee, J.R., 1952, A resume of the Elk Point Formation in view of recent drilling in the Williston Basin: Billings, Montana, Billings Geological Society guidebook, 3rd annual field conference, 1952, p. 64.

McIlreath, I.A., and James, N.P., 1984 Carbonate slopes: *in* Walker, R.G., (ed.), Facies Model, (2nd edition): Geological Association of Canada Reprint Series 1, p.245-258.

McKennit, D.B., 1961, Middle Devonian Elk Point Group in Manitoba: unpublished M.Sc. thesis, University of Manitoba, 113p.

Meijer Drees, N.C., 1994, Devonian Elk Point Group of the Western Canada Sedimentary Basin: *In* Mossop, G.D., and Shetson, I. (compilers), Geological Atlas of the Western Canada Sedimentary Basin: Canadian Society of Petroleum Geologists and Alberta Research Council, p. 129-147.

Meyers, W.J. and Hill, B.E., 1983, Quantitative studies of compaction in Mississippian skeletal limestones, New Mexico: Journal of Sedimentary Petrology, v. 53, p. 231-242.

Montenez, I.P. and Read, J.F., 1992, Fluid-rock interaction history during stabilization of early dolomites, Upper Knox Group (lower Ordovician), U.S. Appalachians: Journal of Sedimentary Petrology, v. 62, p. 753-758.

Morlot, A. von, 1847, Ueber dolomit und seine kunstliche Dartstellung aus Kalkstein: Naturwissenschaftliche Abhandlungen, gesammelt und durch Subscription hrsg. von Wilhelm Haidinger, v.1, p.305-315.

Morrow, D.W., 1973, The Presqu'ile Complex – implications for Middle Devonian paleogeography of northern Alberta and British Columbia: Bulletin of Canadian Petroleum Geology, v. 21, p. 421-434.

Morrow, D.W., 1978, The influence of the Mg/Ca ratio and salinity on dolomitization in evaporite basins: Canadian Society of Petroleum Geologists, Bulletin, v. 26, p. 389-392.

Morrow, D.W., 1982a, Diagenesis 1. Dolomite - part 1: the chemistry of dolomitization and dolomite precipitation: Geoscience Canada, v. 9 p. 5-13.

Morrow, D.W., 1982b, Diagenesis 2. part 2: dolomitization models and ancient dolostones: Geoscience Canada, v. 9, p. 95-107.

Mossop, G.D., and Shetson, I, 1994, Geological Atlas of the Western Canada Sedimentary Basin: Canadian Society of Petroleum Geologists and Alberta Research Council, 510 pp.

Mountjoy, E.W., 1980, Some questions about the development of Upper Devonian carbonate build-ups (reefs), western Canada: Bulletin of Canadian Petroleum Geology, v. 28, p. 315-344.

Mountjoy, E.W. and Halim-Dihardja, M.K., 1991, Multiple phase fracture and fault-controlled burial dolomitization, Upper Devonian Wabamun Group, Alberta: Journal of Sedimentary Petrology, v. 61, p.590-612.

Mountjoy, E.W., Qing, H., and NcNutt, R.H., 1992, Strontium isotopic compositions of Devonian dolomites, Western Canada Sedimentary Basin: significance of sources of dolomitizing fluids: Applied Geochemistry, v. 7, p. 59-75.

Mountjoy, E.W. and Amthor, J.E., 1994, Has burial dolomitization come of age? Some answers from the Western Canada Sedimentary Basin: *in* Purser, B., Tucker, M. and Zenger, D. (eds.) Dolomites: A volume in honour of Dolomieu. Special publication number 21 of the International Association of Sedimentologists, Blackwell Scientific Publications, Cambridge, p. 203-229.

Norris, A.W. and Uyeno, T.T., 1971, Stratigraphy and conodont faunas of Devonian outcrop belts, Manitoba: Geological Association of Canada Special Paper 9, p, 209-224.

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, 280p.

Oglesby, C.A., 1987, Distinguishing between depositional and dissolution thinning: Devonian Prairie Formation, Williston Basin, North America: *in* Carleson, C.G. and Christopher, J.E., (eds.), International Williston Basin Symposium, 5th, Saskatchewan Geological Society, p. 47-52.

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

Perrin, N.A., 1981, Reef facies of Winnipegosis Formation (Middle Devonian), Williston Basin, North Dakota: [abs] American Association of Petroleum Geologists Bulletin, v. 65, p. 969.

Perrin, N.A., 1982a, Environment of deposition of Winnipegosis Formation (Middle Devonian), Williston Basin, North Dakota:[abs] American Association of Petroleum Geologists Bulletin, v. 66, p. 616-617.

Perrin, N.A., 1982b, Environments of deposition and diagenesis of the Winnipegosis Formation (Middle Devonian), Williston Basin, North Dakota: *in* Christopher, J.E. and Kaldi, John, (eds.), International Williston Basin Symposium, 4th, Regina, Saskatchewan, 1982: Regina, Saskatchewan Geological Society Special Publication 6, p. 51-66.

Perrin, N.A., 1987, Depositional environments and diagenesis, Winnipegosis Formation (Middle Devonian), Williston Basin, North Dakota: unpublished Ph.D. dissertation, University of North Dakota, 583p.

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* Longman, N.W., Shaley, K.W., Lindsay, R.F. and Eby, D.E., Rocky Mountain Carbonate Reservoirs: Society of Paleontologists and Mineralogists core workshop 7, p. 125-182.

Pettijohn, F.J., 1957, Sedimentary Rocks. Harper and Row, New York, 718p.

Popp, B.N., Anderson, T.F. and Sandberg, P.A., 1986, Textural, elemental and isotopic variations among constituents in Middle Devonian limestones, North America: Journal of Sedimentary Petrology, v. 56, p. 715-727.

Pratt, B.R. and James, N.P., 1982, Cryptalgal-metazoan bioherms of early Ordovician age in the St. George Group, western Newfoundland: Sedimentology, v. 29, p. 543-569.

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

Powley, D., 1951, Devonian Stratigraphy of central Saskatchewan: Unpublished Master's Thesis, University of Saskatchewan.

Qing, H. and Mountjoy, E.W., 1989, Multistage dolomitization in Rainbow buildups, Middle Devonian Keg River Formation, Alberta, Canada: Journal of Sedimentary Petrology, v. 59, p. 114-126.

Qing, H. and Mountjoy, E.W., 1992, Large scale fluid flow in the Middle Devonian Presqu'ile Barrier, Western Canada Sedimentary Basin: Geology, v. 20, p. 903-906.

Radke, B.M., 1980, Epeiric carbonate sedimentation of the Ninmaroo Formation (Upper Cambrian-Lower Ordovician), Georgina Basin: Bulletin of the Bureau of Mineral Resources Journal of Geology and Geophysics, Australia 5:83-200.

Radke, B.M. and Mathis, R.L., 1980, On the formation and occurrence of Saddle dolomite: Journal of Sedimentary Petrology, v. 50, no. 4, p. 1149-1168.

Randazzo, A.F., Sarver, T.J. and Mertin D.B., 1983, Selected geochemical factors influencing diagenesis of Eocene carbonate rocks, peninsular , Florida, U.S.A: Sedimentary Geology, v. 36, p. 1-14.

Reinson, G.E. and Wardlaw, N.C., 1972, Nomenclature and stratigraphic relationships, Winnipegosis and Prairie Evaporite formations, central Saskatchewan: Bulletin of Canadian Petroleum Geology, v. 20, p. 302-320.

Rosenthal, L.R., 1987, The Winnipegosis Formation of the northeast margin of the Williston Basin: *in* Carleson, C.G. and Christopher, J.E., (eds.), 5th International Williston Basin Symposium, Saskatchewan Geological Society, p. 37-46.

Saller, A.H. and Yaremko, K., 1994, Dolomitization and porosity development in the Middle and Upper Wabamun Group, southeast Peace River Arch, Alberta, Canada: American Association of Petroleum Geology, v. 78, p.1406-1430.

Sandberg, C.A., 1961, Distribution and thickness of Devonian rocks in Williston Basin and in central Montana and in north-central Wyoming: United States Geological Survey Bulletin 1112-D, p. 105-127.

Sandberg, C.A. and Hammond, C.R., 1958, Devonian system in Williston Basin and central Montana: American Association of Petroleum Geologists Bulletin, v. 42, p. 2293-2334.

Sandberg, C.A. and Mapel, W.J., 1967, Devonian of the northern Rocky Mountains and plains: *in* Oswald, D.H., (ed.), International Symposium on the Devonian system: Calgary, Alberta Society of Petroleum Geologists, v. 1, p. 843-877.

Schmidt, V, 1971, Early carbonate cementation in Middle Devonian bioherms, Rainbow Lake, Alberta: *in* Bricker, O.P., (ed.), Carbonate Cements: John Hopkins University Studies in Geology 19, p. 209-215.

Schmidt, V., McDonald, D.A. and McIlreath, I.A., 1980, Growth and diagenesis of Middle Devonian Keg River cementation reefs, Rainbow Field, Alberta: *in* Halley, R.B. and Louks, R.G., (eds.), Carbonate reservoir rocks: Society of Economic Paleontologists and Mineralogists core workshop 1, p. 43-63.

Schreiber, B.C., Friedman, G.M., Decima, A. and Schreiber, E., 1973, Depositional environments of the Upper Miocene (Messinian) evaporite deposits of the Sicilian Basin, Sedimentology, v. 23, p. 729-760.

Schreiber, D.F., Roth, M.S., and Helman, M.L., 1982, Recognition of primary facies characteristics of evaporites and the differentiation of these forms from diagenetic overprints: *in* Handford, C.R., Louks, R.G., and Davies, G.R., (eds.), Depositional and diagenetic spectra of evaporites: Society of Economic Paleontologists and Mineralogists Core Workshop 3, p. 1-32.

Shearman, D.J., and Fuller, J.G.C.M., 1969a, Anhydrite diagenesis, calcitization, and organic laminites, Winnipegosis Formation, Middle Devonian, Saskatchewan: Bulletin of Canadian Petroleum Geology, v. 17, p. 496-525.

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

Shinn, E.A. and Robbin, D.M., 1983, Mechanical and chemical compaction in fine-grained shallow-water limestones: Journal of Sedimentary Petrology, v. 53, p. 595-618.

Shrock, R.R., 1948, A classification of sedimentary rocks: Journal of Geology, v. 56, p. 118-129.

Sibley, D.F., 1982, The origin of common dolomite fabrics: Clues from the Pliocene: Journal of Sedimentary Petrology, v. 52, p. 1087-1100.

Sibley, D.F. and Gregg, J.M., 1987, Classification of dolomite rock textures: Journal of Sedimentary Petrology, v. 57, p. 967-975.

Sloss, L.L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 74, p. 93-114.

Sofer, Z. and Gat, J.R., 1972, Activities and concentrations of oxygen-18 in concentrated aqueous salt solutions: Analytical and geophysical implications: Earth and Planetary Science Letters, v. 15, p. 232-238.

Sofer, Z. and Gat, J.R., 1975, The isotopic composition of evaporating brines: Effect on the isotopic activity ratio in saline solutions: Earth and Planetary Science Letters, v. 26, p. 179-186.

Sonnenfeld, Peter, 1984, Brines and Evaporites: Academic Press Inc., Orlando Florida, 613pp.

Sperber, C.M., Wilkinson, B.H. and Peacor, D.R., 1984, Rock composition, dolomite stoichiometry, and rock water interactions in dolomitic carbonate rocks: Journal of Geology, v.92, p.609-622.

Stanford, R. L., 1989, Sedimentology and diagenesis of the Winnipegosis Formation, southeastern Saskatchewan: Unpublished M.Sc. thesis. University of Alberta, 126 pp.

Streeton, E.G., 1971, The Middle Devonian Winnipegosis Formation of west-central Saskatchewan: unpublished M.A. thesis, University of Saskatchewan, 143p.

Teare, M. 1990, Sedimentology and diagenesis of Middle Devonian Winnipegosis reef complexes Dawson Bay, Manitoba: M.Sc. thesis. McGill University, Montreal, Quebec, 141 pp.

Tyrrell, J.B., 1893, Report on northwestern Manitoba with portions of the adjacent districts of Assiniboia and Saskatchewan: Geological Survey of Canada annual Report, v. 5, p. 1889-1891.

Vail, P.R., Mitchum, R.M. Jr., and Thompson, S. III., 1977, Seismic stratigraphy and global changes in sea level, Part 4: Global cycles of relative changes of sea level: *In* Payton, C.E. (ed.), Seismic stratigraphy - Applications to hydrocarbon exploration. Tulsa, American Association of Petroleum Geologists, Memoir 26, p. 83-97.

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

Van Hees, H., 1958, The Meadow Lake Escarpment - its regional significance to Lower Paleozoic stratigraphy: *in* International Williston Basin Symposium, 2nd, Regina, Saskatchewan, 1958: Bismark, North Dakota Geological Society, and Saskatchewan Geological Society, p. 70-78.

Veizer, J., Lemieux, J., Jones, B., Gibling, M.R., and Savelle, J., 1977, Sodium: Paleosalinity indicator in ancient carbonate rocks: Geology, v. 5, p.177-179.

Veizer, Jan, 1983, Trace elements and isotopes in sedimentary carbonates: *in* Reeder, R.J. (ed.) Reviews in Mineralogy Volume 11 Carbonates: Mineralogy and chemistry. Mineralogical Society of America, p. 265-297

Walker, C.T., 1956, The Middle Devonian rocks of western Saskatchewan: *in* International Williston Basin Symposium, 1st, Bismarck, North Dakota, 1956: Bismarck, North Dakota Geological Society and Saskatchewan Geological Society, p. 131-139.

Walker, C.T., 1957, Correlations of Middle Devonian rocks in western Saskatchewan: Saskatchewan Department of Mineral Resources Report 25, 29p.

Wallace, R.C., 1915, Gypsum and brines in Manitoba: Canada Geological Survey Summary Report, 1914, p. 77-80.

Wallace, R.C., 1925, The Geological formations of Manitoba: Natural History Society of Manitoba, 59p.

Walter, M.R. and Heys, G.R., 1985, Links between the rise of metazoa and the decline of stromatolites: Precambrian research, v. 29, p. 149-174.

Wanless, H.R., 1979, Limestone response to stress: Pressure solution and dolomitization. Journal of Sedimentary Petrology, v. 49, p. 437-462.

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

Wardlaw, N. C., and Schwerdtner, W. M., 1966, Halite-anhydrite seasonal layers in Middle Devonian Prairie Evaporite Formation, Saskatchewan, Canada: Geological Society of America Bulletin, v. 77, p. 331-342.

Wells, A.J., 1962, Recent dolomite in the Persian Gulf: Nature, v. 194, p.274-275.

Whiteaves, J.F., 1891, Description of some new or previously unrecorded species of fossils from Devonian rocks of Manitoba: Proceedings and Transactions of the Royal Society of Canada, v. 8, p. 93-110, pls. 4-10.

Whiteaves, J.F., 1892, The fossils of the Devonian rocks of the islands, shores, or immediate vicinity of Lakes Manitoba and Winnipegosis: Contributions of Canadian Paleontologists, v.1, p. 255-359, pls. 33-47.

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

Wilson, J.L., 1975, Carbonate Facies in Geologic History: New York, Springer-Verlag, 471 pp.

Wilson, N., 1984, The Winnipegosis Formation of south-central Saskatchewan: *in* Lorsong, J.A. and Wilson, M.A., (eds.), Oil and Gas in Saskatchewan: Regina, Saskatchewan Geological Society Special Publication 7, p. 13-15.

Worsley, N. and Fuzesy, A., 1978, The potash-bearing members of the Devonian Prairie Evaporite of southeastern Saskatchewan south of the mining area: *in* Williston Basin Symposium, 4th annual conference, Billings, Montana, 1978: Billings, Montana Geological Society, p. 153-161.

Yont, D.R., 1960, Devonian Winnipegosis reefs in west central Saskatchewan: unpublished M.Sc. thesis, University of Saskatchewan, 55p.

Yont, D.R., 1962, Devonian pinnacle reefs in west central Saskatchewan: [abs] Canadian Mining Journal, v. 83, p. 129.

Zenger, D.H. and Dunham, J.B., 1988, Dolomitization of Siluro-Devonian limestones in a deep core (5,350 M), southeastern New Mexico: *in* Shukla, V. and Baker, P.A. (eds.), Sedimentology and geochemistry of dolostones, Society of Economic Paleontologists and Mineralogists Special Publication No. 43, Tulsa, p. 161-173.

APPENDIX A: CORE EXAMINED

Table A-1: Core examined from the Winnipegosis Formation in North Dakota

NDGS Well #	County	Location	Original Operator	Well Name	KB ft	Winnipegosis Formation Log Top ft	Log Btm ft	Total Thickness ft	Total core described ft
25	Williams	SWSW06-155-095	Amerada Pet. Corp.	Iverson #1	2390	11217	11500	283	198
35	Williams	SWNE31-156-095	Amerada Pet. Corp.	Dilland #1	2329		11638		
38	Bottineau	SWSE31-160-081	California Oil Co.	Thompson #1	1526	6469	6788	319	212
147	McKenzie	NWNW15-152-096	Amerada Pet. Corp.	Wollan #1	2480		12217		
286	Bottineau	SWNE32-164-078	Lion Oil Co.	Erickson #1	1539	5010	5184	179	49
505	Dunn	SENE06-141-094	Socony-Vacuum Oil	Dvorak #1	2296	11010	11208	198	
506	Montrail	SWSE08-158-094	Amerada Pet. Corp.	Blikre #1					
793	Dunn	SENW22-149-091	Mobil Production Co.	Birdbear etc.					
1343	McKenzie	NWSW07-152-094	Amerada Pet. Corp.	Price #3	2199				
2219	Bottineau	SESW06-161-079	California Oil Co.	Henry #4	1494	5595	5770	175	32
2596	Bottineau	SENW19-160-080	Phillips Pet. Co.	Brandt #1	1511	6017	6178	161	28
2638	Bottineau	SWSE12-162-078	Phillips Pet. Co.	Brandvold #1	1495	5038	5167	129	11
2800	Burke	SWNW13-163-089	Amerada Pet. Corp.	Gagnum #1	1887				42.5
4340	Williams	SWSW02-154-095	Pan Am. Pet. Corp.	Marmon #1	1972	11500	11692	192	72
4379	Williams	NWSW25-158-095	Amerada Pet. Corp.	Ives #3	2495	11146	11337	191	23
4423	Divide	NWSW26-162-101	Pan American Pet Corp.	Raaum #1	2249	10073	10238	165	
4510	Williams	SWNE07-154-103	Lamar Hunt	BND Oyloe #1	2252	11771	11922	151	101
4597	Williams	SWNE05-154-103	Lamar Hunt	Voll #1	2338	11865	12021	156	57
4618	Williams	SWNE17-156-103	Amerada Pet. Corp.	Trogstad #1	2413	11646	11800	154	
4790	Bottineau	SESE20-159-081	Union Oil Co. of Cal.	Steen #1	1517	6417	6620	203	
4916	Williams	NESW29-156-102	Lamar Hunt	Harstad #1	2409	11988	2148	160	63
4918	Bottineau	NWSW33-161-082	Marathon oil Co.	Adams #1	1562	6476	6755	279	220
4923	Ward	NWNE05-156-081	Union Oil Co. of Cal.	Olsen #1-B-5	1573	6673	6860	187	
4924	Bottineau	NENE02-161-081	Union Oil Co. of Cal.	Huber #1-A-2	1514	5895	6108	213	109
4992	Ward	NESE02-156-082	Union Oil Co. of Cal.	Anderson #1-1-2	1618	6900	7080	180	103
5088	Montrail	NENW35-156-093	Shell Oil Co.	Texel #21-35	2409	12049	12237	208	236
5158	Ward	NENW13-153-085	Union Oil Co. of Cal.	Hanson #1-C-13	2117	8802	9015	213	50
5184	Bottineau	SENE14-162-077	Champlin Pet. Co.	Dunbar #1	1552	4868	5026	158	17
5185	McHenry	SWSW01-156-077	Champlin Pet. Co.	Best #1 14-1	1503				55
5246	Divide	NENE05-161-095	Shell oil Co.	Tanberg #1	2364	10215	10324	109	179
5257	Montrail	NWSW34-151-090	McCulloch Oil Corp.	Wahner #1-34	2223	11117	11343	226	56
5277	Bottineau	SWSW11-162-077	McMoran Expl. Co.	Tonneson #1	1543	4885	5042	157	26

NDGS Well #	County	Location	Original Operator	Well Name	KB ft	Winnipegosis Formation Log Top ft	Log Btm ft	Total Thickness ft	Total core described ft
5279	McHenry	NESW34-157-076	McMoran Expl.	State #1	1476	5100	5235	135	25
5280	Bottineau	SWSW24-161-076	McMoran Expl. Co.	Deraas #1	1527	4706	4879	173	48
5281	McHenry	SWSW16-158-075	McMoran Expl.	State #2	1470	4790	4922	132	24
5283	McHenry	NENE34-158-077	McMoran Expl. Co.	Fairbrother #1	1477	5242	5398	156	49
5333	Montrail	SESE26-156-093	Shell Oil Co.	Morrow #44X-26	2376				289
5498	Ward	SWNE01-157-082	Marathon Oil Co.	Gowin #1	1559	6760	6947	187	
5692	Bottineau	NENW32-159-082	Kirby Expl. Co.	Brooks #1-32	1587	6870	7036	166	
6296	Renville	NESW09-163-087	Shell Oil Co.	Larson #23X-9	1807	7770	7847	77	37
6535	Bottineau	NENE02-161-083	Shell Oil Co.	Greek #41-2	1589	6469	6788	319	353
6603	Divide	SWSW36-160-096	Chapman Expl., Inc.	State #1-A	2094	10853	11033	180	
6624	Renville	SENW01-161-085	Shell Oil Co.	Osterberg #22X-1	1715	7132	7498	366	76.5
6684	Renville	NENW02-161-085	Shell Oil Co.	Osterberg #21-2	1713	7449			120
7976	Renville	SWSE34-161-087	Shell Oil Co.	Golden #34X-34	1899	8302	8419	117	117
10059	Williams	SENE01-158-096	Fulton Producing Co.	Seaton #1	2347	11385	11582	197	52
10171	Divide	NESW36-161-098	Getty Oil Co.	Wildrose C#36-11	2156G	10475			
10209	Williams	SESW06-158-095	Depco Inc.	McGinnity #24-6	2399	11049	11349	300	114
10348	Divide	NENW30-161-102	HNG Oil Company	Anderson-St.30#2	2104G				33
10353	Divide	CNE32-163-101	Louisiana Land & Expl.	Constantine 41-32	2224G	9716	9933	217	60
10395	Divide	NENE35-161-098	Getty Oil Co.	Wildrose C#35-1	2085				119
10480	Williams	SENW07-158-095	Depco Inc.	Skarderud #22-7	2430				107
10830	Divide	SESE08-163-099	Louisiana Land & Expl.	Thomte 1 44-8	2094G	9573	9730	57	50
11872	Montrail	NWNE29-157-088	Challenger Mins. Inc.	Alvstad 31-29	2738	10020	10254	234	59
12692	Burke	NENE27-161-093	Marathon Oil	Aardvark #27-1	2477	10688	10753	65	58
12786	Montrail	SWNE26-156-091	Marathon Oil	Laredo #26-1					26

APPENDIX B: CORE DESCRIPTIONS

APPENDIX B: CORE DESCRIPTIONS

Introduction

Figure 1.2 (in the text) is a map which shows the location of the cored wells used in this study. The number beside each well is the North Dakota Geological Survey (NDGS) catalogue number. All cores examined are stored at the Wilson M. Laird Core and Sample Library at the NDGS University Station, Grand Forks, North Dakota.

The wetted core was described with the aid of a ten-power hand lens and a binocular, reflected light microscope. Dolomitic and Calcitic intervals were determined by placing a few drops of cold 10% Hydrochloric acid on the core surface (effervescence = calcite). Intervals of similar rock are described as one unit. Core description intervals, measured in feet and converted into meters, are listed by depth, in this appendix, from stratigraphically lowest to highest. There are two columns in this appendix. The column on the left shows the core depth, first in feet then in meters, of the interval described. The column on the right contains the corresponding description.

Descriptions of the cored wells are organized numerically, by their corresponding NDGS catalogue number, in ascending order. The first line of each core description heading contains the NDGS catalogue number and the name of the company which originally drilled the well. The second line shows the location of the well (U.S. Standard Land Office Grid System) and the property owner(s) well name. All townships in North Dakota are north and all ranges are west of the principal baseline and meridian. Below the core description heading there may be an asterisk followed by a statement indicating the condition of the core or the core boxes and how the core was described.

NDGS #25	***Amerada Petroleum Corporation.***
SWSW-6-155W-95N	Iverson #1

* this core was logged box by box due to mislabeled footage and mixed up core within boxes.

11599' - 11589' 3535.4 m - 3532.3 m	**MUDSTONE**. Black to medium gray limestone. Bottom third of interval is laminated, otherwise massive.
11589' - 11559' 3532.3 m - 3523.2 m	**MOTTLED MUDSTONE**. Dark gray, massive slightly fractured limestone in most of interval, otherwise, mottled, brown-gray limestone with minor calcite filled fractures and minor dark gray wisps.

11559' - 11539' 3523.2 m - 3517.1 m	**MUDSTONE**. Variable: massive, black, very fine grained limestone; light gray limestone matrix with dark brown organic? wisps contained within a brown aureole; light brown, massive, very porous limestone, with halite partially to completely filling pores. Large fracture lined with red-brown sylvite and filled with halite. < 5% porosity - vuggy
11539' - 11519' 3517.1 m - 3511.0 m	**MUDSTONE**. Massive, dark gray to black limestone. Rare red-brown sylvite filled fractures. Large vug lined with sylvite and filled with halite. < 1% porosity.
11519' - 11509' 3511.0 m - 3507.9 m	**MUDSTONE**. Massive to discontinuously laminated dark gray - brown limestone. Common halite in vugs. <5% porosity - fracture, vuggy.
11504' - 11495' 3506.4 m - 3503.7 m	**MUDSTONE**. Only 40 cm core actually in box. Mottled, gray and brown limestone (with rare dolomite) in a dark gray to black matrix with minor brown streaks. Rare crinoid fragments. Minor halite in vugs near the top of the interval. < 1% porosity - vuggy, rare interparticle.
11499' - 11484' 3504.9 m - 3501.2 m	3 sections: A) **DOLOMUDSTONE**. Massive, light brown slightly calcitic dolomite with common halite and minor brachiopods. < 5% interparticle porosity, section B) **MUDSTONE**. Discontinuously laminated, dark gray to black and brown limestone, all porosity (~5% - interparticle) is in brown layers only, section C) **DOLOMUDSTONE**. Gray and light gray streaked fissile dolostone.
11487' - 11484' 3501.2 m - 33500.3 m	**CRINOID-BRACHIOPOD WACKESTONE**. Gray and light gray mottled limestone. Abundant brachiopods and crinoids. Minor white dolomite patches, lining pores and as pore fill. Porosity is less than 5%.
11484' - 11474' 3500.3 m - 3497.3 m	**MUDSTONE**. Mottled, dark gray and light gray limestone. Rare brachiopods and very rare crinoids
11474' - 11464' 3497.3 m - 3494.2 m	**BRACHIOPOD-CRINOID MUDSTONE**. Same as 11484' - 11474' with minor brown limestone patches, and slightly more brachiopods and crinoids.

11464' - 11451' 3494.2 m - 3490.3 m	MISSING CORE.
11451' -11446' 3490.3 m - 3488.7	**BRACHIOPOD WACKESTONE**. Dark gray and light gray mottled limestone. Minor brachiopods. Porosity <2%.
11446' - 11436' 3488.7 m - 3485.7 m	**BRACHIOPOD WACKESTONE**. Dark gray limestone. Common brachiopods. Rare crinoids.
11436' - 11426' 3485.7 m - 3482.6 m	**BRACHIOPOD WACKESTONE**. Same as 11446' - 11436'.
11426' - 11416' 3482.6 m - 3479.6 m	**CRINOID WACKESTONE**. Dark gray to black limestone. Common crinoids. Very rare brachiopods.
11416' - 11406' 3479.6 m - 3576.5 m	**WACKESTONE**. Massive black to occasionally mottled dark gray to gray limestone. Rare crinoids and brachiopods.
11406' - 11401' 3476.5 m - 3475.0 m	**BRACHIOPOD WACKESTONE**. Mottled dark gray and gray limestone. Common brachiopods. Rare crinoids.
NDGS# 35 SWNE-31-156-95	***Amerada Petroleum Corp.*** Dilland #1
11663' - 11658' 3554.9 m - 3553.4 m	**INTERLAKE FORMATION**. Irregular, gray and white, non-fossiliferous, dolomitic limestone. ~15% porosity - fenestral, vuggy.
11658' - 11638' 3553.4 m - 3547.3 m	**ASHERN FORMATION**. Red clays.
11638' - 11637' 3547.3 m - 3547.0 m	**ASHERN FORMATION**. Gray clays.
11637' - 11633' 3547.0 m - 3545.3 m	**ANHYDRITIC LAMINATED DOLOMITIC MUDSTONE**. Laminated, dark gray to black limestone with abundant nodular anhydrite. No porosity.
11633' - 11627' 3545.3 m - 3543.9 m	**MUDSTONE**. Swirled to massive, dark gray limestone. Minor anhydrite. ~5% fracture porosity.

11627' - 11617' 3543.9 m - 3540.9 m	**MUDSTONE**. Massive, dark gray limestone. Rare anhydrite. < 1% porosity.
11617' - 11607' 3540.9 m - 3537.8 m	**MUDSTONE**. Massive, dark red-gray limestone. Minor red sylvite. < 2% fracture porosity.
11607' - 11596' 3537.8 m - 3534.5 m	**MUDSTONE**. Massive, light to dark gray limestone. Minor brown streaks. Rare halite and halite molds. Strong red hue over most of interval.
11596' - 11591' 3534.5 m - 3532.9 m	**MUDSTONE**. Swirled, gray-brown limestone. Rare massive anhydrite patches. Rare halite.
11591' - 11587' 3532.9 m - 3531.7 m	**MUDSTONE**. Massive, dark gray limestone. Minor sylvite lined fractures. < 1% fracture porosity.
11587' - 11585' 3531.7 m - 3531.1 m	**FRAGMENTED MUDSTONE**. Fragmented, black and gray-brown limestone. Abundant halite. Fragments are massive, light brown-gray and rounded to subangular. No porosity
11585' - 11582' 3531.1 m - 3530.2 m	**MUDSTONE**. Massive, gray-brown limestone. Minor massive, gray anhydrite. Rare halite. Rare sylvite. ~3% porosity - halite molds, fracture.
11582' - 11581' 3530.2 m - 3529.9 m	**FRAGMENTED MUDSTONE**. Fragmented, gray-brown and black limestone. Similar to 11587' - 11585'.

NDGS #38	***California Oil Company***
SWSE-31-160-81	Thompson #1
11581' - 11572' 3529.9 m - 3527.2 m	**MUDSTONE**. Massive to occasionally streaked, dark gray limestone. Minor halite and sylvite lining fractures. Very rare anhydrite spots.

6542' - 6533' 1994.0 m - 1991.3 m	**ASHERN FORMATION**. Green-gray massive to sparsely laminated limestone. Ashern-Winnipegosis contact is missing.
6533' - 6532' 1991.3 m - 1991.0 m	**DOLOMUDSTONE.** Light brown to cream colored, mottled dolostone. Minor low amplitude stylolites rimming most mottles. Porosity is poor.
6532' - 6526' 1991.0 m - 1989.1 m	**DOLOPACKSTONE to locally DOLOMUDSTONE.** Brown and dark brown mottled dolostone. Common brachiopods. Very rare crinoids. Anhydrite is common as vug fill and minor as a replacement of some brachiopods.
6526' - 6525' 1989.1 m - 1988.8 m	**BRACHIOPOD DOLOPACKSTONE.** Light brown dolostone. Abundant brachiopods. Dissolution seams common. Anhydrite replaced brachiopods common.
6525' - 6517' 1988.8 m - 1986.4 m	**MUDSTONE and very locally PACKSTONE.** Mottled dark brown and light brown limestone. Crinoids and brachiopods are rare and occur in thin layers. Dissolution seams common.
6517' - 6508' 1986.4 m - 1983.6 m	**CRINOID DOLOWACKESTONE.** Mottled dark brown and light brown dolostone. Crinoids are common. Brachiopods are rare. Very rare anhydrite.
6508' - 6490' 1983.6 m - 1978.1 m	**CRINOID DOLOWACKESTONE.** Brown to light brown laminated to mottled dolostone. Brown-black organic seams are common. This interval of core is broken up along fractures which expose the organic material. Crinoids are common. Rare anhydrite. Very rare pyrite.
6490' - 6481.5' 1978.1 m - 1975.6 m	**DOLOMUDSTONE.** Buff colored massive dolostone. Rare crinoids and brachiopods (difficult to identify). Minor anhydrite. Porosity is about 15%, all interparticle and < 1 mm in diameter.
6481.5' - 6477' 1975.6 m - 1974.2 m	**CRINOID DOLOMUDSTONE to CRINOID DOLOWACKESTONE.** Buff to light brown mottled to massive dolostone. Common crinoids. Rare organics wisps. Rare, up to 3 cm patches of massive anhydrite. Anydrite cement common.

6477' - 6475' 1974.2 m - 1973.6 m	**CRINOID DOLOMUDSTONE**. Brown to light brown wispy dolostone. Minor crinoids. Abundant black-brown organic wisps.
6475' - 6465' 1973.6 m - 1970.5 m	**BRACHIOPOD?? DOLOMUDSTONE**. Dark gray-brown, laminated dolostone. Laminations due to abundant, closely spaced black clay seams. Near circular patches of brown dolomite (former brachiopods??) minor; clay seams drape over brachiopods??. Minor anhydrite as void fill.
6465' - 6458' 1970.5 m - 1964.8 m	**DOLOMUDSTONE**. Brown dolostone similar to 6475' - 6465' except for less clay content. Rare crinoids and brachiopods.
6458' - 6450' 1968.4 m - 1966.0 m	**DOLOMUDSTONE**. Mottled light brown massive dolostone.
6450' - 6424' 1966.0 m - 1958.0 m	**DOLOMUDSTONE**. Dark brown and brown-black wispy to mottled dolostone. Brown-black wispy organic/dissolution seams abundant to common. Rare crinoids.
6424' - 6412' 1958.0 m - 1954.4 m	**DOLOMUDSTONE**. Similar to 6450' - 6424'. Brown wispy to mottled dolostone. Brown-black wispy organic/dissolution seams decrease uphole. Rare crinoids. Rare sutured stylolites.
6412' - 6393' 1954.4 m - 1948.6 m	**DOLOMUDSTONE**. Light brown, mottled dolostone. Rare brown-black wisps. Very rare crinoids, but increasing slightly uphole. Minor sutured stylolites.
6393' - 6376' 1948.6 m - 1943.4 m	**CRINOID DOLOMUDSTONE** with occasional 2 cm to 5 cm thick layers of **CRINOID DOLOPACKSTONE**. Light brown to buff, mottled dolostone. Fabric is very similar to last two intervals. Common crinoids. Rare corals. Minor non-sutured stylolites.
6376' - 6369' 1943.4 m - 1941.3 m	**CORAL-CRINOID DOLOWACKESTONE**. Similar to 6393' - 6376'. Common corals and crinoids. Minor bladed anhydrite filling cavities. Very rare pyrite.

6369' - 6367.5' 1941.3 m - 1940.8 m	**CRINOID-CORAL DOLOWACKESTONE**. Similar to 6376' - 6369'. Dark brown color with faint oil smell. Minor bladed anhydrite filling some cavities. Rare rust-brown stains (oxidized pyrite?).
6367.5' - 6356' 1940.8 m - 1937.3 m	**DOLOMUDSTONE**. Mostly mottled to locally laminated, light brown to cream colored dolostone. Rare crinoids and corals. Common anhydrite as fracture fill, cavity fill and cement. Very rare sutured stylolites. Very rare rust-brown stains (oxidized pyrite?).
6356' - 6352' 1937.3 m - 1936.1 m	**BRACHIOPOD DOLOWACKESTONE**. Gray-brown to cream colored, moderately laminated dolostone. Abundant anhydrite cement. Rare, altered brachiopods. Hardground? at 6352.8' (1936.3 m).
6352' - 6351.7' 1936.1 m - 1936.0 m	**ANHYDRITE, HALITE, DOLOSTONE**. Tan to cream colored mottled dolomite with massive, sucrosic, microcrystalline anhydrite minor halite. Conglomeritic.
6351.7' - 6346' 1936.0 m - 1934.3 m	**CONGLOMERATE**. Gray-brown mottled to conglomeritic. The matrix is dark brown to gray-brown, is very fine grained to crystalline, and occasionally exhibits flow structure. Clasts within the conglomerate include; abundant, subrounded, brown to gray-brown, very fine grained to crystalline dolostone fragments similar to the matrix; rare, subangular, dark brown, weakly laminated dolostone; common, gray-brown, subrounded to rounded, anhydrite spotted (patterned dolomite?) fragments of dolostone as large as 6 cm; rare, black, subangular, fine grained granular clasts and; light brown, subrounded, dolostone clasts.
6346' - 6335' 1934.3 m - 1930.9 m	**CONGLOMERATE.** Clast supported, polymictic, poorly sorted conglomerate. The matrix is red-brown grading to light brown near the end of the interval. Clasts include; subrounded to rounded, cryptocrystalline, gray dolostone; light brown, subangular to subrounded, cryptocrystalline dolostone and; clasts as described in 6351.7' - 6346'. Anhydrite fills vugs and is common as a cement. Very rare pyrite near the base of the interval.
6335' - 6330' 1930.9 m - 1929.4 m	**DOLOMUDSTONE**. (Dawson Bay Formation?) Dark brown, mottled dolostone. Bladed anhydrite filling fractures and vugs is common. Minor black-brown wisps.

NDGS #286	***Lion Oil Company***
SWNE-32-164-78	Erickson #1
5136' - 5128' 1565.5 m - 1563.0 m	**BRACHIOPOD DOLOWACKESTONE**. Streaked, dark brown to black-brown dolostone. Brachiopods are common and are commonly replaced by anhydrite. Anhydrite is rare as fracture fill. Streaks consist of black-brown slightly oil stained organic material.
5128' - 5126' 1563.0 m - 1562.4 m	**DOLOMUDSTONE**. Mottled light brown dolostone. All mottles have a very thin black-brown organic rind. Blue-gray anhydrite is common as fracture fill. Fractures are minor and commonly filled with anhydrite.
5126' - 5099.5' 1562.4 m - 1554.3 m	**BRACHIOPOD DOLOWACKESTONE**. Dark brown to black-brown streaky dolostone. Brachiopods are common and are commonly replaced by anhydrite. Anhydrite is rare as fracture fill. Streaks consist of black-brown slightly oil stained organic material.
5099.5' - 5087' 1554.3 m - 1550.5 m	**DOLOMUDSTONE**. Light brown massive to occasionally wispy dolostone. High porosity (15 - 20%), mostly as microvugs. Rare < 2 mm patches of anhydrite. Wisps are black-brown and very discontinuous and may be organic. Thin pyrite lamination at 1551.6 m. 3 cm layer of white crystalline saddle dolomite.

NDGS #793	***Mobil Production Co.***
SENW-22-149-91	Birdbear #1F-22-22-1

* Core boxes are poorly numbered. Core may be a little mixed up.

11534' - 11522' 3515.5 m - 3511.9 m	**BRACHIOPOD CRINOID WACKESTONE to locally PACKSTONE**. Gray and dark gray, mottled limestone. Common brachiopods. Common crinoids. Rare anhydrite. Wispy, discontinuous, randomly oriented, calcite sealed fractures common.

11522' - 11511' 3511.9 m - 3508.6 m	**Missing core.**
11511' - 11501' 3508.6 m - 3505.5 m	**CRINOID WACKESTONE and PACKSTONE**. Gray, mottled to streaked limestone. Crinoids are abundant in layers 5 cm to 8 cm thick, otherwise minor. Minor wispy, randomly oriented, calcite sealed fractures. Brachiopods are rare. Alveolitid coral is very rare.
11501' - 11499' 3505.5 m - 3504.9 m	**CRINOID-CORAL WACKESTONE**. Gray mottled limestone. Abundant crinoids. Common corals - alveolitid and thamnoporid. Minor brachiopods. Rare white, < 1 mm, cubic crystals (dolomite?) in rare vugs.
11499' - 11487' 3504.9 m - 3501.2 m	**Missing core.**
11487' - 11469' 3501.2 m - 3495.8 m	**CORAL-CRINOID WACKESTONE**. Gray and dark gray, mottled to streaked limestone. Common crinoids. Common corals - alveolitid, thamnoporid, and others. Minor brachiopods. Minor vuggy porosity containing common white, < 1 mm cubic, dolomite crystals.
11469' - 11464' 3495.8 m - 3494.2 m	**CORAL-CRINOID WACKESTONE and GRAINSTONE**. Gray and brown, mottled to layered, fine grained granular limestone. Brown areas (layers) contain abundant corals, crinoids, platy stromatoporoids and brachiopods. Gray areas contain abundant corals, common crinoids and rare brachiopods. Porosity is 20% to 30%.
11464' - 11458' 3494.2 m - 3492.4 m	**CORAL-CRINOID WACKESTONE**. Gray and dark gray, mottled limestone. Common corals and crinoids. Very rare brachiopods. Rare white, < 1 mm, cubic dolomite crystals in rare vuggy porosity.
11458' - 11454' 3492.4 m - 3491.2 m	**CRINOID-BRACHIOPOD WACKESTONE**. Gray streaked limestone. Common crinoids. Minor brachiopods. Rare corals.
11454' - 11446' 3491.2 m - 3488.7 m	**BRACHIOPOD-WACKESTONE and PACKSTONE**. Gray to locally brown, mottled to swirled limestone. Common brachiopods. Minor crinoids. Rare corals.

NDGS #2219	***California Oil Company***
SESW-06-161-79	Henry #4

* Poorly labeled core. 3' core intervals labeled as 5'.

5626' - 5613' 1714.8 m - 1710.8 m	**DOLOMUDSTONE**. Wispy to micromottled tan dolostone. Fossil material present but unidentifiable due to extensive dolomitization. ~10% interparticle and microvuggy porosity
5613' - 5595' 1710.8 m - 1705.4 m	**DOLOMUDSTONE**. Laminated tan dolostone. Laminae can be discontinuous and highly porous (possible platy stromatoporoids). Minor stylolites
5595' - 5594' 1705.4 m - 1705.1 m	**STROMATOPOROID DOLOWACKESTONE**. Wispy to streaked dolostone. Minor platy stromatoporoids. Dark brown-black, organic wisps and streaks common.

NDGS #2596	***Phillips Petroleum Co.***
SENW-19-160-80	Brandt #1

* Core logged box by box because core is all mixed up within each box.

6103' - 6099' 1860.2 m - 1859.0 m	**BRACHIOPOD-INTRACLAST WACKESTONE**. Wispy, brown to dark brown limestone. Intraclasts and brachiopods are common. Minor crinoids and rare anhydrite spots.
6099' - 6096' 1859.0 m - 1858.1 m	**BRACHIOPOD WACKESTONE**. Massive to slightly streaked, brown limestone. Minor brachiopods and rare crinoids.
6096' - 6093' 1858.1 m - 1857.1 m	**MUDSTONE**. Discontinuously laminated to streaked, brown and dark brown limestone. Rare crinoids and brachiopods. Most brachiopods are replaced with anhydrite.

6093' - 6089' 1857.1 m - 1855.9 m	**MUDSTONE**. 3/4 of this box is brown, laminated limestone with rare brachiopods. **DOLOMUDSTONE**. 1/4 of this box contains a brown discontinuously laminated dolostone with common dark brown organic patches and wisps. Rare anhydrite spots.
6089' - 6087' 1855.9 m - 1855.3 m	**DOLOMUDSTONE**. Mottled light brown and dark brown dolostone with minor anhydrite patches and rare platy stromatoporoids.
6087' - 6083' 1855.3 m - 1854.1 m	**DOLOMUDSTONE**. Laminated dark brown and brown dolostone. Dark brown wisps (organic?) are common.
6083' - 6080' 1854.1 m - 1853.2 m	**DOLOMUDSTONE**. Streaked and swirled, brown to dark brown dolostone.
6080' - 6077' 1853.2 m - 1852.3 m	**DOLOMUDSTONE**. Streaked and discontinuously laminated, dolostone. Light brown, porous (~25%) patches of < 1 cm are common.
6077' - 6075' 1852.3 m - 1851.7 m	**DOLOMUDSTONE**. Streaked brown dolostone. Minor anhydrite within and around streaks.

NDGS #2638 SWSE-112-162-78	***Phillips Petroleum Co.*** Brandvold #1

* Core is in poor shape. Only 8' of core: supposed to be 11'.

5056.5' - 5053' 1541.2 m - 1540.2 m	**DOLOMUDSTONE**. Massive tan dolostone. Minor dark brown wisps (organic?). Very rare brachiopod molds.
5053' - 5051.5' 1540.2 m - 1539.7 m	**Missing core.**
5051.5' - 5046' 1539.7 m - 1538.0 m	**DOLOMUDSTONE**. Same as 5056.5' - 5053'.

5046' - 5044' 1538.0 m - 1537.4 m	**DOLOMUDSTONE**. Finely laminated to discontinuously laminated, light to dark, brown dolostone. Very rare anhydrite replaced brachiopods.

NDGS #2800 SWNW-13-163-89	***Amerada Petroleum Corp.*** Gagnum #1
8323' - 8321' 2536.9 m - 2536.2 m	**MUDSTONE**. Finely laminated, gray-brown to dark brown limestone. Laminae are 0.5 mm to 20 mm thick (avg. ~3 mm). Small, wispy, calcite filled fractures are minor. Anhydrite rarely is present in these fractures. Trace amounts of pyrite are also found in some of these fractures.
8321' - 8314' 2536.2 m - 2534.1 m	**DOLOMUDSTONE**. Finely laminated, light brown, cream and black dolostone. The transition from limestone to dolostone is over 7 cm and is massive, light brown, with common anhydrite spots. Vertical fractures are rare, and are most commonly filled with dolomite and occasionally anhydrite. Small (< 3 cm) lensoidal patches of anhydrite are rare - laminae drape over these anhydrite lenses.
8314' - 8311' 2534.1 m - 2533.2 m	**DOLOMITIC MUDSTONE**. Wavy laminated, gray-brown and gray limestone with irregular brown dolomite patches. The brown patches are slightly coarser grained - some patches retain laminae some do not. Fractures filled with bladed, white and blue-gray anhydrite are common. Fractures at 8312' (2533.5 m) contain anhydrite, hematite and pyrite from center to fracture wall.
8311' - 8307' 2533.2 m - 2532.0 m	**MUDSTONE**. Finely laminated, gray-brown and brown limestone. Open vertical fractures (0.1 mm to 1.0 mm) with a hematite? aureole are common. Minor stylolites (amplitude < 1 mm.). In upper 20 cm pyrite and anhydrite are common. Pyrite occurs conformably as very thin (< 0.1 mm) laminae and in slightly disconformable lenses (< 0.5 mm thick). The anhydrite is bladed and fills vugs and fractures.

8307' - 8303' 2532.0 m - 2530.8 m	**INTERLAYERED MUDSTONE AND DOLOMUDSTONE.** Laminated and layered, buff dolostone and brown limestone. Layered zones are generally massive, brown limestone with minor anhydrite. Laminated zones are generally buff dolostone with minor anhydrite spots. The top of the laminated dolostone zones have small scale scouring?.
8303' - 8300.4' 2530.8 m - 2530 m	**MUDSTONE with minor DOLOMUSTONE LAYERS.** Laminated brown and gray-brown limestone with small (< 5 mm), white anhydrite and calcite nodules. Minor, < 1 cm thick, dolostone layers.
8300.4' - 8288' 2530.0 m - 2526.2 m	**NODULAR LAMINATED ANHYDRITE.** Nodular, laminated anhydrite with minor dolomite and calcite (10% - 20% carbonate). Nodules occur as layers. Nodules are irregular in shape and thickness. Distribution of calcite and dolomite is irregular.
8288' - 8283' 2526.2 m - 2524.7 m	**NODULAR LAMINATED ANHYDRITE.** Nodular to irregular laminated anhydrite. Abundant irregular white to buff dolomite patches (< 4 mm).
8283' - 8280.5' 2524.7 m - 2523.9 m	**HALITE.** Halite. Irregular halite crystal distribution in layers of up to 30 cm thick. Thin (< 0.5 cm) dolomite interlayers

NDGS #4340 SWSW-02-154-95	***Pan American Petroleum Corp.*** Marmon #1
11550' - 11541' 3520.4 m - 3517.7 m	**BRACHIOPOD WACKESTONE.** Mottled gray and gray-brown limestone with minor dolomite. Common brachiopods and rare crinoids and thamnoporid corals. Abundant near vertical fractures (~8 mm wide) lined with calcite and filled with halite. < 2% porosity - fracture.

11541' - 11521.5'
3517.7 m - 3511.8 m

STROMATOPOROID WACKESTONE TO PACKSTONE. Mottled to streaked, dark gray to gray-brown limestone. Common stromatoporoids - mostly platy, minor bulbous and tabular. Rare thamnoporid and favositid corals. Minor brachiopods. Single solitary coral at 11523'. Very rare Stachyotes. Minor anhydrite in vugs. Minor halite in fractures. This interval becomes more muddy (finer grained matrix) uphole. Stromatoporoids become more abundant uphole. ~ 5% porosity - interparticle, intraparticle, intercrystalline, rare microvuggy.

11521.5' - 11515'
3511.8 m - 3509.8 m

LAMINATED DOLOMITIC MUDSTONE. Laminated to streaked, dark brown limestone. Rare stylolites. Very rare anhydrite (replaced brachiopod fragments). Very rare white saddle dolomite crystals in vugs. ~ 5% porosity - microvuggy, intercrystalline, interparticle.

11515' - 11507'
3509.8 m - 3507.3 m

DOLOMITIC MUDSTONE. Mottled, dark gray and gray limestone. Rare crinoids. Minor vugs - halite filled and calcite lined. Dolomite content gradually increases uphole. < 5% microvuggy porosity.

11507' - 11503'
3507.3 m - 3506.1 m

DOLOMUDSTONE. Mottled to laminated, buff dolostone with minor anhydrite spots. Spots are < 3 mm, irregular shaped and light brown in color. Minor dark gray-brown (argillaceous?) seams. < 3% microvuggy porosity

11503' - 11497'
3506.1 m - 3504.3 m

DOLOWACKESTONE. Disrupted laminated, dark brown dolostone. Common intraclasts < 3 mm in diameter and ovoid to irregular angular shapes. Laminae are black (organic?) and sometimes very discontinuous. Minor vugs (< 5 mm diameter) and always filled with halite. Minor anhydrite. Slight oil stain. ~ 2% porosity - fracture, rare microvuggy.

11497' - 11496'
3504.3 m - 3504.0 m

NODULAR ANHYDRITE.

11496' - 11489'
3504.0 m - 3501.8 m

LAMINATED DOLOMUDSTONE. Disrupted laminated, brown dolostone. Laminae are mostly black and discontinuous to wispy. Some laminated areas may be platy stromatoporoids. Some laminae contain peloids. Common anhydrite.

11489' - 11486'
3501.8 m - 3500.9 m

Missing core.

11486' - 11484'
3500.9 m - 3500.3 m

ANHYDRITE AND DOLOMITE. Mottled, buff dolomite and blue-gray anhydrite. Common coral fragments in dolomite

11484' - 11481'
3500.3 m - 3499.4 m

HALITE. White to dark gray.

11481' - 11478'
3499.4 m - 3498.5 m

DOLOMUDSTONE. Thinly laminated, very fissile (poker chip core) dolostone.

NDGS #4379 — ***Amarada Petroleum Corp.***
NWSW-25-158-95 — Ives #3

11185' - 11182'
3409.2 m - 3408.3 m

BRACHIOPOD PACKSTONE TO BRACHIOPOD WACKESTONE. Layered, black and gray limestone. Abundant brachiopods. Minor crinoids. < 5% porosity - moldic, fracture and intraparticle.

11182' - 11162'
3408.3 m - 3402.2 m

MUDSTONE. Massive to finely laminated, black limestone. Very rare crinoid fragments. Occasional pseudo-conchoidal fractures (i.e. very fine grained).

NDGS #4510 — ***Lamar Hunt***
SWNE-07-154-103 — Oyloe #1

11857' - 11846.5'
3614.0 m - 3610.8 m

CRINOID-BRACHIOPOD WACKESTONE. Mottled, gray and black limestone. Black `inter-mottled areas' contain abundant black (organic?) streaks. Crinoid and brachiopod fragments are common. Codiacean algae, stromatoporoid fragments and favositid corals are of minor occurrence. Rare calcite sealed vertical and horizontal fractures.

11846.5' - 11835' 3610.8 m - 3607.3 m	**STROMATOPOROID WACKESTONE to locally STROMATOPOROID PACKSTONE**. Discontinuously laminated to streaked, oil stained, black-gray limestone with rare dolomitic areas. Common tabular stromatoporoids. Minor crinoids. Rare brachiopods. Rare hexacoral fragments. Single occurrence of a 4 cm (diameter) solitary horn coral. Rare calcite sealed vertical fractures. Rare anhydrite patches (< 1 cm).
11835' - 11818.5' 3607.3 m - 3602.3 m	**DOLOMUDSTONE**. Massive to streaked, and rarely peloidal, heavily oil stained, brown to dark brown dolostone. Common stylolites (up to 3 cm amplitudes). Rare platy stromatoporoids, crinoids, and brachiopods. Contains hydrocarbons.
11818.5' - 11809' 3602.3 m - 3599.4 m	**DOLOMITIC MUDSTONE**. Laminated, to wispy, dark gray, brown and dark brown, dolomitic limestone. Rare tabular and platy stromatoporoids. Rare stylolites (< 3 mm amplitude). Common calcite sealed vertical fractures.
11809' - 11806.5' 3599.4 m - 3598.6 m	**DOLOMUDSTONE**. Laminated, buff to brown dolostone. Minor black, clotted zones. Rare stromatoporoid and brachiopod fragments. Large (6 cm) oil stained, anhydrite patch at 11807.5' (3598.9 m).
11806.5' - 11805' 3598.6 m - 3598.2 m	**MUDSTONE**. Laminated, dark brown and black limestone. Black laminae are argillaceous. Minor dolomite laminae. Rare anhydrite.
11805' - 11802' 3598.2 m - 3597.2 m	**DOLOBINDSTONE**. Disrupted laminated, brown to gray-brown dolostone. Laminae contain rare peloids. Nodular anhydrite layer 10 cm thick at 3597.1 m. .
11802' - 11801' 3597.2 m - 3596.9 m	**PATTERNED DOLOSTONE.** Brown and gray.
11801' - 11797' 3596.9 m - 3595.7 m	**STROMATOPOROID DOLOWACKESTONE.** Laminated, brown to gray-brown dolostone. Common stromatoporoids. Minor patches with common anhydrite spots. Rare stylolites.
11797' - 11793' 3595.7 m - 3594.5 m	**DOLOMUDSTONE**. Mottled, gray-brown and brown dolostone. Minor dolomite filled vertical fractures. Rare anhydrite. Rare microstylolites.

11793' - 11788' 3594.5 m - 3593.0 m	**PATTERNED DOLOSTONE.** Brown and gray.
11788' - 11783.5' 3593.0 m - 3591.6 m	**MUDSTONE.** Mottled, dark gray and dark brown limestone. Rare halite in vugs. Very rare pyrite. Burrowed?.
11783.5' - 11778.5 3591.6 m - 3590.1 m	**DOLOMITIC MUDSTONE to DOLOMUDSTONE.** Streaked to patterned, dark brown dolomitic limestone. White dolomite crystals (0.8 mm) common in black streaked areas. Dolomite content increases uphole to totally dolostone in the upper 15 cm of this interval. Minor anhydrite spots. Minor halite in vugs. Rare halite filled vertical fractures. Lower contact shows soft sediment deformation.
11778.5' - 11777.5' 3590.1 m - 3589.8 m	**DOLOMITIC ?BINDSTONE.** Streaked to laminated, dark brown to gray-brown, partially dolomitic limestone. Laminae contain rare peloids. Minor halite. Rare anhydrite.
11777.5' - 11776' 3589.8 m - 3589.3 m	**DOLOMITIC MUDSTONE.** Laminated to streaked dolomitic limestone. Halite common in vugs.
11776' - 11774' 3589.3 m - 3588.7 m	**HALITE** with minor streaked dolomudstone.
11774' - 11768' 3588.7 m - 3586.9 m	**DOLOMUDSTONE.** Laminated to streaked, brown dolostone. Common anhydrite spots. Minor halite.
11768' - 11765.5' 3586.9 m - 3586.1 m	**INTERLAYERED HALITE AND DOLOMUDSTONE.** Interlayered halite and finely laminated dolomite. Rare anhydrite spots in the dolomite.
11765.5' - 11756' 3586.1 m - 3583.2 m	**DOLOMUDSTONE.** Finely laminated, brown to dark brown dolomitic limestone. Anhydrite layers and lenses are common. Halite in vugs common.

NDGS #4597	***Lamar Hunt***
SWNE-05-154-103	Voll #1
11954' - 11950.5' 3643.6 m - 3642.5 m	**STROMATOPOROID WACKESTONE.** Streaked to wavy laminated, dark brown to black limestone. Common stromatoporoid fragments. Minor brachiopod fragments. Rare stylolites. ~10% porosity -interparticle, fracture.
11950.5' - 11943' 3642.5 m - 3640.2 m	**BRACHIOPOD WACKESTONE.** Streaked to laminated, dark brown-black, oil stained limestone. Common brachiopods and brachiopod fragments. Rare corals and stromatoporoids (bulbous and platy). Very rare stylolites. ~10% porosity - interparticle, fracture, moldic?.
11943' - 11935' 3640.2 m - 3637.8 m	**BRACHIOPOD-STROMATOPOROID DOLOMITIC WACKESTONE.** Streaked to laminated, dark brown-black, oil stained, partly dolomitic limestone. Common brachiopods. Minor, massive and tabular stromatoporoids. All fossils are calcitic. Most brachiopods have been dissolved. Stromatoporoids are all partially dissolved. Rare halite in vugs. 15%- 20% porosity - moldic, interparticle, vuggy, fracture.
11935' - 11930' 3637.8 m - 3636.3 m	**STROMATOPOROID WACKESTONE.** Streaked to laminated, dark brown-black, oil stained limestone. Minor tabular and platy stromatoporoids. Rare brachiopods. Very rare corals. Rare stylolites.
11930' - 11927' 3636.3 m - 3635.3 m	**DOLOGRAINSTONE.** Laminated, very fine grained (silt to very fine sand), dark brown, oil stained calcitic dolostone. Minor calcite. Rare stylolites. 15% porosity - interparticle.
11927' - 11924.5' 3635.3 m - 3634.6 m	**DOLOMITIC MUDSTONE.** Mottled to laminated, dark brown, dolomitic limestone. Rare *Thamnopora* and platy stromatoporoids. Minor halite in vugs. 10% porosity - moldic, vuggy, interparticle, fracture.
11924.5' - 11918.5' 3634.6 m - 3632.8 m	**DOLOMITIC BOUNDSTONE? / DOLOMITIC MUDSTONE.** Laminated to massive, gray to tan dolomitic limestone. rare corals. Minor stylolites. massive stromatoporoids. Anhydrite is common as needles and spots.

11918.5' - 11916' 3632.8 m - 3632.0 m	**DOLOMITIC BINDSTONE.** Laminated (stromatolitic), dark brown to black limestone grading to mottled, dark brown dolostone. Slightly oil stained. Rare globular and platy stromatoporoids. Minor anhydrite in vugs. 15% - 20% porosity - moldic, interparticle, minor vuggy
11916' - 11914' 3632.0 m - 3631.4 m	**ANHYDRITE.** Nodular to `chicken wire' anhydrite with gray limestone. Abundant black anhydrite needles in limestone.
11914' - 11911.5' 3631.4 m - 3630.6 m	**DOLOMUDSTONE.** Laminated, brown to buff dolostone. Slight green hue to some laminae. Common anhydrite as vug fill.
11911.5' - 11908' 3630.6 m - 3629.6 m	**DOLOMUDSTONE.** Massive (fine to coarse silt size) grading to laminated, dark brown, oil stained dolostone.
11908' - 11902.5' 3629.6 m - 3627.9 m	**ANHYDRITIC DOLOMUDSTONE.** Discontinuously laminated to disrupted, brown to buff dolostone. Common anhydrite patches, spots and needles. Rare halite in vugs. Minor, localized oil stains. Very poor porosity due to anhydrite.
11902.5' - 11897.5' 3627.9 m - 3626.4 m	**DOLOMUDSTONE.** Laminated to locally massive, gray to brown dolostone. Common anhydrite patches. Common calcite sealed fractures.
11897.5' - 11894' 3626.4 m - 3625.3 m	**PATTERNED DOLOSTONE**. Buff and dark gray.

NDGS #4618	***Amerada***
NENW-17-156-103	Trogstad #1
11758' - 11734.5' 3583.8 m - 3576.7 m	**CRINOID BRACHIOPOD WACKESTONE**. Mottled, dark gray and black limestone. Common crinoids, mostly in 1 cm - 4 cm layers. Common brachiopods. Rare Thamnoporid corals. Very rare bulbous stromatoporoids. Rare celestite? in lower 1.5 m. Very rare halite. < 2% porosity - fracture, moldic?.

11734.5' - 11711' 3576.7 m - 3569.5 m	**CORAL-CRINOID WACKESTONE**. Mottled, dark gray and black limestone. Minor brown dolomitic patches. Common hexacorals (up to 5 cm thick). Common crinoids and thamnoporid corals. Minor stromatoporoids - platy, tabular, bulbous. Very rare solitary rugosan coral. < 5% porosity in matrix - interparticle, fracture, minor microvuggy, rare moldic?. ~15% porosity in corals - mostly in hexacorals.
11711' - 11692' 3569.5 m - 3563.7 m	**STROMATOPOROID BOUNDSTONE**. (WACKESTONE??). Mottled, dark gray and black limestone grading to streaked, black and brown limestone. Common stromatoporoids - massive, bulbous, tabular, platy. Minor crinoids. Rare hexacoral and thamnoporid corals. Minor celestite?. < 2% porosity - intraparticle (in stromatoporoids).
11692' - 11687' 3563.7 m - 3562.2 m	**DOLOMITIC MUDSTONE**. Streaked, black and brown dolomitic limestone. Common halite. Rare celestite?. ~10% - 15% dolomite. ~10% - 15% porosity - interparticle, moldic?, fracture.
11687' - 11678' 3562.2 m - 3559.5 m	**LAMINATED DOLOMITIC MUDSTONE**. Coarsely laminated, brown and black dolomitic limestone. Dolomite increases uphole from ~ 15% to ~60%. Minor anhydrite. ~10% - 15% porosity - intercrystalline (increases slightly uphole).
11678' - 11674' 3559.5 m - 3558.2 m	**DOLOMUDSTONE**. Wavy laminated (stromatolitic?) to massive, buff to brown dolostone. Common stylolites in wavy laminated areas. < 5% porosity - intercrystalline, rare moldic (from halite).
11674' - 11672.5' 3558.2 m - 3557.8 m	**DOLOMITIC MUDSTONE**. Massive to irregular, brown and black limestone. < 5% dolomite. ~10% - 15% porosity - intercrystalline. rare fracture.
11672.5' - 11669' 3557.8 m - 3556.7 m	**ANHYDRITIC DOLOMUDSTONE**. Swirled, light gray and brown dolostone and anhydrite. No porosity.
11669' - 11667' 3556.7 m - 3556.1 m	**DOLOMITIC MUDSTONE**. Laminated, black and brown dolomitic limestone. Minor halite. < 5% porosity - intercrystalline, fracture.

11667' - 11665' 3556.1 m - 3555.5 m	**DOLOMUDSTONE**. Anhydrite spotted, brown dolostone. Spots are anhydritic and halite and halite molds. ~15% porosity - moldic (from halite), intercrystalline.
11665' - 11661' 3555.5 m - 3554.3 m	**ANHYDRITIC DOLOMUDSTONE**. Swirled, buff anhydritic dolostone. No porosity.

NDGS #4790 — Union Oil Co. of California
SESE-20-159-81 — Steen #1

6451' - 6439.5' 1966.3 m - 1962.7 m	**CRINOID DOLOWACKESTONE**. Swirled and streaked, buff dolostone. Common crinoids. Rare thamnoporid corals. Very rare alveolitid coral fragments. Minor blue-gray, bladed anhydrite. Rare pyrite in anhydrite only. Rare white, saddle dolomite crystals in rare vugs. ~20% porosity - intercrystalline, rare vuggy.
6439.5' - 6436' 1962.7 m - 1961.7 m	**THROMBOLITIC DOLOBOUNDSTONE**. Clotted to locally massive, brown to gray-brown dolostone. Common thrombolites. Rare tabular stromatoporoids and alveolitid coral fragments. Very rare thamnoporid and solitary rugosan corals. Common, < 1 mm white, saddle dolomite crystals in fractures. Rare bladed, blue-gray anhydrite. ~8% - 10% porosity - intercrystalline, fracture, microvuggy.
6436' - 6433' 1961.7 m - 1960.8 m	**CORAL DOLOWACKESTONE** (DOLOFLOATSTONE?). Massive, porous, gray-brown to light brown dolostone. Common digitate coral fragments. Minor tabular stromatoporoids. Rare crinoids and codiacean algae. Minor bladed, blue-gray anhydrite. ~20% - 25% porosity - interparticle, moldic, intraparticle, intercrystalline, rare vuggy
6433' - 6427' 1960.8 m - 1959.0 m	**CODIACEAN ALGAE DOLOWACKESTONE**. Swirled, brown dolostone. Common codiacean algae. Rare tabular stromatoporoids and crinoids. Common white, euhedral, < 1 mm dolomite crystals. Rare patch of bladed, blue-gray anhydrite with rare pyrite. ~15% - 20% porosity - intercrystalline, vuggy.

NDGS #4916 NESW-29-156-102	***Lamar Hunt*** Harstad #1
12071' - 12060' 3679.2 m - 3675.9 m	**CORAL WACKESTONE to locally CORAL PACKSTONE**. Mottled, dark gray and black fossiliferous limestone. Common colonial corals (Favositid and others) - up to 20 cm thick. Common thamnoporid corals. Rare crinoids. Very rare brachiopods. Rare halite in vugs. Very rare anhydrite. Porosity between 5% and 10% - vuggy, intraparticle, interparticle.
12060' - 12047' 3675.9 m - 3671.9 m	**CORAL BRACHIOPOD WACKESTONE**. Mottled, dark gray and brown limestone. Minor corals and brachiopods. Rare crinoids.
12047' - 12031' 3671.9 m - 3667.0 m	**STROMATOPOROID CRINOID WACKESTONE**. Mottled, dark gray and dark brown limestone. Abundant stromatoporoids - bulbous and platy. Common crinoids. Minor corals. Rare brachiopods mostly replaced with anhydrite.
12031' - 12027' 3667.0 m - 3665.8 m	Weakly dolomitic **CRINOID WACKESTONE**. Mottled to streaked, gray-brown to gray limestone. Weakly dolomitic. Abundant crinoids. Rare stromatoporoids and brachiopods. Rare anhydrite as porosity occlusions and brachiopod replacement. Porosity ~10% - mostly interparticle, minor moldic, vuggy and fracture.
12027' - 12018' 3665.8 m - 3663.1 m	**STROMATOPOROID WACKESTONE**. Laminated to streaked, gray-brown and gray, dolomitic limestone. Common stromatoporoids. Minor brachiopods. Rare crinoids. Rare anhydrite as fill and/or replacement of brachiopods. Porosity is < 5%.
12018' - 12017.1' 3663.1 m - 3662.8 m	**DOLOMITIC MUDSTONE**. Mottled and swirled, buff to brown, dolostone. Roughly 95% dolomitic, 5% calcitic. Sharp lower contact overlain by 8 cm breccia containing minor brachiopods and rare crinoids. 10% - 15%, mostly vuggy, porosity.
12017.1' - 12016' 3662.8 m - 3662.5 m	**DOLOMUDSTONE**. Massive, very fine grained, medium brown dolostone. Rare very fine grained pyrite.

12016' - 12015'
3662.5 m - 3662.2 m

DOLOMITIC MUDSTONE. Finely laminated, dark brown and dark gray dolostone. This interval becomes more calcitic uphole.

12015' - 12010.1'
3662.2 m - 3660.7 m

DOLOMITIC FOSSILIFEROUS WACKESTONE. Mottled, dark brown and gray dolostone. Minor stromatoporoids, corals and brachiopods. All allochems are calcitic and the matrix is completely dolomite. Rare halite and anhydrite. 10% - 15% porosity - vuggy, intraparticle, interparticle and moldic?

12010.1' - 12008.1'
3660.7 m - 3660.1 m

DOLOMITIC MUDSTONE. Mottled to massive, buff to brown limestone. Minor dolomite. Minor bladed anhydrite.

12008.1' - 12008'
3660.1 m - 3660.0 m

PATTERNED DOLOSTONE.

NDGS #4918 — ***Marathon Oil Co.***

NWSW-33-161-82 — Adams #1

* Core in drawers and may be slightly mixed up.

6710' - 6704.1'
2045.2 m - 2043.4 m

CRINOID WACKESTONE to PACKSTONE. Mottled, light brown and dark brown limestone. Non-sutured seams common. Minor crinoids. Rare brachiopods. 10 cm dark brown, crinoid dolopackstone at 2043.85 m. 10% - 15% porosity - vuggy, moldic, fracture.

6704.1' - 6703.2'
2043.3 m - 2043.1 m

CODIACEAN ALGAE-CORAL DOLOWACKESTONE. Dark brown dolostone. Common corals and codiacean algae. Faint oil smell.

6703.2' - 6696'
2043.1 m - 2040.9 m

CODIACEAN ALGAE WACKESTONE. Mottled, light brown and gray-brown limestone. Common codiacean algae. Minor brachiopods. Very rare corals. Anhydrite patch (3 cm diameter) near top of interval. Non-sutured seams are common. Fractures (< 2 mm) are common. 10% porosity - fracture, moldic, intraparticle.

6696' - 6693' 2040.9 m - 2040.0 m	**FOSSILIFEROUS DOLOMITIC PACKSTONE**. Mottled and spotted, brown dolomitic limestone. Crinoids and brachiopods are common. Dolomite appears in irregular, dark brown patches. Anhydrite streaks and patches are common.
6693' - 6688.1' 2040.0 m - 2038.5 m	**CRINOID-BRACHIOPOD PACKSTONE**. Mottled brown limestone. Common crinoids and brachiopods. Common non-sutured seams.
6688.1' - 6682.7' 2038.5 m - 2036.9 m	**CODIACEAN ALGAE WACKESTONE**. Mottled to lensoidal, light brown to gray-brown limestone interlayered with streaked, dark brown limestone. Rare, local dolomite. Common codiacean algae -abundant near stylolites. Minor brachiopods and corals. Rare crinoids. 5% - 10% porosity - moldic, vuggy, intraparticle.
6682.7' - 6680' 2036.9 m - 2036.1 m	**DOLOMUDSTONE**. Mottled to massive, dark brown to black dolostone. Rare crinoids. Faint oil smell. 10% porosity - intercrystalline.
6680' - 6670.3' 2036.1 m - 2033.0 m	**CODIACEAN ALGAE WACKESTONE to PACKSTONE**. Mottled light brown limestone. Common codiacean algae. Minor brachiopods. Minor stylolites. Minor anhydrite as vug fill and rarely cement. 10% - 15% porosity - vuggy, fracture, interparticle, intraparticle.
6670.3' - 6666' 2033.0 m - 2031.8 m	**GASTROPOD? DOLOPACKSTONE**. Streaked, dark brown dolostone. Common (organic?)stringers. Common gastropods? (< 1 mm). Minor crinoids. Faint oil smell. 15% porosity - intraparticle, interparticle.
6666' - 6647.5' 2031.8 m - 2022.2 m	**STROMATOPOROID DOLOWACKESTONE**. Streaked to locally massive, brown dolostone. Hemispherical stromatoporoids from 6660' to 6654'. Rare crinoids. Very rare brachiopods and coral fragments. Common bladed anhydrite patches. 5% - 10% porosity - interparticle, intraparticle, moldic, rare vuggy.
6647.5' - 6641' 2022.2 m - 2021.2 m	**CRINOID BRACHIOPOD PACKSTONE**. Mottled (nodular looking), light brown limestone. Common brachiopods and crinoids. Anhydrite cement common. 20% - 25% porosity - interparticle, intraparticle, minor fracture.

6641' - 6630' 2021.2 m - 2020.8 m	**DOLOMUDSTONE**. Massive to occasionally wispy, dolostone. Very rare crinoids. Poor porosity - rare vuggy
6630' - 6604' 2020.8 m - 2012.9 m	**PELOIDAL-FOSSILIFEROUS DOLOPACKSTONE to DOLOGRAINSTONE**. Mottled, brown to light brown dolostone. Common brachiopods, codiacean algae, crinoids, peloids, oncoids?. Minor corals. Anhydrite is common as cement, vug filler and replacement of brachiopods. White dolomite patches are common. Porosity is 10% to locally 30% - moldic, interparticle, intraparticle, minor vuggy.
6604' - 6599' 2012.9 m - 2011.4 m	**PELOID BRACHIOPOD DOLOWACKESTONE to locally DOLOPACKSTONE**. Massive, light brown dolostone. Common brachiopods and peloids. Rare anhydrite. 15% - 20% porosity.
6599' - 6590.5' 2011.4 m - 2008.8 m	**BRACHIOPOD DOLOPACKSTONE to DOLOGRAINSTONE**. Mottled, dark brown dolostone. Abundant brachiopods. Brachiopod valves are commonly filled with loose unconsolidated sediment (may be a product of drilling or handling of core). Very rare anhydrite. 10% - 15% porosity - mostly intraparticle, minor interparticle.
6590.5' - 6581.3' 2008.8 m - 2006.0 m	**DOLOMUDSTONE**. Streaked, dark brown dolostone. Common alternating 5 cm - 15 cm layers of non-sutured stylolite swarms and massive dolostone. Rare coral fragments. Very rare crinoids.
6581.3' - 6578' 2006.0 m - 2005.0 m	**DOLOMUDSTONE**. Streaked, brown dolostone. White, sucrosic dolomite patches are abundant and usually rimmed by a very thin (< 0.1 mm), black (organic??) lamination. Minor codiacean algae. Rare brachiopods and crinoids.
6578' - 6570' 2005.0 m - 2002.5 m	**CRINOID-BRACHIOPOD-CORAL DOLOPACKSTONE**. Mottled, tan to brown dolostone. Common crinoids, brachiopods, and corals. Crinoid and brachiopod abundance decreases uphole and the abundance of corals increases uphole. Rare anhydrite. 10% porosity - intraparticle, interparticle, moldic, fracture, vuggy.

6570' - 6561.1' 2002.5 m - 1999.8 m	**DOLOMUDSTONE**. Swirled to lensoidal, brown to locally rusty brown dolostone. Minor codiacean algae. Rare brachiopods and crinoids. Rare bladed anhydrite in vugs. Single occurrence of black anhydrite? (powders yellow and is very soft) in vug at 6563.2'.
6561.1' - 6548' 1999.8 m - 1995.8 m	**CORAL DOLOPACKSTONE**. Mottled, dark brown and light brown dolostone. Common white sucrosic dolomite patches. Common coral fragments patches.
6548' - 6542' 1995.8 m - 1994.0 m	**CORAL DOLOPACKSTONE**. Mottled dark brown dolostone. Common corals. Bladed anhydrite in vugs common. 25% - 30% porosity - mostly intraparticle, minor vuggy.
6542' - 6537.5' 1994.0 m - 1992.6 m	**PELOID DOLOWACKESTONE**. Massive to locally swirled dolostone. Common peloids. Minor crinoids. Rare coral fragments.
6537.5' - 6518' 1992.6 m - 1986.7 m	**CORAL DOLOPACKSTONE**. Mottled, tan to brown dolostone. Common coral fragments. Small 1 mm - 2 mm hollow tubes (coral??) locally abundant but overall of minor occurrence. Bladed anhydrite is common in vugs. 5% - 10% porosity - intraparticle, vuggy, moldic.
6518' - 6506.8' 1986.7 m - 1983.3 m	**DOLOBINDSTONE**. Laminated to locally mottled, light brown to brown dolostone. Laminae are 1 mm - 5 mm thick, light brown to buff and contain very good porosity. Coral fragments are minor to rare and only found in the mottled areas. Anhydrite content increases uphole to about 5% in the uppermost 30 cm.
6506.8' - 6498' 1983.3 m - 1980.6 m	**DOLOMUDSTONE**. Mottled to wispy, gray-brown to dark gray dolostone. Common anhydrite streaks. Rare pyrite. Porosity is < 1%, if any at all.
6498' - 6494.1' 1980.6 m - 1979.4 m	**ANHYDRITIC DOLOMUDSTONE**. Spotted, dark gray-brown grading to dull gray grading to pink-gray dolostone. Anhydrite as small < 2 mm spots and in vugs. Pyrite present in some vugs but generally very rare.

6494.1' - 6490' 1979.4 m - 1978.2 m	**PRAIRIE EVAPORITE**. Mottled, red-brown to pink evaporites. Minor anhydrite. Abundant sylvite.

NDGS #4923 NWNE-05-156-81	*Union Oil Co. of California* Olsen #1-B-5
6735' - 6696.5' 2052.8 m - 2041.1 m	**DOLOMUDSTONE**. Swirled to locally mottled, buff to brown dolostone. Very rare crinoids. Rare blue-gray anhydrite. Common black organic? streaks. ~10% - 15% porosity - intercrystalline, minor vuggy, rare fracture.
6696.5' - 6686' 2041.1 m - 2037.9 m	**DOLOMUDSTONE**. Streaked to irregular, buff dolostone. Very rare crinoids. Rare anhydrite. ~20% - 25% porosity, intercrystalline, fracture, rare vuggy.
6686' - 6681' 2037.9 m - 2036.4 m	**MASSIVE DOLOMUDSTONE**. Massive, buff dolostone. Minor blue-gray, bladed anhydrite. Rare massive anhydrite; has a very thin white dolomite? rim. ~20% porosity - intercrystalline, microvuggy, rare fracture.
6681' - 6673' 2036.4 m - 2033.9 m	**DOLOBINDSTONE** (STROMATOLITIC). Wavy laminated (stromatolitic?) to locally massive, buff dolostone. Common massive anhydrite and white dolomite. ~25% porosity - intercrystalline, fenestral, rare vuggy.

NDGS #4924 NENE-02-161-81	*Union Oil Company of California* Huber #1-A-2
6019' - 6012' 1834.6 m - 1832.5 m	**CRINOID DOLOWACKESTONE**. Discontinuously laminated to wispy, brown to dark brown dolostone. Abundant crinoids. Rare brachiopods. Common black-brown organic? wisps. 25% porosity -microvuggy, interparticle, moldic.

6012' - 5989' 1832.5 m - 1825.4 m	**CRINOID DOLOWACKESTONE to DOLOPACKSTONE.** Mottled and wispy, light brown to brown dolostone. Abundant black-brown organic? wisps. Common crinoids. Very rare stylolites.
5989' - 5950' 1825.4 m - 1813.6 m	**DOLOMUDSTONE.** As in 6012' - 5989'. Rare crinoids.
5950' - 5946.5' 1813.6 m - 1812.5 m	**DOLOMUDSTONE.** Swirled, light brown to buff dolostone. Bladed anhydrite minor. 30% porosity. Most porosity is in buff areas.
5946.5' - 5945' 1812.5 m - 1812.0 m	**ANHYDRITIC DOLOMUDSTONE.** Swirled, light brown, buff and dark brown dolostone. Common anhydrite needles and blades. Very rare crinoids.
5945' - 5941' 1812.0 m - 1810.8 m	**DOLOMUDSTONE.** Wispy brown dolostone. Common black-brown organic? wisps. Rare bladed anhydrite.
5941' - 5928' 1810.8 m - 1806.9 m	**DOLOMUDSTONE.** Mottled to streaked, brown to dark brown dolostone. Rare bladed and sucrosic anhydrite. Burrows? at 5932'. Slightly oil stained. Common calcite sealed fractures. 30% porosity - microvuggy, intercrystalline, fracture.
5928' - 5926' 1806.9 m - 1806.2 m	**DOLOMUDSTONE.** Swirled, buff and brown dolostone. Black-brown organic? wisps are common. 20% intercrystalline porosity.
5926' - 5920' 1806.2 m - 1804.4 m	**CRINOID DOLOWACKESTONE.** Mottled, brown to dark brown dolostone. Common blue-gray anhydrite in fractures and patches. Minor crinoids. Rare corals. 10% intercrystalline porosity.
5920' - 5917.5' 1804.4 m - 1803.7 m	**CODIACEAN ALGAE DOLOWACKESTONE.** Massive to clotted, dark brown dolostone. Common codiacean algae. Minor corals. Rare platy stromatoporoids.
5917.5' - 5900' 1803.7 m - 1798.3 m	**STROMATOPOROID DOLOWACKESTONE / DOLOBOUNDSTONE.** Mottled to streaked, tan to brown dolostone. Common stromatoporoids. Rare codiacean algae and crinoids. Minor blue-gray, bladed anhydrite.

NDGS #4992 NESE-02-156-82	***Union Oil Co. of California*** Anderson #1-I-2
6939' - 6921.5' 2115.0 m - 2109.7 m	**CORAL DOLOWACKESTONE.** Mottled to wispy, light brown dolostone. Abundant black wisps with light brown aureole. Rare stylolites. Minor alveolitid corals. Very rare Thamnoporid corals. Rare anhydrite as vug fill.
6921.5' - 6915' 2109.7 m - 2107.7 m	**CORAL DOLOWACKESTONE.** Mottled and streaked, dark brown and gray-brown dolostone. Rare thamnoporid and Alveolitid corals. Common anhydrite stringers. Common bladed anhydrite in vugs. 10 cm layer of anhydrite at 6919.5': top half is bladed, blue-gray; bottom half is white massive. Very faint oil smell.
6915' - 6912' 2107.7 m - 2106.8 m	**DOLOBINDSTONE.** Laminated, dark brown dolostone. Anhydritized fossils? common. Common conformable anhydrite patches. Laminae are 1 mm - 20 mm thick.
6912' - 6910' 2106.8 m - 2106.2 m	**DOLOMUDSTONE.** Streaked to swirled, brown, tan and buff dolostone. Common anhydrite. <3% porosity.
6910' - 6907' 2106.2 m - 2105.3 m	**DOLOMUDSTONE.** Laminated, light brown dolostone. Abundant stromatoporoids. Minor white, anhydrite laminae.
6907' - 6905.5' 2105.3 m - 2104.8 m	**ANHYDRITIC DOLOMUDSTONE.** Laminated, light brown and white, anhydrite and dolostone.
6905.5' - 6894' 2104.8 m - 2101.3 m	**BRECCIATED DOLOMUDSTONE.** Swirled to fragmented, green-gray dolostone. Fragments are dolomitic and 1 mm - 50 cm across. Matrix and fragments are very similar. Fragments are either massive or laminated. Minor anhydrite. No porosity.
6894' - 6836' 2101.3 m - 2114.1 m	**BRECCIATED DOLOMUDSTONE.** Fragmented, polymictic, variably colored dolostone. Fragments are subangular to angular and 1 mm - 60 mm across. Interval grades into and out of fragment supported and mud supported fabrics. Minor calcite in matrix. Rare anhydrite filled fractures. Rare spotted anhydrite. Very rare pyrite.

NDGS #5088	***Shell Oil Company***
NENW-35-156-93	Texel #21-35
12246' - 12241' 3732.6 m -3731.4 m	**ASHERN FORMATION**. DOLOMUDSTONE. Streaked to wispy, gray to gray-brown dolostone. Very rare anhydrite. No visible fossils.
12242' - 12238' 3731.4 m - 3730.1 m	**ASHERN FORMATION**. DOLOMUDSTONE. As above with rare streaks.
12238' - 12231.9' 3730.1 m - 3728.3 m	**BRECCIATED DOLOMUDSTONE**. Fragmented grading to mottled, gray to light brown dolostone. Ashern/Winnipegosis contact?. Fragments are angular to subrounded, < 4 cm diameter, light brown dolostone (Ashern). Matrix is gray mudstone (Winnipegosis).
12231.9' - 12230' 3728.3 m - 3727.7 m	**DOLOMUDSTONE**. Massive grading to mottled, gray-brown grading through brown to dark brown dolostone. Rare black seams (clay?/organic?).
12230' - 12223.5' 3727.7 m - 3725.7 m	**MUDSTONE**. Mottled, dark brown and gray limestone. Dolostone to limestone is transitional over ~45 cm. Gray (mottled) areas have a light brown rim which grades into the dark brown `matrix' Probable erosional surface at 3726.6 m. Dark brown matrix is very finely laminated.
12223.5' - 12146' 3725.7 m - 3702.1 m	**CRINOID-BRACHIOPOD WACKESTONE to PACKSTONE**. Mottled, dark gray to brown-black limestone. Common to abundant crinoids and brachiopods. Fossils occur mostly in the brown-black `matrix' area. Calcite sealed fractures common.
12146' - 12127' 3702.1 m - 3696.3 m	**CRINOID BRACHIOPOD WACKESTONE**. Streaked grading to laminated, dark gray to black limestone. Upper contact is transitional from overlying interval (boundary placed at >50% brown-black area). Crinoids common. Minor brachiopods.

12127' - 12089' 3696.3 m - 3684.7 m	**CRINOID BRACHIOPOD MUDSTONE to WACKESTONE**. Massive to streaked, black to dark gray limestone. Minor brachiopods and crinoids.
12089' - 12086' 3684.7 m - 3683.8 m	**DOLOMITIC MUDSTONE**. Massive to streaked, dark gray to brown-black dolomitic limestone. Rare fossils. ~30 % dolomite.
12086' - 12064.5' 3683.8 m - 3677.3 m	**DOLOMITIC MUDSTONE**. Layered nodular, dark gray-brown to brown, dolomitic limestone. Dolomite (~20%) occurs as brown patches between layered nodules.
12064.5' - 12057' 3677.3 m - 3675.0 m	**STROMATOPOROID WACKESTONE**. Streaked to finely laminated, dark gray to gray-brown limestone. Stromatoporoids common - mostly bulbous. Brachiopods and thamnoporid corals very rare.
12057' - 12046' 3675.0 m - 3671.6 m	**DOLOMUDSTONE**. Massive to sparsely laminated, brown to dark brown dolostone. Rare stromatoporoid fragments. Minor stylolites at ~45 degrees to core axis. Laminae become more frequent uphole. < 1% porosity - fracture.
12046' - 12033' 3671.6 m - 3667.6 m	**MUDSTONE**. Streaked to occasionally grainy, gray-brown to black limestone. Rare anhydrite. Poor porosity (<5%).
12033' - 12023' 3667.6 m - 3664.6 m	**PELOIDAL? PACKSTONE**. Grainy to laminated, brown limestone. Grainy fabric may be peloids. Black anhydrite needles common at base of interval. Porosity 8 - 10% - interparticle, vuggy.
12023' - 12018' 3664.6 m - 3663.1 m	**ANHYDRITIC DOLOMUDSTONE**. Black anhydrite spotted buff dolostone (patterned dolostone?). Minor 'chicken wire' anhydrite layers. Minor black anhydrite needles. No porosity.
12018' - 12015' 3663.1 m - 3662.2 m	**NODULAR ANHYDRITE**. Nodular anhydrite with minor brown dolostone.
12015' - 12010' 3662.2 m - 3660.6 m	**NODULAR ANHYDRITE** with rare dolomite.

NDGS #5158 NENW-13-153-85	***Union Oil Co. of California*** Hanson #1-C-13
8875' - 8856' 2705.1 m - 2699.3 m	**CRINOID MUDSTONE to MUDSTONE.** Massive to slightly streaked, gray-green limestone. Crinoids common in bottom 1.5 m and grade to very rare at top of interval.
8856' - 8851' 2699.3 m - 2697.8 m	**SILTY MUDSTONE.** Finely laminated, dark green-gray limestone. Laminae consist of silt to sand particles with very fine scale cross-bedding interlayered with green-gray mud.
8851' - 8847' 2697.8 m - 2696.6 m	**FOSSILIFEROUS WACKESTONE.** Streaked to discontinuously laminated, green-gray limestone. Abundant, dark brown brachiopods ($<$ 0.05 mm). ~5% finely disseminated pyrite.
8847' - 8846.5' 2696.6 m - 2696.4 m	**DOLOMITIC MUDSTONE.** Laminated to clotted, brown grading to gray.
8846.5' - 8845.5' 2696.4 m - 2696.1 m	**DOLOMUDSTONE.** Laminated, buff to light brown dolostone. Rare blue-gray anhydrite.
8845.5' - 8843' 2696.1 m - 2695.3 m	**ANHYDRITIC DOLOMUDSTONE.** Laminated to swirled, anhydritic, buff dolostone. Minor halite in vugs.
8843' - 8839' 2695.3 m - 2694.1 m	**DOLOMUDSTONE.** Massive, dull green-brown dolostone. Laminated near bottom contact. Minor dark brown molluscs ($<$ 0.05 mm).
8839' - 8836' 2694.1 m - 2693.2 m	**DOLOMUDSTONE.** Mottled, green-brown dolostone. Rare anhydrite.
8836' - 8835' 2693.2 m - 2692.9 m	**DOLOMUDSTONE.** Laminated, buff and black dolostone. Minor sylvite?.
8835' - 8834.5' 2692.9 m - 2692.8 m	**DOLOMUDSTONE.** Streaked to massive, buff dolostone. Minor sylvite at base of interval. Minor halite in vugs. Minor dissolved cubic halite crystals.

8834.5' - 8833' 2692.8 m - 2692.3 m	**PATTERNED DOLOSTONE.**
8833' - 8830' 2692.3 m - 2691.4 m	**DOLOMUDSTONE.** Finely laminated, brown to gray dolostone. Common halite. Rare sylvite.
8830' - 8828.5' 2691.4 m - 2690.9 m	**PATTERNED DOLOSTONE.**
8828.5' - 8827' 2690.9 m - 2690.5 m	**EVAPORITIC DOLOMUDSTONE.** Mottled, gray-brown dolostone, with abundant halite and sylvite.
8827' - 8825.5' 2690.5 m - 2690.0 m	**PATTERNED DOLOSTONE.**
8825.5' - 8825' 2690.0 m - 2689.9 m	**PELOIDAL DOLOGRAINSTONE.** Grainy, dark brown dolostone. Grains are all peloids.

NDGS #5184 SENE-14-162-77	***Champlin - Bridger*** Dunbar #1
4881' - 4875.5' 1487.7 m - 1486.1 m	**PELOIDAL DOLOGRAINSTONE.** Slightly wispy, granular, brown dolostone. Abundant peloids. Minor crinoids. Rare brachiopods and *amphipora*?. 25% - 30% porosity - interparticle, moldic, microvuggy. Rare white sucrosic dolomite patch.
4875.5' - 4873' 1486.1 m - 1485.3 m	**DOLOMUDSTONE.** Mottled, brown dolostone. Abundant, black-brown organic? wisps. 4 cm, blue-gray, sucrosic anhydrite layer at 1485.7 m.
4873' - 4871.5' 1485.3 m - 1484.8 m	**CODIACEAN ALGAE? DOLOPACKSTONE.** Streaked, stylolitic, brown to dark brown calcitic dolostone. Common codiacean algae. Common brown-black organic? stringers.
4871.5' - 4869.5' 1484.8 m - 1484.2 m	**DOLOMITIC MUDSTONE.** Finely laminated, buff, brown to dark brown dolostone. Minor calcitic laminae.
4869.5' - 4864' 1484.2 m - 1482.5 m	**ANHYDRITIC DOLOMUDSTONE.** Swirled to rarely patterned, buff to gray dolostone. Blue-gray anhydrite, and buff dolomite all swirled together.

NDGS #5185	***Champlin Pet. Co.***
SWSW-01-156-77	Best #1 14-1
5284' - 5274' 1610.6 m - 1607.5 m	**DOLOMITIC WACKESTONE.** Streaked to wispy, dark brown dolomitic limestone. Dolomite is in small patches. Minor brachiopods - replaced by anhydrite. Minor stylolites. Possible (highly altered) platy stromatoporoids. Very rare massive, blue-gray anhydrite patch. ~20% porosity - intercrystalline, rare interparticle.
5274' - 5263' 1607.5 m - 1604.2 m	**DOLOMITIC STROMATOPOROID-BRACHIOPOD WACKESTONE (FLOATSTONE?).** Streaked to wispy, dark brown dolomitic limestone. Disseminated dolomite increases uphole. Dolomite in matrix only. Common brachiopods - decreasing uphole. Common stromatoporoids - bulbous, minor tabular. Minor favositid corals. Rare crinoids. Very rare codiacean algae. Rare stylolites. Gray-brown, bladed celestite? common within stromatoporoids. Rare, <2 cm fossiliferous packstone layers adjacent to bulbous stromatoporoids. ~20% porosity - intercrystalline, intraparticle (corals and stromatoporoids).
5263' - 5257' 1604.2 m - 1602.3 m	**DOLOWACKESTONE.** Swirled grainy (silt size) brown dolostone. Rare calcitic areas (allochems?). Allochems difficult to identify - highly altered. 12 cm blue-gray, bladed anhydrite layer at top of interval. ~15% porosity - interparticle, intercrystalline, rare moldic.
5257' - 5245' 1602.3 m - 1598.7 m	**DOLOMITIC STROMATOPOROID WACKESTONE (FLOATSTONE?).** Swirled and streaked, dark brown dolostone grading to dolomitic limestone uphole. Common stromatoporoids - bulbous, tabular, platy. Minor brachiopods. Allochems are always calcitic. Very rare hexacoral fragments. Rare 5 cm fossiliferous packstone layer adjacent to stromatoporoid. Bladed celestite? common within stromatoporoids. ~ 15% porosity - intercrystalline, interparticle, intraparticle, very rare fracture.

5245' - 5242' 1598.7 m - 1599.6 m	**DOLOMITIC BRACHIOPOD WACKESTONE**. Swirled to streaked, dark brown dolomitic limestone. Black organic? streaks common. Minor brachiopods. Other unidentifiable allochems are minor. ~ 30% - 40% disseminated dolomite. Common anhydrite as patches and fracture fill. ~10% intercrystalline porosity.
5242' - 5238' 1599.6 m - 1596.5 m	**DOLOMITIC STROMATOPOROID WACKESTONE (FLOATSTONE?)**. Streaked, dark brown slightly dolomitic limestone. ~10% - 20% disseminated dolomite through matrix only. Common stromatoporoids - platy, bulbous, tabular. Rare brachiopods and crinoids. Very rare gastropods. Common stylolites. Common anhydrite. ~10% porosity - intercrystalline, interparticle, intraparticle.
5238' - 5233' 1596.5 m - 1595.0 m	**DOLOMITIC FOSSILIFEROUS PACKSTONE**. Grainy and wispy, dark brown and brown dolomitic limestone. < 10% disseminated dolomite. Unidentifiable dolomitic fossils common - highly altered. Minor anhydrite patches. ~15% porosity - interparticle, intraparticle.
5233' - 5230' 1595.0 m - 1594.1 m	**PELOIDAL PACKSTONE**. Massive, granular, gray-brown limestone. Common peloids. Rare intraclasts. Rare codiacean algae. Common interparticle anhydrite. Minor stylolites. < 5% interparticle porosity.
5230' - 5229' 1594.1 m - 1593.8 m	**LAMINATED DOLOMITIC MUDSTONE to DOLOMUDSTONE**. Wispy to laminated, light brown, dolomitic limestone. Common conformable anhydrite laminae. Rare pyrite. No porosity.

~~~~~~

NDGS #5246	***Shell Oil Co.***
NENE-05-161-95	Tanberg #1
10380' - 10376.5' 3163.8 m - 3162.8 m	**RED DOLOMUDSTONE.** (INTERLAKE FORMATION?). Mottled, red-brown dolostone.
~~~~~~

10376.5' - 10372' 3162.8 m - 3161.4 m	**INTERLAYERED LIMESTONE AND ANHYDRITE.** Chicken-wire, white and blue-gray anhydrite interlayered with swirled to massive, gray to gray-brown limestone.
10373' - 10358' 3161.4 m - 3157.1 m	**MUDSTONE.** Massive, gray to gray-brown limestone. Rare anhydrite.
10358' - 10356' 3157.1 m - 3156.5 m	**DOLOMUDSTONE.** Mottled brown and gray dolostone. Gray mottles are elongate and contain abundant anhydrite spots.
10356' - 10334' 3156.5 m - 3149.8 m	**ASHERN FORMATION.** Streaked, gray-brown clay. Minor calcite and dolomite.
10334' - 10328' 3149.8 m - 3148.0 m	**ASHERN FORMATION.** Massive, black, calcitic clay?
10328' - 10323' 3148.0 m - 3146.5 m	**MUDSTONE.** ASHERN FORMATION. Mottled to streaked, gray to gray-brown limestone. Very poor porosity (<3%).
10323' - 10319' 3146.5 m - 3145.2 m	**DOLOMUDSTONE.** ASHERN FORMATION. Sparsely streaked to massive, brown-gray dolostone. Minor calcite sealed horizontal fractures.
10319' - 10305' 3145.2 m - 3141.0 m	**MONOMICTIC CONGLOMERATE / DOLOMUDSTONE.** (TOP OF ASHERN FORMATION?). Fragmented, streaked to laminated, brown to light gray-brown dolostone.
10305' - 10300' 3141.0 m - 3139.4 m	**CRINOID MUDSTONE.** Mottled to nodular, dark gray limestone. Transitional lower contact over ~20 cm. Minor crinoids. Very rare brachiopods.
10300' - 10280.5' 3139.4 m - 3133.5 m	**CRINOID WACKESTONE.** Mottled, dark gray and gray-brown limestone. Common to abundant crinoids. Minor brachiopods
10280.5' - 10276' 3133.5 m - 3132.1 m	**CODIACEAN ALGAE WACKESTONE.** Mottled to massive, gray limestone. Common codiacean algae. Rare brachiopods and crinoids. Very rare coral.

10276' - 10272' 3132.1 m - 3130.9 m	**BRACHIOPOD WACKESTONE**. Mottled to spotted, brown and dark brown limestone. Common brachiopods. Minor crinoids. Very rare coral. White sucrosic anhydrite patches common in mottled areas.
10272' - 10266' 3130.9 m - 3129.1 m	**MUDSTONE**. Finely laminated, gray to black limestone. Minor vertical, calcite sealed fractures. Rare stylolites. Rare anhydrite patches (< 1 cm).
10266' - 10241' 3129.1 m - 3121.5 m	**MUDSTONE**. Laminated, tan to gray-brown limestone. Common stylolites. Laminae are sometimes discontinuous. Minor calcite sealed vertical fractures.
10241' - 10222' 3121.5 m - 3115.7 m	**DOLOMUDSTONE**. Laminated to massive and anhydrite spotted, light brown dolostone. Common black-brown organic? wisps. 5% -10% porosity - interparticle.
10222' - 10201' 3115.7 m - 3109.3 m	**NODULAR ANHYDRITE**. Nodular anhydrite with spotted, brown dolostone and local white sucrosic dolomite.

NDGS #5257 NWSW-34-151-90	*McCulloch Oil Corp.* Wahner #1-34
11175' - 11173.5' 3406.1 m - 3405.7 m	**MUDSTONE**. Streaked to laminated, gray-brown and gray limestone. < 5% microvuggy porosity.
11173.5' - 11172' 3405.7 m - 3405.2 m	**DOLOMUDSTONE**. Massive to irregularly laminated dolostone. Rare crinoids. Very rare anhydrite. Minor silty laminae. ~5% porosity - interparticle, microvuggy.
11172' - 11170.5' 3405.2 m - 3404.8 m	**DOLOPACKSTONE**. Granular (fine sand size) massive to irregularly streaked brown dolostone. Grains are unidentifiable. Matrix is dolomitic. ~ 10% porosity - interparticle.

11170.5' - 11166.5' 3404.8 m - 3403.5 m	**DOLOMUDSTONE**. Massive to swirled, dark brown to gray-brown dolostone. Minor laminae fine upward from silt to mud. Minor soft sediment deformation features. Erosional surface? at 11167.5': laminated dark brown to black dolostone over light brown massive dolostone. < 2% porosity - fracture, microvuggy.
11166.5' - 11163' 3403.5 m - 3402.5 m	**MUDSTONE**. Massive to streaked, brown to gray limestone. Common anhydrite. Minor black anhydrite needles. ~15% porosity - interparticle, microvuggy, vuggy.
11163' - 11151.5' 3402.5 m - 3399.0 m	**DOLOMUDSTONE**. Discontinuously laminated to patchy to spotted, cream to light brown and gray dolostone. Minor blue-gray anhydrite. Rare halite in vugs. Minor vertical fractures with cream colored aureole. < 3% porosity.
11151.5' - 11146' 3399.0 m - 3397.3 m	**MUDSTONE**. Laminated dark brown and gray-brown limestone. Rare pyrite streaks. Very rare halite in fractures. Very poor porosity (<3%).
11146' - 11145' 3397.3 m - 3397.0 m	**MUDSTONE**. Laminated, gray and brown limestone. Minor carbonate sand lenses. Common white calcite crystals in vugs.
11145' - 11144.3' 3397.0 m - 3396.8 m	**DOLOMITIC MUDSTONE**. Wispy, gray-brown dolomitic limestone. Minor pink salt in fractures and vugs.
11144.3' - 11142' 3396.8 m - 3396.1 m	**MUDSTONE**. Swirled, gray-brown dolostone. Near patterned dolostone. < 1% porosity.
11142' - 11141' 3396.1 m - 3395.8 m	**MUDSTONE**. Swirled, gray to dark brown limestone. Rare pink salt at lower contact. < 1% porosity.
11141' - 11137.5' 3395.8 m - 3394.7 m	**LAMINATED DOLOMITIC MUDSTONE**. Laminated, gray brown and buff dolomitic limestone. Halite and pink salt common. Most laminae contain a fining upward sequence, from fine sand size to mud size. < 1% porosity - vugs.
11137.5' - 11132' 3394.7 m - 3393.0 m	**LAMINATED MUDSTONE**. Laminated dark brown and gray-brown limestone. Halite in vugs common. Pink salt common in fractures. ~ 3% porosity - vuggy (from salt dissolution?).

11132' - 11130' 3393.0 m - 3392.4 m	**MUDSTONE**. Laminated gray-brown limestone with abundant salt. Highly desiccated core.
11130' - 11128' 3392.4 m - 3391.8 m	**MUDSTONE**. Massive to streaked, dark gray-brown limestone. Abundant pink salt in fractures. < 2% porosity.
11128' - 11119' 3391.8 m - 3389.1 m	**DOLOMUDSTONE**. Massive to streaked, gray-brown to gray dolostone. Common halite and pink salt. 5% - 10% porosity - fracture, vuggy.

NDGS #5277	***McMoran Exploration Co.***
SWSW-11-162-77	Tonneson #1
4910' - 4906' 1496.6 m - 1495.3 m	**AMPHIPORA DOLOWACKESTONE**. Streaked to discontinuously laminated, brown dolostone. Amphipora common. Rare solitary horn coral. ~10 % porosity - intercrystalline, interparticle, moldic.
4906' - 4897' 1495.3 m - 1492.6 m	**AMPHIPORA DOLOWACKESTONE**. Mottled to streaked, chalky, brown dolostone. Common Amphipora. Minor anhydrite spots. ~15% porosity -intercrystalline, moldic, microvuggy.
4897' - 4895' 1492.6 m - 1492.0 m	**DOLOMUDSTONE**. Massive, chalky, buff dolostone. Very rare dark brown laminae near top of interval. ~20% intercrystalline porosity.
4895' - 4884 1492.0 m - 1488.6 m	**DOLOMUDSTONE**. Laminated, buff dolostone. Minor anhydrite. 10% - 15% porosity - intercrystalline.

NDGS #5279	*McMoran Exploration Co.*
NESW-34-157-76	State #1
5121' - 5107' 1560.9 m - 1556.6 m	**CRINOID WACKESTONE**. Variably streaked and laminated, dark brown limestone. Crinoids common. Rare brachiopods. Rare branched coral. Stylolite at upper contact. 10% porosity - intercrystalline. Minor dolomite patches.
5107' - 5104' 1556.6 m - 1555.7 m	**PATTERNED LIMESTONE?**. Near patterned, gray to cream limestone.
5104' - 5102' 1555.7 m - 1555.1 m	**MUDSTONE**. Wavy laminated and swirled, cream limestone.
5102' - 5101' 1555.1 m - 1554.8 m	**PATTERNED LIMESTONE?**. Same as 5107' - 5104'.
5101' - 5090' 1554.8 m - 1551.4 m	**DOLOMUDSTONE**. Laminated and swirled, cream and brown dolostone. Laminated areas have ~10% intercrystalline porosity. Cream colored areas have extremely poor porosity (near 0%).
NDGS #5280	*McMoran Exploration Co.*
SWSW-24-161-76	Deraas #1
4750' - 4715' 1447.8 m - 1437.1 m	**STROMATOPOROID-CORAL PACKSTONE to BOUNDSTONE**. Mottled to streaked, granular, tan to brown limestone. Abundant stromatoporoids - bulbous, massive, tabular, and minor platy. Common crinoids. Common Thamnoporid and solitary horn corals. Minor brachiopods. 20% - 30% porosity - vuggy, interparticle, intraparticle, moldic, minor fracture and microvuggy. Rare anhydrite in vugs and patches. Rare stylolites.
4715' - 4710.8' 1437.1 m - 1435.9 m	**FOSSILIFEROUS GRAINSTONE**. Slightly streaked, grainy, brown limestone. Abundant peloids. Common crinoids. Minor alveolitid coral fragments. Rare platy stromatoporoids. Common anhydrite in vugs and as cement. Minor stylolites. ~15% porosity - interparticle, microvuggy.
4710.8' - 4705.5' 1435.9 m - 1434.2 m	**DOLOMUDSTONE**. Finely laminated with swirled interbeds, buff to gray-brown dolostone. Bladed, blue-gray anhydrite common in vugs and fractures.

4705.5' - 4702'
1434.2 m - 1433.2 m

ANHYDRITIC DOLOMUDSTONE. Swirled, gray and blue-gray anhydrite and dolostone. Common zones of patterned dolostone. Rare pyrite.

NDGS #5281 — *McMoran Exploration Co.*
SWSW-16-158-75 — State #2

4814' - 4799' 1467.3 m - 1462.7 m	**DOLOMITIC MUDSTONE**. Discontinuously laminated to massive, light brown limestone. Minor brachiopods. Rare codiacean algae. Possible burrows at 4812'. Common anhydrite as replacement and spots. Very rare globular stromatoporoids. Minor dolomite patches. ~5% - 10% intercrystalline porosity.
4799' - 4798' 1462.7 m - 1462.4 m	**DOLOMUDSTONE**. Finely laminated dolostone. Minor anhydrite. ~15% intercrystalline porosity.
4798' - 4796' 1462.4 m -1461.8 m	**DOLOMITIC ANHYDRITE**. Swirled, gray anhydrite and cream dolostone. < 1% porosity (if any).
4796' - 4795' 1461.8 m - 1461.5 m	**DOLOMUDSTONE**. Massive to streaked buff dolostone.
4795' - 4790' 1461.5 m - 1460.0 m	**DOLOMITIC ANHYDRITE**. Interlayered and interlaminated, anhydrite and dolostone. No porosity. Anhydrite is mostly gray and blue-gray.

NDGS #5283 — *McMoran Expl. Co.*
NENE-34-158-77 — Fairbrother #1

5290' - 5274'
1612.4 m - 1607.5 m

FOSSILIFEROUS WACKESTONE. Brown, streaked to irregular limestone. Common crinoids, some as large as 1 cm in diameter. Common brown-black wisps, mostly occurring in swarms. Minor brachiopods, mostly replaced by anhydrite: some as large as 3 cm. Minor codiacean algae. Rare alveolitid corals. Rare solitary horn corals. Rare thamnoporid corals. Rare bryozoans?. Rare oncoids. Very rare stromatoporoid fragments. ~10% - 15% porosity - intercrystalline, interparticle, intraparticle.

5274' - 5263' 1607.5 m - 1604.2 m	**STROMATOPOROID-BRACHIOPOD-CORAL-CRINOID PACKSTONE.** Brown, irregular to streaked limestone with rare dolomite. Common stromatoporoids - platy, tabular and bulbous forms. Common brachiopods, crinoids, thamnoporid and solitary corals. Minor codiacean algae. Minor anhydrite. ~10% -15% porosity - intercrystalline, interparticle, intraparticle.
5263' - 5253' 1604.2 m - 1601.1 m	**CORAL-CRINOID WACKESTONE.** Brown, fine grained granular to slightly wispy limestone with rare dolomite patches. Common crinoids. Minor corals. Rare brachiopods. Rare platy stromatoporoids. Codiacean algae common only in the upper 10 cm of interval. ~8% - 10% porosity - interparticle.
5253' - 5250.5' 1601.1 m - 1600.4 m	**LAMINATED DOLOMUDSTONE.** Buff to cream colored, laminated to locally mottled dolostone. Anhydrite is common only in the mottled areas, otherwise absent. Very chalky texture, with very good porosity and permeability. ~20% intercrystalline porosity.
5250.5' - 5245' 1600.4 m - 1598.7 m	**LAMINATED DOLOMUDSTONE.** Buff colored, chalky, laminated to locally massive dolostone. Minor anhydrite.
5245' - 5243.5' 1598.7 m - 1598.2 m	**ANHYDRITIC DOLOMUDSTONE.** Mottled blue-gray anhydrite and buff dolostone.
5243.5' - 5241' 1598.2 m - 1597.5 m	**ANHYDRITIC DOLOMUDSTONE.** Gray-brown, swirled to mottled, almost patterned dolostone. Common anhydrite in fractures and patches.

NDGS #5333	***Shell Oil Co.***
SESE- 26-156-93	Morrow #44X-26
12163' - 12155.1' 3707.3 m - 3704.9 m	**MUDSTONE.** Mottled, dark brown and dark gray limestone. Possible burrows?. Common non-sutured seams. Rare brachiopods. Rare halite in vugs. Minor anhydrite.
12155.1' - 12153' 3704.9 m - 3704.2 m	**BRACHIOPOD PACKSTONE.** Streaked, black to dark gray limestone. Very abundant brachiopods. < 1% porosity.

12153' - 12140.5' 3704.2 m - 3700.4 m	**BRACHIOPOD-CRINOID WACKESTONE.** Mottled, dark gray and black limestone. Rare, star-shaped crinoid ossicles at 12152.8'. Crinoids and brachiopods common.
12140.5 ' - 12135.5' 3700.4 m - 3698.9 m	**CRINOID WACKESTONE.** Mottled dark gray and black limestone. Sharp lower contact. Minor pyrite at lower contact. Common crinoids. Rare brachiopods. Rare vugs lined with calcite.
12135.5' - 12132' 3698.9 m - 3687.8 m	**CRINOID-BRACHIOPOD PACKSTONE** to locally GRAINSTONE. Mottled, dark gray to black limestone. Very abundant crinoids. Common brachiopods.
12132' - 12094' 3687.8 m - 3686.3 m	**CRINOID WACKESTONE.** Mottled, dark gray and black limestone. Abundant crinoids. Minor brachiopods. Rare <u>Stachyotes</u>?? at 12222'. Very rare gastropod. Common fractures lined with calcite. Minor anhydrite as replacement.
12094' - 12087' 3686.3 m - 3684.1 m	**CRINOID-BRACHIOPOD WACKESTONE to PACKSTONE.** Mottled, gray and black limestone. Abundant crinoids. Common brachiopods. Mottles are smaller than above and there is more black `matrix' than gray mottles. Rare anhydrite.
12087' - 12065' 3684.1 m - 3677.4 m	**BRACHIOPOD WACKESTONE.** Streaked to finely laminated, dark gray to black limestone. Common brachiopods. Minor crinoids.
12065' - 12044.5' 3677.4 m - 3671.2 m	**MUDSTONE.** Sparsely laminated, black limestone. Rare brachiopods.
12044.5' - 12012' 3671.2 m - 3661.3 m	**CRINOID WACKESTONE.** Mottled to spotted and locally laminated, black to dark gray limestone. Minor crinoids. Fine laminae in the non-mottle area drape over mottles and anhydrite spots.
12012' - 12007' 3661.3 m - 3659.7 m	**DOLOMITIC WACKESTONE.** Streaked to mottled, black to gray-brown dolomitic limestone. Rare stromatoporoids. Minor anhydrite as vug fill and replacement.

12007' - 11971' 3659.7 m - 3648.8 m	**STROMATOPOROID-CORAL BOUNDSTONE**. Streaked to mottled, black to dark gray, partially dolomitic limestone. Abundant stromatoporoids and stromatoporoid fragments - globular, tabular, platy, and encrusting. Common thamnoporid corals. Minor brachiopods. Rare alveolitid and favositid corals. Minor Amphipora. Minor dolomite patches. ~10% porosity - interparticle, intercrystalline, intraparticle, vuggy, fracture. Major stromatoporoid zones near 11984.5', 11996' and 11971'.
11971' - 11960.8' 3648.8 m - 3645.7 m	**PELOIDAL GRAINSTONE**. Irregularly mottled to grainy, dark gray to dark brown limestone. Minor amphipora. Minor halite. ~10% porosity - vuggy, intraparticle, interparticle.
11960.8' - 11959' 3645.7 m - 3645.1 m	**DOLOMUDSTONE**. Weakly laminated, anhydrite spotted, buff dolostone. Gradation from limestone (11971' - 11960.8') to dolostone over 2 cm. Upper contact grades from dolostone to limestone over 12 cm. Minor patterned dolostone zones.
11959' - 11956' 3645.1 m - 3644.2 m	**PELOIDAL GRAINSTONE**. Grainy to sparsely laminated, dark brown to gray brown limestone. Abundant peloids. 1 cm anhydrite needles common in upper 3 cm of interval subjacent to anhydrite.
11956' - 11952.5' 3644.2 m - 3643.1 m	**NODULAR ANHYDRITE**. Nodular anhydrite with minor limestone. Limestone zones have ~5% fenestral porosity.
11952.5' - 11950.8' 3643.1 m - 3642.6 m	**ANHYDRITIC DOLOMITIC MUDSTONE**. Laminated to massive and layered, anhydrite halite, limestone and dolostone. Some (very few) laminae may be stromatolitic.
11950.8' - 11941' 3642.6 m - 3639.6 m	**HALITE**. (PRAIRIE EVAPORITE FORMATION)
11941' - 11933' 3636.6 m - 3637.2 m	**DOLOMITIC MUDSTONE**. Laminated, brown dolomitic limestone.
11933' - 11907' 3637.2 m - 3629.3 m	**HALITE**.
11907' - 11905' 3629.3 m - 3628.6 m	**DOLOMUDSTONE**. Finely laminated, gray-brown dolostone.

11905' - 11888'
3628.6 m - 3623.5 m

HALITE.

11888' - 11883'
3623.5 m - 3621.9 m

DOLOMITIC MUDSTONE. Laminated, brown dolomitic limestone.

11883' - 11874'
3621.9 m - 3619.2 m

HALITE AND DOLOMUDSTONE.

NDGS #6296	***Shell Oil Co.***
NESW-09-163-87	Larson #23X-9

* Core is slightly scrambled.

7818' - 7811' 2382.9 m - 2380.8 m	**MUDSTONE.** Finely laminated, gray to dark brown limestone. Stylolites common.
7811' - 7804.5' 2380.8 m - 2378.8 m	**DOLOMUDSTONE.** Finely laminated, light brown dolostone. Rare stylolites. Rare halite in fractures. Minor (< 2 mm) lenses of anhydrite.
7804.5' - 7801' 2378.8 m - 2377.7 m	**MUDSTONE.** Laminated, dark gray and brown limestone. Common brown coarser grained (fine sand size), higher porosity (~20%), patches in an otherwise wavy laminated limestone.
7801' - 7792' 2377.7 m - 2375.0 m	**DOLOMUDSTONE.** Finely laminated, buff dolostone. Laminae thickness rarely reach 4 cm.
7792' - 7789' 2375.0 m - 2374.1 m	**ANHYDRITIC DOLOMITIC MUDSTONE.** Finely laminated, alternating dolomite and limestone. Common anhydrite patches. Calcitic laminae (up to 5 mm thick) and appear `boudinaged' (looks like intestines).
7789' - 7781' 2374.1 m - 2371.6 m	**DOLOMITIC ANYDRITE.** Nodular laminated, gray and light brown.

NDGS #6535 NENE-02-161-83	***Shell Oil Co.*** Greek #41-2
6818' - 6816' 2078.1 m - 2077.5 m	**ASHERN FORMATION**. Streaked, red-brown, dolomitic clay. < 2% porosity.
6816' - 6795' 2077.5 m - 2071.1 m	**ASHERN FORMATION**. Streaked and swirled, green-gray, occasionally red, dolomitic clay. < 2% porosity.
6795' - 6783' 2071.1 m - 2067.5 m	**ASHERN FORMATION**. Streaked and irregularly laminated, green-gray to gray-brown dolomitic clay. ~3% porosity - interparticle.
6783' - 6770' 2067.5 m - 2063.5 m	**BRACHIOPOD WACKESTONE**. Streaked to discontinuously laminated, gray-brown limestone. Minor brachiopods (in < 20 cm layers). Rare crinoids. Rare stylolites. Very rare pyrite. Rare anhydrite. Porosity increases uphole from ~2% (interparticle) to 5% - 8% (interparticle).
6770' - 6764' 2063.5 m - 2061.7 m	**DOLOMITIC CRINOID WACKESTONE**. Streaked to discontinuously laminated, gray-brown and brown limestone. Minor dolomite patches (< 1 cm). Common crinoids. Minor brachiopods. Rare stylolites. ~10% porosity - intercrystalline, rare moldic and fracture.
6764' - 6761' 2061.7 m - 2060.8 m	**DOLOMUDSTONE**. Irregularly streaked to wispy, gray-brown to buff dolostone. Rare crinoids. Common black-brown organic? wisps with buff aureole (aureole has < 6 mm radius). Rare white saddle dolomite crystals in vugs. Very rare white, sucrosic dolomite blebs. ~10% - 15% porosity - intercrystalline, microvuggy.
6761' - 6758' 2060.8 m - 2059.9 m	**DOLOMITIC MUDSTONE**. Massive, light brown dolomitic limestone. Minor (calcitic) crinoids Common white, saddle dolomite crystals in vugs. ~25% - 30% porosity - interparticle, vuggy, intercrystalline.

6758' - 6739' 2059.9 m - 2054.1 m	**MISSING CORE.**
6739' - 6709' 2054.1 m - 2044.9 m	**DOLOMITIC MUDSTONE.** Streaked, gray-brown to light brown limestone. Minor dolomite. Minor crinoids. Rare brachiopods. Very rare platy stromatoporoids. Common stylolites. Very rare white, saddle dolomite in vugs. Very rare anhydrite. ~20% porosity - intercrystalline, vuggy, rare moldic.
6709' - 6676' 2044.9 m - 2034.8 m	**MISSING CORE.**
6676' - 6656' 2034.8 m - 2028.8 m	**MUDSTONE.** Irregularly streaked, light brown to light gray-brown limestone. Rare crinoids and brachiopods. Very rare white, dolomite crystals in vugs. ~ 15% porosity - vuggy, intercrystalline, rare moldic?.
6656' - 6652' 2028.8 m - 2027.5 m	**FOSSILIFEROUS? DOLOPACKSTONE.** Massive, light brown dolostone. Common highly altered fossils??. ~8% porosity - vuggy, interparticle, intercrystalline.
6652' - 6646' 2027.5 m - 2025.7 m	**MISSING CORE.**
6646' - 6614' 2025.7 m - 2016.0 m	**DOLOMITIC WACKESTONE.** Streaked to highly stylolined, light and dark brown limestone. Minor brachiopods. Rare thrombolitic structures. Very rare crinoids. Rare brown dolomite patch. Rare white dolomite crystals in vugs. ~25% porosity - vuggy, moldic, intercrystalline, fracture.
6614' - 6610.5' 2016.0 m - 2014.9 m	**DOLOMITIC STROMATOPOROID? WACKESTONE.** Irregularly laminated (stromatoporoids??) to swirled, brown to light brown and gray-brown dolomitic limestone. Common platy stromatoporoids?. Vugs commonly lined with white crystalline dolomite. ~25% porosity - vuggy, interparticle, intercrystalline, intraparticle, moldic.
6610.5' - 6605' 2014.9 m - 2013.2 m	**MASSIVE CRYSTALLINE DOLOSTONE.** Massive, white crystalline dolostone (80% of interval) interlayered with dolomitic stromatoporoid wackestone (20% of interval) (as in 6614' - 6610.5'). ~15% intercrystalline porosity in white, massive dolostone areas. ~25% porosity in dolomitic stromatoporoid wackestone areas.

6605' - 6597' 2013.2 m - 2010.8 m	**STROMATOPOROID DOLOBOUNDSTONE.** Discontinuously laminated to occasionally thrombolitic, brown dolostone. Minor platy and tabular stromatoporoids. Common light brown dolomite lining vugs. Rare white, saddle dolomite crystals in vugs. ~25% porosity - vuggy, interparticle, intercrystalline, intraparticle.
6597' - 6570' 2010.8 m - 2002.5 m	**MISSING CORE.**
6570' - 6547.5' 2002.5 m - 1995.7 m	**THROMBOLITIC DOLOBOUNDSTONE.** Massive to locally clotted, dark gray-brown dolostone. Minor tabular stromatoporoids. Minor thrombolitic structures. Rare crinoids. Rare light brown dolomite patches. ~20% porosity - fenestral, vuggy, interparticle, intercrystalline.
6547.5' - 6536' 1995.7 m - 1992.2 m	**DOLOMUDSTONE.** Massive to streaked, light brown dolostone. Rare crinoids. Minor stylolites. 20% - 25% porosity - intercrystalline, microvuggy, rare moldic?.
6536' - 6522.5' 1992.2 m - 1988.1 m	**MISSING CORE.**
6522.5' - 6517' 1988.1 m - 1986.4 m	**DOLOMUDSTONE.** Massive to streaked, light brown dolostone. Rare crinoids. Very rare thamnoporid corals. ~15% porosity - interparticle, microvuggy.
6517' - 6505.5' 1986.4 m - 1982.9 m	**DOLOBINDSTONE.** Laminated, light brown to locally buff and dark brown dolostone. Laminae are stromatolitic. Rare *Thamnopora*. Minor stylolites. Very rare anhydrite. ~20% porosity -fenestral, microvuggy, intercrystalline.
6505.5' - 6500' 1982.9 m - 1981.3 m	**ANHYDRITIC DOLOMUDSTONE.** (possible collapse structure??). Fragmented to swirled, gray to dark gray, anhydritic dolostone. Most fragments are laminated: some are massive. Rare blue-gray, bladed anhydrite. No porosity.
6500' - 6467' 1981.2 m - 1971.1 m	**RED (ARGILLACEOUS??) DOLOMUDSTONE.** (top of Winnipegosis Formation). Swirled to massive, RED, argillaceous?? dolostone. Minor anhydrite. < 1% fracture porosity.

6467' - 6465' 1971.1 m - 1970.5 m	**DOLOMUDSTONE**. Fragmented to swirled, gray dolostone. Common sutured contacts between fragments. Fragments are massive.

NDGS #6603	***Chapman Exploration Inc.***
SWSW-36-160-96	State #1-A
10862' - 10853' 3310.7 m - 3308.0 m	**LAMINATED DOLOMUDSTONE**. Laminated, gray and brown dolostone. ~1% fracture porosity.
10853' - 10850' 3308.0 m - 3307.1 m	**PELOIDAL DOLOGRAINSTONE**. Grainy, brown and dark gray dolostone. Abundant 1 mm - 4 mm peloids. Vague layering of peloids - ~4 cm - 12 cm layers. Rare bulbous stromatoporoids. < 5% interparticle porosity.
10850' - 10842' 3307.1 m - 3304.6 m	**ANHYDRITIC DOLOMUDSTONE**. Streaked and swirled, gray-brown anhydritic dolostone. Common patches of blue-gray and white anhydrite. Minor halite in lowest 10 cm. No porosity.

NDGS #6624	***Shell Oil Co.***
SENW-01-161-85	Osterberg #22X-1
7208.5' - 7205' 2197.2 m - 2196.1 m	**THROMBOLITIC DOLOBOUNDSTONE**. Massive and clotted, dark brown and black dolostone. Abundant thrombolitic structures. Some thrombolitic structures are rimmed with stromatoporoids?. Rare stromatoporoids. Very rare thamnoporid corals. Rare white, dolomite crystals in vugs. 10% - 15% porosity - intercrystalline, moldic?, vuggy.
7205' - 7199' 2196.1 m - 2194.3 m	**DOLOMUDSTONE**. Grainy to occasionally discontinuously streaked, light brown dolostone. 15% - 20% porosity - intercrystalline, rare microvuggy. Very rare anhydrite.
7199' - 7195' 2194.3 m - 2193.0 m	**STROMATOPOROID? DOLOWACKESTONE**. Grainy to occasionally streaked, light brown, dolostone. Common stromatoporoid? (fragments?). 20% - 25% porosity - intercrystalline, microvuggy, moldic?.

7195' - 7192.5' 2193.0 m - 2192.3 m	**FOSSILIFEROUS DOLOFLOATSTONE.** Fragmented, green-gray, porous dolostone. Green hue may be due to disseminated pyrite. Fragments are stromatoporitic, stromatolitic? and intraclasts. Stylolitic upper contact. Rare anhydrite. ~25% porosity - interparticle, intercrystalline, microvuggy, moldic?.
7192.5' - 7187' 2192.3 m - 2190.6 m	**DOLOMUDSTONE.** Swirled to soupy, gray to black dolostone. Rare anhydrite. Very rare pyrite. No porosity.
7187' - 7185' 2190.6 m - 2190.0 m	**DOLOMUDSTONE.** Wispy, white to green-gray dolostone. Wisps are green and up to 4 mm long. No porosity.
7185' - 7180' 2190.0 m - 2188.5 m	**ANHYDRITIC DOLOMUDSTONE.** Swirled to plastically fragmented, gray-brown dolostone. Common interfragmental anhydrite. Very rare pyrite. No porosity.
7180' - 7132' 2188.5 m - 2173.8 m	**RED ARGILLACEOUS DOLOMUDSTONE.** Plastically fragmented to rarely wavy laminated, argillaceous, RED dolostone. No porosity.

NDGS #6684 NENW-02-161-85	*Shell Oil Co.* Osterberg #21-2
7569' - 7561' 2307.0 m - 2304.6 m	**ASHERN FORMATION.**
7561' - 7528' 2304.6 m - 2794.5 m	**ASHERN FORMATION.** Laminated to massive, green-gray dolomitic? clay.
7528' - 7527' 2794.5 m - 2794.2 m	**DOLOMUDSTONE.** Mottled to almost nodular, buff dolostone. Ashern - Winnipegosis transition.
7527' - 7515' 2794.2 m - 2790.6 m	**CRINOID WACKESTONE.** Mottled with black streaks and discontinuous laminae, dark gray limestone. Minor brachiopod fragments. Crinoids are rare to common; increasing uphole. Rare stylolites. Rare anhydrite. < 2% porosity.

7515' - 7504'
2790.6 m - 2287.2 m

CRINOID WACKESTONE. Mottled, gray limestone. Abundant crinoids. Common wisps to discontinuously laminated organics?. Rare brachiopods. < 1% porosity.

7504' - 7490'
2287.2 m - 2282.9 m

LAMINATED MUDSTONE. Laminated, gray and black streaked limestone. Common stylolites. Rare calcite sealed fractures. ~2% fracture porosity.

7490' - 7477'
2282.9 m - 2279.0 m

LAMINATED DOLOMITIC MUDSTONE. Laminated, buff dolostone with minor limestone. Anhydrite sealed fractures common. Fracture at 7479' is truncated by laminae. ~20% porosity - intercrystalline, fracture.

7477' - 7472'
2279.0 m - 2277.5 m

LAMINATED MUDSTONE. Laminated, gray limestone. Common stylolites. Sagging of `laminae groups' common. Anhydrite common in sagged areas. Buff, porous dolostone common near anhydrite. Anhydrite in bladed pseudo-rosettes common.

7472' - 7465'
2277.5 m - 2275.3 m

LAMINATED DOLOMITIC MUDSTONE. Laminated, buff dolomitic limestone. Similar to 7590' - 7477'.

7465' - 7449'
2275.3 m - 2270.5 m

ANHYDRITE. Wavy, layered anhydrite, dolostone and rare limestone.

NDGS #7976 — ***Shell Oil Co.***

SWSE-34-161-87 — Golden 34X-34

8419' - 8384.8'
2566.1 m - 2555.7 m

WACKESTONE. Mottled, tan to gray-brown limestone. Minor brachiopods. Rare crinoids and stromatoporoids. Common bladed, blue-gray anhydrite in vugs. Very common white, 1 mm - 3 mm saddle dolomite crystals in vugs. ~30% porosity - mostly vuggy and interparticle, minor intraparticle.

8384.8' - 8382'
2555.7 m - 2554.8 m

DOLOMITIC BRACHIOPOD PACKSTONE Irregularly swirled, brown, white patchy, dolomitic limestone. Brachiopods common although altered and difficult to recognize. Minor crinoids. White patches, are sucrosic dolomite. ~20% porosity - microvuggy, interparticle, minor fracture..

8382' - 8375' 2554.8 m - 2552.7 m	**BRACHIOPOD-CORAL DOLOMITIC WACKESTONE.** Mottled, grading to streaked, light brown to gray brown, dolomitic limestone. Minor brachiopods. Minor corals, including rare Alveolitid corals. White saddle dolomite in vugs common.
8375' - 8369' 2552.7 m - 2550.9 m	**CRINOID-BRACHIOPOD DOLOWACKESTONE.** Mottled and swirled, brown to gray-brown, mostly dolostone. Minor brachiopods and crinoids. Rare solitary horn corals. Common white saddle dolomite crystals in vugs.
8369' - 8367' 2550.9 m - 2550.3 m	**DOLOMUDSTONE.** Massive to sparsely laminated, gray-brown dolostone. ~15% patchy interparticle porosity. Laminae are argillaceous?.
8367' - 8361' 2550.3 m - 2548.4 m	**CORAL-STROMATOPOROID-CRINOID DOLOPACKSTONE / DOLOBOUNDSTONE.** Irregularly laminated to massive to laminated, gray brown and brown dolostone. Irregularly laminated areas contain common corals and crinoids and minor brachiopods. Massive areas contain common corals - alveolitid and solitary horn corals; and rare crinoids. Laminated areas are massive stromatoporoids. 30 cm 'clotted fabric' at 8362' (thrombolitic??).
8361' - 8349' 2548.4 m - 2544.8 m	**MISSING CORE.**
8349' - 8339' 2544.8 m - 2541.7 m	**STROMATOPOROID-CORAL DOLOWACKESTONE / DOLOBOUNDSTONE** Laminated to 'micro'-mottled gray-brown to buff dolostone. Laminae are probably stromatoporoids. Common corals. Other allochems can not be identified due to extensive alteration.
8339' - 8330' 2541.7 m - 2539.0 m	**MISSING CORE.**
8330' - 8327' 2539.0 m - 2538.1 m	**DOLOWACKESTONE.** Mottled to streaked, gray-brown to gray dolostone. Minor platy stromatoporoids. Minor thamnoporid corals. Minor black wispy, organic? seams. ~25% porosity - vuggy, fracture moldic, intraparticle.

8327' - 8324' 2538.1 m - 2537.2 m	**CORAL DOLOWACKESTONE.** Mottled dark brown and brown dolostone. Abundant corals - alveolitid and thamnoporid. Rare crinoids and brachiopods. Slight oil stain. ~25% porosity - intraparticle (corals), interparticle, moldic, vuggy, fracture.
8324' - 8318.8' 2537.2 m - 2535.6 m	**DOLOMUDSTONE.** Mottled, tan to gray-brown dolostone. Common black wisps. Minor stylolites. Rare corals. Rare amphipora??.
8318.8' - 8317.8' 2535.6 m - 2535.3 m	**ANHYDRITIC DOLOMUDSTONE.** Layered cream colored anhydrite and brown dolostone. < 1% porosity, if any.
8317.8' - 8311' 2535.3 m - 2533.2 m	**CORAL DOLOPACKSTONE.** Mottled, dark brown, oil stained dolostone. Abundant thamnoporid corals. Rare brachiopods and stromatoporoids. Very rare crinoids.
8311' - 8308.1' 2533.2 m - 2532.3 m	**DOLOBOUNDSTONE.** Laminated, brown to dark brown, oil stained dolostone. ~10% porosity - fenestral, vuggy, fracture. Gray anhydrite in first 6 cm of interval. Laminae are stromatoporoids.
8308.1' - 8306.2' 2532.3 m - 2531.7 m	**NODULAR ANHYDRITE** with minor dolostone.
8306.2' - 8305' 2531.7 m - 2531.4 m	**NODULAR ANHYDRITE.** Nodular anhydrite and anhydritic dolostone. Minor black wisps.
8305' - 8302' 2531.4 m - 2530.4 m	**PELOIDAL DOLOPACKSTONE?** Irregular, brown and dark brown anhydritic dolostone. Abundant peloids. Abundant anhydrite.

NDGS #10059	*Fulton Producing Co.*
SENE-01-158-96	Seaton #1

11159' - 11133.5'
3401.3 m - 3393.5 m

BRACHIOPOD PACKSTONE. Streaked to mottled, black, very oil rich limestone. Very abundant brachiopods (~40%). Brachiopods size averages ~ 1 cm. Minor crinoids. Rare anhydrite in minor fractures. Brachiopods are all calcite filled and have 'fuzzy' valve boundaries (no original shell material left - replaced by anhydrite).

11133.5' - 11117'
3393.5 m - 2288.5 m

BRACHIOPOD-CRINOID WACKESTONE. Mottled to streaked, black to black-brown, oil rich dolomitic limestone. Common brachiopods. Minor crinoids. Rare corals. Rare anhydrite. Very rare dolomite; occurs enveloping some black, organic? wisps.

11117' - 11113'
3388.5 m - 3387.2 m

DOLOMITIC BRACHIOPOD PACKSTONE. Mottled, gray-brown and black dolomitic limestone. Black areas are limestone (mostly allochems). gray-brown areas are dolostone (mostly matrix). Minor brachiopods. Rare crinoids in dolostone areas. Common brachiopods and minor crinoids in limestone areas.

11113' - 11107'
3387.2 m - 3385.4 m

BRACHIOPOD DOLOWACKESTONE. Mottled, brown to dark brown dolostone. Common brachiopods. Large 6 cm amplitude stylolite at 11108'. Rare anhydrite.

NDGS #10171	*Getty Oil Co.*
NESW-36-161-98	Wildrose #35-11

10518' - 10494'
3205.9 m - 3198.6 m

FOSSILIFEROUS MUDSTONE. Wispy, dark brown-gray limestone. Rare brachiopods. Rare Amphipora near top of interval. Very rare thamnoporid corals. Very rare solitary rugosan coral. Rare anhydrite patches. Very rare pyrite in anhydrite patches. Rare stylolites. ~2% interparticle porosity.

10494' - 10492' 3198.6 m - 3198.0 m	**AMPHIPORA WACKESTONE.** Wispy, gray and brown limestone. Very rare dolomite patches. Common Amphipora. Rare stylolites. Minor anhydrite spots. < 2% porosity - interparticle.

~~~~~~

NDGS #10209 SESW-06-158-95	*Depco Inc.* McGinnity #24-6

* Entire core is at least mildly oil stained. Porosity is ~5% - 25%.

11142' - 11136.5' 3396.1 m - 3394.4 m	**DOLOMITIC BRACHIOPOD WACKESTONE.** Mottled, brown dolomitic limestone. Common brachiopods. Minor codiacean algae. Very rare crinoids. Slightly oil stained. Rare anhydrite. Large stylolite (3 cm amplitude) at 11137'.
11136.5' - 11133' 3394.4 m - 3393.3 m	**BRACHIOPOD DOLOPACKSTONE.** Streaked, dark gray-brown dolostone. Abundant brachiopods. Large stylolite (6 cm amplitude) at 11136'. Oil stained. Dolomite content gradually increases over this and last interval.
11133' - 11125.5' 3393.3 m - 3391.1 m	**DOLOMITIC MUDSTONE.** Massive to slightly wispy, brown, dolomitic limestone. Rare brachiopods. Heavily oil stained grading to lightly oil stained near top of interval.
11125.5' - 11116' 3391.1 m - 3388.2 m	**STROMATOPOROID DOLOWACKESTONE.** Irregular patchy, dark brown and light brown, mostly dolostone. Common stromatoporoid fragments. Rare brachiopods. Very rare thamnoporid corals. Most allochems are calcitic (but not all). Matrix is mostly dolomitic. ~5% intercrystalline porosity.
11116' - 11096' 3388.2 m - 3382.1 m	**STROMATOPOROID-CORAL BOUNDSTONE?/FLOATSTONE?.** Mottled, highly fractured, dark brown to gray-brown, limestone. Common stromatoporoids. Minor brachiopods. Minor Amphipora?. Minor thamnoporid corals. Rare alveolitid corals. Rare solitary horn coral. Very rare 'clotted' fabric (thrombolitic). Fractures are all sealed with calcite.
~~~~~~

11096' - 11092' 3382.1 m - 3380.8 m	**FOSSILIFEROUS MUDSTONE**. Mottled, dark brown and gray limestone. Rare stromatoporoids and brachiopods. Very rare thamnoporid corals. Slight oil stain.
11092' - 11082' 3380.8 m - 3377.8 m	**CODIACEAN ALGAE-STROMATOPOROID WACKESTONE**. Mottled to spotted, gray-brown and dark brown limestone. Abundant codiacean algae. Minor stromatoporoids. Rare Thamnoporid corals. Very rare brachiopods and solitary horn coral. Slight oil stain. Abundant calcite sealed fractures. Rare halite in vugs. Very rare light brown dolomite patches.

NDGS #10348 NENW-30-161-102	***HNG OIL Co.*** Anderson state 30 #2
10080' - 10077.5' 3072.4 m - 3071.6 m	**STROMATOPOROID WACKESTONE**. Gray-brown streaked limestone. Minor stromatoporoids - globular and platy. Very rare brachiopods.
10077.5' - 10063' 3071.6 m - 3067.2 m	**DOLOMUDSTONE**. Dark brown mottled and wispy dolostone. Black-brown (organic?) streaks common. Rare stromatoporoids - globular and platy. Slight oil stain throughout interval.
10063' - 10060' 3067.2 m - 3066.3 m	**DOLOMITIC MUDSTONE**. Dark brown streaked to poorly laminated dolomitic limestone. Transition from underlying dolostone to dolomitic limestone spans 50 cm. Minor white crystalline anhydrite patches. Rare brachiopods and crinoids.
10060' - 10055' 3066.3 m - 3064.8 m	**CORAL-STROMATOPOROID WACKESTONE(FLOATSTONE?)**. Dark brown to gray-brown streaked limestone. Abundant corals -thamnoporid, other branching corals. Minor massive stromatoporoids. Rare platy stromatoporoids. Very slight oil stain throughout interval.

10055' - 10053.5' 3064.8 m - 3064.3 m	**MUDSTONE**. Light brown and light gray-brown mottled to nodular limestone. Minor < 1 mm wisps of anhydrite.
10053.5' - 10049' 3064.3 m - 3062.9 m	**DOLOMITIC MUDSTONE** (DOLOMITIC BINDSTONE?). Light gray-brown, laminated to spotted, almost patterned dolostone. Laminated areas are gray-brown and light brown and generally between 4 mm and 10 mm thick. Anhydrite spots are irregular to ovoid and < 4 mm across.
10049' - 10047.9' 3062.9 m - 3062.6 m	**DOLOBINDSTONE**. Dark brown and brown finely laminated dolostone. Laminae have a clotted texture.
10047.9' - 10047' 3062.6 m - 3062.3 m	**ANHYDRITIC MUDSTONE**. Finely laminated gray and brown limestone. Abundant anhydrite needles.

NDGS #10353 NENW-32-163-101	***Louisiana Land Co.*** Constantine 41-32 #1
9781' - 9775' 2981.2 m - 2979.2 m	**CRINOID WACKESTONE**. Mottled and streaked, gray and brown limestone. Minor crinoids. Rare brachiopods. Very rare stromatoporoid.
9775' - 9773.5' 2979.2 m - 2979.0 m	**CRINOID DOLOWACKESTONE**. Mottled, brown-gray dolostone. Common crinoids. Rare thamnoporid corals. Minor anhydrite needles.
9773.5' - 9771' 2979.0 m - 2978.2 m	**CRINOID DOLOWACKESTONE**. Mottled to locally streaked, dark brown dolostone. Minor crinoids. Minor (bitumen stained) irregular black patches surrounded by a halo of light brown crystalline dolomite.
9771' - 9765' 2978.2 m - 2976.4 m	**DOLOBOUNDSTONE to DOLOWACKESTONE**. Mottled and wispy, dark brown to gray-brown dolostone. Dark brown mottles are stromatoporoids. Gray-brown areas are silt size dolomite. Common (bitumen stained) irregular black patches with a light brown dolomite halo. Minor crinoids. ~10% porosity - intercrystalline, vuggy, fracture, rare intraparticle. Common anhydrite and halite as vug fill.

9765' - 9761' 2976.4 m - 2975.2 m	**MISSING CORE.**
9761' - 9759' 2975.2 m - 2974.5 m	**DOLOBOUNDSTONE to DOLOWACKESTONE.** Same as 9771' -9765'. Halite common in vugs.
9759' - 9752.5' 2974.5 m - 2972.6 m	**DOLOWACKESTONE.** Streaked to locally mottled, dark brown to gray-brown dolostone. Minor bulbous stromatoporoids. Minor irregular bitumen patches with a light brown dolomite halo. Halite in vugs common (up to 2 cm).
9752.5' - 9751' 2972.6 m - 2972.1 m	**MISSING CORE.**
9751' - 9740.5' 2972.1 m - 2968.9 m	**STROMATOPOROID-CODEACIAN ALGAE DOLOWACKESTONE.** Streaked to wispy and discontinuously laminated, dark gray-brown dolostone. Common stromatoporoids (fragments?). Common to minor codiacean algae. Rare crinoids. < 5% porosity - vuggy (mostly filled by halite), interparticle.
9740.5' - 9733.2' 2968.9 m - 2966.7 m	**PELOIDAL DOLOPACKSTONE.** Mottled to discontinuously laminated, dark brown dolostone. Abundant peloids. Rare ~20 cm peloidal layers. Common codiacean algae? in mottled areas. Minor tabular stromatoporoids and rare globular stromatoporoids. Discontinuous laminae are very porous and the mottled areas are not. < 1% overall porosity.
9733.2' - 9730' 2966.7 m - 2975.7 m	**DOLOMUDSTONE.** Laminated, gray to buff dolostone. Very rare 10 cm patterned dolomite area. Abundant anhydrite needles. Rare anhydrite patches. No porosity.
9730' - 9725.5' 2975.7 m - 2964.3 m	**DOLOMUDSTONE.** Disrupted laminated to streaked, gray-brown to gray dolostone. Minor tabular stromatoporoids. Minor peloids. Common anhydrite as vug fill and replacement. No porosity.
9725.5' - 9723' 2964.3 m - 2963.6 m	**DOLOBINDSTONE** (stromatolitic). Laminated, brown dolostone. Abundant anhydrite in 5 cm - 8 cm zones. ~2% porosity - microvuggy.

9723' - 9721' 2963.6 m - 2963.0 m	**LAMINATED DOLOMUDSTONE**. Weakly laminated to mottled, gray-brown to brown dolostone. Rare < 3 cm peloidal layer. Common halite.

NDGS #10395 NENE-35-161-98	*Getty Oil Co.* Wildrose C#35-1
10493' - 10429' 3198.3 m - 3178.6 m	**CRINOID-BRACHIOPOD WACKESTONE to MUDSTONE**. Mottled, dark gray to black limestone. Abundant black discontinuous laminae of clay?. Common crinoids. Common brachiopods. Minor to rare thamnoporid corals. Very rare favositid coral and stromatoporoids. Common fractures. Porosity < 3%.
10429' - 10421' 3178.6 m - 3176.3 m	**DOLOMITIC MUDSTONE**. Discontinuously laminated to mottled, gray-brown limestone. Common stylolites (up to 16 mm amplitude). Very rare crinoids and brachiopods.
10421' - 10405' 3176.3 m - 3171.4 m	**DOLOMITIC CODIACEAN ALGAE WACKESTONE**. Finely laminated to streaked, dark gray to gray limestone. Dolomite content increases slightly downhole. Minor brachiopods. Common codiacean algae in the upper 1 meter on interval. Rare gastropods. Very rare crinoids. Rare anhydrite as vug fill.
10405' - 10401.2' 3171.4 m - 3170.3 m	**DOLOMUDSTONE**. Massive, light gray-brown dolostone. Upper contact missing.
10401.2' - 10400.8' 3170.3 m - 3170.2 m	**LAMINATED DOLOMUDSTONE**. Laminated, black and dark gray dolostone. Minor finely dispersed pyrite.
10400.8' - 10399' 3170.2 m - 3169.6 m	**DOLOMUDSTONE**. Massive to minor laminated, gray dolostone.
10399' - 10397.5' 3169.6 m - 3169.2 m	**DOLOMUDSTONE**. Laminated, dark gray and brown dolostone.
10397.5' - 10396' 3169.2 m - 3168.7 m	**DOLOMITIC MUDSTONE**. Laminated to streaked, dark gray to black dolostone and limestone.

10396' - 10389'
3168.7 m - 3166.6 m

MUDSTONE. Massive to locally mottled and streaked, gray-brown to gray limestone. Rare corals. Rare encrusting stromatoporoids. Rare disseminated dolomite. Minor anhydrite in vugs.

10389' - 10388.4'
3166.6 m - 3166.4 m

BINDSTONE. Laminated, dark brown and brown limestone. Laminae are stromatolitic. Rare prism cracks in stromatolitic laminae. Rare 4 cm peloidal GRAINSTONE layer. Common anhydrite patches.

10388.4' - 10387'
3166.4 m - 3166.0 m

ANHYDRITE. Mottled, dark gray limestone interlayered with `chicken wire' anhydrite.

10387' - 10386.2'
3166.0 m - 3165.7 m

PELOIDAL GRAINSTONE to PACKSTONE. Massive to discontinuously laminated, dark brown limestone. Anhydrite needles common in lower 5 cm. Common peloids in upper 15 cm. Laminated areas are stromatoporoids. Abundant halite in vugs.

10386.2' - 10385.6'
3165.7 m - 3165.5 m
3165.8

NODULAR ANHYDRITE.

10385.6' - 10381.6'
3165.5 m - 3164.3 m

DOLOMITIC PELOIDAL PACKSTONE. Grainy, dark brown limestone. Abundant peloids. Minor tabular stromatoporoids. Common halite. Minor anhydrite. Possible calcrete (pyrite replaced).

10381.6' - 10376.1'
3164.3 m - 3162.6 m

ANHYDRITIC DOLOMUDSTONE. Mottled to locally laminated and streaked, gray-brown to gray dolostone. Abundant gray anhydrite. Minor white anhydrite.

10376.1' - 10374'
3162.6 m - 3162.0 m

NODULAR ANHYDRITE. Nodular, blue-gray anhydrite with buff to pinkish gray dolostone. Common halite in vugs and fracture fill.

NDGS #10480 — ***Depco Inc.***

SWNE-07-158-95 — Skarderud #22-7

11205' - 11204.5'
3415.3 m - 3415.1 m

MUDSTONE. Slightly streaked, black limestone. Rare corals, crinoids and brachiopods. Fossils difficult to identify due to dissolution.

11204.5' - 11203' 3415.1 m - 3414.7 m	**BRACHIOPOD PACKSTONE.** Mottled to nodular, black and gray limestone. Brachiopods common. Calcite crystals common in deformed vugs. Common horizontal and vertical fractures. Porosity is poor, except in fractures.
11203' - 11202' 3414.7 m - 3414.4 m	**INTRACLAST WACKESTONE.** 2 - 3 cm fragments of cream colored limestone in a dark gray limestone matrix. Matrix is very fine grained and comprises ~60% of the interval. Fragments display a `ghost structure' similar to stromatoporoids. Minor vertical stylolites sinistrally offset layers by 5 mm.
11202' - 11192' 3414.4 m - 3411.3 m	**BRACHIOPOD PACKSTONE.** Mottled to nodular, black and gray limestone. Abundant brachiopods. Rare crinoids. Minor calcite sealed fractures. <3% porosity.
11192' - 11174' 3411.3 m - 3405.8 m	**BRACHIOPOD WACKESTONE.** Mottled and wispy, gray-brown and gray limestone. Common brachiopods. Rare crinoids. Very rare stromatoporoids. Very rare thamnoporid corals. Rare stylolites. Very rare white dolomite always found near fractures.
11174' - 11163' 3405.8 m - 3402.5 m	**DOLOWACKESTONE.** Mottled and wispy, dark brown, oily dolostone. Minor fossils (difficult to identify due to alteration). Minor stylolites. ~10% porosity - interparticle, minor fracture, moldic, rare vuggy. Mottles are almost always rimmed with a thin black rim. Rare halite in vugs.
11163' - 11159' 3402.5 m - 3401.3 m	**DOLOMUDSTONE.** Massive, oil stained, black-brown dolostone. A brecciated zone (tectonic fracture?), running parallel to the core axis, is at least 5 cm wide and is seen between 11163' - 11160.5'. Contact between the brecciated zone and the massive dolostone is sharp (over 3 mm) and is lined with a thin cream to brown dolomite.
11159' - 11140' 3401.3 m - 3395.5 m	**DOLOMUDSTONE.** Mottled, dark brown and brown, oil stained dolostone. Oil content gradually decreases uphole. Rare crinoids and brachiopods. Possible rare platy stromatoporoids. Common vertical fractures. Minor halite in some fractures.

11140' - 11138' 3395.5 m - 3394.9 m	**STROMATOPOROID-CORAL DOLOPACKSTONE.** Fossiliferous, brown and gray-brown dolostone. Fossils are all calcitic, matrix is all dolomitic. Common stromatoporoids and corals. Minor brachiopods and crinoids. Rare oil stains.
11138' - 11121' 3394.9 m - 3389.7 m	**DOLOMITIC STROMATOPOROID PACKSTONE to STROMATOPOROID BOUNDSTONE.** Irregularly laminated to swirled, brown-gray limestone. Minor dolomitic areas near upper and lower contacts. Abundant stromatoporoids. Rare corals and crinoids. Very rare brachiopods. Vertical fracture (<0.05 mm) swarms common. Minor halite. ~20% - 25% porosity - fracture, vuggy, intraparticle, interparticle, moldic?.
11121' - 11115' 3389.7 m - 3387.9 m	**ANHYDRITIC DOLOWACKESTONE.** Swirled, white to cream, anhydrite and dolostone. Minor corals. Rare stromatoporoids. Rare crinoids. Rare peloidal layers. Porosity is negligible. Gradational upper contact. Common anhydrite.
11115' - 11108.1' 3387.9 m - 3385.7 m	**DOLOMITIC MUDSTONE.** Mottled, dark brown and gray limestone. Minor dolomite and white anhydrite. Common halite. Common vertical fractures - mostly filled with halite. Less than 5% porosity - intercrystalline, fracture.
1108.1' - 11106' 3385.7 m - 3385.1 m	**DOLOMUDSTONE.** Laminated, dark brown dolostone. Minor halite and anhydrite. 20 cm mottled, white anhydrite at lower contact.
11106' - 11102' 3385.1 m - 3383.9 m	**DOLOMUDSTONE.** Laminated, gray-brown dolostone. Abundant anhydrite.
11102' - 11098' 3383.9 m - 3382.7 m	**ANHYDRITIC DOLOMUDSTONE.** Laminated, brown dolostone. Halite in fractures and vugs common. Common anhydrite - usually in layers < 2 cm thick.

NDGS #10830	***Louisiana Land and Expl. Co.***
SESE-8-163-99	Thomte 1 44-8
9639' - 9635' 2938.0 m - 2936.7 m	**CORAL DOLOWACKESTONE**. Dark gray-brown streaked and finely laminated dolostone. Laminated zones are minor. Minor corals. Rare brachiopods. Common anhydrite as fracture fill and replacement of brachiopods. Rare halite. Very rare stylolites (4 mm amplitude).
9635' - 9630.5' 2936.7 m - 2935.4 m	**DOLOMUDSTONE**. Dark gray-brown and light brown mottled dolostone. Black-brown (organic?) wisps are surrounded by a light brown area, all within a dark gray-brown matrix. Rare stylolites (< 5 mm ampl.) Unsealed vertical fractures common.
9630.5' - 9596' 2935.4 m - 2924.9 m	**DOLOMUDSTONE**. Dark brown, streaked to discontinuously laminated dolostone. Oil stained throughout interval. Common stylolites (< 5 mm ampl.). Anhydrite is common in ovoid 'spots' 1 mm to 4 mm across. Minor pyrite patches < 1 mm across, mostly very close to stylolites. Minor black-brown (organic?) wisps. An organic wisps containing pyrite is found crosscutting a stylolite. Pyrite was also found inside an anhydrite 'spot' surrounded by black-brown organic matter at the termination of a stylolite. Overall pyrite is rare and is usually associated with stylolites. Very rare platy stromatoporoids and Thamnopora. Rare halite in minor fractures near the top of the interval.
9596' - 9589' 2924.9 m - 2922.7 m	**AMPHIPORA DOLOWACKESTONE to locally DOLOPACKSTONE**. Dark brown, streaked to wispy dolostone. Abundant amphipora?. Minor anhydrite spots. Rare stylolites. Pyrite and hematite rare.
9589' - 9585' 2922.7 m - 2921.5 m	**DOLOMUDSTONE**. Dark brown to gray-brown streaked dolostone. Rare amphipora. Rare stylolites. Rare anhydrite spots. Very rare pyrite.
9585' - 9581' 2921.5 m - 2920.3 m	**DOLOBINDSTONE**. Wavy laminated dolostone interlayered with intestine-shaped laminae of anhydrite. Abundant stylolites at laminae contacts. Locally dispersed pyrite.

9581' - 9579' 2920.3 m - 2919.7 m	**DOLOBINDSTONE**. Gray-brown to gray and brown laminated dolostone. Common stylolites. Common vertical fractures. Rare pyrite.

NDGS #11872	***Challanger Minerals Inc.***
NWNE-29-157-88	Alvstad #31-29
10091' - 10083' 3075.7 m - 3073.3 m	**STROMATOPOROID CODIACEAN ALGAE DOLOBOUNDSTONE (DOLOPACKSTONE?).** Irregularly laminated to laminated, light brown to brown, dolostone. Common globular stromatoporoids. Common codiacean algae. Minor brachiopods. Rare corals. White dolomite commonly replaces fossils except stromatoporoids. White, sucrosic anhydrite common in < 6 cm layers in lowest 30 cm of interval. Rare stylolites. Fossil microstructure poorly preserved in stromatoporoids and some corals, otherwise no microstructure preserved.
10083' - 10066' 3073.3 m - 3068.1 m	**FOSSILIFEROUS DOLOPACKSTONE**. Swirled to irregular, light brown to dark brown dolostone. Common codiacean algae. Minor globular and platy stromatoporoids - replaced with cream-colored sucrosic dolomite and poorly preserved microstructure. Minor crinoids and corals. Rare identifiable brachiopods. All fossils identified by external morphology only -very poor internal preservation. Minor bladed anhydrite. ~ 25% porosity - interparticle, minor moldic.
10066' - 10053' 3068.1 m - 3064.2 m	**DOLOMUDSTONE**. Nodular to mottled, cream and brown dolostone. Abundant black stylolines. Identification of fossils is impossible due to high degree of alteration. ~ 25% - 30% porosity- interparticle, rare moldic. rare anhydrite spots.
10053' - 10039' 3064.2 m - 3059.9 m	**FOSSILIFEROUS? DOLOMUDSTONE** Streaked to irregularly mottled dolostone. Fossils unidentifiable. Common bladed anhydrite. Common sutured mottle contacts. ~15% porosity - interparticle, microvuggy. .

10039' - 10033' 3059.9 m - 3058.1 m	**BRACHIOPOD DOLOWACKESTONE.** Mottled (on a small scale), brown dolostone. Common brachiopods (partially preserved). Sutured contacts common. ~15% - 20% porosity - interparticle, moldic?.

NDGS #12692 NENE-27-161-93	***Marathon Oil*** Aardvark #27-1
10739' - 10731.5' 3273.2 m - 3271.0 m	**BRACHIOPOD WACKESTONE.** Mottled, gray and black limestone. Common brachiopods. Minor crinoids. Rare bladed anhydrite in vugs.
10731.5' - 10714' 3271.0 m - 3265.6 m	**MUDSTONE.** Finely laminated, gray limestone. Common stylolites at laminae contacts. Common calcite sealed vertical fractures.
10714' - 10699.5' 3265.6 m - 3261.2 m	**MUDSTONE.** Alternating laminated and massive limestone. Laminae are occasionally wavy. Minor anhydrite. Rare pyrite. Stylolites common - mostly at contacts between massive and laminated areas. Massive areas contain common elongate, discontinuous anhydrite streaks. Minor calcite sealed vertical and horizontal fractures.
10699.5' - 10696' 3261.2 m - 3260.1 m	**LAMINATED MUDSTONE.** Disrupted, laminated brown limestone. White, sucrosic anhydrite seams (8 mm thick) common. Large, internally clotted pendant structure (burrow???) at 10699' surrounded with gray anhydrite with black anhydrite spots which disrupt the laminae. Pendant structure is 6 cm high and spans the width of core (~8 cm).
10696' - 10690' 3260.1 m - 3258.3 m	**LAMINATED MUDSTONE.** Finely laminated, gray-brown to brown limestone. Rare, 1 mm dolomite laminae. Common anhydrite spots. Very rare calcite sealed vertical fractures.
10690' - 10689.6' 3258.3 m -3258.2 m	**DOLOMUDSTONE.** Massive, brown dolostone. Very rare, < 2 mm anhydrite spots.

10689.6' - 10688' 3258.2 m - 3257.7 m	**ANHYDRITIC MUDSTONE**. Nodular laminated limestone. Rare (< 2 mm) dolomite laminae. Common anhydrite.
10688' - 10687' 3257.7 m - 3257.4 m	**MUDSTONE**. Massive, gray-brown.
10687' - 10679' 3257.4 m - 3255.0 m	**ANHYDRITE**. Nodular laminated anhydrite with common calcitic and dolomitic areas.

NDGS #12786 SWNE-26-156-91	***Marathon Oil*** Lerado #26-1
11020' - 11013' 3358.9 m - 3356.8 m	**DOLOMITIC MUDSTONE**. Massive, gray-brown limestone with irregular patches of dolostone (~80% limestone, 20% dolostone). Dolostone patches can be up to 20 cm across. Horse-tail stylolites common in limestone areas only. Rare brachiopods. Rare anhydrite. Dolostone patches contain minor internal laminae. Dolostone patches have a 1 mm - 2 mm aureole of buff dolomite -transition between dolostone and limestone?. Rare saddle dolomite crystals at 11018.5'. < 5% porosity - intercrystalline, microvuggy, moldic.
11013' - 11011.5' 3356.8 m - 3356.3 m	**DOLOMITIC MUDSTONE**. Similar to 11020' - 11013'. Smaller dolostone patches (< 5 cm). Slightly darker in color. ~15% porosity - vuggy, intercrystalline, moldic. Upper contact is very sharp - interval ends with a stylolite.
11011.5' - 11009' 3356.3 m - 3355.5 m	**DOLOMUDSTONE**. Streaked to irregular, buff dolostone. Streaks are black (organic?). < 1% porosity.
11009' - 11005' 3355.5 m - 3354.3 m	**DOLOMITIC BRACHIOPOD-CODIACEAN ALGAE WACKESTONE**. Discontinuously laminated, dark brown-gray limestone. Minor light brown dolomitic patches. Minor brachiopods and codiacean algae. Rare crinoids. Common stylolites. Rare saddle dolomite crystals. ~15% porosity - vuggy, moldic, intercrystalline.

11005' - 10993' 3354.3 m - 3350.7 m	**STROMATOPOROID DOLOBOUNDSTONE**. Layered, dark brown-gray and brown dolostone. Layers are highly altered stromatoporoids (no preserved internal structure). Common tabular and rare globular stromatoporoids. Rare (3 cm - 4 cm) codiacean algae layers - porosity here reaches 25%. Rare anhydrite. Minor saddle dolomite in vugs. ~ 15% - 20% porosity - vuggy, interparticle, intercrystalline, rare moldic.
10993' - 10989' 3350.7 m - 3349.4 m	**CODIACEAN ALGAE DOLOPACKSTONE**. Massive, light brown grading to dark brown dolostone. Abundant codiacean algae. Rare platy stromatoporoids. ~ 15% porosity - vuggy, fenestral, intercrystalline.
10989' - 10987.8' 3349.4 m - 3349.1 m	**CODIACEAN ALGAE DOLOPACKSTONE**. Massive, light brown dolostone. Abundant codiacean algae. Minor crinoids. Rare stromatoporoids. ~25% porosity - interparticle, intraparticle, rare vuggy.
10987.8' - 10982' 3349.1 m - 3347.3 m	**DOLOWACKESTONE**. Massive, dark brown, oil stained dolostone. Common thamnoporid corals. Minor platy stromatoporoids. Rare crinoids. Rare stylolites. ~10% porosity - intercrystalline, interparticle, intraparticle, rare microvuggy.
10982' - 10979.5' 3347.3 m - 3346.6 m	**CORAL DOLOBAFLESTONE** (DOLOFLOATSTONE?). Massive, light to dark brown dolostone. Common branching corals. Matrix is oil stained and dolomud. ~15% porosity - intraparticle, intercrystalline, vuggy.
10979.5' - 10974' 3346.6 m - 3344.9 m	**DOLOWACKESTONE**. Swirled and clotted, dark brown, oil stained dolostone. Rare massive? and platy stromatoporoids. Rare codiacean algae, crinoids and corals. Rare bladed, blue-gray anhydrite. Abundant black (organic?) streaks.
10974' - 10970.5' 3344.9 m - 3343.8 m	**PELOIDAL DOLOPACKSTONE?**. Granular, dark brown dolostone. Rare globular stromatoporoids. Rare bladed, blue-gray anhydrite in vugs. Rare halite. Rare sucrosic dolomite patches (< 10 cm).

10970.5' - 10969' 3343.8 m - 3343.4 m	**DOLOMUDSTONE**. Swirled, brown dolostone. Abundant, black (organic?) streaks. Common stylolites.
10969' - 10964' 3343.4 m - 3341.8 m	**FOSSILIFEROUS DOLOWACKESTONE**. Clotted and swirled, dark brown dolostone. Minor platy stromatoporoids and thamnoporid corals. Rare crinoids. Single occurrence of a hexacoral. Common stylolites. Rare anhydrite. Abundant halite. ~10% - 15% porosity - interparticle, intercrystalline, intraparticle.

APPENDIX C: SAMPLE LOCATIONS

APPENDIX C: SAMPLE LOCATIONS

TABLE OF CONTENTS
*****PAGE NUMBERS APPLY TO APPENDIX C ONLY***

SAMPLE LOCATIONS

Introduction

Core samples were collected with the permission of the Wilson M. Laird Core and Sample Library in Grand Forks, North Dakota. Sample sizes were roughly 1 cubic inch and were cut to thin section dimensions. Core samples taken are listed in the table below.

Core samples are prefixed by the NDGS well number and individual core samples are numbered sequentially according to drilled core depths. A brief comment about each sample is given in the last column.

NDGS #35

KB = 2390'

Sample Number	Drill Depth	depth (m Subsea)	Comments
35-1	11660'	-2,844	Silurian, Interlake Fm. - Dolo.
35-2	11638'	-2,837	Red, Ashern Formation.
35-3	11633'	-2,836	Base of Wpgosis. - Anhydrite blobs in limestone.
35-4	11612'	-2,829	Red to gray-black mudstone.

NDGS #793

KB = 2102'

Sample Number	Drill Depth	depth (m Subsea)	Comments
793-1	11448'	-2848.7	Algal?/Coral?
793-2	11486.8'	-2860.5	Stromatoporoid?/Coral?
793-3	11508.5'	-2867.1	Coral/Crinoid?Brach.
793-4	11511'	-2867.9	Crinoid-Brach. layer.
793-5	11524'	-2871.8	Mottled L.S. w/Brachs.

NDGS #2638

KB = 1495'

Sample Number	Drill Depth	depth (m Subsea)	Comments
2638-1	5053'	-1,084.5	Massive Dolo.
2638-2	5045.5'	-1,082.2	Laminated Dolo.

NDGS #2800

KB = 1887'

Sample Number	Drill Depth	depth (m Subsea)	Comments
2800-1	8300'	-1954.7	Anhydrite and dolomite.
2800-2	8302'	-1955.2	Interlaminated Limestone and dolostone.
2800-3	8305'	-1956.2	Interlaminated Limestone and dolostone.
2800-4	8307'	-1956.8	Laminated limestone with anhydrite and pyrite.
2800-5	8312'	-1958.3	limestone with anhydrite and pyrite.
2800-6	8312.5'	-1958.5	limestone and dolostone.
2800-7	8314'	-1959.0	Laminated dolostone.

NDGS #4340

KB = 1972'

Sample Number	Drill Depth	depth (m Subsea)	Comments
4340-1	11547'	-2918.5	Mottled Wackestone (Lower Wpgosis).
4340-2	11543'	-2917.2	Mottled Wackestone with dolomite patches.
4340-3	11530'	-2913.3	Stromatoporoid (patch reef).
4340-4	11519'	-2909.9	Mudstone (same stuff as just below pinnacle reef).
4340-5	11509'	-2906.9	White dolomite in microvugs of mottled areas.
4340-6	11506'	-2906.0	Discontinuously laminated dolostone.
4340-7	11503'	-2905.0	Dark brown dolostone.
4340-8	11495'	-2902.6	Disrupted laminated dolostone with anhydrite.
4340-9	11494'	-2902.3	Dolomudstone.
4340-10	11493.5'	-2902.2	Massive (?peloidal) Dolostone.
4340-11	11489'	-2900.8	Laminated and ?peloidal dolostone.

NDGS #4597

KB = 2338'

Sample Number	Drill Depth	depth (m Subsea)	Comments
4597-1	11928'	-3227.8	Massive, oily dolomudstone.
4597-2	11925'	-3226.9	Dolomitic allochems in massive, oily dolomudstone.
4597-3	11924.5'	-3226.7	Striped stromatoporoid.
4597-4	11924'	-3226.6	Partial dolostone.
4597-5	11922'	-3226.0	Stromatolitic?.
4597-6	11920'	-3225.4	Partial dolostone, celestite (anhydrite) needles.

4597-7	11918'	-3224.8	Stromatolitic.
4597-8	11917'	-3224.5	Partial dolostone, oily.
4597-9	11913'	-3223.3	Massive, oily, vaguely laminated dolostone.
4597-10	11909'	-3222.0	Disrupted laminated, oily dolostone.
4597-11	11896'	-3218.1	Patterned dolostone.

NDGS #4618

KB = 2413'

Sample Number	Drill Depth	depth (m Subsea)	Comments
4618-1	11758'	-2848.4	Anhydrite in crinoid Brach. wackestone.
4618-2	11742'	-2843.5	crinoid wackestone with organics?/argillaceous.
4618-2.5	11731'	-2840.1	Stromatoporoid - replaced.
4618-3	11729.5'	-2839.5	Hexacoral.
4618-4	11726'	-2838.6	Dolomitic patch in coral crinoid wackestone.
4618-5	11701'	-2831.0	Globular stromatoporoid in stromatoporoid wackestone.
4618-6	11698'	-2830.1	Platy stromatoporoid
4618-7	11689'	-2827.3	Porous dolomitic patches in dolomitic mudstone.
4618-8	11682'	-2825.2	Laminated dolomitic mudstone.
4618-9	11676'	-2823.3	laminated dolomitic mudstone (stromatolitic??).
4618-9.5A	11667'	-2820.6	Dolostone limestone contact.
4681-9.5B	11667'	-2820.6	(Dolostone limestone contact?)
4618-10	11666'	-2820.3	Porous dolomudstone.

NDGS #4790

KB = 1517'

Sample Number	Drill Depth	depth (m Subsea)	Comments
4790-1	6449'	-1503.3	Swirled, porous, crinoid dolowackestone.
4790-2	6444.5'	-1501.9	Crinoids in swirled, porous, crinoid dolowackestone.
4790-3	6439'	-1500.2	Clotted texture.
4790-4	6436'	-1499.3	Contact - clotted area and coral dolofloatstone.
4790-5	6430'	-1497.5	Codiacean algae (white dolomite crystals).

NDGS #4923

KB = 1573'

Sample Number	Drill Depth	depth (m Subsea)	Comments
4923-1	6732.5'	-1572.6	Middle of swirl - near massive fabric.
4923-2	6727'	-1570.9	Same as 4923-1.
4923-3	6725'	-1570.3	Streaked dolostone.
4923-4	6694'	-1560.9	Porous, stylolitic dolostone with anhydrite.
4923-5	6683'	-1557.5	Massive dolomudstone with moldic porosity.
4923-6	6682'	-1557.2	Anhydrite - dolomite rim in massive dolomudstone.
4923-7	6680.5'	-1556.8	Stromatolitic dolostone. (platy stromatoporoids.)
4923-8	6673'	-1554.5	Stromatolitic area with fenestral porosity.

NDGS #4924

KB = 1514'

Sample Number	Drill Depth	depth (m Subsea)	Comments
4924-1	5920'	-1342.9	Coral, Brach. in Dolo.
4924-2	5926.5'	-1344.9	Cream surfaced Dolo.
4924-3	5951'	-1352.4	Mottled Dolo.
4924-4	6015'	-1371.9	Coral? in Dolostone.

NDGS #5088

KB = 2409'

Sample Number	Drill Depth	depth (m Subsea)	Comments
5088-1	12015'	-2938.9	Anhydrite and Dolo.
5088-2A	12019'	-2929.1	Patterned Dolo.
5088-2B	12019'	-2929.1	Patterned Dolo.
5088-3	12021'	-2930.0	Anhydrite needles in L.S.
5088-4	12022.5'	-2930.2	Patterned Dolo.
5088-5	12027'	-2931.6	Nearly massive Packstone.
5088-6	12030'	-2932.5	Clotted fabric.
5088-7	12033'	-2933.4	Anhydrite needles.
5088-8	12037.5'	-2934.8	Soft sed. deformation?
5088-9	12061.5'	-2942.1	Stromatoporoids.
5088-10	12064.5'	-2943.0	Stromatoporoids.

5088-11A	12075'	-2946.2	Layered mottles.
5088-11B	12075'	-2946.2	Layered mottles.
5088-12	12078'	-2947.1	Altered Brachs.???
5088-13	12141'	-2966.3	Layered mottles.?
5088-14	12157'	-2971.2	Fracture.
5088-15	12163.5'	-2973.2	Fracture.
5088-16	12181'	-2978.5	Mostly matrix.
5088-17	12198'	-2983.7	Crinoids.
5088-18	12205'	-2985.8	Mostly mottles.
5088-19A	12219'	-2989.2	Brach. zone.
5088-19B	12219'	-2989.2	Brach. zone.
5088-20	12223'	-2991.3	Gray/dark brown mottled.
5088-21	12225'	-2991.9	Mottled.
5088-22	12226.5'	-2992.4	Erosion surface?
5088-23	12228.5'	-2993.0	Wpgosis.
5088-24	12229'	-2993.1	Ash/Wpgosis. transition.
5088-25	12230'	-2993.4	Ash/Wpgosis. transition.
5088-26	12232'	-2994.0	Ash/Wpgosis. transition.
5088-27	12233'	-2994.4	Ash/Wpgosis. transition.
5088-28	12235'	-2995.0	Ash/Wpgosis. transition.
5088-29	12240'	-2996.5	Ashern Fm.
5088-30	12244'	-2997.7	Ashern Fm.

NDGS # 5158

KB = 2117'

Sample Number	Drill Depth	depth (m Subsea)	Comments
5158-1	8830'	-2046.1	Mottled Dolo. w/Halite/Sylvite.
5158-2	8835'	-2047.6	Laminated buff to black Dolo.
5158-3	8836.1'	-2048.0	Mottled almost patterned Dolo.
5158-4	8844.1'	-2049.5	Dolo. w/brown Anhydrite.
5158-5	8849'	-2051.9	Grey/green Brach. Dolomudstone.
5158-6	8854'	-2053.4	Laminated siltstone/mudstone.
5158-7	8869'	-2058.0	Gray/green mudstone.

NDGS # 5184

KB = 1552'

Sample Number	Drill Depth	depth (m Subsea)	Comments
5184-1	4869.5'	-1011.2	Laminated porous dolostone.
5184-2	4870'	-1011.3	Spotted to patterned dolostone.
5184-3	4873'	-1012.2	Stylolites (Lots) in dolostone.
5184-4	4878'	-1013.8	Massive porous dolostone.

NDGS # 5185

KB = 1503'

Sample Number	Drill Depth	depth (m Subsea)	Comments
5185-1	5283'	-1152.1	Streaked dolomitic wackestone.
5185-2	5280'	-1151.2	Streaked dolomitic wackestone.
5185-3	5274'	-1149.4	Stromatop. in dolomitic wackestone.
5185-4	5273'	-1149.1	Celestite (anhydrite) blades in stromatoporoid.
5185-5	5273.5'	-1179.7	Bulbous stromatop. with small `debris' layers.
5185-6	5270'	-1148.2	Same as 5185-5 with celestite (anhydrite) blades.
5185-7	5269.9'	-1148.2	Same as 5185-6.
5185-8	5268'	-1147.6	Tabular stromatoporoid.
5185-9	5263'	-1146.0	Stromatoporoid with bladed celestite (anhydrite).
5185-10	5261'	-1145.4	Swirled dolowackestone.
5185-11	5259'	-1144.8	Dolowackestone subjacent to anhydrite layer.
5185-12	5255'	-1143.6	Alveolitid coral and stromatop: anhy. xtls.
5185-13	5252.5'	-1142.8	Discontinuous laminations.
5185-14	5252.4'	-1142.8	Thamnopora directly above 5185-13.
5185-15	5250.5'	-1142.2	Bulbous stromatoporoid with `debris' layer.
5185-16	5250.4'	-1142.2	Debris layer with platy stromatoporoid.
5185-17	5346.5'	-1171.5	Bulbous stromatop. with stylolites anhydrite).
5185-18	5241'	-1139.3	Dolomitic stromatop. floatstone? /wackestone.
5185-19	5237'	-1138.1	Anhydrite in dolomitic fossiliferous packstone.
5185-20	5235'	-1137.5	Dolomitic fossiliferous packstone.
5185-21	5232'	-1136.6	Codiacean algae in peloidal grainstone.
5185-22	5230'	-1136.0	Dolomudstone with pyrite.
5185-23	5229'	-1157	Stromatolitic.

NDGS # 5257

KB = 2223'

Sample Number	Drill Depth	depth (m Subsea)	Comments
5257-1	11167.5'	-2726.3	Contact: Laminated limestone/Swirled dolostone.
5257-2	11166'	-2725.8	Black (?anhydrite) needles.
5257-3	11158'	-2723.4	Aureole around fracture.
5257-4	11146'	-2719.7	Displaced dolomite layer in limestone.
5257-5	11141'	-2718.2	Disrupted dolostone laminae.

NDGS # 5277

KB = 1543'

Sample Number	Drill Depth	depth (m Subsea)	Comments
5277-1	4896'	-1022.0	laminated area of otherwise massive dolostone.
5277-2	4896.5'	-1022.1	Massive dolostone.
5277-3	4899'	-1022.9	Dolostone.
5277-4	4902'	-1023.8	?Codiacean algae? in dolostone.
5277-5	4906'	-1025.0	?Codiacean algae? in Dolostone.
5277-6	4906.5'	-1025.2	?Codiacean algae? in Dolostone

NDGS # 5279

KB = 1476'

Sample Number	Drill Depth	depth (m Subsea)	Comments
5279-1	5100'	-1104.6	Laminated dolostone.
5279-2	5102'	-1105.2	Pattern (looking) limestone.
5279-3	5103'	-1105.5	Laminated limestone.
5279-4	5108'	-1107.0	Massive limestone.
5279-5	5112'	-1108.3	Anhydrite replaced brachs. in limestone.

NDGS # 5280

KB = 1527'

Sample Number	Drill Depth	depth (m Subsea)	Comments
5280-1	4717'	-972.3	Stromatoporoid in fossiliferous grainstone.
5280-2	4716'	-972.0	Stromatop. and thamnopora in foss. grainstone.
5280-3	4715'	-971.1	Fossiliferous packstone.
5280-4	4711'	-970.5	Fossiliferous packstone.
5280-5	4710'	-970.2	Laminated dolomudstone.

NDGS # 5281

KB = 1470'

Sample Number	Drill Depth	depth (m Subsea)	Comments
5281-1	4798'	-1014.4	Laminated porous dolostone.
5281-2	4802'	-1015.6	Red Algae in limestone.
5281-3	4806.5'	-1017.0	Codiacean algae in streaked limestone.

NDGS # 5283

KB = 1477'

Sample Number	Drill Depth	depth (m Subsea)	Comments
5283-1	5251.5'	-1150.5	Massive dolostone, very few laminae.
5283-2	5252'	-1150.6	Laminated buff dolostone.
5283-3	5253'	-1150.9	Wavy laminated limestone.
5283-4	5254'	-1151.2	Codiacean algae, minor anhydrite in limestone.
5283-5	5270'	-1156.1	Thamnopora in limestone.

NDGS # 5333

KB = 2376'

Sample Number	Drill Depth	depth (m Subsea)	Comments
5333-1	11878'	-2896.2	Salt.
5333-2	11917.8'	-2908.3	Salt.
5333-3	11938'	-2914.5	Limestone.
5333-4	11949'	-2917.9	Salt.
5333-5	11951.5'	-2918.6	Dolo./L.S.,Anhydrite, Halite.
5333-6	11954'	-2919.4	Nodular Dolo.
5333-6.3	11955.5'	-2919.8	Peloidal grainstone layer in nodular anhydrite.
5333-6.5	11955.8'	-2919.9	Nodular anhydrite and peloidal dolost. contact.
5333-7	11956'	-2920.0	Anhydrite needles.
5333-8	11956.5'	-2920.1	Dark brown limestone.
5333-9	11959'	-2920.9	Upper contact.
5333-10	11959.5'	-2921.1	Patterned Dolo.
5333-11	11960'	-2921.2	Patterned Dolo.
5333-12	11961'	-2921.5	Dolo. contact (lower).
5333-13	11964'	-2922.4	Clotted texture.
5333-14	11966.5'	-2923.2	Clotted texture.
5333-15	11969'	-2923.9	Clotted texture.

5333-16	11971'	-2924.6	Bulbous Stromatoporoid.
5333-17	11972'	-2924.9	Coral (amphipora?).
5333-18	11975'	-2925.8	Coral (amphipora?).
5333-19	11977'	-2926.4	Coral w/encrusting Stromatoporoid.
5333-20	11978'	-2926.7	Corals.
5333-21	11980'	-2927.3	Big coral.
5333-22A	11984.5'	-2928.7	Big Stromatoporoid.
5333-22B	11984.5'	-2928.7	Big Stromatoporoid.
5333-23	11988'	-2929.7	Stromatoporoid frags/Thamnopora/burrows.
5333-24	11992'	-2931.0	Coral and Stromatoporoid.
5333-25	11993'	-2931.3	Platy Stromatoporoid.
5333-26	11996'	-2932.2	Thamnopora w/ encrusting Stromatoporoid.
5333-27	11997'	-2932.5	Thamnopora w/ encrusting Stromatoporoid.
5333-28	11999'	-2933.1	Stromatoporoid.
5333-29	12001'	-2933.7	Favositid and Alveolitid corals.
5333-30	12004'	-2934.6	Bulbous Stromatoporoid.
5333-31	12005'	-2934.9	Reef seds.
5333-32	12006'	-2935.2	Stromatoporoid.
5333-33	12007'	-2935.5	Partial Dolo.
5333-34	12008'	-2935.8	Partial Dolo.
5333-35	12010.5'	-2936.6	Partial Dolo.
5333-36A	12011'	-2936.7	Partial Dolo.
5333-36B	12011'	-2936.7	Partial Dolo.
5333-37	12011.5'	-2936.9	Partial Dolo.
5333-38	12014'	-2937.7	Probable Brachs. w/cement.
5333-39	12015.5'	-2938.1	Probable Brachs. w/cement.
5333-40	12029'	-2942.2	Probable Brachs. w/cement.
5333-41	12032'	-2943.1	Probable Brachs. w/cement.
5333-42	12037'	-2944.7	Probable Brachs. w/cement.
5333-43	12040'	-2945.6	Red/laminated Brach. zone.
5333-44	12055'	-2950.2	Mudstone.
5333-45	12065'	-2953.2	Mudstone w/minor Brachs.
5333-46	12081'	-2958.1	Brach. zone.
5333-47	12097'	-2963.0	Brown patch w/fractures.
5333-48A	12109'	-2966.6	Gastropod.
5333-48B	12109'	-2966.6	Gastropod.
5333-49	12122'	-2970.6	Stachyotes.
5333-50	12128'	-2972.4	Anhydrite filled Brach.

5333-51	12140.5'	-2976.2	Internal contact, minor pyrite rim around clasts.
5333-52	12143'	-2977.0	Large Brach.
5333-53	12152.8'	-2980.0	Mottled grey/black-star shaped Crinoids.
5333-54	12160.5'	-2982.3	Lam. mottled grey/brown- Algal? Burrowed?
5333-55	12162.8'	-2983.0	Same as sample 54, but not laminated.

NDGS # 6535

KB = 1589'

Sample Number	Drill Depth	depth (m Subsea)	Comments
6535-1	6811'	-1591.7	Red, Ashern formation.
6535-2	6791.5'	-1585.7	Green-gray, Ashern Formation.
6535-3	6777'	-1581.3	Streaked mudstone - base of Wpgosis. Fm.
6535-4	6763'	-1577.0	Black-brown wisp with auriole.
6535-5	6732'	-1567.6	?
6535-6	6644'	-1540.8	White crystalline dolomite in limestone.
6535-7	6641'	-1539.8	Dolomitic wackestone.
6535-8	6638'	-1538.9	White, crystalline dolomite.
6535-9	6613'	-1531.3	Stromatoporoid?
6535-10	6610.6'	-1530.6	Stromatoporoid?
6535-11	6609'	-1530.1	Massive, white crystalline dolomite.
6535-12	6597.5'	-1526.6	Thrombolite.
6535-13	6479'	-1490.5	Red, argillaceous Wpgosis. Fm.

NDGS # 6603

KB = 2093'

Sample Number	Drill Depth	depth (m Subsea)	Comments
6603-1	10855'	-2670.7	Laminated limestone.
6603-2	10852'	-2669.7	Peloidal dolostone.
6603-3	10850'	-2669.1	Stromatoporoid in peloidal dolostone.
6603-4	10849'	-2668.8	Peloidal dolostone.

NDGS # 6624

KB = 1715'

Sample Number	Drill Depth	depth (m Subsea)	Comments
6624-1	7208.5'	-1674..5	Thrombolite.
6624-2	7206.5'	-1673.8	Thrombolitic texture.
6624-3	7202'	-1672.4	Massive crystalline dolomite.
6624-4	7194'	-1670.0	Pyrite, v. porous.
6624-5	7187'	-1667.9	Swirled , gray dolomudstone.
6624-6	7186'	-1667.6	White with green streaks - dolostone.
6624-7	7177'	-1664.8	Red, argillaceous Wpgosis Fm.
6624-8	7139'	-1653.2	Red, argillaceous Wpgosis Fm.

NDGS # 6684

KB = 1713'

Sample Number	Drill Depth	depth (m Subsea)	Comments
6684-1	6511'	-1462.4	Crinoid wackestone to packstone.
6684-2	7502'	-1764.5	Laminated mudstone.
6684-3	7489'	-1760.5	Laminated dolomudstone.
6684-4	7474'	-1756.0	Contorted laminated mudstone.
6684-5	7469'	-1754.4	Anhydrite speckled dolostone.
6684-6	7458'	-1751.1	layered anhydrite/dolostone/little limestone.
6684-7	7485'	-1759.3	

NDGS # 10209

KB = 2399'

Sample Number	Drill Depth	depth (m Subsea)	Comments
10209-1	11104'	-2653.3	Thrombolite (limestone) in reef zone.
10209-2	11107'	-2654.3	Thrombolite and stromatoporoid in reef zone.
10209-3	11099'	-2651.8	Thrombolite and stromatoporoid in reef zone.

NDGS # 10395

KB = 2085'

Sample Number	Drill Depth	depth (m Subsea)	Comments
10395-1	10471'	-2556.1	Halite hopper trace filled with anhydrite.
10395-2	10469'	-2555.4	Stachyotes in crinoid wackestone.
10395-3	10434'	-2544.8	Thamnopora and stromatoporoid fragment.
10395-4	10426'	-2542.3	Streaked dolomitic (disseminated) limestone.
10395-5	10415'	-2539.0	Coral (Alveolitid??).
10395-6	10406'	-2536.2	Codiacean algae.
10395-7	10398'	-2533.8	Discontinuously laminated dolomitic limestone.
10395-8	10394.5'	-2532.7	Solitary rugosan coral / encrusting stromatoporoid.
10395-9	10394'	-2532.6	Altered stachyotes.
10395-10	10385'	-2529.8	Peloidal packstone.
10395-11	10381'	-2528.6	Caliche?, pyritized.

NDGS # 10480

KB = 2430'

Sample Number	Drill Depth	depth (m Subsea)	Comments
10480-1	11119'	-2648.4	Swirled anhydrite/dolostone - corals.
10480-2	11112'	-2646.3	Possible thrombolite.
10480-3	11111.5'	-2646.1	Possible thrombolite.
10480-4	11111'	-2646.0	Possible thrombolite.

APPENDIX D: DESCRIPTION OF GEOCHEMICAL SAMPLES AND RESULTS OF GEOCHEMICAL ANALYSES.

Table D-1. (cont).

Table D-1. Description of samples used in geochemical analyses.

Sample	DOLOMITE TYPE	FACIES	LITHOFACIES	DESCRIPTION OF CORE SAMPLE
286-1	SADDLE	Dolomudstone	Crinoid-brachiopod wackestone	White, crystalline saddle dolomite.
2638-1	IDIO-E	Dolomudstone	Mudstone	Tan, massive dolomudstone.
2638-2	IDIO-E	Dolomudstone	Mudstone	Sub-sample gray-brown lamination.
2800-3	IDIO-E	Interlayered Mudstone and Dolomudstone	Laminated mudstone	Buff, massive dolomudstone with rare (<0.5 mm) anhydrite.
2800-7	IDIO-E	Dolomudstone	Laminated mudstone	Sub-sample from tan lamination.
4340-2	IDIO-S	Dolomitic Brachiopod Wackestone	Fossiliferous packstone and boundstone	Sub-sample from dark gray area between mottles.
4618-10	XENO-A	Dolomudstone	Mudstone	Brown, massive dolostone.
4790-1	IDIO-E	Crinoid Dolowackestone	Fossiliferous packstone and boundstone	Swirled and streaked. Sub-sample from middle of swirl, between streaks.
4790-2A	IDIO-E	Crinoid Dolowackestone	Fossiliferous packstone and boundstone	Swirled and streaked. Sub-sample from middle of swirl, between streaks.
4790-2B	ALLOCHEM	Crinoid Dolowackestone	Fossiliferous packstone and boundstone	Sub-sample: dolomitized crinoid ossicles.
4790-3	IDIO-S	Thrombolitic Doloboundstone	Fossiliferous packstone and boundstone	'Bulk sample'. Sub-sample includes clotted and matrix areas.
4790-4A	IDIO-S	Thrombolitic Doloboundstone	Fossiliferous packstone and boundstone	Sub-sample from massive, gray-brown dolostone area.

Table D-1. (cont).

Sample	DOLOMITE TYPE	FACIES	LITHOFACIES	DESCRIPTION OF CORE SAMPLE
4790-4B	SADDLE	Thrombolitic Doloboundstone	Fossiliferous packstone and boundstone	Saddle dolomite lining pore space.
4923-3	IDIO-E	Dolomudstone	Mudstone	Sub-sample from tan, massive area.
4924-4A	XENO-S	Crinoid Dolowackestone	Crinoid-brachiopod wackestone	Sub-sample from brown dolostone matrix.
4924-4B	ALLOCHEM	Crinoid Dolowackestone	Crinoid-brachiopod wackestone	Sub-sample from dolomitized crinoids.
5158-3	ANKERITE	Dolomudstone	Mudstone	Massive, green-brown.
5185-22	IDIO-E	Dolomitic Mudstone to Dolostone	Mudstone	Sub-sample from light brown laminae.
5277-1	XENO-A	Dolomudstone	Mudstone	Sub-sample from light brown laminae.
5277-4A	ALLOCHEM	Amphipora Dolowackestone	Peloidal packstone	Sub-sample from dolomitized allochems.
5277-4B	IDIO-E	Amphipora Dolowackestone	Peloidal packstone	Sub-sample from brown dolostone matrix.
5279-1	XENO-A	Dolomudstone	Patterned Dolostone	Sub-sample from light brown swirls.
5279-3	IDIO-E	Dolomitic Mudstone	Patterned Dolostone	Sub-sample from white swirls.
6535-4	XENO-S	Dolomudstone	Crinoid-brachiopod wackestone	Sub-sample from gray-brown area.
6535-11	IDIO-S	Massive crystalline dolostone	Coral-stromatoporoid doloboundstone	White-brown massive crystalline dolomudstone.

Table D-1. (cont).

Sample	DOLOMITE TYPE	FACIES	LITHOFACIES	DESCRIPTION OF CORE SAMPLE
6603-2	XENO-S	Peloidal Dolopackstone	Fossiliferous packstone and boundstone	Sub-sample from light brown matrix.
6603-3	XENO-S	Peloidal Dolograinstone	Fossiliferous packstone and boundstone	Sub-sample: small gray dolomudstone layer.
6624-5	XENO-A	Dolomudstone	Mudstone	Sub-sample from light gray swirled areas.
10395-7	IDIO-E	Dolomudstone	Fossiliferous packstone and boundstone	Subsample from light gray laminae.
10395-11	IDIO-S	Anhydritic Dolomudstone	Fossiliferous packstone and boundstone	Sub-sample: gray-brown massive areas.

Table D-2. Electron microprobe data. All data are expressed in weight percent oxide.

Sample #	Sample location (thin section, crystal location)	Dolomite type	MgO (wt%)	FeO (wt%)	CaO (wt%)	Na_2O (wt%)	MnO (wt%)	SrO (wt%)	ZnO (wt%)	CO_2 (wt%)
P1	4790-3 #1 core	Saddle	22.016		30.962					47.021
P2	4790-3 #1 rim	Saddle	22.073		31.500		0.023		0.038	46.366
P3	4790-3 #2 core	Xeno-S	21.564	0.016	31.149			0.033	0.051	46.900
P4	4790-3 #2 rim	Xeno-S	21.850	0.180	31.465			0.023	0.055	46.450
P5	6624-3 #1 rim	Idio-E	21.709	0.124	31.018		0.062		0.040	47.047
P6	6624-3 #1 core	Idio-E	21.422	0.277	30.589			0.015		47.712
P7	6624-3 #2 core	Xeno-S	21.767	0.066	31.362		0.036			46.762
P8	6624-3 #2 rim	Xeno-S	21.818	0.087	31.552				0.073	46.467
P9	6624-3 #3 rim	Idio-E	21.847	0.121	31.024		0.039			46.969
P10	6624-3 #3 core	Idio-E	21.846	0.139	31.046		0.025	0.023		46.584
P11	5257-3 #1 rim	Idio-E	18.732	0.318	34.168	0.044		0.056		46.738
P12	5257-3 #1 core	Idio-E	22.037	0.046	31.261			0.013		46.656
P13	5257-3 #2 rim	Xeno-S	18.722	0.192	33.260	0.088	0.016			47.723
P14	5257-3 #2 core	Xeno-A	21.570	0.046	31.241					47.142
P15	4597-10 #1 pt1	Xeno-A	20.268	0.110	32.873		0.039			46.710
P16	4597-10 #2 rim		21.142	0.258	32.169		0.024		0.163	46.245
P17	4597-10 #2 core		20.436	0.085	33.108		0.039	0.029		46.333
P18	4340-5 #1 pt1	Xeno-A	20.117	0.150	33.317					46.416
P19	4340-5 #2 pt1	Idio-S	19.773	0.285	33.383		0.021	0.013		46.537
P20	4340-5 #2 pt2	Idio-S	19.925	0.288	33.643			0.028		46.144

Table D-2. (Cont.). Electron microprobe data

Sample #	Sample location (thin section, crystal location)	Dolomite type	MgO (wt%)	FeO (wt%)	CaO (wt%)	Na_2O (wt%)	MnO (wt%)	SrO (wt%)	ZnO (wt%)	CO_2 (wt%)
P21	10395-10 #1 pt1		20.275	0.240	33.231		0.018			46.230
P22	10395-10 #1 pt2		21.161	0.194	32.110					46.535
P23	10395-10 #1 pt3	Allochem	19.408	0.521	33.720			0.014		46.349
P24	10395-10 #2 gr2		20.632	0.214	32.293		0.048			46.811
P25	10395-10 #2 gr1 pt1		20.330	0.135	33.193		0.027		0.024	46.286
P26	10395-10 #2 gr1 pt2		20.709	0.440	32.167		0.074			46.610
P27	10395-10 #2 gr1 pt3		19.842	2.112	31.354		0.042	0.018		46.651
P28	4618-7 #2 pt1	Allochem	21.616	0.307	30.905		0.076			47.096
P29	4618-7 #2 pt2	Allochem	21.872	0.276	30.597		0.073	0.011		47.182
P30	4618-7 #1 core	Idio-E	20.723	0.114	32.394		0.026			46.743
P31	4618-7 #1 rim	Idio-E	17.455	0.026	36.317		0.036			46.166
P32	4618-7 #3 brt zone		20.413	0.432	32.543		0.072	0.023	0.020	46.521
P33	4618-7 #3 dk zone		21.394	0.075	31.766		0.022	0.013		46.733
P34	286-1 #1 incl	Saddle	18.199	3.701	31.629		0.082	0.013		46.389
P35	286-1 #1 nr rim	Saddle	20.587	0.122	32.148		0.038			47.105
P36	286-1 #1 core	Saddle	21.254	0.120	31.515			0.051		47.107
P37	286-1 #2 core	Saddle	20.966	0.100	32.194			0.011		46.704
P38	4790-4 #3 rim	Xeno-S	22.041	0.038	32.090	0.013	0.036		0.042	45.740
P39	4790-4 #3 core	Xeno-S	21.622	0.034	31.709	0.011				46.617
P40	4790-4 #2 core	Xeno-S	21.851	0.199	31.329			0.016	0.029	46.586
P41	4790-4 #1 rim	Saddle	22.119		31.517					46.359

Table D-2. (Cont.). Electron microprobe data

Sample #	Sample location (thin section, crystal location)	Dolomite type	MgO (wt%)	FeO (wt%)	CaO (wt%)	Na_2O (wt%)	MnO (wt%)	SrO (wt%)	ZnO (wt%)	CO_2 (wt%)
P42	4790-4 #1 core	Saddle	22.060		31.714					46.222
P43	6535-4 #2 core	Allochem	21.562	0.082	31.074					47.282
P44	6535-4 #1	Allochem	21.157	0.439	31.004		0.018			47.337
P45	6535-4 #3	Idio-E	20.576	0.129	31.772		0.020		0.036	47.467
P46	4340-6 #1 core	Xeno-A	19.182	0.050	34.117					46.647
P47	4340-6 #2 core	Xeno-A	19.915	0.289	32.440					47.354
P48	4340-6 #3 core		20.200	0.060	32.441	0.068		0.013	0.016	47.215
P49	4340-6 #3 rim		19.713	0.044	34.150					46.094
P50	4790-5 #1 rim	Saddle	21.865		31.093					47.042
P51	4790-5 #1 core	Saddle	21.828	0.017	31.326				0.011	46.817
P52	4790-5 #3 pt1 core	Xeno-S	21.757		30.987		0.027		0.039	47.190
P53	4790-5 #3 pt2 mid	Xeno-S	21.712	0.246	30.768		0.050	0.020		47.216
P54	4790-5 #3 pt3 edge	Xeno-S	21.876	0.226	30.491				0.032	47.374
P55	4790-5 #2 rim	Anhy	21.896		31.423		0.016	0.016		46.660
P56	4790-5 #2 core	Anhy	22.110		31.019		0.024			46.843

Table D-.3 Stable isotope data.

Sample loc.	depth (meters Subsea)	Dolomite Type	Dolomite $\delta^{18}O$ (PDB)	Dolomite $\delta^{13}C$ (PDB)	Calcite $\delta^{18}O$ (PDB)	Calcite $\delta^{13}C$ (PDB)	XRD minerallogy % dolomite	% calcite	% ankerite	% anhydrite	% halite	% quartz	Facies	Lithofacies	Geographic Zone
5277-4A	1023.8	Allochem	-5.90	1.79			97	3					*Amphipora* Dolowackestone	Peloidal Packestone	East
4924-4B	1371.9	Allochem	-6.62	2.13			98			2			Crinoid Dolowackestone	Fossiliferous Wackestone	East
4790-2B	1501.9	Allochem	-5.44	2.28			99			1			Crinoid Dolowackestone	Fossiliferous Wackestone	East
5158-3	2048.0	Ankerite	-2.74	2.39			2	2	80	3	10	3	Dolomudstone	Mudstone	East
5279-3	1105.5	Idio-E	-2.20	2.35	-1.59	2.12	84	15		1			Crinoid Wackestone	Crinoid-Brachiopod Wackestone (Lwr. Wpgosis)	East
5185-22	1136.0	Idio-E	-2.45	2.16			1			9			Laminated Dolomitic Mudstone to Dolostone	Mudstone	South
2638-1	1084.5	Idio-E	-5.58	1.13			90			10			Dolomudstone	Mudstone	East
2638-2	1082.2	Idio-E	-6.41	-0.10			77	5		10		8	Dolomudstone	Mudstone	East
10395-7	2533.8	Idio-E	-5.27	1.22			100						Dolomudstone	Mudstone	East
4790-1	1503.3	Idio-E	-6.63	2.01			97	1			2		Crinoid Dolowackestone	Fossiliferous Wackestone	East
5277-4B	1023.8	Idio-E	-4.80	2.03			100						*Amphipora* Dolowackestone	Peloidal Packestone	East
4790-2A	1501.9	Idio-E	-5.49	2.22			98		1	1			Crinoid Dolowackestone	Fossiliferous Wackestone	East
4923-3	1570.3	Idio-E	-5.65	2.50			100						Dolomudstone	Mudstone	East
2800-7	1958.9	Idio-E	-7.03	2.56			85	5		8	2		Dolomudstone	Laminated Mudstone (Ratner)	Central
2800-3	1956.2	Idio-E	-6.34	3.13			85			15			Interlayered Mudstone and Dolomudstone	Laminated Mudstone (Ratner)	Central
4790-4A	1499.3	Idio-S	-6.91	1.25			97	1		2			Thrombolitic Doloboundstone	Fossiliferous Wackestone	West
10395-11	2525.6	Idio-S	-6.71	1.31			90				10		Dolomitic Peloidal Packstone	Peloidal Packstone	West
4790-3	1500.2	Idio-S	-8.37	1.70			95	3				2	Thrombolitic Doloboundstone	Fossiliferous Wackestone	East

Table D-.3 Stable isotope data (cont).

Sample loc.	depth (meters Subsea)	Dolomite Type	Dolomite		Calcite		XRD minerallogy						Facies	Lithofacies	Geographic Zone
			$\delta^{18}O$ (PDB)	$\delta^{13}C$ (PDB)	$\delta^{18}O$ (PDB)	$\delta^{13}C$ (PDB)	% dolomite	% calcite	% ankerite	% anhydrite	% halite	% quartz			
4340-2	2917.2	Idio-S	-5.13	1.92	-3.72	2.01	71	18		2	4	5	Dolomitic Brachiopod Wackestone	Fossiliferous Wackestone to Grainstone	East
6535-11	1530.1	Idio-S	-6.90	2.21			77	1		22			Massive crystalline dolostone	Coral Stromatoporoid Boundstone	East
286-1		Saddle	-8.22	-0.55			99	1					Dolomudstone	Crinoid-brachiopod wackestone (Lwr. Wpgosis.)	West
4790-4B	1499.3	Saddle	-6.28	1.88			97	2		1			Thrombolitic Doloboundstone	Fossiliferous Wackestone	East
5279-1	1104.6	Xeno-A	-6.98	-0.02	-4.18	0.50	91	7			1	1	Dolomudstone	Patterned Dolostone	East
6624-5	1667.9	Xeno-A	-7.23	0.70			58	2		35		5	Fossiliferous dolofloatstone	Fossiliferous wackestone to grainstone	East
5277-1	1022.0	Xeno-A	-6.12	1.06			96	1				3	Dolomudstone	Mudstone	Central
4618-10	2820.3	Xeno-A	-6.97	1.33	-4.39	1.97	87	6		2	5		Dolomudstone	Mudstone	East
6535-4	1577.0	Xeno-S	-3.05	2.56			85			15			Dolomudstone	Crinoid-Brachiopod Wackestone (Lwr. Wpgosis)	Central
4924-4A	1371.9	Xeno-S	-7.34	1.56			92	1		4	3		Crinoid dolowackestone	Fossiliferous Wackestone	East
6603-2	2669.4	Xeno-S	-6.61	2.65			85	2		3	10		Peloidal dolopackestone	Peloidal packstone	West
6603-3	2668.6	Xeno-S	-6.00	3.38			86			14			Peloidal dolopackestone	Peloidal packstone	East

APPENDIX E: EQUIPMENT OPERATING CONDITIONS

Epi-Fluorescence Microscopy

Unpolished thin sections were examined at the Department of Geological Sciences, University of Manitoba using a Nikon Optiphot microscope mounted with an episcopic fluorescence attachment with a blue-violet excitation filter block (436 nm main wavelength). The blue-violet excitation filter block configuration used is as follows: excitation filter = EX 400 - 440 λ; diachroic mirror = DM455; barrier filter = BA480.

Cathodoluminescence Microscopy

Polished thin sections were examined at the Department of Geological Sciences, University of Manitoba by cathodoluminescence microscopy using a Technosyn cold cathodoluminescence unit mounted on a NIKON optiphot microscope. The unit was operated at 20 kV with an average gun current of 350 mA (microAmperes).

Scanning Electron Microscopy

Gold coated core samples were examined at the Department of Geological Sciences, University of Manitoba using a Cambridge Stereoscan 120 scanning electron microscope (SEM) under control of a Kontron IBAS Image Analyser. A Kevex 7000 energy dispersive X-ray spectrometer (EDS) and a back scattered electron (BSE) detector (solid state, 4 elements) were also used in conjunction with the SEM. The SEM was operated with an accelerating voltage of between 20kV and 30kv.

Electron Microprobe Analysis

Representative, polished thin sections were carbon coated and then analyzed at the Department of Geological Sciences, University of Manitoba using a Cameca Camebax SX-50 electron microprobe, equipped with three crystal spectrometers and a backscattered electron (BSE) detector. The operating conditions during analysis were 20 kV accelerating voltage, a 15 nA beam current, 10 μm beam diameter and 10 s counting time. Values were reported in wt % oxide. Detection limits are estimated to be Na = 0.02 wt %; Mn = 0.03 wt %; Zn = 0.09 wt %; Sr = 0.095 wt %; (R. Chapman, pers. comm., 1996). The standards used were dolomite (Mg), siderite (Fe, Mn), calcite (Ca), albite (Na) and strontianite (Sr).

X-ray Diffractometry

Powdered carbonate samples were placed on thin sections and analysed using a Phillips PW diffractometer with Ni-filtered, CuKα radiation of 30 kV/15mA.

Stable Isotope Analysis

Carbon and oxygen isotope analyses of selected samples were performed using methods of McCrea (1950) at the University of Waterloo.. Powdered carbonate samples were reacted with 100% phosphoric acid at 50°C for approximately 45 minutes for calcite and 48 hours for dolomite. Separation of CO_2 from different carbonate phases in multi-carbonate samples was done by differential chemical leaching methods of Al-Aasm et al.

(1990). The collected CO_2 gas for each carbonate fraction was analysed on a VG Prism mass spectrometer. The phosphoric acid fractionation factors used were 1.01.25 for calcite and 1.01065 for dolomite at 25°C (Friedman and O'Neil, 1977). Precision (1σ) was monitored through daily analysis of a standard and was better than $0.2^{o}/_{oo}$ for both $\delta^{13}C$ and $\delta^{18}O$.

IMAGE EVALUATION
TEST TARGET (QA-3)

150mm

6"

APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989