SEDIMENTARY DEPOSITIONAL ENVIRONMENT
OF THE PRAIRIE EVAPORITE FORMATION,
SASKATOON REGION, SASKATCHEWAN

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by

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perennial source of inspiration and encouragement, they never stopped believing in me even when I faltered.
This thesis attempts to reconstruct the environments in which the potash-bearing, Prairie Evaporite Formation (Middle Devonian) of the Elk Point Basin was deposited, using preserved primary sedimentary features. Evidence from cores, thin sections and mine observations indicates that sedimentation was not continuously subaqueous, but episodic, with periods of desiccation recorded throughout the formation.

Deposition of the Prairie Evaporite Formation began with a major drop of the sea-level, leaving most of the basin desiccated and the carbonate mounds of the underlying Winnipegosis Formation exposed. Fed by seepage through barriers, the region became a carbonate mudflat environment with patchy brine pools between the carbonate mounds, and this was succeeded by a salt-pan environment. The Whitkow Member, which was deposited under these conditions, filled approximately half of the original relief of the intermound depressions. Subsequently, sea-level rose sufficiently high to flood the area episodically, resulting in sedimentation of the Shell Lake Member in intertidal to supratidal environments.

The filling of the basin and concomitant regression of the sea brought the area under a more continental influence during the Leofnard Member deposition. Except for the northernmost part, where salt-pan environments persisted, most of the study area developed into a pericontinental salt lake environment. A considerable amount of potash may have been deposited with halite syndepositionally, probably during the peak of the evaporative conditions, and was prone to early diagenetic alteration under periodic subaerial conditions.

The model presented provides a more dynamic and more realistic picture of the changing depositional environments. This not only leads to a better understanding of the deposit itself, but also may help to overcome some of difficulties in potash mining that relate directly to the conditions during the time of deposition.
1. INTRODUCTION

The Prairie Evaporite Formation has been one of the most important resources of Saskatchewan for three decades. Potash production from this formation began in 1962 (Fuzesy, 1982) and expanded continuously, reaching 8.3 million tonnes $K_2O$ equivalent in 1988 (Freeman, 1989). This total makes up more than 90% of Canada’s production or roughly one-fifth of the annual world production. Currently there are 10 active mines in the province, as shown in Figure 1.1.

Coincident with its economic development, a large amount of research on the geology of the Prairie Evaporite Formation was conducted during the 1960’s and early 1970’s, but far less has been done since then. The most extensive study was that of Holter (1969) which is still referred to frequently today. The rest dealt with specific aspects of the formation, e.g., the primary versus secondary origin of potash minerals (Schwerdtner, 1964; Wardlaw, 1968), the cyclicity of the deposit (Klingspor, 1966), layering in halite (Wardlaw and Schwerdtner, 1966), the underlying laminites (Shearman and Fuller, 1969; Davies and Ludlam, 1973), and the stratigraphy (Reinson and Wardlaw, 1972).

Ideas regarding evaporite deposition have shifted from dominantly geochemical to a more interdisciplinary approach over the past 20 years. Increasing emphasis has been given to the sedimentological, biological, and climatic aspects of the evaporitic environment. Direct observations on modern analogues have led to insights of the processes operating and the resultant products of various evaporitic settings. The knowledge gained from such endeavors has shed new light on our understanding of evaporites. Given the economic importance of the Prairie Evaporite Formation, a reinterpretation using an up-to-date approach is now appropriate. Through comparative sedimentology, this study attempts to interpret the depositional environment of the formation using sedimentary features.
Figure 1.1 Location map of active potash mines in Saskatchewan (modified from Fuzesy, 1982).
1.1 REGIONAL GEOLOGIC FRAMEWORK

The Prairie Evaporite Formation is a part of the sedimentary sequence deposited in the Middle Devonian Elk Point Basin of Western Canada. This intracratonic basin extended diagonally from northwestern Alberta across the Prairies into western Manitoba, and to the northern part of Montana and North Dakota (Figure 1.2). It was bounded to the north by the Canadian Shield and to the west and south by prominent arches, namely the Western Alberta Arch and the Central Montana Uplift. In addition, there were two major positive elements, the Peace River-Athabasca Arch and the Meadow Lake Escarpment, which divided the vast single basin into three subbasins, the Northern Alberta, the Central Alberta, and the Saskatchewan, respectively.

The sediments of the Elk Point Basin are predominantly evaporitic and were laid down in the three subbasins (Fig. 1.3). The sea transgressed into the area from the northwest (Grayston et al., 1964; Holter, 1969; and Porter et al., 1982) and initially inundated the Central Alberta Subbasin where the Lotsberg Formation was deposited. Continued subsidence and downwarping of the basin allowed the sea to flood the Northern Alberta Subbasin, leading to the deposition of the Ernestina Lake and Cold Lake Formations. Later, the Meadow Lake Escarpment foundered and the sea overflowed into the Saskatchewan Subbasin. It was this transgression that was the most extensive, as seen from the widespread deposition of the Winnipegosis and Prairie Evaporite Formations and their equivalents throughout the region. The Second Red Bed Member of the overlying Dawson Bay Formation marks a significant break in the depositional record of the Saskatchewan Subbasin.
Figure 1.2 Major structural elements during deposition of the Elk Point Group sediments (from Holter, 1969; thickness of the Elk Point Group in metres from Zharkov, 1984).
Figure 1.3 Facies distribution in the Elk Point Basin behind the Presqu’ile Barrier Reefs (top left), from carbonate, to anhydrite, to halite and potash at the distal end (from Zharkov, 1984; based on Holter, 1969).
1.2 THE DEPOSITIONAL ENVIRONMENT OF THE PRAIRIE EVAPORITE: A REVIEW

Interpretations of the depositional environment of evaporites generally reflect the more or less classical "barred basin model" first put forward by Ochsenius in 1877 (Stewart, 1963). This model was modified by several authors for various deposits, and a review of these works is presented in Hsu (1972). In the Elk Point Basin, restricting conditions have been attributed to the Presqu'ile Barrier reefs located at the southeastern flank of the Tathlina Uplift (Grayston et al., 1964; Klingspor, 1969; Maiklem, 1971; also see Fig. 1.3). A thick carbonate-anhydrite succession was deposited behind the reef complex and passed southeastward into halite and bittern salts at the distal end.

Alternating halite-anhydrite layers in the lower part of the formation were thought to represent annual deposition by Wardlaw and Schwerdtner (1966). Using an average rate of 5 cm per year from modern salinas, they calculated that the 200 m salt section could have formed in only 4,000 years. Within such a short geological time span the basin subsidence would have been negligible. Therefore, they concluded that the initial depth must have been close to the total thickness of the salt and that the basin was gradually filled up. This view was shared by Klingspor (1969), who suggested that the progression from shelf carbonates at the entrance of the basin to potash at its southeastern end was the result of brine differentiation of the inland sea. Later, Maiklem (1971) proposed a mechanism of evaporative drawdown to explain the lowering of the basin brine behind the barrier reefs.

A major challenge of these ideas emerged from the studies of modern salt pans in Baja California, Mexico, by Shearman (1970). He reported that the layering in halite rocks was not annual but was the product of repeated reworking of salt pan halite by early diagenetic processes. The petrography of these halite rocks revealed striking similarities to those of the Prairie Evaporite described previously by Wardlaw and
Schwerdtner (1966). This implied that deposition of the layered halite took place in shallow depressions on tidal flat areas and not, as previously suggested, under a standing body of water of a few hundred metres depth.

Another focus of the debate has been the origin of the organic laminites that occur directly below the formation. These sediments are critical to any environmental interpretation because they mark the end of extensive carbonate deposition and the beginning of evaporite deposition. Citing algal-laminated sediments along the supratidal flats of the Persian Gulf as a modern analogue, Fuller and Porter (1969) and Shearman and Fuller (1969) interpreted the laminites as supratidal deposits. The implication was that the water had dropped from reef-top level to reef-base level before halite deposition, thus reducing the former inland sea to brine-logged algal flats. Davies and Ludlam (1973), on the other hand, suggested that deposition took place at a depth of at least 50 metres, so that the laminated sediments could be excluded from wave action. Moreover, the lateral continuity of the laminites, quoted as 25 km by Davies and Ludlam (1973) and 190 km by Kendall (1975), was very unlikely for any supratidal deposits.

1.3 STATEMENT OF THE PROBLEM

It is apparent from this brief review that the depositional environments of the Prairie Evaporite Formation remain uncertain. One reason for this may be that none of the previous studies was carried out systematically on the entire sequence, probably due to the then limited availability of core. Most potash exploration wells penetrated only the upper two potash units, and petroleum wells were aimed primarily at carbonates either above or below the Prairie Evaporite Formation, thus they did not core the entire salt section. This precluded any chance to follow the progressive development of the sequence step by step.

A second, and perhaps more important reason is that, until recently,
investigations of evaporites have rarely treated them as sedimentary rocks. Evaporitic sequences have traditionally been compared with theoretical or experimental sequences from evaporating seawater, from carbonates, to sulphates, and to halides. Their basic sedimentological parameters are frequently neglected. Certainly they are precipitated from concentrated brine, but within the depositional realm they are subject to modification by many sedimentary processes, including the effects of winds, waves, currents, etc.. These processes can lead to the formation of sedimentary structures similar to those found in siliciclastics and carbonates.

There are numerous well-documented examples of sedimentary features in ancient evaporites: e.g. cross-bedding and ripple marks in the Michigan Basin (Dellwig and Evans, 1969; Dellwig, 1972) and the Permian Basins (Lowenstein, 1982), desiccation cracks in Triassic halite, England (Tucker, 1981), gypsum conglomerate in Sicily (Hardie and Eugster, 1971), several types of ripple marks in Neogene gypsum of the Western Desert, Egypt (Youssef, 1988), and many others. The preservation of these features refutes the idea of their pervasive destruction after deposition, and at the same time encourages attempts to use them in interpretation of their depositional environments.

1.4 APPROACH TO THE PROBLEM

The aim of this research is to reconsider evaporites of the Prairie Evaporite Formation not as chemical precipitates alone but also as sedimentary rocks. Consequently, reconstruction of the environments in which they were formed will be based on the evidence from inherent sedimentary features. This approach has not been previously carried out systematically in Saskatchewan, even though some sedimentary structures have been described, e.g., layering in halite (Wardlaw and Schwerdtner, 1966), polygonal mudcracks (Baar, 1974; Mossman et al., 1982).

In many circumstances where evaporite minerals grow subaqueously in
concentrated brines, additional clues can be deduced from crystalline fabrics and associated features. Competitive growth of gypsum and halite, and the truncation and dissolution of such crystals are among the common fabrics. Detailed descriptions, the processes of formation, and implications for the depositional environment of these features are given by Arthurton (1973) and Lowenstein and Hardie (1985) for halite, and Schreiber (1978) and Warren and Kendall (1985) for gypsum.

The major difficulty in applying this approach is that evaporites are highly susceptible to subsequent alteration and recrystallization. Such processes tend to obliterate the primary features and replace them with secondary ones. Therefore, one has to be able to distinguish the primary features which provide valuable genetic information from the secondary features produced during diagenesis. Considerable progress has been made through direct field observation of modern analogues and laboratory experiments. A recent compilation of such studies, including the criteria for the recognition and distinction of primary and secondary features, is outlined by Hardie et al. (1985). Their results provide the basis for many interpretations made during this research.

1.5 RESEARCH PROCEDURES AND METHODS

The study area covers the six potash mines around Saskatoon along an east-west trend, and extends from the major salt-solution area to the south across the main potash body to its northern limit where only halite is present (Fig. 1.4). Underlying the Prairie Evaporite Formation there is extensive development of the carbonate mounds of the Winnipegosis Formation, particularly around the area east of Saskatoon. The maximum known thickness of the mounds is 105 m (Wilson, 1985). As will be shown in this study, these mounds had great influence on the succeeding deposition of the Prairie Evaporite Formation.

The main source of information for this study has come from examination of
Figure 1.4 Location map of the study area showing all well locations and the three cross-section lines (area of salt solution and the edge of the Patience Lake Submember from Holter, 1969)
cores held at the Subsurface Geological Laboratory in Regina. A total of 13 wells, some of which are confidential, with an aggregate length of 936 m has been logged, and 52 samples were collected for further petrographic studies. Two wells contained a complete section of the formation. For the rest, only parts of the formation were cored. In describing anhydrite, this author used the terminology proposed by Maiklem et al. (1969). No formal classification of halite and potash was established; therefore, the description was based on basic parameters such as composition, colour, texture, crystal size, and transparency, in accordance with the work of Langford et al. (1987).

It is worth noting some details regarding classification of anhydrite proposed by Maiklem et al. (1969). The classification is based on two basic properties - structure and texture. The structural types refer to the shape and spatial relationship of the anhydrite masses within the rock. These types are defined and classified on the basis of four parameters, external form, anhydrite-to-matrix relationship, bedding, and distortion. The textural types refer to the shape, size, and spatial relationship of the individual anhydrite crystals or cleavage flakes. For the texture, laths are elongate crystals with a length greater than 0.5 mm; felted texture is a mass of randomly oriented, lath-shaped crystals whose length is less than 0.5 mm; and subfelted texture is a combination of microcrystalline and felted anhydrites.

All the anhydrite in the Prairie Evaporite Formation falls in the "not crystal shape" category, and the most common structure is "mosaic". According to Maiklem et al. (1969), the mosaic anhydrite is "coalesced anhydrite masses which are approximately equidimensional and in which matrix is lacking. The boundaries are partly thin films of organic or silic material and partly indistinct". This structure is analogous to "chicken-wire" used by some authors, i.e., Kinsman (1966). "Bedded" is added to the anhydrite that shows bedding, usually organic laminae, and "distorted" is added to the one that shows deformation.

Standard methods for thin section preparation were used, but because the study material was highly soluble, all instruments had to be oil-based. Thick slabs were
mounted on 5 x 7.5 cm glass slides by epoxy resin or M-Bond AE 10/15 and left to harden overnight. Both adhesives give similar results, but the latter appears to be slightly more durable. The sample surfaces were then dry-ground on a grinding wheel, and the final polishing was done by hand using sandpaper grit 180 and 400 respectively. To prevent any further deterioration from atmospheric moisture, the thin sections were covered by cover slips.

Core analyses and petrography were supplemented by direct observations in three potash mines. The observations were carried out in the Cominco, PCS Cory, and PCS Allan mines at different intervals in the mining horizons and shaft declines. This allowed comparison of observations recorded from core with exposures, and permitted lateral tracing over a distance. Moreover, many large-scale features, not detectable in the cores, could now be seen.

Throughout this thesis, the abbreviated names for the wells will be used. For example, the PCS Lanigan 4-28-32-23W2 well will be referred to as the Lanigan 4-28 well. A complete list of the wells and their legal subdivisions is presented in Table I of the Appendix.

Correlation from well to well is based on a combination of geological, where the core is available, and geophysical logs. However, there are areas between the cored wells for which the correlation is based on geophysical logs alone. There are eight wells in total, and these are listed in Table II of the Appendix. Three cross-sections (in pocket), one longitudinal and two across the study area, have been prepared to illustrate regional variations in the formation. The lines of the cross-sections are shown in the map of the study area (Fig. 1.4).
2. STRATIGRAPHY AND CORRELATION

The Prairie Evaporite Formation of the Elk Point Group (Middle Devonian) is composed predominantly of halite, potash, anhydrite, and minor carbonates. Lying at a depth of 400 m at its northern limit, the formation dips gently southwestward to 2750 m at its southern limit with an average dip of 2 to 7 m per km (Holter, 1969). The thickest part, locally more than 200 m, of the Prairie Evaporite Formation appears as a narrow belt running diagonally across the study area or broadly coinciding with the locations of potash mines.

The edges of the formation are partly depositional and partly erosional. Anhydrite and argillaceous beds are found in place of halite just south of Prince Albert before the formation tapers and finally disappears farther north due both to gradational thinning and truncation (Fig. 2.1). Along the southern edge, a major region of salt dissolution has long been recognized in the area known as the Swift Current Platform, where only anhydrite is found. Westward from this area, the depositional limit can be mapped as it gradually changes to anhydrite and a nearshore argillaceous facies that onlaps the Western Alberta Ridge (Holter, 1969).

2.1 A Brief History on Stratigraphic Subdivision

The Prairie Evaporite Formation was the topmost formation of the Elk Point Group, a name introduced in Saskatchewan and Manitoba by Baillie (1953) for all the strata between the eroded Lower Paleozoic surface and the Dawson Bay Formation of the Manitoba Group. The Elk Point Group, by this definition, consisted in ascending order of red and grey dolomitic shales of the Ashern Formation, carbonates of the Winnipegosis Formation, and evaporites of the Prairie Evaporite Formation. For consistency with the usage in Alberta, Van Hees (1956) and Grayston et al. (1964) later included the Dawson Bay Formation and the overlying First Red Bed of the Souris...
Figure 2.1 Isopach map and areal distribution of the main rock types in the Prairie Evaporite Formation (thickness in metres from Zharkov, 1984; based on Holter, 1969).
River Formation in the Elk Point Group.

2.1.1 The Underlying and Overlying Formations

Jones (1965) subdivided the Winnipegosis Formation into Lower and Upper Members at the base of the regionally developed, carbonaceous-argillaceous unit. The Lower Member is often described as a platform carbonate, whereas the buildups of Upper Member are commonly termed banks because of the lack of frame-building organisms which might qualify them as reefs (Wardlaw and Reinson, 1971). The contact with the overlying Prairie Evaporite Formation is generally gradational "with the exception of sequences overlying some of the carbonate banks" (Jones, 1965). From seismic study, Gendzwill (1978) found that the thick carbonate banks were not as massive as previously thought and suggested using "mounds" instead.

The stratigraphy of the Winnipegosis and Prairie Evaporite Formations was revised by Reinson and Wardlaw (1972). The Ratner Member, which included laminated carbonate and enterolithic anhydrite, was added to the upper part of the Winnipegosis Formation in the interbank areas (Table 2.1). The contact with the Prairie Evaporite Formation was picked at the uppermost carbonate unit of the Ratner Member, but where the Ratner is not fully developed, it is difficult to distinguish anhydrite of the two formations. However, enterolithic anhydrite, anhydrite interlaminated with carbonate, and bituminous partings were considered typical of the Ratner Member (Reinson and Wardlaw, 1972). The position of this member was disputed by Kendall (1975), who considered the laminated carbonate and anhydrite of the Ratner Member to be part of the overlying evaporitic sequence and therefore suggested that the Ratner Member should be the base of the Prairie Evaporite Formation.

The Prairie Evaporite Formation is invariably overlain unconformably by the Second Red Bed Member of the Dawson Bay Formation. Since the introduction of this
Table 2.1  A summary of major stratigraphic subdivisions of the Prairie Evaporite Formation.
formation by Baillie (1953), there have been some further subdivisions, notably those of Walker (1957) and Lane (1959), but the widely accepted one is that of Dunn (1982) who proposed four members, which in ascending order are: the Second Red Bed, Burr, Neely, and Hubbard Evaporite.

2.1.2 The Prairie Evaporite Formation

Subdivision of the Prairie Evaporite Formation began when Jordan (1967, 1968) assigned the names Whitkow Salt, Shell Lake Gypsum (including the Quill Lake Member), and Leofnard Salt, from bottom to top. The regional stratigraphic relationships among these units were questionable at that time, so Holter (1969) instead suggested informal terms, such as: Lower Anhydrite, Lower Salt, Middle Anhydrite, and Upper Salt. He also named the four prominent potash-bearing units, in ascending order, as Esterhazy Member, White Bear Marker Bed, Belle Plain Member, and Patience Lake Member. The White Bear Marker Bed was later given member status by Worsley and Fuzesy (1979) because it was well-developed and traceable over a large area in the southeastern portion of the province.

The identity and lateral continuity of the rock units proposed earlier by Jordan (1967, 1968) were subsequently confirmed by Reinson and Wardlaw (1972) in central Saskatchewan. They gave member status to the Whitkow and Shell Lake units, and redefined the Quill Lake as marker beds in the Shell Lake Member. This study follows the regional stratigraphic framework of the Elk Point Basin outlined by Meijer Drees (1986). According to this framework, the top of the Elk Point Group is placed at the top of the First Red bed, the Prairie Evaporite Formation is subdivided into the Whitkow, Shell Lake, and Leofnard Members, and the Ratner Member is in the Winnipegosis Formation. However, one discrepancy still exists - the status of the White Bear unit which is assigned as a "marker bed" instead of "submember". This author considers it more appropriate to assign the same status to all potash units, because it has been
shown that the White Bear unit is well-developed and comparable to the others (Worsley and Fuzesy, 1979). Therefore, all potash units will be given a "submember" status in this thesis.

It is important to note that, according to Meijer Drees (1986), the Second Red Bed of the Dawson Bay Formation has been renamed as "the Lower Red Bed Member". This name will be used herein.

2.2 The Reference Well

For the purpose of describing, subdividing, and correlating the rock units in the study area, a stratigraphic reference well is required. The Lanigan 4-28-32-23W2 well has been chosen, based on the following criteria:-

1) It is a cored well containing a complete interval from the Second Red Bed, through the Prairie Evaporite Formation, to the uppermost part of the Winnipegosis Formation. It is, therefore, ideal for carrying out all the basic procedures of the study, i.e., measuring the section, lithologic description and recording of sedimentary features, and sampling, etc..

2) All rock units are present, starting with the Whitkow Member (including the basal anhydrite), Shell Lake Member and the Quill Lake marker beds, and Leofnard Member with four potash units. Such a succession provides an excellent opportunity to observe the relationships between these units. Moreover, there are a few more thin anhydrite units that can be used as additional markers if necessary.

3) The well was drilled in 1981, thus the core is still in good condition. The accompanying geophysical logs show minor changes in lithology, such as an interbedded succession of anhydrite-carbonate, very well.

Figure 2.2 shows the stratigraphy, the formal subdivisions, gross lithology, thicknesses, and the accompanying geophysical logs of the reference well. Additional marker beds, the Marker #1 and #2, which are used in subdividing the members into
Figure 2.2 Stratigraphy of the reference well and accompanying geophysical logs, showing formal subdivision, gross lithology, thicknesses, and provisional markers. The lithologic column also indicates relative abundance of the components.
"Units" in the succeeding chapters, are also shown. The units are meant to facilitate the
description of the rock sequence not for formal stratigraphic usage. They will be given
initial capitals in order to make a clear distinction from the descriptive terms.

2.3 The Stratigraphy of the Reference Well

2.3.1 The Whitkow Member

Overlying the erosional surface of the carbonate mounds (Winnipegosis Formation), the Whitkow Member in the reference well begins with Basal Anhydrite Unit (2.1 m) containing carbonate rudite at the base (Fig. 2.3), then passes upward to distorted mosaic and massive anhydrites. The change from these anhydrites to the overlying halite is abrupt and probably resulted from a rapid change in brine composition. The halite is translucent and most halite crystals have zoned structure - hoppers, cornets, or chevrons. Thin anhydrite partings, usually less than a centimetre thick, occur within the halite interval locally. The frequency and thickness of the partings are generally greater in the lower part of the member than in the upper part.

A dominantly anhydrite interval occurs about midway through the Whitkow Member. Because of its position, Holter (1969) named it "intermediate anhydrite", and this name will be used herein. The Intermediate Anhydrite Unit (4.4 m) begins with massive and mosaic anhydrites overlying a thin recrystallized halite zone directly below. From the anhydrites, the rock passes upward across an erosional surface into a thin carbonate interval (50 cm) made up ofstromatolitic, wavy-laminated, and finely-laminated dolomitic mudstones (Fig. 2.4). The rest of this unit is mostly bedded mosaic and mosaic anhydrite, having a sharp contact with the overlying translucent halite.
PLATE I

Rock units in the reference well and their stratigraphic relationship. Core diameter is 10 cm.

Figure 2.3 Erosional contact (broken line) between the packstone-wackestone of the underlying carbonate mound (Winnipegosis Fm) and the Basal Anhydrite Unit of the Prairie Evaporite Formation. Note abundant carbonate lithoclasts in the Basal Anhydrite Unit and pore-filling anhydrite (arrows) below the contact. 1181-1183 m.

Figure 2.4 Contacts between 1) halite of the Whitkow Member and massive-mosaic anhydrite of the Intermediate Anhydrite Unit (arrow A), and 2) massive-mosaic anhydrite and the carbonate interval in the Intermediate Anhydrite Unit (arrow B). The metal tape is 0.5 m. 1164-1168 m.

Figure 2.5 Sharp contact between mosaic anhydrite and the lowermost grainstone bed of the Quill Lake marker beds. Note intermittent alternation of darker mudstone laminae in grainstone. 1142-1144 m.

Figure 2.6 An example of alternation of sylvinite bed (to the left) and banded halite from the Belle Plain Submember. 1030-1033 m.

Figure 2.7 The contact (arrow) between the Leofnard Member of the Prairie Evaporite Formation and the Lower Red Bed Member (Dawson Bay Fm), which is marked by a thin zone of wavy-laminated anhydrite. Note banded halite in the two left boxes of the core. The metal tape is 0.5 m. 999-1002 m.
2.3.2 The Shell Lake Member

The Shell Lake Member is composed mainly of anhydrite with some carbonate intercalations. The base of the member is massive anhydrite (1 m) which truncates the halite below in the same way as was seen in the Intermediate Anhydrite Unit. The massive anhydrite is overlain by a thick sequence (22 m) of alternating mosaic anhydrite and laminated dolomitic mudstone up to the base of the Quill Lake marker beds. There are four distinct beds of the dolomitic mudstone, the lowermost one, which is also the thickest, is shown in Figure 2.2. Those farther up the sequence are thin beds alternating with the mosaic anhydrite.

An erosional surface separates the first grainstone bed of the Quill Lake marker beds from the unit below (Fig. 2.5). The marker beds have three prominent grainstone beds with a combined thickness of 4.6 m. These grainstone beds are interbedded with mosaic anhydrite in the lower part, and with laminar anhydrite from above the middle bed up to the top of the member. The change from mosaic to laminar anhydrite is obscure, probably as a result of diagenetic overprint in the rock.

2.3.3 The Leofnard Member

The interval from the top of the Shell Lake Member to the Marker #1 (11.5 m) is recrystallized halite which shows a marked contrast with halite elsewhere in the core. The degree of recrystallization decreases above the marker, and the rock appears more massive. This type of halite spans an interval of about 35 m, or roughly from the Marker #1 to #2. A few metres below the Marker #2, halite becomes banded. The banded halite dominates the upper half of the Leofnard Member, except where potash-bearing beds are present (Fig. 2.6). Halite in this member differs from the Whitkow Member in that it has reddish colour, and it generally lacks zoned crystals and anhydrite partings. Insoluble materials in the halite are predominantly dolomitic mud and clays.
There are four potash submembers in the upper 80 m of the Leofnard Member namely, the Esterhazy (17.5 m thick), the White Bear (8.3 m thick), the Belle Plain (12.1 m thick), and the Patience Lake (19.3 m thick). Potash minerals first appear as reddish specks at about 4 m above the base of the member or just above the Marker #1, and are more prevalent in the potash-bearing units. Each potash submember is basically an interval of thin potash-rich horizons that are separated by relatively barren halite. Except for the uppermost metre of the White Bear Submember, where a small amount of sylvite is present, potash in the lower two submembers of the reference well is exclusively carnallite. A mixture of sylvite and carnallite is found in the lower half of the Belle Plain unit before carnallite gives way to sylvite up-section.

The contact with the Lower Red Bed Member is a dissolution surface and is marked by a thin zone of wavy-laminated anhydrite (Fig. 2.7). Above this is a zone (20 to 30 cm) of crudely-mixed red dolomitic mudstone that is locally brecciated, and clear halite which, in turn, is succeeded entirely by mudstone.

2.4 Variations From the Reference Well

Considerable variations are apparent when one attempts to correlate the rock units in the study area. These variations include lithology, stratigraphic position, and thickness of the units. A large part of the variations in the Whitkow and Shell Lake Members clearly relates to the position of the well with respect to the underlying carbonate mounds. The Leofnard Member is more uniform, but the difficulty is that there seems to be no rule for predicting the occurrence of sylvite and carnallite. A summary of the variations in each member is given below.
2.4.1 The Whitkow Member

Halite with abundant zoned crystals is ubiquitous. Even beyond the study area, grab samples (collected by Don Chipley, University of Saskatchewan) of this member from the PCS Rocanville Mine (Fig. 1.1), are of the same type. One minor difference among the wells logged is in the spacing between anhydrite partings. In the Cominco 2-16 well, the spacing in the lower half rarely exceeds 10 cm, but in the upper half, it varies from 5 to 30 cm. In contrast, in the Outlook Crown No.1, the lower part of the member has only a few partings in an interval about 15 m thick.

Most variation is found in the distribution of the anhydrites. First, no Intermediate Anhydrite Unit was found in the Cominco 2-16 well, and the unit does not show up in the geophysical logs of other wells studied. Second, and more important, is the relationship with the Winnipegosis Formation. The Cominco 2-16 well has a fully-developed Ratner Member. Therefore, the contact is gradational from the carbonate of the Ratner Member to the Basal Anhydrite Unit (Fig. 2.8). This type of contact was described elsewhere by Reinson and Wardlaw (1972), and it differs from the erosional contact in the reference well. The organic laminae in the Basal Anhydrite Unit are very distinct. Some anhydrite beds clearly show enterolithic structure. The Basal Anhydrite Unit here is 70 cm thick.

The Basal Anhydrite Unit in the Outlook Crown No.1 well is similar to that of the reference well but has no ruditic component. It is only 15 cm thick, lying sharply upon the fine, wavy-laminated dolomitic mudstone of the Winnipegosis Formation. The contact with the overlying formation is gradational, similar to that of the Cominco 2-16 well.

Considering the whole member, the thickness of the Whitkow Member varies inversely with the underlying Winnipegosis Formation. It is thin near the mounds and thickens towards the intermound areas. This is evident in the work of Holter (1969),
Variations in lithology and stratigraphic relationships of the rock units from those in the reference well. Core diameter is 10 cm.

**Figure 2.8** Gradational contact (arrow) between the dolomitic mudstone of the Ratner Member (Winnipegosis Fm) and the distorted bedded mosaic anhydrite (Basal Anhydrite Unit, Prairie Evaporite Fm). The metal tape is 0.5 m. **Cominco 2-16 well, 1200-1203 m.**

**Figure 2.9** Bedded mosaic anhydrite (Shell Lake Mbr) and the overlying halite (Leofnard Mbr). **Osler 3-28 well, 1010-1014 m.**

**Figure 2.10** A small amount of carnallite (arrow) filling the interstices of halite with well-preserved chevron structures in the Leofnard Member. **Osler 16-24 well, 880 m.**

**Figure 2.11** A zone of dissolution and recrystallization below the contact (arrow) between the Leofnard Member and the Lower Red Bed Member. Note the banded halite in the two rows of the left core box and the absence of wavy-laminated anhydrite zone at the contact. **U.S. Borax 9-26 well, 1012-1014 m.**
and in the study area. For example, in the Cominco 2-16 well the Whitkow Member is about 53 m, compared to 38.1 m in the reference well.

### 2.4.2 The Shell Lake Member

An anhydrite-carbonate sequence similar to the reference well also occurs in the Drake 4-29 well. Nineteen metres of the member, which geophysical logs indicate to 35 m thick, are cored. This sequence is comparable to those in the mosaic anhydrite and laminated carbonate, the Quill Lake marker beds, and the laminar anhydrite of the reference well. It contains two grainstone beds, the thicker one is about a metre, and the other is only 20 cm thick.

Another mosaic anhydrite-laminated carbonate is found in the Outlook Crown No.1 well. Both the upper contact with the Leofnard Member and the lower contact with the Whitkow Member are missing. However, it is interesting to see that the Whitkow Member is only 15 m thick, and consequently, the stratigraphic position of the Shell Lake Member is the lowest among the wells studied. This is because the Winnipegosis mounds are poorly-developed in this area (Jones, 1965), and as shown by Wilson (1985), they are only 15 to 30 m high. The genetic association between the Shell Lake Member and the mounds has long been known (i.e., Reinson and Wardlaw, 1972), and it is confirmed here.

A relatively thin Shell Lake Member, composed only of bedded mosaic anhydrite is found in the Cominco 2-16 and Osler 3-28 wells. In the Cominco 2-16 well, the anhydrite is about 5 m thick and has sharp contacts with the overlying and underlying halites. Anhydrite of the Osler 3-28 well also has a sharp contact with the overlying halite, but the cored section (5 m thick) does not contain the lower contact. The anhydrites in both wells have a vague nodular structure or are, locally, almost massive with wavy carbonate streaks, but the organic laminae are clearly visible (Fig. 2.9).
2.4.3 The Leofnard Member

Compared to the lower members, the Leofnard Member is less variable. The thickness of the member ranges from 110 m, as in the reference well, to 132 m in the Cominco 2-16 well. Only in the southeastern portion of the study area are all four potash submembers present. Westward of the PCS Allan Mine, the Esterhazy and White Bear units thin across the area of high carbonate mounds east of Saskatoon, indicating the influence of the mounds on the deposition of the lower two potash submembers (see cross-sections).

The occurrence of sylvite and carnallite in the submembers is inconsistent. For example, in the Allan area, carnallite occurs in the lower part of the Belle Plain Submember of the U.S. Borax 9-26 well similar to that of the reference well, but in the Elstow 5-26 well, no carnallite is present. Normally, carnallite is absent in the Patience Lake Submember, but in the C.M. & S. Vanscoy 4-10-35-8W3 well, it occupies the lower half of the unit (McVittie, pers. comm., 1990).

At the northern end of the study area, there is no recognizable potash submember. Nevertheless, a small amount of carnallite is present in the uppermost part of the member in the Osler 16-24 well where it occurs as a cement filling interstices of the upward-growing chevron halite crystals (Fig. 2.10). The same type of carnallite is also recorded in the Marysburg #1 well. Additionally, a thin zone of recrystallization (30 cm) made up of coarse-grained sylvite and halite is present directly below the Lower Red Bed Member of the Dawson Bay Formation.

In most of the wells examined there is a prominent zone of wavy-laminated anhydrite at the contact between the Leofnard Member and the Lower Red Bed Member similar to that of the reference well. However, in the U.S Borax 9-26 and Marysburg #1 wells, such a zone is absent. The contact is marked by a zone of dissolution and an abrupt increase of brown or mottled mud below the Lower Red Bed Member (Fig. 2.11).
2.5 Well Locations in the Depositional Context

To understand the variations in the formation, particularly in the Whitkow and Shell Lake Members, it is necessary to consider the relationship of the well locations and the distribution of the rock units with respect to the underlying carbonate mounds. The basis of this understanding derives from a compilation of the studies of Jordan (1967), Wardlaw and Reinson (1971), Reinson and Wardlaw (1972), and Wilson (1985). It is clear that halite of the Whitkow Member is present in the intermound areas, and the thickest part of the member lies between the two given carbonate mounds. All anhydrites, on the other hand, are thicker at locations adjacent to the mounds and thin away from them.

From the map showing the distribution and thickness of the upper Winnipegosis mounds produced by Wilson (1985), the reference well is located just south of an area where the mound (or mounds) is 60 to 90 m high. The presence of the halite and anhydrites of the Whitkow Member, and the thick Shell Lake Member (including the Quill Lake marker beds) indicate a location in an intermound area, but quite close to the mound (Fig. 2.12). The combined thickness of these two members is also comparable to the height of the mound. At present, a more precise location is impractical because the size, shape, and the extent of the mound are only partly known. Such limitations led Wilson (1985) to use a symbolic representation of the mounds (Fig. 7 of Wilson, 1985) rather than an isopach map, in order to avoid misrepresentation.
Figure 2.12 Schematic diagram of the locations of the three representative wells in a depositional context, showing variations of the Whitkow and Shell Lake Members in relation to the carbonate mounds (not geographical locations). The Leofnard Member is not correlated.
3. SEDIMENTOLOGY AND PETROGRAPHY
OF THE WHITKOW MEMBER

This chapter describes in detail the lithology of the Whitkow Member, both at megascopic and microscopic scales. For the purpose of this study, the member is subdivided into three units, and provisional names are assigned as Basal Anhydrite, Translucent Halite, and Intermediate Anhydrite. Figure 3.1 shows this subdivision, and it includes the lithology, and sedimentary features of the rock units in the reference well. The lithology of the corresponding units from other wells will also be described, and the differences or similarities will be highlighted.

It should first be noted here that in this thesis the lithologic description rather than the facies description is preferred. This is because of the range of variations within the rocks of practically similar appearance, but which carry different genetic messages. Thus, defining proper facies limits is difficult. Another reason is the complications caused by diagenesis. Diagenetic overprints are known to produce rocks that superficially resemble those produced syndepositionally in different environments. For example, mosaic anhydrite produced by burial diagenesis can be quite similar to anhydrite from a tidal flat environment or from a deep-sea setting (Dean et al., 1975; Clark, 1980). Thus if the term "nodular anhydrite facies" was assigned to an anhydrite interval, confusion as to its environmental implication would occur.

3.1 Basal Anhydrite Unit

3.1.1 Lithology and Sedimentary Features

In the reference well, the Basal Anhydrite Unit lies unconformably upon the Winnipegosis carbonate. The unconformity is demonstrated by an erosional surface
Figure 3.1 A schematic diagram of the Whitkow Member in the reference well, showing provisional subdivision of the member, its gross lithology, and sedimentary features.
and the truncation of the anhydrite crystals that lie directly below it. (Fig. 3.2). The lowermost part of the Basal Anhydrite Unit is ruditic anhydrite containing various types of carbonate lithoclasts, some of which have abundant acicular anhydrite crystals. The sand- to pebble-sized clasts are grainstone-packstone or bioclasts, while the larger ones are mudstone, commonly showing microbial lamination. These clasts are intermixed at the base but mudstone clasts become dominant upward. An abrupt decrease in the quantity of clasts occurs over a 50 cm interval, and where present in small amounts, the clasts appear as thin streaks bordering irregular or nodular anhydrite masses (Fig. 3.3). Up section, the rock becomes distorted mosaic and massive anhydrites. These two varieties of anhydrite are typical of the Basal Anhydrite Unit. Undulating brown carbonate laminae, some with organic films, are common in the light grey anhydrite mass. Some carbonate laminae are disrupted, but some are continuous across the core, giving the anhydrite a poorly bedded appearance.

A more pronounced laminaton in anhydrite is found in the Cominco 2-16 well where the Basal Anhydrite Unit is distorted bedded mosaic. Brown or black organic material sandwiching the light grey anhydrite beds is very marked. Although variable, the bedding is generally thin at the base and increases to more than a centimetre upward towards the overlying halite. Distortion of the laminae and enterolithic structure are visible at places, indicating a displacive origin of much of the anhydrite (Fig. 3.4). No desiccation cracks were found in the rock. The underlying Ratner Member is composed mostly of fine- to wavy-laminated dolomitic mudstone.

In the Outlook Crown #1 well, there is also an interval of dolomitic mudstone (Ratner Member) directly underlying the Basal Anhydrite Unit. Most of the rock is broken into chips along the plane of lamination. However, wavy lamination with distinct birds-eye fenestral fabrics is common at several locations (Fig. 3.5). Some small anhydrite laths showing random orientation are also present.
PLATE III

Lithology and sedimentary features in the Whitkow Member.

Figure 3.2 The contact between the wackestone-packstone of the carbonate mound and ruditic anhydrite of the Basal Anhydrite Unit. Note two small erosional surfaces (large arrows) and truncation of the anhydrite crystals (arrow) directly below the contact. Reference well, 1182 m, scale bar = 2 cm.

Figure 3.3 Carbonate rudites in the Basal Anhydrite Unit, displaced and cemented by nodular anhydrite. Reference well, 1181 m, scale bar = 2 cm.

Figure 3.4 Distorted bedded mosaic anhydrite with enterolithic structures in the Basal Anhydrite Unit. Cominco 2-16 well, 1202.5 m, scale bar = 2 cm.

Figure 3.5 Fine-and wavy-laminated dolomitic mudstone of the Ratner Member (Winnipegosis Fm) which directly underlies the Basal Anhydrite Unit. Note fenestral fabrics (arrows) in the upper part. Outlook Crown #1 well, 1397.5 m, scale bar = 2 cm.

Figure 3.6 Photomicrograph of a well-preserved crinoid arm plate whose internal cavity is filled by crystalline anhydrite (A). Reference well, 1182.5 m, scale bar = 0.5 mm, cross-nicols.
3.1.2 Petrography of Ruditic Anhydrite

The grainstone-packstone clasts are peloidal with a wide variety of bioclasts. Among the common ones are crinoidal plates and columnals, calcispheres, ostracodes, and microbial filaments. These fossils are dolomitized and their internal cavities are filled with coarse crystalline anhydrite (Fig. 3.6). Many clasts contain randomly oriented, lath-shaped anhydrite crystals. The majority of the clasts are well rounded, indicating that they were transported into the site.

In contrast, the mudstone lithoclasts are somewhat angular and larger, and they are more likely to have formed in situ. Many show evidence of physical disruption (Fig. 3.7) in the form of fractures, intrastratal cracks, and slump features. These indicate that lithification of the original sediments occurred prior to their incorporation in the ruditic anhydrite. The laminated fragments have thin brown microbial films with anhydrite laths and small clusters of pyrite. The non-laminated mudstone is usually represented by fragments afloat in the anhydrite matrix.

The anhydrite matrix has a microcrystalline to subfelted texture. The anhydrite is generally aligned horizontally, but where coarse fragments are present, it enfolds or flows along intergranular spaces. Dolomite clots, streaks, or rhombs, which were probably derived from mudstone framework, are dispersed in the adjacent matrix and diminish over a short distance away from it.

Small amounts of anhydrite fill pore-spaces and fractures. This type of anhydrite occurs as an equigranular mosaic up to 150 microns across in small openings, and tends to form coarse, stubby laths in larger ones. It is also found in the interlaminar areas of the laminated mudstone where these consist of microsparite, which has higher porosity than the predominant micrite.
PLATE IV

Lithology and sedimentary features in the Whitkow Member.

Figure 3.7 Photomicrograph of physical disruption of the mudstone lithoclasts in ruditic anhydrite. **Reference well, 1182 m**, scale bar = 0.5 mm, cross-nicols.

Figure 3.8 Photomicrograph of displacive anhydrite nodules (As) in probable microbial mats. **Cominco 2-16 well, 1202.5 m**, scale bar = 1 mm, plane polarized light.

Figure 3.9 Typical lithology of the Translucent Halite Unit, with thin anhydrite partings. **Cominco 2-16 well, 1174-1177 m**, the metal tape = 0.5 m.

Figure 3.10 Truncation of bottom-nucleated, chevron halite crystals by both the overlying anhydrite parting (brown) and adjacent clear halite crystals (H). **Reference well, 1155 m**, scale bar = 1 cm.

Figure 3.11 Photomicrograph showing subfelted anhydrite crystals (A) along the boundary of zoned halite crystals. **Reference well, 1155 m**, scale bar = 0.5 mm, plane polarized light.
3.1.3 Petrography of the Other Anhydrites

Petrographically, most of the anhydrite in the Basal Anhydrite Unit, whether it is distorted bedded, bedded mosaic, distorted mosaic or massive, appears similar. This is because all have been diagenetically overprinted. The dominant processes seem to have been conversion from gypsum to anhydrite and subsequent anhydritization which tend to obliterate the primary signatures of the rocks.

The anhydrite is still mostly microcrystalline to subfelted. Crystal alignment varies from one place to another, perhaps due to differential mobility of and original crystal slush or to early differential compaction during the time of formation. There are several areas in the microcrystalline anhydrite where coarse, euhedral laths or wheatsheaf fabrics are found. Holliday (1973) interpreted the same types of anhydrite in the Upper Permian evaporites of England as a product of selective recrystallization of finer anhydrite crystals.

The areas with organic lamination are the areas where preferred crystal alignment can best be seen. The anhydrite nodules show subhorizontal orientation and are usually bound by the laminae, indicating displacive origin (Fig. 3.8). It is probable that they were originally gypsum.

Thin partitions between anhydrite nodules are made up of dolomicrite and organic films. They are host sediments that were displaced by anhydrite crystal growth, thereby producing wavy lamination in the rocks. In cases where relatively thick films are present, the lamination is more prominent. Localized decomposition of the organic component led to the development of voids along the films which were subsequently filled by stubby anhydrite and halite cements. The relationship between organic films and pores clearly supports the fenestral origin of the latter.
3.2 Translucent Halite Unit

3.2.1 Lithology and Sedimentary Features

Halite in the Translucent Halite Unit is typically granoblastic and coarsely crystalline, with crystal sizes ranging from 0.3 to 0.6 cm, but coarser crystals up to 1.2 cm are not uncommon. Zoned structures, formed by variations in the density of fluid inclusions, are obvious in most crystals. Euhedral crystals are abundant in the intervals in which anhydrite parting are sparse or absent. Vertically-oriented chevron crystals, on the other hand, are found in the intervals with abundant anhydrite partings. The halite showing zoned structure makes up about 90% of this unit in all wells, giving it a uniform "white and clean" appearance (Fig. 3.9).

Clear, inclusion-free halite occurs sporadically below the anhydrite partings and, in places, occurs within the areas of zoned crytals. Representing dissolution and recrystallization, the presence of clear halite does not affect the thin anhydrite laminae directly above, and some zoned halite crystals are still preserved nearby (Fig. 3.10). This observation indicates the subtlety and limited extent of the recrystallization processes. At the same time these processes are more likely to be syndepositional, or else the disturbance in the anhydrite partings would probably have been apparent.

Another feature in the Translucent Halite Unit is olive-green banding which is found in the lower part of the section. The banding is formed as a result of an increase in anhydrite content over an interval of 3 to 5 cm. The boundaries of the bands are not as sharp as those of anhydrite partings. Some of the bands include anhydrite laminae, suggesting therefore, that the processes that formed laminae and bands are quite similar.
3.2.2 Petrography

The zoned halite crystals are very irregular and highly variable in size. The original crystals must have been larger but were broken up and reworked resulting in random orientation of the grains. Moreover, they were partly dissolved by less-concentrated brines afterward. This is demonstrated by the presence of anhydrite as small microcrystalline mushes or subsfeted crystals along grain boundaries of zoned halite (Fig. 3.11). Some entirely clear halite grains penetrate the zoned structure with curved boundaries. It is clear that deposition of the halite sequence was not a single-step process, but was complicated by later dissolution and reprecipitation before it was buried and compacted.

In the intervals where anhydrite partings are common, chevron halite with upward-growing orientation is abundant. Crystals that are up to 2 or 3 cm long are common. They grew on top of the underlying anhydrite and those in the uppermost part of each halite bed are sharply truncated by overlying anhydrite beds (Fig. 3.12). Below the anhydrite partings there are dissolution pipes and clear halite, both sharply cut the nearby zoned halite crystals. This relationship implies that there was a direct contact of the less-concentrated brine, and that the latter brine infiltrated the already-deposited halite. Continued evaporation, together with dissolution of the existing halite, brought the brine to the level where sulphate and later on halite could form.

3.3 Intermediate Anhydrite Unit

3.3.1 Lithology and Sedimentary Features

In general, the major rock types are similar to those in the Basal Anhydrite Unit. Massive anhydrite usually shows a tint of bluish grey and light grey, with faintly planar alignment. Overlying this is the laminated carbonate portion in which the rock
changes back and forth over a short interval from stromatolitic, to wavy- and fine millimetre-scaled laminated dolomitic mudstone (Fig. 3.13) with fenestral fabrics in places. There are dense anhydrite laminae intercalated in the laminated mudstone section, and they become increasingly common upward. Several conspicuous vertical cracks, probably synaeresis cracks, are found in places; all are filled with halite.

The base of the main anhydrite directly overlying carbonate rocks is bedded mosaic where flat-lying nodules are bounded by organic laminae. Laminar anhydrite occurs locally, and soft-sediment deformation is expressed as microfolds, and distortion of the anhydrite laminae (Fig. 3.14). Up section, the rock grades into mosaic anhydrite with undulating carbonate streaks and, locally, massive anhydrite.

3.3.2 Petrography of Massive Anhydrite

This variety of anhydrite has a large amount of felted and lath-shaped crystals, making it the coarsest among the various types of anhydrite. Accessory components are micritic clots of variable sizes, some of which are round, in an anhydrite matrix. At locations where the density of these particles is low, the felted anhydrite shows a strong horizontal alignment like a schistose texture, but where the carbonate particles are present, the alignment is poor (Fig. 3.15). This implies that the carbonate particles were already at least partially lithified while the process of anhydrite crystal alignment, presumably compaction, was taking place, and that the carbonate obstructed the deformation. Selective recrystallization leading to the formation of locally coarse, lath-shaped anhydrite similar to those in other fine-grained anhydrites, is common.

3.3.3 Petrography of Finely-Laminated Carbonate

The lamination in the finely-laminated carbonate is very pronounced and usually occurs at a millimetre-scale. The carbonate particles are predominantly mud,
PLATE V

Lithology and sedimentary features of the Whitkow Member.

Figure 3.12 Photomicrograph showing truncation of zoned halite crystals by an anhydrite parting (dark) and clear halite crystal (to the right). Reference well, 1155 m, scale bar = 1 mm, plane polarized light.

Figure 3.13 Alternation of stromatolitic, wavy-, and fine-lamination in dolomitic mudstone of the Intermediate Anhydrite Unit. Note fenestral fabrics (arrows) in the core. Reference well, 1166 m, scale bar = 5 cm.

Figure 3.14 Overturned fold in laminar anhydrite, lower part of the Massive Anhydrite Unit. Reference well, 1165 m, scale bar = 2 cm.

Figure 3.15 Photomicrograph showing different degrees of deformation in massive anhydrite due to the presence of carbonate particles (C). Reference well, 1167 m, scale bar = 1 mm, cross-nicols.

Figure 3.16 Photomicrograph of reversed graded bedding in the finely-laminated dolomitic mudstone of the Intermediate Anhydrite Unit. Note roundness of many carbonate grains (arrows) indicating a detrital origin. Reference well, 1166 m, scale bar = 0.5 mm, plane polarized light.

Figure 3.17 Photomicrograph of the same sample as in Figure 3.16 showing primary porosity in the carbonate laminae as a control of diagenetic anhydrite (A) crystallization. Scale bar = 0.5 mm, plane polarized light.
some have high roundness and good sorting. A small amount of micrite is found in the form of undulating laminae. The carbonate sediments may occur as single laminae or may form couplets bounded by organic films. In the latter case, there is a gradual increase in grain size upward, with micrite underlying the coarser particles, thus giving reversed graded bedding (Fig. 3.16). From the roundness and sorting, this type of bedding is more likely to be the result of fluctuating energy of the depositing media rather than changing brine chemistry.

Anhydrite laths up to 1 mm long are present in some laminae, particularly those that are well-sorted. Most of these crystals are confined within a single lamina, with only a few penetrating through it. The occurrence of these laths is clearly related to the porosity and the amount of brine trapped in each lamina. The size, shape, and orientation of the laths are controlled to a large degree by the space available in the surrounding carbonate grains (Fig. 3.17). They, therefore, postdate the carbonates. The remaining intergranular spaces in these laminae are filled with halite.

### 3.3.4 Petrography of Bedded Mosaic and Mosaic Anhydrite

The gross characteristics of these rocks resemble those in the Basal Anhydrite Unit. Microcrystalline anhydrite is the main constituent with dolomite rhombs clustering along the brown organic laminae or dispersed in the matrix. Nodular structure in anhydrite can be seen where the partitioning organic matter is still preserved. In locations where the rock is laminated, distortion and disruption is apparent. The interlaminar spaces and cracks are plugged by clear halite. A few authigenic quartz crystals are also found in these anhydrites. Both the lamination and the nodular structure become less distinct upward.
4. SEDIMENTOLOGY AND PETROGRAPHY

OF THE SHELL LAKE MEMBER

The Shell Lake Member is subdivided here into four units which in ascending order are: Massive Anhydrite, Mosaic Anhydrite-Laminated Carbonate, the Quill Lake marker beds, and Laminar Anhydrite. A diagrammatic log, showing subdivision of the rock units, and the associated sedimentary features, is shown in Figure 4.1. This subdivision is only applicable to wells that are near the mounds, such as the Lanigan 4-28 and Drake 4-29 wells, and thus have thick anhydrite-carbonate sequences. Those from the centre of the intermound areas, e.g., the Cominco 2-16 well, have only a thin bedded mosaic anhydrite section. For these, no further subdivision is necessary, and the description of the same rock types in the Basal Anhydrite and the Intermediate Anhydrite units is applicable.

4.1 Massive Anhydrite Unit

4.1.1 Lithology and Sedimentary Features

The main component of this unit is massive anhydrite, but there is a thin interval of highly distorted anhydrite at the base, lying on the dissolution surface of the underlying halite. The highly distorted anhydrite is light grey with a coarse and wispy appearance due to the presence of thick, brown, and broken organic laminae which help accentuate the flow pattern in the rock. The degree of deformation decreases upward over an interval of 20 cm from the base as massive anhydrite appears. Due to incomplete coring, the existence of the highly distorted and massive anhydrites in the Drake 4-29 well cannot be verified.
Figure 4.1 A schematic diagram of the Shell Lake Member in the reference well, showing provisional subdivision of the member, its gross lithology, and sedimentary features.
4.1.2 Petrography

The highly distorted anhydrite is basically microcrystalline to subfelted, and, less commonly, felted anhydrite with remnants of microbial-derived materials. Abundant carbonate particles are dispersed in the matrix and clustered densely along wavy organic laminae. Flowage in the rock is best exhibited at locations where the organic laminae are abundant. Undulation, steep inclination, and overturned folding of the laminae are ubiquitous (Fig. 4.2). These structures do not show any common orientation, indicating that they are only local phenomena. Microscopic pyrite is also present. The petrography of the massive anhydrite closely resembles that in the Intermediate Anhydrite Unit (p. 42), and its description, therefore, will not be repeated.

4.2 Mosaic Anhydrite-Laminated Carbonate Unit

4.2.1 Lithology and Sedimentary Features

About two-thirds of the Shell Lake Member is made up of mosaic to massive anhydrite and laminated carbonate. Lying sharply on massive anhydrite of the previous unit, the Mosaic Anhydrite-Laminated Carbonate Unit begins with light brown, microbial-laminated dolomitic mudstone that passes upward, across a thick microbial lamina, into mosaic anhydrite with thin mudstone streaks. The carbonate is present locally as thin wavy laminae in the grey anhydrite matrix. The next carbonate bed lies sharply on this anhydrite, and the same sequence of carbonate to anhydrite is repeated. Except for the four distinct beds in the lower part which are mappable, the rest of the dolomitic mudstone is too thin to be shown on the diagram (Fig. 4.1).

Starting from a small quantity of needles in the laminated mudstone, anhydrite usually shows a sudden increase in the areas of thick organic laminae. Accompanying this increase is the very fine-grained anhydrite. It is clear, even from hand specimens,
PLATE VI

Lithology and sedimentary features in the Shell Lake Member.

Figure 4.2 Photomicrograph of overturned microfolds and distortion in highly distorted bedded anhydrite of the Massive Anhydrite Unit. Dark areas are organic films clustered with carbonate particles. Reference well, 1144 m, scale bar = 1 mm, plane polarized light.

Figure 4.3 Disturbance in dolomitic mudstone host (brown) due to growth of displacive anhydrite (grey). Where the growth is extensive, the host becomes streaks in anhydrite matrix. Reference well, 1142 m, scale bar = 2 cm.

Figure 4.4 An abrupt change from laminated dolomitic mudstone to mosaic anhydrite across an erosion surface. Note a minor erosional surface (arrow) and a zone of intraclasts (I) below the main erosional surface. Outlook Crown #1 well, 1369 m, scale bar = 5 cm.

Figure 4.5 Photomicrograph of swelling and broken laminae in laminated dolomitic mudstone. Yellow crystals are pore-filling anhydrite. Reference well, 1142 m, scale bar = 1 mm, cross-nicols.

Figure 4.6 Photomicrograph of displacive microcrystalline anhydrite (A) that splits the mudstone laminae (dark) apart. Reference well, 1138 m, scale bar = 1 mm, cross-nicols.

Figure 4.7 Rectangular outline of microcrystalline anhydrite (A) which probably suggests that it is a pseudomorph after a gypsum precursor. Same sample as in Figure 4.6, scale bar 0.5 mm, cross-nicols.
that the very fine-grained anhydrite has intruded along planes of lamination in the mudstone. As a result of extensive growth, the mudstone laminae were split apart (Fig. 4.3). The degree of disturbance varies according to the extent of anhydrite development. At its maximum, the original carbonate is present only as wavy streaks in the nodular mosaic and distorted nodular mosaic anhydrite.

This rock unit is also present in the Drake 4-29 and Outlook Crown No.1 wells, both of which are located close to the carbonate mounds. The Drake 4-29 well has a wider spectrum of anhydrite of mosaic affinity and laminated dolomitic mudstone similar to the reference well, while the sequence in the Outlook Crown #1 well shows clear breaks in the depositional record. The change from the laminated mudstone to mosaic and massive anhydrites usually occurs across a zone of intraclasts and an erosional surface (Fig. 4.4). Wavy or distorted carbonate streaks in anhydrite are also apparent.

4.2.2 Petrography

The laminated mudstone consists of two main components, the dominant one being microcrystalline dolomite which is usually darker in colour, and dolomite silt. Each can be found separately or in association with the other, and in places are bound by organic films. The laminae are not planar, but highly swelling and frequently broken (Fig. 4.5). Some peloidal sediments with structure grumeleuse and intraclasts are also present locally. The variations in grain size are always abrupt, suggesting fluctuating energy levels of the depositional media.

Lath-shaped anhydrite is randomly oriented in the laminated carbonate. Some laths terminate against, and a few penetrate across, the thin organic films. A small amount of carbonates is usually incorporated into the laths, which suggests that anhydrite must have formed from interstitial brines within the carbonate sediments. A rapid increase of anhydrite laths occurs preferentially adjacent to thick organic
laminae. This may have resulted from the impermeability of these laminae, because
the brine migration occurred preferentially along the planes of lamination, and not
across them.

The alternation of laminated mudstone and anhydrite is not depositional but is
the result of displacive growth of anhydrite in the laminated carbonate host. Where the
growth is not very extensive, the various stages in anhydrite development are visible.
Nodular and elongate masses of subfreted and microcrystalline anhydrite first
originate in pore spaces in the muddy host (Fig. 4.6). The presence of organic laminae
places a constraint to vertical expansion of anhydrite, therefore the anhydrite growth
tends to be horizontal and gradually separates the carbonate laminae. At its maximum
extent, anhydrite splits all laminae apart.

Because it displaces the lath-shaped anhydrite as well as the laminated
carbonate, the microcrystalline anhydrite must have formed later. It may have
originated from the pre-existing anhydrite laths because some occurs within the areas
occupied by laths. However, some must also have formed from pore fluids through a
gypsum precursor, as shown by many angular nodules and stubby rectangular gypsum
pseudomorphs in the matrix (Fig. 4.7). It is uncertain which type is the more abundant.

A small volume of the rock consists of reworked sediments, as examplified by
resedimented anhydrite. The anhydrite fragments are mostly elongate, subangular to
subrounded, although they are well rounded locally. They lie subhorizontally in the
finer matrix and, in turn, are cemented by microcrystalline anhydrite and organic-rich
clay (Fig. 4.8). With a decreasing amount of fragments, nodular mosaic anhydrite
takes over the section. Some intraclastic carbonates are also found, but due to
subsequent alteration, they cannot be identified with confidence. Probably they are
both peloidal and bioclastic in origin.
PLATE VII

Lithology and sedimentary features in the Shell Lake Member.

Figure 4.8 Photomicrograph of subangular anhydrite lithoclasts cemented by microcrystalline anhydrite and organic-rich clays (brown). **Outlook Crown #1 well, 1381 m**, scale bar 0.5 mm, plane polarized light.

Figure 4.9 Disruption and upward-buckling of the organic-rich laminae (dark brown) in grainstone. **Drake 4-29 well, 1119 m**, scale bar = 2 cm.

Figure 4.10 Intrastratal cracks (arrows) projecting downward from a common surface, probably representing desiccation cracks. **Drake 4-29 well, 1125 m**, scale bar = 2 cm.

Figure 4.11 Photomicrograph of peloids (dark), calcisphere (Ca), and concentric ooid (O), and crinoid ossicle (Cr) in grainstone. Note binding of the sediments by microbial mats (black). **Drake 4-29 well, 1125 m**, scale bar = 0.5 mm, plane polarized light.

Figure 4.12 Photomicrograph showing normal graded bedding in grainstone from peloid- and intraclast-dominated laminae to carbonate sand, to silt and mud with microbial mats. **Reference well, 1117 m**, scale bar = 0.5 mm, plane polarized light.
4.3 The Quill Lake Marker Beds

4.3.1 Lithology and Sedimentary Features

In the reference well, there are three prominent grainstone beds in the Quill Lake marker beds. These beds are composed of centimetre-scale laminae of alternating grainstone and dolomitic mudstone with diffuse boundaries. The grain-dominated laminae are light brown and porous whereas the muddy ones are somewhat darker and usually contain wavy organic films, probably microbial mats. In some mudstone laminae, grainstone occurs as discontinuous or broken laminae, and in pockets.

The grainstone in the Drake 4-29 well has generally coarser particles, higher porosity (now occluded with halite), and more organic materials. Prominent cracks several centimetres long, disruption, and upward buckling of the organic-rich laminae are commonly found (Fig. 4.9). Additionally, in some places there are many small intrastratal cracks projecting downward from common surfaces in some places (Fig. 4.10). Intraclastic particles of both carbonate and anhydrite can be seen locally.

Well-developed Quill Lake marker beds were observed only in these two wells, but lesser development was also noted in the Outlook Crown #1 well. There, pockets of grainy sediments are located in the upper part of the mosaic anhydrite-laminated carbonate section, generally resembling that of the reference well.

4.3.2 Petrography

Most of the grainy laminae are composed of particles that include peloids, intraclasts, and fine carbonate sand in a finer-grained matrix. Even with dolomitization, some of the sand-sized particles still maintain a high degree of roundness, indicating a detrital origin for the grains. Commonly associated with these sediments are calcispheres, algal fragments, echinoderm columnals and plates, and,
rarely concentric ooids (Fig. 4.11). Although these sediments are usually well-mixed, there are a few laminae in which peloids or intraclasts dominate. Grain orientation is generally horizontal but some of the particles are vertically oriented which suggests rapid settling out of the water column whose energy level was decreasing.

Muddy laminae are composed of finer carbonate sediments ranging in size from very fine sand to clay. The change from the coarse-grained laminae to the muddy laminae is abrupt. Although not always in a consistent order, many laminae show normal grading patterns that begin with peloid- and intraclast-dominated bases, followed by carbonate sand and mud with wavy organic films (Fig. 4.12). The thickness of these laminae is in the range of a few millimetres, and their surfaces are typically sinuous probably due to current action and compaction.

Accessory minerals are anhydrite, small amounts of halite in intergranular spaces, and disseminated pyrite. Anhydrite has two modes of occurrence - lath-shaped crystals and pore-filling. In places, the anhydrite laths cut through both the framework material and the cement (Fig. 4.13). This implies that they postdate all the carbonates, and were therefore, formed by diagenesis. The size and shape of the pore-filling anhydrite, on the other hand, are clearly controlled by the available porosity in the rock. The timing of anhydrite formation is uncertain, but it is speculated that the pore-filling anhydrite was formed some time after its lath-shaped counterpart. Radiating fibrous forms found in some larger pores probably indicate that there was no gypsum precursor.

4.4 Laminar Anhydrite Unit

4.4.1 Lithology and Sedimentary Features

The Laminar Anhydrite Unit first appears above the middle grainstone bed, but the change is rather obscure, probably as a result of diagenesis. The rock is composed of
PLATE VIII

Lithology and sedimentary features in the Shell Lake Member.

Figure 4.13 Photomicrograph showing two modes of occurrence of anhydrite, - lath-shaped (blue) and microcrystalline (A). Both cross-cut the carbonate grains (dark). Drake 4-29 well, 1115 m, scale bar = 0.5 mm, cross-nicols.

Figure 4.14 Typical contact between laminar anhydrite (light grey) and grainstone (brown). Note the presence of thin lense of grainstone below the contact (arrow). Drake 4-29 well, 1115 m, scale bar = 1 cm.

Figure 4.15 A disrupted surface (arrow) probably due to desiccation in laminar anhydrite overlying stromatolitic mudstone (white). The surface is, in turn, overlain by a thin layer of intraclasts (l) before the laminar anhydrite returns. Reference well, 1113 m, scale bar = 2 cm.

Figure 4.16 A desiccation surface in anhydritic mud laminae (light greenish grey). Note stromatolitic mudstone with fenestral fabrics below. Reference well, 1112 m, scale bar = 2 cm.

Figure 4.17 Photomicrograph of a large, angular carbonate fragment with iron-oxide staining (dark). Note the disruption in the underlying anhydrite lamina in the form of micro-tepee structure (arrow). Reference well, 1111 m, scale bar = 0.5 mm, cross-nicols.

Figure 4.18 A micro-scale erosional surface indicated by dolomitic mudstone intraclasts similar to the underlying laminae and a vertical crack at the eroded surface. Reference well, 1112 m, scale bar = 0.5 mm, cross-nicols.
alternating bands of greenish grey and grey anhydrite, ranging in thickness from a few millimetres to a centimetre. None of these bands is continuous across the core; all are broken apart. The Laminar Anhydrite Unit is also found at a corresponding interval in the Drake 4-29 well. There, the intraclasts comprise both carbonate grains and angular anhydrite fragments that in places are almost half a centimetre across.

The contacts between the laminar anhydrite and the alternating grainstone beds are abrupt. However, it is common to find a few thin lenses of grainstone in the laminar anhydrite directly below each grainstone beds (Fig. 4.14). Rather than breaks in the depositional record, these contacts probably mark abrupt changes in energy level of the depositing media.

Thin zones of stromatolitic carbonate occur at different levels in the section, some containing evidence of desiccation. The rock usually begins with undulating stromatolitic carbonate and salt-filled fenestral porosity, then gradually passes upward into laminar anhydrite with intraclasts. The lamination in the anhydrite is broken up shortly thereafter (Fig. 4.15). Above this anhydrite, there is a layer a few centimetres thick composed of sand-sized intraclasts which show crudely graded bedding before returning to wavy-banded anhydrite. The sudden appearance of these intraclasts suggests a rapid change in the energy of the depositing media.

Another desiccation feature is found just above the topmost grainstone bed. Again, it starts with stromatolitic carbonate of alternating light brown and dark brown laminae (Fig. 4.16). Bird's eye structures are conspicuous in the lighter areas. Disruption of these laminae is obvious in the upper part, and coincides with the increasing amount of greenish grey mud. A more pronounced disruption occurs higher in the section where the finely-laminated mudstone is broken up by vertical cracks several centimetres long.
4.4.2 Petrography

There are two types of microcrystalline anhydrite, one with carbonate allochems and the other with very few or none. The different appearance of the alternating anhydrite bands is due to variable amounts of carbonate particles, as well as the size and arrangement of the microcrystalline anhydrite. The brownish carbonate particles are usually present as fine clots and small lenticular bodies, tens of microns to a few hundred microns across. Some large fragments, reaching 2 mm, and with iron oxide staining, are also found (Fig. 4.17). Anhydrite in the areas that lack these particles tends to be slightly coarser-grained and loosely-packed, whereas that with carbonate particles is finer and denser.

The fine-grained bands are likely to represent the primary accumulation of anhydrite in an environment which had a nearly constant supply of carbonate particles. It is difficult to imagine how the homogeneous mixture of both minerals could have formed by processes other than settling out from the same brine column. These bands are disturbed by the presence of coarser anhydrite. That is to say that the coarser anhydrite is of displaceve origin. The disturbance due to the displacive growth is expressed in forms of broken lamination, distortion, microfolding, and micro-tepee structures.

Some micro-scale erosional surfaces that are found in the rock provide evidence of desiccation. These erosional surfaces are indicated by the presence of dolomitic mud intraclasts, up to a few millimetre across, bordering the area between the underlying mud lamina and the overlying anhydrite-dolomite lamina (Fig. 4.18). Small desiccation cracks are filled with clear halite and anhydrite. Disruption and distortion of the laminae in nearby locations are also apparent.
5. SEDIMENTOLOGY AND PETROGRAPHY
OF THE LEOFNARD MEMBER

The halite and potash of the Leofnard Member are subdivided in this thesis by two marker beds, Marker #1, and #2 (Fig. 5.1). The variable characteristics of the halite are used to describe the member. The first unit is Recrystallized Halite, covering most of the interval from the top of the Shell Lake Member to the base of the Marker #1. The next unit, which spans the interval between Marker #1 to the point a few metres below the Marker #2, is Massive Halite. This is the unit that contains the Esterhazy and the White Bear Submembers. Above the Marker #2 is the alternating sequence of Banded Halite and Potash Beds, attaining a combined thickness of about 64 m. The Belle Plain and the Patience Lake Submembers are a part of this rock unit, and both will be described separately from the Banded Halite Unit because of their distinct lithology and mineralogy.

It is emphasized here that the boundaries of each rock type are not as well-defined as in the members below. This is because of the sporadic occurrences of one rock type in the other units. For example, recrystallized halite is found in great quantities in the Recrystallized Halite Unit, but it also occurs locally in the Massive Halite or Banded Halite Units; the banded type of halite is found in places in the Massive Halite Unit and becomes more abundant in the upper 60 m.

Insoluble seams are rare in the lower half of the member, but they become more and more prevalent in the upper half. They contain a number of sedimentary features, and are dealt with in a separate section. Because of their similarity, the Marker #1 and #2 beds are described together.
Figure 5.1 A schematic diagram of the Leofnard Member in the reference well, showing provisional subdivision of the member, its gross lithology, and sedimentary features.
5.1 Recrystallized Halite Unit

5.1.1 Lithology and Sedimentary Features

The Recrystallized Halite Unit is conspicuous in core because it lacks visible stratification and has extremely large crystals, locally up to ten centimetres. Insolubles, which are dominantly green or grey, are confined to interstitial spaces of the recrystallized crystals (Fig. 5.2). Some insolubles show very fine vertical layering indicating that they were formed from a highly viscous residue expelled during recrystallization. As indicated by a prominent vertical alignment, this clayey slush must have slurried downward along the existing spaces in the salt. Up section, the crystal size of the halite decreases somewhat, but is still very coarse compared to that elsewhere in the formation.

Where recrystallization is less extensive, halite with some broken anhydrite partings is still preserved. Although the zoned structure in halite is not distinctive, it is likely that, prior to recrystallization, translucent halite similar to that of the Whitkow Member existed up to this level. The horizontally-wavy surfaces in the core (Fig. 5.3) are interpreted as either erosional or truncation surfaces. They are clearly marked by the thin overlying anhydrite partings. Some millimetre-scale, anhedral carnallite crystals are disseminated locally in the halite.

The recrystallized halite appears to be localized because it is absent at the corresponding stratigraphic level in the Cominco 2-16 and the Osler 3-28 wells. The interval in these two wells is occupied by translucent (mostly zoned crystals) halite with anhydrite partings instead. This observation supports the earlier suggestion that the recrystallized halite in fact was originally translucent halite.
PLATE IX

Lithology and sedimentary features in the Leofnard Member.

Figure 5.2 Recrystallized halite with dark green insolubles (arrows) along crystal boundaries. Note the lack of stratification in the core. Reference well, 1108-1110 m, scale bar = 10 cm.

Figure 5.3 Horizontally-wavy undulating surfaces (arrows) marked by thin anhydrite. These surfaces are interpreted as truncational surface similar to those in the Translucent Halite Unit of the Whitkow Member. Reference well, 1105 m, scale bar = 10 cm.

Figure 5.4 Tiny anhydrite flakes incorporated into growth planes of the recrystallized halite and tightly-packed anhydrite masses along the grain boundaries. Reference well, 1110 m, scale bar = 1 mm, cross-nicols.

Figure 5.5 Green insolubles (arrow) flooring the bottom of a large carnallite pocket. More carnallite is also present in the interstices of halite. Osler 3-28 well, 903 m, scale bar = 5 cm.

Figure 5.6 Anhedral sylvite (deep red) filling interstices of the zoned halite crystals. Reference well, 1050 m, scale bar = 0.5 mm, plane polarized light.

Figure 5.7 Goethite (needles) and hematite (orange plates) inclusions in carnallite. The dominant orientation of goethite is probably parallel to c-axis of the carnallite. Reference well, 1076 m, scale bar = 0.2 mm, cross-nicols.
5.1.2 Petrography

In thin sections, recrystallized halite is very transparent because of the lack of fluid inclusions and a low insoluble content. The insolubles, mostly anhydrite, have two modes: tiny flakes, 100 to 250 microns across along growth planes of halite, and microcrystalline masses along halite crystal boundaries (Fig. 5.4). The alignment of the anhydrite flakes suggests that they were incorporated into halite crystals during recrystallization. Much of the microcrystalline masses are tightly-packed; they are probably those that were deposited along with the originally translucent halite and/or those that were expelled and squeezed by growth of the surrounding halite. There must have been some minor dissolution after recrystallization because the halite crystal boundaries are irregular and are bordered by mushy microcrystalline anhydrite.

Within the insolubles, there are brown angular clasts and wavy streaks of dolomicrite. Some fine dolomite rhombs, probably derived from these clasts and streaks, are dispersed in anhydrite. Microscopic-scale pyrite, also disseminated in places in the anhydrite, is another minor accessory.

5.2 Massive Halite Unit

5.2.1 Lithology and Sedimentary Features

The Massive Halite Unit is extensive, and it constitutes a large portion of the lower half of the member, as evidenced in the Lanigan 4-28, Osler 3-28, and the Cominco 2-16 wells. This halite is light brown or pale orange, and has a granoblastic texture. Crystal size is in the range of a few centimetres. Most of the salt is recrystallized, judging from the lack of bedding and the rarity of zoned fluid-inclusions. However, the degree of recrystallization is much less than the Recrystallized Halite Unit. Associated in the Massive Halite Unit is a small amount of
bright brick red carnallite. It occurs interstitially between coarser halite crystals. Sylvite is found only in the uppermost few metres of this rock unit.

A small amount of insolubles is present in the Massive Halite Unit in the form of seams (rare) and interstitial clots. The seams are associated with erosional or truncation surfaces similar to those in the Recrystallized Halite Unit. The clots usually align along halite crystal boundaries, suggesting that they were redistributed during halite recrystallization. More insolubles are apparent adjacent to carnallite, and in such cases, they tend to floor the bottom of the carnallite pockets (Fig. 5.5). There is a noticeable change in the colour of the insolubles from dominantly green or greenish grey in the lower half of the unit to brown in the upper half. An overall reddening of the unit is obvious, particularly from the White Bear Submember upward.

From a few percent in most of the massive halite, the carnallite content gradually increases to 10% or more in the Esterhazy and White Bear Submembers. The increase is so subtle that only with the help of geophysical logs can the submember boundaries be picked. In areas of higher potash content, such as the upper part of the Esterhazy unit, carnallite pockets are coarser than elsewhere in the submember. The pockets range in size from fractions of a centimetre to 4x5 cm² at some locations. The relationship with the surrounding halite and the constant vertical orientation of these pockets suggest that they were formed by concentrated brines migrating downward through the halite host. Therefore, the carnallite in the massive halite is not primary, but the timing of recrystallization is inconclusive.

5.2.2 Petrography

Halite crystals in this unit also lack zoned fluid inclusions and contain virtually no insolubles in the crystals. Two different types of boundaries are apparent: undulating and straight-line compromise boundaries. The undulating boundaries which resemble those in the translucent halite of the Whitkow Member, are the result
of minor dissolution. A small amount of carbonate mud may be found along this type of boundary. The straight crystal boundaries have interfacial angles of approximately 120°, and thus represent contemporaneous recrystallization of halite crystals in that location (Hardie et al., 1985).

Carnallite and sylvite fill the interstitial spaces, their size and shape being controlled by the surrounding halite crystal outlines. At locations where recrystallization is less severe, remnants of zoned halite crystals are still visible, and the anhedral crystals of potash, usually sylvite, project vertically into them (Fig. 5.6). These kinds of relationship indicate that neither the carnallite nor the sylvite was precipitated directly from the standing body of the brine. Instead, they were formed from highly-concentrated interstitial brines.

The red colouration in the carnallite results from iron oxide inclusions. Hematite is present as tiny plates, from 30 to 60 microns in length, that are dispersed rather uniformly, and goethite as acicular crystals, from 50 to 200 microns long, that show dominant orientation parallel to the probable c-axis (Fig. 5.7). Some crystals appear to be clear, inclusion-free. It is suggested, in accordance with Wardlaw (1968), that carnallite has at least two different generations, both with and without inclusions.

Sylvite has much smaller, deep red inclusions that tend to concentrate at the crystal rims. Nevertheless, there are sylvite aggregates that show the same type of inclusions as seen in carnallite and these can show common alignment across crystal boundaries (Fig. 5.8). These sylvite crystals could have originally been a large single carnallite crystal that has been transformed to sylvite. Further support for this suggestion is the vuggy nature of the area which probably resulted from partial leaching during the transformation.
Lithology and sedimentary features in the Leofnard Member.

Figure 5.8 Inclusions similar to those in Figure 5.7 are also found in some sylvite. Note 1) the common orientation of the inclusions (arrows) across the grain boundaries, and 2) voids (V). Reference well, 1054 m, scale bar = 0.5 mm, plane polarized light.

Figure 5.9 Alternation of sylvite bed (right) and banded halite (left) which contains lesser quantities of sylvite. Also, note the vertical orientation of sylvite in the banded halite. Honolulu 6-2 well, 919-921 m, scale bar = 10 cm.

Figure 5.10 Sylvite (bright orange) occurs as vertical cement in the interstices of the upward-growing halite crystals (broken lines) in banded halite. Reference well, 1024 m, scale bar = 2 cm.

Figure 5.11 An abrupt change from banded halite interval to sylvite (right row) across a prominent insoluble seam (arrow). Cominco 2-16 well, 1031-1034 m, scale bar = 10 cm.

Figure 5.12 Minor dissolution of zoned halite in the areas adjacent to the insoluble clots; some of the clots follow halite cubic outlines (arrows). Reference well, 1024 m, scale bar = 0.5 cm, plane polarized light.

Figure 5.13 A well-preserved zoned halite crystal (centre) within high-grade sylvite. Note some euhedral, clear halite crystals (Hs) nearby and the confined green insolubles (I) along the crystal boundaries. Ore zone of the PCS Cory Mine, unspecified depth, scale bar = 1 cm.
5.3 Banded Halite Unit

5.3.1 Lithology and Sedimentary Features

The term "banded halite" is used as an equivalent term for the "shadow banded salt" which is a common term used in Saskatchewan potash mines (McVittie and Danylik, pers. comm., 1990) for halite with these characteristics. It is very common in the upper half of the Leofnard Member and is present in all the cored wells in the study area.

Banding in the Banded Halite Unit is the result of a sharp increase in insoluble content, but without truncation of the underlying halite. The bands are typically about one to two centimetres thick, and the spacing between them varies from 10 to 30 cm. This type of halite occurs intermittently below the White Bear unit, passing through the Marker #2 and dominates the upper half of the Leofnard Member. It is present as short sections from 2 to 4 m thick, coinciding roughly with the low-potash content or barren salt intervals. In other words, the Banded Halite sections alternate with potash-rich beds, and exhibit an inverse relationship to potash mineralization (Fig. 5.9). Erosional surfaces have been recorded at some locations in the Belle Plain and Patience Lake Submembers (see Fig. 5.1). The banded halite is found as high in the sequence as the uppermost metre of the formation.

The halite is pale orange or light brown, fine-grained (usually less than 1 cm), with a granoblastic texture. Much of the halite shows minor recrystallization, however, many crystals retain part of their original zoned structures. It is more common to find halite with chevron structure just above the insoluble bands. Locally, the chevron halite crystals are up to 1.2 cm long.

Between insoluble bands, sylvite occurs sporadically as a vertical cement in interstices of the upward-growing halite crystals (Fig. 5.10). This suggests a syndepositional or an early diagenetic origin for sylvite, the mineral having
precipitated within halite sediments. The timing of sylvite precipitation or its precursor is certainly before the deposition of the overlying band which represents a new influx of the less-concentrated brine. Both the orientation and position with respect to the banding preclude the possibility that sylvite was formed from any later events.

The change from banded halite to potash beds can be gradual, or abrupt when an insoluble seam is present (Fig. 5.11). This demonstrates that the insoluble seams are one of the factors controlling brine migration, but perhaps not exclusively. The other major factor would be the original porosity of the salt itself.

5.3.2 Petrography

Zoned halite crystals are abundant in the Banded Halite. Those with chevron structure occur above the banding, and between these vertically-oriented crystals, green insolubles normally fill the interstices. Halite crystals with hopper structure are common farther upward from the band. There are areas where these zoned crystals have been partly corroded by minor dissolution.

There is a close relationship between areas of dissolution and the presence of insolubles in the banded halite. Zoned structures are replaced by clear halite in areas adjacent to the insoluble masses, whether the latter are infills between crystals or disseminated clots within them (Fig. 5.12). Some of the clots follow the cubic outlines of halite. There seems to be no process capable of producing this kind of relationship other than incorporation of the insolubles during halite crystallization.

Sylvite usually occurs as anhedral fingers with reddened rims produced by small inclusions. Its syndepositional or early diagenetic origin is verified by its relationship with remnants of the halite with zoned structure. Some sylvite has relics of carnallite along its rims, as seen from slightly different relief and anisotropic properties. This suggests that sylvite was formed through subsequent alteration of a
carnallite precursor. However, the petrographic evidence that all sylvite was formed after carnallite remains inconclusive.

5.4 Potash Beds

5.4.1 Lithology and Sedimentary Features

The potash beds that constitute the Belle Plain and the Patience Lake Submembers are basically a mixture of different proportions of recrystallized salts in which most of the primary features have been destroyed. The "sylvinitic" is typically brick red but of variable shades. Halite and sylvite are tightly interlocking with granoblastic texture in fine-grained rocks, and porphyroblastic where coarser. The halite crystals are anhedral to euhedral and commonly larger than the sylvite crystals in both rock types. In most cases the sylvite is present as matrix between halite crystals. Insolubles adjacent to sylvite are dominantly green or greenish grey.

The variable appearance of the rocks is mainly due to the reddish colouration in the sylvite which, in turn, depends on the amount and distribution of the tiny inclusions within it. Halite, on the other hand, is generally transparent or has tints of brown, grey, and orange. Other contributors are grain size, texture, insoluble content, etc.. Based on these parameters, Langford et al. (1987) and Boys (1990) constructed a micro-scale stratigraphy of the mining horizon for correlation and improved characterization of the ore at the PCS Cory Mine.

Large, euhedral halite lacking zoned structure represents the product of recrystallization. The confinement of insoluble clots along grain boundaries also indicates that insoluble materials have probably been redistributed to their present location. Recrystallization, nevertheless, must have taken place on a micro-scale. Good evidence for such subtle processes is the presence of zoned halite crystals which are very well-preserved adjacent to euhedral, inclusion-free recrystallized halite even
in high-grade ore (Fig. 5.13). Had the process been a pervasive phenomenon, there would probable have been greater segregation of these components.

5.4.2 Petrography

Much of potash description can be made on hand specimens due to the relatively coarse crystal size and the ease of recognition of the minerals. The information derived from thin sections is related more to microscopic crystal relationship and the paragenesis of the mineral phases.

Sylvite usually has rounded rims with red or purplish red linings that are a result of dense inclusions clustering along them. In places, these linings are up to 500 microns thick with wavy wisps pointing toward the centre of the crystal. The change in colour is usually sharp due to an abrupt decrease in the inclusion density. Gradational changes are not as common. The inclusions in sylvite are very small, unevenly distributed, and lack preferred orientation.

The relationship between sylvite and halite is clearly a replacive one. The outer faces of sylvite crystals that abut against clear halite are sharply terminated by the crystal faces of the halite. Across the crystal boundary on the halite side, there is an area which has a distribution pattern of inclusions similar to that in the sylvite on the other side (Fig. 5.14). From this relationship, it is concluded that halite has replaced and inherited a part of the inclusions from the pre-existing sylvite. There are locations where halite has entirely replaced sylvite crystals, as shown by the red inclusions marking outlines of the former sylvite in what is now halite (Fig. 5.15).

In the lower part of the Belle Plain Submember, similar replacive relationships between halite and carnallite have also been observed. There, many carnallite crystals are seen floating in a large, transparent halite crystal. These carnallite crystals show exactly the same alignment of the inclusions and twin planes. It is likely that the carnallite must have originally been one single crystal, which the transparent halite
PLATE XI

Lithology and sedimentary features in the Leonard Member.

Figure 5.14 Similar distribution of the inclusions (arrows) in anhedral sylvite (S) and euhedral halite crystals (H). Porcupine 8-28 well, 1298 m, scale bar = 1 mm, plane polarized light.

Figure 5.15 Relics of inclusions (arrows) in halite (H), which are comparable to those in the nearby sylvite (S). The same sample as Figure 5.14, scale bar 0.5 mm, plane polarized light.

Figure 5.16 Sheetcracks in an insoluble seam (dark), filled with halite (H) and sylvite (S) at centre. Reference well, 1007 m, scale bar = 1 mm, plane polarized light.

Figure 5.17 Faint cross-stratification in granular halite. Reference well, 1015 m, scale bar = 5 cm.

Figure 5.18 Rounded dolomite grains (arrows) and euhedral to subhedral anhydrite crystals (As) which are randomly oriented in insoluble seam. Reference well, 1021 m, scale bar = 0.2 mm, plane polarized light.

Figure 5.19 Halite in insoluble seam. The displacive nature of the halite is indicated by incorporation of the insoluble host into halite crystal structure. Reference well, 1002 m, scale bar = 0.5 mm, plane polarized light.
subsequently replaced.

Therefore, in addition to the syndepositional or early diagenetic relationship with zoned halite observed elsewhere, there is also evidence to the replacement of both carnallite and sylvite by clear halite. Obviously, crystallization, recrystallization and replacement processes are far more complex than that described here and are beyond the scope of this thesis.

5.5 Insoluble Seams

5.5.1 Lithology and Sedimentary Features

Apart from becoming more common in the upper half of the Leofnard Member, insoluble seams also carry a sizeable amount of sedimentary features. The seams may occur individually or as units containing several closely-spaced seams. Their thickness varies from a few millimetres to a few centimetres. Exceptionally thick ones, up to half a metre, are found above the Patience Lake Submember. These seams are similar to "chaotic mudstone-halite" described by Handford (1981). They are a crude mixture of mud and large, transparent, subhedral to euhedral halite crystals.

Most of the insoluble seams are reddish brown, but greenish colour is present in the lower portion of some seams. Halite crystals, rarely larger than half a centimetre, is usually present in variable amounts. Generally, the seam boundaries are well-defined, particularly the lower ones, making truncation of the underlying salt surface more noticeable.

The most common sedimentary features in, and adjacent to, the insoluble seams are vertical and horizontal sheetcracks. These openings are frequently filled with halite. Locally, tiny vertical sylvite crystals fill the central part of the sheetcracks (Fig. 5.16). This is an indication that sylvite-saturated brines have migrated along these cracks. Other features include erosional surfaces, some with sylvite intraclasts, and
mud-filled dissolution pipes. Both indicate periods of subaerial exposure at the site. Halite in some insoluble seams is granular, occasionally with milky cores made up of zoned structure. Faint cross-stratification, probably rippled surfaces can be seen locally in these granular halite intervals (Fig. 5.17).

5.5.2 Petrography

What is generally called "insolubles or clay" is in fact a heterogeneous mixture of mainly dolomitic mud, clay minerals, anhydrite, and small amounts of quartz and feldspar. More details on mineralogy of the "clay seams" are presented in Mossman et al. (1982), and Boys (1990). In thin sections, lath-shaped crystals of anhydrite stand out conspicuously from the rest. Their well-defined boundaries, random orientation, and tiny carbonate inclusions all suggest a diagenetic origin (Fig. 5.18). Another mode of anhydrite is as coarser, angular to rounded, microcrystalline aggregates. It is difficult to determine whether they represent diagenetic conversion from original gypsum, as seen earlier in the carbonate-anhydrite interval of the Shell Lake Member, or whether they are intraclasts. Abundant authigenic quartz crystals showing random orientation are common along insoluble-halite boundaries.

Most of the halite within insoluble seams is recrystallized or displacive. The straight-line boundaries with 120° interfacial angles attest to contemporaneous crystallization for much of the halite. Locally, minor dissolution has modified the boundaries to some extent. The majority of the halite crystals have incorporated a variable amount of the mud in their crystal structures (Fig. 5.19), signifying displacive growth in a damp muddy setting (Hardie et al., 1985). Zoned halite crystals are found sporadically in the areas of insoluble seams. These crystals are truncated by the insoluble seams that directly overlie them or by dissolution pipes extending downward from the seams. A few chevron halite crystals can be found above the seams and they still maintain upward-growth position. They imply that the site could have been
ponded temporarily before returning to dryness.

The granular halite shows a marked contrast to other forms nearby because of the roundness of the grains. Most are clear but some do have zoned fluid inclusions indicating that they were originally formed subaqueously (Fig. 5.20). A reddish brown mud matrix holds them together. The granular halite is interpreted to represent halite grains from exposed localities, that were eroded, transported, and redeposited by wind.

Minor amounts of sylvite are found in and near the insoluble seams (Fig. 5.21). Its occurrence and position with respect to the surrounding halite suggest that it was formed later from seepage that flowed along the interstitial pores between salt grains. This type of sylvite indicates lateral migration of the brines from which sylvite precipitated. The question of whether it had a carnallite precursor remains uncertain.

5.6 Marker #1 and #2

Both markers in the reference well are zones of laminar anhydrite. The Marker #1 is about 2 m thick, and Marker #2 is only 60 cm. Truncation of the underlying halite by these anhydrite beds is marked. Displacive halite crystals occur sporadically in the anhydrite, and disturbance in anhydrite laminae is apparent (Fig. 5.22). Incorporation of the anhydritic host during crystallization of halite led to formation of skeletal structure in some halite crystals. Above the anhydrite beds, numerous chevron halite crystals up to 2.5 cm high are common. The bottom-nucleated crystals indicate shallow subaqueous conditions (Hardie et al., 1985), therefore, further confirming the subaqueous origin of the laminar anhydrite directly below. The petrography of these markers is similar to the laminar anhydrite in the Shell Lake Member and will not be repeated here.

The presence of Marker #1 cannot be verified in other wells due to the lack of cored section in the eastern half of the study area. It is absent in the Osler 3-28 and the Cominco 2-16 wells. In contrast, Marker #2, although thinner, is traceable from the
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Lithology and sedimentary features in the Leofnard Member.

Figure 5.20 Sub- to well rounded granular halite, some with distinctive zoned structure (arrows). Reference well, 1015 m, scale bar = 0.5 mm, plane polarized light.

Figure 5.21 Sylvite crystals (S) forming along insoluble layers (dark). Note truncation of the underlying zoned halite crystals (H). Reference well, 1021 m, scale bar = 1 mm, plane polarized light.

Figure 5.22 Disturbance in anhydrite laminae by displacive growth of halite crystals (H), some of which show skeletal structure (arrows) due to the presence of anhydritic mud host in the crystal structure. Reference well, 1098 m, scale bar = 2 cm.

Figure 5.23 Stromatolitic structures in dolomitic mudstone of the Marker #2. Osler 16-24 well, 885 m, one division on the scale bar is 1 cm.

Figure 5.24 Brecciated dolomitic mudstone and wavy-laminated anhydrite at the contact between the Prairie Evaporite Formation and the Lower Red Bed Member of the Dawson Bay Formation. Note the coarse-grained, recrystallized halite (H) in the lowermost part of the sample. Reference well, 1000 m, scale bar = 2 cm.
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Lanigan to Allan areas. It is also present at the corresponding intervals in the Dundurn 13-18, the Cominco 2-16, and the Osler 3-28 wells, but only the lower part of the marker is anhydrite. The upper part is dolomitic mudstone with local stromatolitic structure (Fig. 5.23). Although the Marker #2 in these wells may not be exactly the same unit, the time-frame in which it was deposited must have been contemporaneous. The Marker #2, thus, represents the basin-wide freshening period in the study area.

5.7 The Contact With the Lower Red Bed Member

Banded halite prevails until the uppermost metre of the Leofnard Member where it is replaced by coarse recrystallized halite. The zone of recrystallization is about 60 cm thick, and at the contact with the red dolomitic mudstone of the Lower Red Bed Member in most wells, there is a thin zone (4 to 5 cm thick) made up of brecciated dolomitic mudstone and wavy microbial lamination (Fig. 5.24). The lowermost part of the brecciated zone is composed of sand-size breccias, passing into crinkly microbial-laminated anhydrite, coarser breccias, and the massive part of the red beds. All pore spaces are plugged by clear or orange halite.

Dissolution and recrystallization of the uppermost halite clearly represent a period of freshening. This interpretation is further supported by the microbial-laminated anhydrite and mottled mudstone. At the same time, brecciation of the mudstone indicates that the area was subject to exposure intermittently before the mudstone deposition became firmly established.
6. MINE OBSERVATIONS

The difficulties of working only with core and the absence of salt outcrops were partly compensated by the exposures in potash mines. Observations have been carried out at the Cominco, the PCS Cory, and the PCS Allan Mines (Fig. 1.1). The ore zones of these three mines are in the upper part of the Patience Lake Submember. In addition to the mining horizon, observations were extended into the "declines" which are designed to provide an access for personnel and equipment to service the mine shafts. The declines thus penetrate to stratigraphic levels much deeper than the ore zone itself. Mine observations provided the opportunity to record, and observe several large-scale features that were not detectable in the core.

Similar in approach to studying outcrops, the work included measuring sections, lithologic description and photography, etc. The measured sections were then plotted at their respective locations alongside the log in the area. For comparison, the diagrammatic logs of the sedimentary features observed in all three mines during this study are shown in Figure 6.1 a, b, and c.

6.1 Cominco Mine

The Cominco Mine is located about 30 km west of Saskatoon near the town of Vanscoy. The Prairie Evaporite Formation in this area contains only the upper two potash units, the Patience Lake Submember, and the Belle Plain Submember which starts tapering and disappears completely a few kilometres farther west. The detailed subsurface stratigraphy, including the upper half of the Prairie Evaporite Formation, was recorded during the shaft construction by Price and Ball (1973). The mining horizon is in the interval commonly known as "A-Zone". A diagramatic log of the sedimentary features recorded in the Cominco Mine during this study is given in Figure 6.1a.
Figure 6.1  A combined diagrammatic logs of the measured sections from the declines, (a) from the Cominco Mine; (b) from the PCS Cory Mine; and (c) from the PCS Allan Mine.
6.1.1 Section CM1: Below the Belle Plain Submember

This is the lowest section that was measured in the Cominco Mine, and is about 10 m thick. It consists dominantly of banded halite, with patchy occurrences of massive and recrystallized halites. The most striking features in this interval are metre-scaled, v-shaped open fissures cutting into the banded halite (Fig. 6.2). Their edges thrust upward on both sides. The top parts of the fissures can be as wide as 30 cm and narrow down along their length to the bottom. Recrystallized halite lines the outer walls, and small amounts of brown clay and sylvite fill the centre with mirror symmetry. Such cracks are numerous over a distance no less than 30 m, and the spacing between them is normally less than a metre.

These open fissures are interpreted as the sectional view of salt polygons. The comparable features are reported from the Cheshire Salt of England, where Tucker (1981) suggested that thermal contraction is the mechanism responsible formation. However, it seems that other workers on several modern evaporites prefer to explain the formation of salt polygons by expansion of halite crust due to continual precipitation of halite in the capillary zone (Lowenstein and Hardie, 1985; Warren, 1989; Khalifa and El-Haddad, 1989). The infilling of the fissures can result either from runoff or from groundwater drawn up by capillary action, or both; the insolubles are introduced to the site by recharges or winds. Sylvite in the centre testifies for syndepositional precipitation within the openings rather than any secondary processes. Supersaturation of sylvite is reached when sylvite-saturated brine cools down as it percolates into the salt beds (Lowenstein and Spencer, 1990).

A prominent 1.8 m interval of dominantly dolomitic mudstone beds (Marker #2) alternates with massive salt about midway in the section. The lowest and also the thickest bed is 70 cm thick, and the rest are in the range of 1 to 10 cm. In the thickest bed, a brecciated zone of cobble-sized mudstone fragments marks the base, and the rock passes across an undulating surface into massive, and laminated, greenish brown
PLATE XIII

Sedimentary features observed in the Cominco Mine. Locations of these features are shown in Figure 6.1a. Except where stated otherwise, all the metal tapes are 0.5 m long.

Figure 6.2 V-shaped, open fissures (arrows) cutting into banded halite.

Figure 6.3 Dolomitic mudstone of the Marker #2. Note the underlying mudstone cobbles (arrow) and the undulating stromatolites in the uppermost part of the marker. Cracks (filled with orange halite) in the mudstone are probably due to synaeresis.

Figure 6.4 Longitudinal ripples on the roof of the decline shaft (arrow indicates the crest direction). The area is approximately 4 m².

Figure 6.5 Dissolution surface with vertical pits which are filled by dark brown insolubles and clear, recrystallized halite.

Figure 6.6 A vertical pit projecting downward from a thin insoluble seam. The pit is lined with clear halite and, at centre, deep red sylvite (arrow). The metal tape is 1 m long.

Figure 6.7 Massive halite with a general vertical orientation of sylvite (orange). Vague banding is visible locally.

Figure 6.8 Small desiccation cracks (arrows) at the bottom of the insoluble seam. The seam is about 15 cm thick.
mudstone. Disruption in the rock creates a relief, causing the microbial laminae to form small domal structures locally (Fig. 6.3). The planar lamination in the mudstone returns above this, and in the uppermost part of the bed, the rock becomes more anhydritic.

About 3 m up-section, low amplitude, longitudinal ripples are exposed on the mine roof in the area of the banded halite (Fig. 6.4). They are asymmetrical and comparable to catenary swept ripples produced by currents (Kayumba, pers. com., 1990). These ripples are important in that they strongly support the interpretation of subaqueous deposition of the banded halite.

6.1.2 Section CM2: The top of the Belle Plain Submember

Section CM2 is located just beneath the uppermost potash bed of the submember. It is about 3 m high, and the rock is still banded and massive halites. There is a distinct dissolution surface with many irregular vertical pits, up to 50 cm deep, at the base of the section (Fig. 6.5). The spacing between the pits ranges from 10 to 30 cm. These pits are filled with dark brown insolubles and a minor amount of halite. Both the dissolution surface and the pits must have formed by a direct contact between the exposed salt surface and the fresher brines - rain or surface runoff. The insolubles might have been brought in together with the floods or might have been eolian dust that was bound on the damp salt surface. Overlying this surface is a dark brown insoluble seam five to seven centimetres thick.

Higher up in this section, narrow vertical pits of 1 m deep are filled with transparent halite and, restricted at the centre, deep red sylvite (Fig. 6.6). These pits must have been large vertical cracks where sylvite was precipitated syndepositionally in the environment from the brine trapped in the cracks. The same mechanism of cooling of the sylvite-saturated brine (Lowenstein and Spencer, 1990) may still apply.
6.1.3 Section CM3: Above the B-Zone

This short section is located at about 3 m above the B-Zone in the Patience Lake Submember. Banded halite predominates in the lower part of the section. The banding becomes poorly-defined upward due to minor recrystallization, and the rock has a rather massive appearance. Sylvite is disseminated in the interstitial spaces of this halite, showing preferred vertical orientation (Fig. 6.7). This type of sylvite resembles that in the massive halite described from cores.

6.1.4 Section CM4: Above the Ore Zone

This section spans an interval of about 10 m, starting from the top of the uppermost potash bed into the overlying halite. It is a section in which several thick seams of chaotic mudstone-halite are present. Associated with the clay seams are prominent desiccation cracks which are overlain by pale green and brownish green insoluble infills projecting downward into the underlying salt (Fig. 6.8). They are traceable laterally everywhere on the exposed wall.

In the uppermost metre of the section, in front of the hoist, there are well-developed, extensive desiccation polygons on the roof (Fig. 6.9). The size of these polygons is in the range of one to one and a half metres across. Bordering the salt polygons is clear halite which appears dark in the photograph. When the polygons on the roof are traced to the mining wall, they merge into vertical pits. It is, therefore, concluded that many of the dissolution pits seen in section are parts of polygonal networks.
Sedimentary features observed in the Cominco, PCS Cory, and PCS Allan Mines. Locations of these features are shown in Figure 6.1.

Figure 6.9 Metre-scale salt polygons (arrows) on the roof. The Cominco Mine.

Figure 6.10 The Marker #2 overlying dissolution surface. Also note the lack of stromatolites (hammer as scale). The PCS Cory Mine.

Figure 6.11 A dissolution pit (arrow) filled with recrystallized halite. The metal tape is 0.5 m long. The PCS Cory Mine.

Figure 6.12 An example of chaotic mudstone-halite which is common in insoluble seams, particularly in the upper half of the Leofnard Member. The PCS Cory Mine.

Figure 6.13 Salt polygons with distinctive zonation of the infilling halite. The PCS Allan Mine, scale bar = 0.5 m

Figure 6.14 Reappearance of stratification in the upper part of the massive halite as indicated by thin insoluble seams. The PCS Allan Mine, scale bar = 1 m.

Figure 6.15 The Marker #2 in the PCS Allan Mine is significantly thinner than that in both the Cominco (Figure 6.3) and the PCS Cory (Figure 6.10) Mines.
6.2 PCS CORY MINE

The PCS Cory Mine, located about 9 km west of Saskatoon, has general geology and stratigraphy similar to those of the Cominco Mine. Previous studies undertaken at this mine include the stratigraphy of the shaft (Price and Ball, 1971), the microstratigraphy and correlation of potash rock types in the ore zone (Langford et al., 1987), clay seam mineralogy and salt anomalies (Boys, 1990). A diagramatic log of the sections measured during this study is shown in Figure 6.1b. A few more marker beds formally established by Phillips (1982) are necessary to the description of the sections; their stratigraphic locations are also shown.

6.2.1 Section CO1 : The Base of the Decline

This section is about 5 m thick and includes the interval from the base of the decline, which lies at 1079 m from the surface (Danyluk, pers. comm., 1990), to the top of the Marker #2. The section is composed of massive and recrystallized halites containing a small amount of carnallite, but lacking any recognizable sedimentary features. Carnallite occurs as vertical cement in the interstices of halite crystals; both anhedral and subhedral crystals are present. Locally, subhedral carnallite crystals up to 4x5 cm² are found.

The massive halite is overlain by the Marker #2. The contact is an undulating dissolution surface with shallow pipes, 10 to 15 cm deep. In common with that at the Cominco Mine, the marker comprises several dominantly dolomitic mudstone beds, and a small proportion of anhydrite. The lowermost bed is the thickest (90 cm) but lacks undulating stromatolites, although much of the lamination is probably related to cyanobacteria. The remaining mudstone beds are only a few centimetres thick, alternating with the massive halite.

The thick mudstone bed can be divided into three portions (Fig. 6.10). Directly
above the contact with the underlying salt, the rock is made up of lenticular laminae of mainly dark grey anhydrite that alternate with lighter grey dolomitic mudstone laminae. It then grades upward into light greenish brown, massive mudstone, and back to lenticular anhydrite-dolomite at the top. To deposit sulphates and carbonates without much dissolution of the underlying salt, the salt surface must have been effectively sealed. This can be explained by a drastic drop of sulphate solubility as the new influx entered the halite saturation field (Holser, 1979). However, the amount of brine involved must have also been limited, or else more extensive dissolution could have occurred. After a period of carbonate deposition in the middle part of the marker, the brine concentration was gradually elevated toward halite deposition again.

Fluctuations of the brine concentration between halite and anhydrite fields are obvious in the thin beds above. Finally, halite deposition resumed permanently.

6.2.2 Section CO2: The Base of the Patience Lake Submember

The middle part of the studied interval covers the section from the Allan Marker Bed (Phillips, 1982) to the base of the lowermost potash bed in the Patience Lake Submember. It is dominated by banded halite with intermittent intercalations of thin insoluble seams, usually no more than a centimetre thick. The insoluble seams become more abundant as the base of the submember, which is marked by a 23 cm thick reddish brown seam, is reached. Dissolution pipes are common along the contact.

The insoluble seam passes abruptly upward into a sylvinite bed. The boundary is diagenetic rather than depositional, and represents the lower limit of sylvite recrystallization. Halite crystals in the sylvinite range from subhedral to anhedral, while the sylvite fills the intercrystalline spaces. The reddish colour of the potash bed fades away from the sylvinite-insoluble seam contact, perhaps indicating a genetic link between colour distribution in potash bed and the hematite in the insolubles as suggested by Boys (1990).
6.2.3 Section COS: Above the Ore Zone

The final section contains two insoluble seams that are usually referred to by the miners as 4-ft Clay and 10-ft Clay (Phillips, 1982), indicating their approximate respective distances above the potash ore zone. The lower 2 cm of the 4-ft Clay is composed of greenish grey, discontinuous anhydritic laminae, but the upper 10 cm is mostly reddish brown insolubles with small displacive halite crystals in places. The change from the green anhydritic laminae to the insolubles is abrupt. Several dissolution pipes, up to 40 cm deep, project downward from the base of the "clay seam" into the banded halite below (Fig. 6.11). They are filled mainly by clear halite and a small amount of greenish grey anhydritic mud. The processes that formed the pipes and the infilling sediments are similar to those described previously.

The highest exposure that can be observed in the mine is the 10-ft Clay. It is chaotic mudstone-halite which is a mixture of large euhedral halite crystals and brown insolubles, about half a metre thick (Fig. 6.12). In fact, many other "clay seams" have a small amount of displacive halite in them but this seam is highly distinctive.

6.3 PCS ALLAN MINE

The PCS Allan Mine is located about 45 km east of Saskatoon, approximately in the middle of the study area. Although only the upper two potash units are well-developed, on logs small gamma-ray peaks are noticeable at the interval corresponding to the Esterhazy submember. The White Bear Submember is virtually absent. The mine is operating in the lower part of the A-Zone. Figure 6.1c shows a diagramatic log of the sections observed in this study.
6.3.1 Section AL1: The Base of the Decline

Located 80 m below the mining horizon, the base of the decline at PCS Allan Mine falls in the interval corresponding to the Esterhazy Submember. The first section spans about 20 m, and is composed mostly of grey, massive halite. The size of the halite crystals ranges from 3 to 5 cm. Carnallite and grey insolubles occur in small amounts interstitially, generally with a vertical orientation.

Extensive polygonal cracks are found on the mine roof. Each polygon, half a metre or more across, is made up of dull grey halite contrasting markedly with the clear halite that lines the margins. Some polygons show pronounced colour zoning of the infilling halite. Each zone is brown-stained at the margin, passing into cloudy white halite, and finally clear halite at the centre (Fig. 6.13). The zonation is mirrored symmetrically on the other half of the crack.

There are two important points to note. First, desiccation occurred during the deposition of the Esterhazy Submember which is about 80 m from the top of the formation. These polygons are the deepest yet recorded. Second, the preservation of the polygons, despite recrystallization, confirms the very subtle nature of the subsequent changes in the salt.

The decrease in crystal size is quite obvious up section, where vague lamination becomes apparent. Prominent insoluble seams can be seen at the uppermost part of the section (Fig. 6.14), and can be traced everywhere along the wall. This observation implies that the extent of recrystallization decreases upward, and that the brines that caused dissolution and recrystallization in the halite ascended from below. Therefore, it is in agreement with Gendzwill (1978) who invokes the water released from the underlying carbonate mounds as the cause of dissolution in the salt. For carnallite, the same conclusion obtained from the core is still valid, it postdates recrystallization.
6.3.2 Section AL2 : Marker #2

This marker is about 50 cm thick, standing out conspicuously from the massive halite wall of the decline. The contact is abrupt across a minor dissolution surface. At the base, the rock is dark grey to black anhydrite, probably indicating formation under euxinic conditions. The colour is lighter as the rock becomes more dolomitic in the upper half (Fig. 6.15). Lamination in the dolomitic part is microbial, indicating a change to hypersaline environment. The very shallow brine depth and periodic desiccation is reflected in the disruption and upward buckling of parts of the laminae.
7. DEPOSITIONAL ENVIRONMENTS AND EARLY DIAGENESIS

This chapter will attempt to integrate the evidence from the preceding chapters into a broader perspective, unit by unit. The implications with respect to the depositional environment derive from comparison with modern evaporites, as well as their ancient analogues that have been previously interpreted by other workers. Nevertheless, like many other "saline giants", there is no single modern analogue that can readily explain the deposition of formation as a whole.

In the following discussion, the subject of gypsum-anhydrite conversion will not be considered. The mineralogy of the rocks refers to the present one, unless stated otherwise. In fact, both gypsum and anhydrite could have formed initially in different environmental conditions, i.e., gypsum in hypersaline pools, and anhydrite by interstitial precipitation at high temperatures and salinities or by dehydration of gypsum, but all were converted to anhydrite after burial. Detailed discussion on the formation and the transformation of gypsum and anhydrite is given by Kinsman (1974) and Holser (1979).

7.1 Depositional Environments of the Whitkow Member

The Whitkow Member consists of two main units - the Basal Anhydrite and the Translucent Halite, the Intermediate Anhydrite Unit is only present locally. At locations close to the carbonate mounds, such as the reference well, the lowermost part of the Basal Anhydrite Unit contains ruditic fragments derived from the mounds. The rock passes upward into mosaic anhydrite and its bedded or distorted varieties, while anhydrites from the centre of the intermound depressions, such as the Cominco 2-16 well, tend to show more prominent lamination. The Translucent Halite Unit, on the other hand, is practically the same throughout the study area.
7.1.1 Basal Anhydrite Unit

There are two types of clasts in the ruditic anhydrite - the bioclastic particles and laminated mudstone intraclasts. The bioclastic fragments are comparable to those in the Peloidal Grainstone Facies described by Wilson (1985), and therefore, are probably derived from subaerial erosion of local carbonate mounds, while the laminated mudstone fragments were formed and fragmented \textit{in situ}. The paucity of bioturbation, the presence of microbial mats and the anhydrite laths within them, all testify for an elevated brine concentration. The mudstones are interpreted as having formed in mudflats bordering intertidal hypersaline lagoons. The lithology and sedimentary features of the mudstone are similar to those reported from the Trucial Coast of the Persian Gulf by Purser and Evans (1973) and Butler \textit{et al}. (1982), and from Shark Bay, Western Australia, by Davies (1970), and Logan \textit{et al}. (1974).

The distorted mosaic and massive anhydrites are problematic due to obliteration of most of the primary fabrics by diagenetic overprints. That they are of supratidal sabkha origin is ruled out by several essential criteria. These anhydrites do not form part of a typical shallowing-upward sequence, from subtidal to intertidal and supratidal sediments (Shearman, 1966, 1980), and they are not matrix-dominated (cf. Warren and Kendall, 1985). Erosional surfaces, due to the constraints imposed by the thickness of the capillary zone, which in modern sabkhas is usually less than a metre thick above the groundwater table (Butler, 1969; Patterson and Kinsman, 1981), are absent. It must be kept in mind, however, that this part of the basal anhydrite is less than 2 m thick. Its thickness is barely beyond such constraints.

No comparable anhydrite has been found in the literature. Nevertheless, it seems possible that the selenite or laminated gypsum of the Sicilian Basin described by Schreiber \textit{et al}. (1976) and the poorly laminated selenite from coastal salinas of southern Australia by Warren (1982), if converted to anhydrite, would produce a lithology similar to the distorted mosaic and massive anhydrites. In accordance with
the suggested diagenetic products of the selenite put forward by Warren and Kendall (1985), the distorted mosaic and massive anhydrites are provisionally interpreted as having been precipitated initially as laminated selenite in a broad, shallow salina setting. The distorted fabrics could have been a result of gypsum dehydration and compaction by the overlying sediments, and later diagenetic overprinting.

A different picture emerges from the distorted bedded mosaic anhydrite in the Cominco 2-16 well, which grades upward from the underlying Ratner Member of the Winnipegosis Formation. Due to its close relationship with the Ratner Member, this anhydrite is important in relation to the controversy of a deep-water versus shallow-water origin for the evaporites. As noted in the earlier review (p. 6), Shearman and Fuller (1969) interpreted this part of the Prairie Evaporite Formation as a supratidal deposit; in contrast, Wardlaw and Reinson (1971), Davies and Ludlam (1973), and Kendall (1975) believed that it was deposited under a brine column of 50 to 200 metres depth.

Subaqueous deposition of the distorted bedded mosaic anhydrite is manifested by the good bedding which resulted from salinity fluctuations of the parent brines (cf. Warren, 1982). Supporting evidence comes from graded bedding of the intraclasts in the carbonate laminae of the underlying Ratner Member. Part of the anhydrite in the distorted bedded mosaic anhydrite shows flat-lying nodules bound by microbial laminae, which is comparable to the "varved gypsum-organic sediments" in a shallow (50 cm) but perennial brine pool in southern Sinai reported by Kushnir (1981). After crystallization, the gypsum crystals continue to grow in algal mats from the interstitial brines and disturb the algal lamination. To justify the annual deposition, implied by the "varves" in the basal anhydrite, is difficult.

Variable degrees of distortion and development of enterolithic structure in different laminae of the distorted bedded mosaic anhydrite are apparent. Shearman (1985) suggests that lit par lit variation like this is the result of the changes in chemistry of the interstitial brines penecontemporaneously with deposition. This
distinguishes it from alteration by diagenesis which commonly has a pervasive nature. Fluctuation of the brine chemistry is certainly not characteristic of the deep-water environment.

Further support for the shallow-water setting is the wavy-laminated mudstone in the Outlook Crown #1 well. The lithology and the degree of lamination in this mudstone are comparable to those in the Ratner Member, but the distinct difference is the fenestral fabrics which are reliable evidence for intertidal to supratidal sediments (Shinn, 1968; 1983). At least this mudstone demonstrates that the lamination in the Ratner Member does not necessarily indicate deep-water conditions.

Putting this all into a depositional context, the distorted bedded mosaic anhydrite is interpreted as having been deposited in a shallow perennial brine pool environment. Given that the Cominco 2-16 well is located near the central part of an intermound depression (Fig. 2.14), some perennial brine bodies occupying the hydrological lows of probably a few square kilometres in size could have existed. The deposit was originally well-laminated gypsum and was altered syndepositionally to its present lithology. Even though there is no firm indication regarding the brine depth, the sedimentary characteristics of the anhydrite clearly favour a shallow-water environment.

7.1.2 Translucent Halite Unit

The truncation of the zoned crystals, some with vertical chevron structures, indicates direct contact between the salt surface and the less-concentrated brine. This brine also produced small dissolution cavities on and within the salt as it moved downward. The combination of further dissolution, which raised the brine salinity, and evaporation led to the formation of early diagenetic clear halite in these cavities. These halites match the criteria for recognition of salt-pan halites given by Lowenstein and Hardie (1985). They are also comparable to the modern halite rocks reported from
coastal Baja California, Mexico (Shearman, 1970), and the MacLeod Basin, western Australia (Logan, 1987).

Halite with anhydrite partings predominates in the lower half of the member. The spacing between the anhydrite partings falls in the range of 5 to 10 cm, and increases upward. This may reflect the rapid dry-and-flood nature of the evaporite surface during the early transition from intertidal to salt-pan environments. In contrast, above the Intermediate Anhydrite, the rock appears more massive, and the anhydrite partings are rare and very thin. This also holds true in the Cominco 2-16 well where the Intermediate Anhydrite is absent. It is clear that more stable shallow salt-pan conditions became established during that time.

The coastal salt-pan environment of the translucent halite agrees well with the previous suggestion by Shearman (1970), who pointed out the similarity between the salt in the Whitkow Member and the salt-pan deposits of Baja California. The lower part of the Muskeg Formation, which is an equivalent of the Prairie Evaporite Formation in Alberta, was also interpreted by Brodylo and Spencer (1987) as representing a salt-pan environment. The current interpretation provides strong support for the shallow-water origin of the underlying Basal Anhydrite Unit.

7.1.3 Intermediate Anhydrite Unit

Dissolution and recrystallization of the salt-pan halite below the Intermediate Anhydrite are marked. The massive anhydrite was probably precipitated as fine-grained gypsum from mixing of the highly-concentrated brine in the pan and the fresher influxes. Several mechanisms may be used to explain such deposition. Raup (1982) has demonstrated experimentally that gypsum could precipitate from mixing of the brines of different concentrations. According to Holser (1979), there is a sharp drop of calcium sulphate solubility in the halite-saturation field, which means that all calcium sulphate in the brine should precipitate as the less-concentrated brines enter
the salt pans. An example from the modern environment is found in the ponds in the intertidal area of Shark Bay, western Australia (Logan et al., 1974).

Subsequent selective recrystallization resulted in the formation of the coarser anhydrite laths (Holliday, 1973). These laths could have been formed accompanying the development of a strong horizontal "gneissic texture" similar to that in metamorphic rocks. This process occurred some time after deposition because the carbonate particles clearly obstructed the development of the later crystal orientation.

The successive alternation of the dolomitic mudstone, from stromatolitic to wavy-laminated to finely-laminated, suggests rapidly changing and repetitive environmental conditions. The well-laminated carbonate may appear like varved sediments of deep-water origin, but sediments with this degree of lamination have also been reported from pools in the intertidal zone (e.g. Kinsman and Park, 1976). More importantly, the associated rocks exhibit features that characterize intertidal to supratidal sediments, including for example, microbial-lamination, fenestral structure, and desiccation cracks (Lucia, 1972; Shinn, 1983). This carbonate sequence is thus interpreted as forming in broad ephemeral tidal ponds of the intertidal zone.

At the transition from carbonate to anhydrite, there is a zone of prominent organic laminae and small flat-lying anhydrite nodules. This rock is comparable both to the displacive gypsum in supratidal algal flats of the Trucial Coast (Kinsman, 1969) and to that in the shallow brine pool of southern Sinai (Kushnir, 1981). From the environmental viewpoint both are possible within the intertidal realm. The rest of the Intermediate Anhydrite Unit is bedded mosaic anhydrite with fenestral fabric, and the interpretation of shallow hypersaline lagoonal deposition also applies.

The occurrence of the Intermediate Anhydrite is very patchy. It is found only in areas close to the mounds, such as in the reference well. The cause of such localized flooding that led to deposition of the Intermediate Anhydrite is unclear, because it appears that during this time the salt-pan conditions still persisted elsewhere. This is indicated by translucent halite with anhydrite partings in the Outlook Crown #1 and
7.2 Depositional Environments of the Shell Lake Member

The Shell Lake Member can be correlated basin-wide, although differences exist. Around the edges of intermound depressions, this member is composed of a thick anhydrite-carbonate sequence, but in the central parts only thin bedded mosaic anhydrite, similar to that in the Whitkow Member is found. The following discussion will, therefore, focus mainly on the more complex sequence of the anhydrite and carbonate.

7.2.1 Massive Anhydrite Unit

Highly distorted and massive anhydrites were formed in shallow brine pool and salt pan environments similar to those described previously for the Intermediate Anhydrite. Supporting evidence includes the thick organic laminae, probably microbial mats, and the clustered dolomicrite along them. The rock has undergone soft-sediment deformation, particularly the lowermost part, causing distortion and breakage of the laminae. The triggering mechanism can be attributed either to differential compaction in the sediments or to lateral stress from displacive growth of the anhydrite crystals.

7.2.2 Mosaic Anhydrite-Laminated Carbonate Unit

The wavy-laminated mudstone has sedimentary characteristics suggesting a low-energy intertidal area. Microbial lamination and the lack of bioturbation testify for areas of hypersaline brine. Although not very extensive, birds-eye structures, and cracks in the laminated sediments represent the periods of subaerial exposure (Shinn,
Numerous lath-shaped anhydrite (formerly gypsum) crystals, which are a typical diagenetic mineral of this setting (Filling et al., 1965; and Butler et al., 1982), also support this interpretation. The site received intraclastic, peloidal, and silt-sized sediments from the more seaward sources, probably during high tides or occasional storms.

Another complication arises when considering the sequence of alternating mosaic anhydrite and wavy-laminated dolomitic mudstone. Some intervals in the lower part of the sequence match typical sabkha succession in which the rock passes upward from lagoonal sediments to microbial mats then to nodular anhydrite, but the greater part above does not. The alternation appears to be the result of intrusion of mosaic, or locally massive, anhydrite into the existing laminated mudstone, causing thickening of the deposit. Although thickening of the sediments in a sabkha-chenier complex is possible (Schreiber et al., 1982), this sequence still lacks the erosional surfaces which are to be expected. Unless it is accepted that they have been obliterated by such diagenetic growth, a further explanation, other than vertical stacking up of the sabkha cycles, is required.

It is well known that anhydrite with nodular structure can be formed by processes other than those associated with the supratidal zone of sabkhas (Kendall, 1984). Replacement anhydrite forming at shallow depth around the edges of carbonate shoals in the Elk Point Basin is discussed by Bebout and Maiklem (1973). Jacka (1981) also suggests that, in the Permian and Maverick Basins of Texas, much of the anhydrite was produced by replacement at shallow depth of burial. Clark (1980), on the other hand, believes that anhydritization of the carbonates in the Zechstein Basin of Europe occurred at a depth ranging from 300 to 600 m. Texturally, all the anhydrite mimics the sabkha anhydrite.

In the Shell Lake Member, displacement of the wavy-laminated mudstone by anhydrite is evident in both hand specimens and thin sections. The petrography also shows that the anhydrite cross-cuts carbonate particles and poikilitically encloses
some of them. In places, the microcrystalline anhydrite has dusty inclusions which are probably the remnants of organic-rich carbonate. The anhydrite is, therefore, both displacive and replacive. These processes must have taken place prior to lithification of the carbonate, that is to say, at shallow depth of burial.

The mosaic anhydrite and laminated mudstone in the Outlook Crown #1 well is less problematic. Intraclasts, disruptions, and erosional surfaces in the rock are clearer, and each carbonate-anhydrite interval is usually a metre or less thick. This sequence can, therefore, be explained by sabkha cycles, however, it is possible that subsequent anhydritization could have occurred.

It is concluded here that the mosaic anhydrite and laminated carbonate were deposited initially in restricted, intertidal lagoonal to supratidal environments. Early diagenetic anhydrite displaced and replaced a part of the wavy-laminated carbonate, and as a result thickened the original deposit. The delicate balance that accommodated these processes remains unclear. It may be related to basin subsidence, dissolution of the underlying salt, the high sedimentation rate, and sea-level changes. Burial diagenesis may also have occurred at a considerable depth and resulted in another episode of replacement.

### 7.2.3 The Quill Lake Marker Beds

The sedimentary characteristics of the grainstone beds reflect fluctuations of energy during deposition, rapid accumulation, and weak winnowing of the fines. The irregularity and pinching-out of the peloid-intraclast laminae in the muddy matrix do not favour a stable subaqueous setting. On the contrary, periodic subaerial conditions are confirmed by small desiccation cracks, disruption of thick microbial laminae, birds-eye structures, and the light brown colour of the rock. Similar types of sediments are documented from the inland algal marshes of Andros Island, Bahamas (Shinn et al., 1969; Hardie and Ginsburg, 1977) and Shark Bay, western Australia (Davies, 1970).
The fluctuating energy can be attributed to storms, which are a widespread phenomenon in tidal flats (Hardie and Garrett, 1977; also see; Illing et al., 1965 and Davies, 1970). Storm floods are capable of transporting significant amounts of coarse carbonate grains from subtidal areas onto the supratidal marsh. As they wane, finer sediments settle out, and algae re-establish themselves on the damp muddy surface. These sediments are subject to burrowing activities of algae, leading to micritization of the grains.

A crucial implication comes from the ooids in the grainstone beds of the Drake 4-29 well. Although only present in small amounts, they indicate the close proximity of a near-normal marine environment. The concentric ooids are commonly formed on warm, shallow carbonate platforms by accretion on grains that are in motion induced by tidal currents and waves (Bathurst, 1976; Scoffin, 1987; and Tucker and Wright, 1990). Together with other carbonate grains, they were brought into the supratidal flats by storms, possibly through small tidal channel complexes.

7.2.4 Laminar Anhydrite Unit

The fine lamination in the laminar anhydrite suggests subaqueous deposition. The alternating laminae of anhydrite and anhydrite-dolomite in such environments are usually the result of variation in brine concentration (Warren, 1985). A similar lamination in a shallow gypsum pond (0.5 m) in the MacLeod Basin is attributed to small-scale fluctuations in salinity, including seasonal climatic changes, heat waves (increased evaporation), rainfall variations, and incursions of brackish water that cause dilution (Logan, 1987). A few short intervals with stromatolites and mudcracks, indicating intertidal conditions, also resulted from such variations. Periods of complete desiccation in the pond are expressed by micro-tepees and disruptions of the laminae.
The sedimentary parameters of the rock are comparable to the recent gypsum in the Hutt and Leeman Lagoons (Arakel, 1980), and the MacLeod Basin (Logan, 1987) in Western Australia. Some ancient deposits that have been assigned to this environment are the Messinian evaporites of Sicily (Hardie and Eugster, 1971; Schreiber, 1973).

Another mode of dolomite in this anhydrite is the brown "pepper" that is disseminated in some laminae. Although most of the carbonate is present as tiny aggregates, larger ones are not uncommon (see Fig. 4.16). These allochthonous sediments could have been brought into the gypsum ponds almost constantly either by winds or ephemeral fluvial streams from exposed areas which were mostly carbonate rocks. The presence of brown oxidized sediments in the upper part of the Shell Lake Member suggests the close proximity of the land. On the other hand, the ponds were still within the reach of storms or high tides. This is demonstrated by thin beds and lenses of peloidal sediments that in a few places are intercalated within the laminar anhydrite.

In a depositional framework, the pond environment is interpreted as being located landward of the algal marsh. The decrease, both in frequency and thickness of the peloids upward, implies a shift of the site away from marine influence. The presence of angular, brown carbonate lithoclasts, which have never been previously recorded, supports the interpretation. They can only have been transported for a short distance.

7.3 Depositional Environments of the Leofnard Member

Recrystallized and massive halites constitute the lower half of the Leofnard Member, while banded halite and potash beds dominate the upper half. The sporadic appearance of carnallite may be noted at a few metres above the contact with the underlying anhydrite-carbonate rocks. Potash in the lower two submembers, the Esterhazy and the White Bear, is predominantly carnallite with a small amount of
sylvite in the uppermost metres of the White Bear Submember. Sylvite begins to dominate the Leofnard Member from above the Marker #2 upward, and it becomes the only potash mineral present in the Patience Lake Submember in most of the wells.

### 7.3.1 Recrystallized and Massive Halite Units

Most of the primary features in both types of halite were destroyed during diagenesis. However, faint indicators of salt-pan halite have been recognized in the lower part of the member. This, coupled with the presence of the zoned halite and anhydrite partings in the Osler 3-28 and Cominco 2-16 wells, strongly suggests that salt-pan environments still prevailed. In the upper part of the Massive Halite Unit, the overall colour of the salt becomes brownish or reddish due to the increasing mud content. It is speculated that the original deposit may have resembled the banded halite which is still preserved well up the section.

Several lines of evidence suggest periods of exposure, including, for example, erosional surfaces in the Recrystallized Halite and Massive Halite Units and salt polygons in the Esterhazy Submember. Numerous insoluble seams with dissolution pipes and pits were the result of dissolution by less-concentrated brines or fresher water.

Some recrystallization of these halites could, in part, be related to the influence of the less-concentrated brine that existed during deposition of the thin laminar anhydrite (Marker #1). However, a far larger amount of water is probably required to produce massive recrystallization in an interval almost 40 m thick. Mine observations indicate that the degree of recrystallization diminishes upward, implying that the water could have come from below. Dissolution of halite at PCS Allan, for example, has been attributed to the fresher brines expelled from the Winnipegosis mounds by compaction resulting from sediment loading (Gendzwill, 1978; Wilson, 1985). If this is the case, the amounts of water derived from this source are likely capable of producing
extensive recrystallization in halite.

The formation of carnallite in this sequence is also linked to recrystallization. It never shows any form of stratification, but is confined to the interstices of the halite. Carnallite here may have precipitated from the highly-concentrated slurry that moved vertically through the interconnected voids towards the end of halite recrystallization. Clay first floored or lined the voids, followed by carnallite precipitation. Redistribution of clay and carnallite in the same manner is discussed by Harville and Fritz (1986) from the Permian Basin of Texas.

7.3.2 Banded Halite Unit

The main difference between the Banded Halite and the salt-pan halite is that the dark bands in the Banded Halite Unit do not truncate the bottom-nucleated, zoned halite crystals. Muddy sediments were laid down on the salt floor and precipitation of halite continued. Subaqueous deposition is indicated by the small current-ripple surfaces observed at the Cominco Mine. However, there are lines of evidence that indicate frequent desiccation, including truncation of zoned halite by insoluble seams and dissolution pipes underneath, metre-scale polygons, and vertical pits. Apparently, this halite is analogous to the "bedded halite" of the Permian Basin, Texas, which Hovorka (1987) interpreted as being deposited under "perennial brine pool" conditions.

From mostly anhydrite in the lower part of the formation, the insoluble fraction is now more variable and composed, in order of abundance, of dolomite, clay minerals and anhydrite (Boys, 1990). The decrease in anhydrite and the appearance of other minerals suggest a change in the source of the brines or a change in their composition. Either the marine brines have lost sulphate or they may have been mixed with groundwater of somewhat different composition. If the brines are derived from seawater, then most sulphate must have been removed elsewhere in the basin, presumably as gypsum or anhydrite. For the lower part of the formation, Kendall (1989)
suggested that the gypsum or anhydrite was formed when calcium-bearing brines flowed through the carbonate mounds and mixed with marine-derived (sulphate-bearing) brines. Precipitation of sulphates in the areas adjacent to the mounds also lends additional support to anhydritization of the underlying Shell Lake Member at shallow depth of burial.

The term "pericontinental salt lake" is proposed in this thesis for the depositional environment of the Banded Halite Unit. It differs from the "perennial brine pool" of Hovorka (1987) in two aspects, - much more frequent desiccation and a more continental setting in the sense of the significant contribution it received from the land. The size of the salt lake could have been several tens or hundreds of square kilometres, considering the possible area between the mounds. At the same time, it differs from the "salt pan" as defined by Lowenstein and Hardie (1985) and as applied to the Whitkow Member in that it was not dry for most of the time. Rather, it was somewhat perennial with periods of desiccation. The water supply may derive partly from periodic marine incursion and partly from continental sources in the forms of surface runoff and occasional storm-floods. The extent of storm-flood in an evaporitic environment can be very large. This is examplified by flooding of Lake Eyre, Australia, during 1949-1952 period in which the flood covered an area of approximately 8,000 km² with an average depth of 4m (Hardie et al., 1978). During the periods of desiccation, the pericontinental salt lake would probably have characteristics essentially similar to the "salt pan" environment.

The pericontinental salt lake environment replaced the salt-pan environment at about 10 to 15 metres above the base of the Leofnard Member, and lasted, except during the deposition of the Marker #2 and its equivalents, until the end of the formation. It is difficult to pinpoint the exact location where it starts in the massive halite such as in the reference well. However, a change to brownish or reddish colours is evident within an interval of a few metres at this location.
7.3.3 Potash Beds

There is an overwhelming amount of evidence that supports a secondary origin of the sylvinitite beds. The important sources are geochemical (Schwerdtner, 1964; Wardlaw, 1968), petrographical (Wardlaw, 1968; Fuzesy, 1983), fluid inclusion and isotopic (Baadsgaard, 1987; Chipley and Kyser, 1989), and stratigraphic (Holter, 1969; Worsley and Fuzesy, 1979). In fact, although scanty, there are some primary features left in the potash beds, in amounts sufficient to provide clues to the depositional environments.

Sylvite in the banded halites, for example in the uppermost metre of the White Bear Unit and those separating the potash beds, appears to be syndepositional or very early diagenetic. Its occurrence as a vertical cement between the chevron halite precludes the interpretation that it was formed by secondary precipitation. Infiltration of sylvite-saturated brines in the salt at depth is unlikely because of cementation by interstitial precipitation of early diagenetic halite and compaction. It has been shown (Casas and Lowenstein, 1989) from several present-day salt deposits that below a depth of about 45 m the porosity in halite is practically zero. Instead, potash could have formed near the peak of the evaporating cycles when the dense, sylvite-saturated brine infiltrated the halite downwards and was trapped just above the impermeable clay bands. A possible mechanism to precipitate sylvite is cooling of such brine in the porous halite substrate (Lowenstein and Spencer, 1990), which induces the brine to supersaturation with respect to sylvite.

Carnallite in the wells along the northern end of the study area (Osler 3-28, Osler 16-24 and Marysburg #1 wells) also carries the same genetic message. Although unmappable due to its poorly-developed nature, the carnallite fills the interstices between halite crystals deposited in a salt-pan environment, therefore indicating a syndepositional origin. Again, the cooling mechanism (Lowenstein and Spencer, 1990) may apply. In fact, this carnallite is comparable to that reported from non-marine
playas of the southeastern Soviet Union (Valyashko, 1972), and in the Qaidam Basin of western China (Lowenstein et al., 1989).

The high-grade potash beds, particularly the Belle Plain and the Patience Lake Submembers, may have originally been banded halite intervals with a high potash content. This speculation is based on their overall appearance and the associated insoluble seams, as well as the disseminated insolubles (dolomite, clays, and anhydrite) within them. At locations with a lesser degree of recrystallization, the syndepositional relationship between sylvite and halite is still apparent.

In summary, there are two types of depositional environments in the Leofnard Member - coastal salt pan and pericontinental salt lake. The former prevailed in the north (around Osler and north of Humboldt, Fig. 1.4) throughout the whole member, but in the central portion of the study area and southward, pericontinental salt lake conditions developed soon after the Leofnard Member began. The timing of the transition is just before the deposition of the Esterhazy Submember.

There was a brief interruption by the tidal flat environment during deposition of the Marker #2, and the pericontinental salt lake environment returned soon afterward. The primary deposit was modified by several subsequent alteration events which led to enrichment of sylvite around the central part of the study area, leaving this member along the northernmost part relatively undisturbed.

7.3.4 Insoluble Seams

Insoluble seams represent nearly dry or subaerially exposed periods of the pericontinental salt lake environment. This is indicated by the close association between the insoluble seams and the desiccation and/or dissolution features both in core and mining wall. The insolubles (dolomite, anhydrite, clays) could have derived from three main sources: the dissolution and resedimentation of those in the deposited salts, the sediment load accompanying flash floods and surface runoffs, and airborne...
dust. It is likely that the seams were produced by the combination of all sources.

Temporary ponding on surface of the salt by fresher recharges, whether from rainstorms or floods, not only dissolved and recycled the underlying sediments but also led briefly to reducing conditions at the brine-sediment interface. As noted in many thick insoluble seams, their lowermost part is frequently greenish grey or grey, and the colour turns reddish in the upper part. The change in colour indicates a change to more oxidizing conditions as the brine level dropped or the site dried up.

The reddish colour results from iron oxides which could not have come from those in seawater alone because iron content in seawater is very small (Braitsch, 1971). Other contributors are the sediments derived from the continent. The presence of rounded dolomite grains testifies for a detrital component of the insolubles. Iron oxides (e.g. hematite, goethite) are formed in the sediments by diagenetic processes under surface or near surface conditions (Turner, 1980). In the case of salt deposits, Fracasso and Hovorka (1986) and Hovorka (1987) attributed the reddish colour to oxidized iron stains in clays and clay coats.

The sedimentary features in the insoluble seams (desiccation cracks, sheetcracks, dissolution pits, etc.) are comparable to those in the saline and dry mudflat environments described from modern saline lake systems by Hardie et al. (1978). To distinguish these two types of environment is perhaps impractical because, from mine observations, both are usually present at different locations in one seam. Nevertheless, the seams that are of chaotic mudstone-halite are indicative of the saline mudflat environment (Handsford, 1981; 1982). They were formed by repetitive dry and flood periods that caused multiple dissolution and reprecipitation of salt in a muddy residue.

The granular halite showing cross-stratification has never been reported in the literature. The zoned structures in some of the halite grains suggest that they were formed subaqueously as chevrons or hoppers, whereas their roundness is likely to be the result of reworking. At the same time, the red mud matrix indicates oxidizing
conditions as commonly found in red bed deposits (Turner, 1980). It is suggested that the granular halite represent the wind-blown halite grains derived from exposed salt crusts nearby. These originally subaqueous halite grains were transported and redeposited during the dry salt pan periods of the pericontinental salt lake environment.

7.3.5 Marker #1 and #2

The environment in which both markers were deposited was similar to that of the laminar anhydrite in the upper part of the Shell Lake Member, shallow, tidal ponds on supratidal flats. The displacive and skeletal halites disturb anhydrite lamination, and therefore, postdate the anhydrite. These halites resemble those reported from within the sediments along the southern shore of the Dead Sea and from the Salina salt of the Michigan Basin (Gornitz and Schreiber, 1981). It seems logical that the displacive and skeletal halites were formed within the anhydritic muddy floor of the salt pans or pericontinental salt lakes.

Variation in the Marker #1 is not apparent because it is found only in the reference well, but the variation in the Marker #2 is quite marked. The Marker #2 at Lanigan is predominantly laminar anhydrite, and it becomes slightly more dolomitic at Allan, particularly in the upper part (see Fig. 6. 15). In the area around Saskatoon-Osler, it was formed in an intertidal environment, as indicated by laminated dolomitic mudstones with stromatolites and local disruptions. This environment is also traceable southward to the Dundurn 13-18 well.

The Marker #2 was probably a basin-wide phenomenon (see cross-sections) although it is not necessarily one single, continuous lithologic unit. It represents an extensive, but brief, period of brine freshening. The less evaporitic environment around Saskatoon suggests a better communication in that area with marine conditions, compared to the area around Lanigan and Allan. Perhaps there were some
tidal channels that provided more access to recharge from the sea. The pericontinental salt lake environment returned to the Lanigan-Allan area shortly after the interruption, but the salt pan environment dominated the area around Osler-Saskatoon-Dundurn for some time before being succeeded by the pericontinental salt lake conditions.
8. DEPOSITIONAL MODEL OF THE PRAIRIE EVAPORITE FORMATION

This chapter will attempt to reconstruct the depositional model of the Prairie Evaporite Formation from the preceding interpretations of individual units. The limited number of the cored wells allows only a conceptual representation. However, in order to visualize the deposition and the resultant sedimentary suites during the discussion, it is necessary to refer occasionally to the rock sequences in some locations in the study area. It is emphasized that the model presented is based primarily on the information available around the Saskatoon region. Nevertheless, it has broader implications to the Elk Point Basin as a whole in several aspects, i.e., basin development, stratigraphy and correlation, basin subsidence, and sea-level changes, etc..

8.1 A Review on Evaporite Depositional Models

Before reconstructing the model for the Prairie Evaporite Formation, it is important to review briefly those that have been used to explain the deposition of thick evaporites. Several models have been developed for various deposits, which Kendall (1984) has categorized them into three groups - Deep Water-Deep Basin, Shallow Water-Shallow Basin, and Shallow Water-Deep Basin. Figure 8.1 is a schematic diagram of these models, and a brief discussion on their essential characteristics, with reference to some deposits, is given below.

8.1.1 Deep Water-Deep Basin Model

This model emphasizes a high rate of evaporite deposition compared to possible rates of basin subsidence, and the fact that evaporites are usually located in topographic depressions. While the rate of evaporite deposition is 2 to 5 cm/y for
Figure 8.1 A diagram showing the three depositional models of evaporites (from Kendall, 1984).
gypsum and 2 to >10 cm/y for halite (Schreiber, 1988), the rate of basin subsidence is probably 0.1 mm/y (Kendall, 1984). Thus, the basin must have been initially deep or else it would not have been able to accommodate evaporites several hundred metres thick. This is similar to the model proposed by Wardlaw and Schwerdtner (1966) for the Prairie Evaporite (see 1.2).

In this model seawater flows in as a perennial surface inflow and a barrier system (structural elements, reefs, etc.) causes the restriction. Carbonates, sulphates, and soluble salts are deposited penecontemporaneously along the differentiation path of the brine, from lower salinity mineral phases near the source of the inflow to higher salinity phases more basinward. With continued deposition, the basin is gradually filled.

8.1.2 Shallow Water-Shallow Basin Model

The basin is shallow and remains so throughout its history. The deposit is characterized by sedimentological and geochemical evidence that suggest shallow water or subaerial environments. To deposit a thick evaporite succession, this model requires approximately the same rate of basin subsidence as the rate of evaporite deposition. This may be the case for some thin evaporites at the top of sedimentation cycles such as in the Ordovician rocks of the Williston basin, Saskatchewan (Kendall, 1976). In modern settings, the areas with rapid basin subsidence are perhaps the fault-block grabens, as for example the Ethiopian sector of the African Rift (Warren, 1989). Both carbonates and siliciclastics may occur in association with evaporites.

8.1.3 Shallow Water-Deep Basin Model

This model was developed to account for the deposition of evaporites that contain evidence of shallow-water or subaerial environments in a pre-existing deep
basin. Strong support of the model has come from the Deep Sea Drilling Project which discovered a thick, shallow-water to subaerial evaporite deposits beneath the Mediterranean. Based on such evidence, Hsü et al. (1973) deduced that, during the Late Miocene, the floor of the Mediterranean was about 2,000 m below the contemporary Atlantic sea-level. A very similar interpretation, but with waters only about 100 m deep, was implied for the Elk Point Basin when Shearman and Fuller (1969) suggested that the organic laminites below the Prairie Evaporite Formation were a supratidal deposit. Such an interpretation directly implies that the basin was desiccated at the beginning of Prairie Evaporite deposition.

A desiccated basin, as in this model, must create a major sink for regional groundwater flow. Therefore, in addition to any seepage from the sea, there should also be a significant amount of continental waters entering the basin. In such a large, deep basin, the environmental conditions would be extreme, i.e., high air temperature, high brine temperature, and very low humidity (Kendall, 1984).

8.2 The End of the Winnipegosis Formation

Clues to the nature of the environmental conditions at the end of deposition of the Winnipegosis Formation lie at the contact between the two formations and in the Basal Anhydrite Unit. The contact between the carbonate mound and the basal anhydrite in the reference well is erosional, and truncation of the acicular anhydrite crystals is marked (Fig. 3.2). The pore-filling anhydrite could have been formed primarily in vadose conditions; or if it was originally gypsum, it would have been formed in very shallow water. Overlying this contact are ruditic fragments (disrupted mudstone, bioclasts) derived from erosion of local mounds. Both imply a period of erosion and subaerial exposure of the carbonate rocks at this location.

Subaerial exposure of the mounds is supported by Kendall (1989), who suggests a genetic link between the deposition of the Prairie Evaporite Formation and the
regional dolomitization of the underlying carbonate strata. The desiccated basin could provide large elevation heads to induce ground- and formation-waters to flow into it, and consequently, result in dolomitization of the carbonates adjacent to and below the evaporite basin. Kendall (1989) further claims that the presence of pisolitic gravels and "presumed" travertine deposits near the mounds are evidence for the calcium-rich, continental waters seeping into the basin through the mounds.

Coupled with the depositional environment of the basal anhydrite, it appears that there was a major drop of the sea-level at the end of the Winnipegosis time. Such a drop resulted in a large desiccated basin that was completely separated from the sea by the extensive carbonate mounds (Fig. 8.2). The magnitude of the sea-level drop is unknown. However, having the mounds as a barrier system, the sea-level was not necessarily as low as the base of the mounds as suggested by Shearman and Fuller (1969). There is a possibility of structural or tectonic elements, probably the extensions of the known ones, acting as a barrier; but this cannot be verified due to erosion of the rock record.

Following erosion of the carbonate mounds, deposition of the Prairie Evaporite Formation began. Perennial brine pools occupied the hydrological lows of the intermound depressions in which the microbial-laminated mudstone and enterolithic anhydrite were deposited. At the same time, intense evaporation on the exposed areas such as the lower slopes of the mounds led to intrasediment precipitation of anhydrite, incorporating the ruditic fragments. Transgressive pulses resulted in intertidal mudflat conditions from which the laminated mudstone was deposited on the ruditic anhydrite, and with sediment disruption occurring during regressive pulses. The whole region was finally transformed into patchy, shallow hypersaline salinas in which the poorly-laminated selenite (now anhydrite) precipitated.

Considering the height and distribution of the mounds (see Wilson, 1985), the deposition of the basal anhydrite could not have been uniform throughout the study area. It is more likely that the deposition took place in isolated intermound
Figure 8.2 A model of the depositional environment at the end of the Winnipegosis Formation deposition and the beginning of the Prairie Evaporite Formation.
depressions and proceeded under local conditions but within a broad, similar environmental framework. More variety of the basal anhydrite is to be expected as more cored wells become available.

8.3 Deposition of the Whitkow Member

With continued evaporation, the area developed into ephemeral salt pans. The pans could have been fed by both marine- and continental-derived brines. From the areal extent, the salt thickness, and the lack of evidence suggesting prolonged periods of subaerial exposure, it is likely that the marine supply was quite regular, much probably in forms of seepage. This could have resulted in deposition of the carbonate and anhydrite along the perimeter of the mounds by brine mixing (Kendall, 1989), with the remaining brine flowed toward the centre of the intermound depression. To allow such seepage, the basin floor must have been below the sea-level. An additional contribution could have come from meteoric waters, i.e., rainstorms and groundwaters. The brine depth in the pans is not known, but based on modern analogues, it is speculated that it was from a few centimetres to a few metres.

Fluctuations in the environmental conditions are reflected in the common intercalation of anhydrite partings in the halite, especially in the lower half of the member. One such fluctuation resulted in the prominent Intermediate Anhydrite Unit which represents a brief period of freshening, leading to ponding and intertidal conditions, locally. However, salt pan deposition continued elsewhere, and the repetitive salt pan cycles gradually filled a part of the basin floor, reducing the relief between the mounds.
8.4 Deposition of the Shell Lake Member

More anhydrite partings in the uppermost metres of the Whitkow Member indicate a basin-wide transgression, presumably in a series of pulses. Inundation may have begun with small amounts of less-concentrated brines, because the dissolution of the underlying salt is not extensive. Gypsum (now anhydrite) was precipitated rapidly from the standing brines which, in turn, limited further dissolution. This protection was also enhanced by the presence of microbial mats.

At the margins of the intermound depressions, such as in the Lanigan and Outlook areas, deposition was very dynamic. A narrow belt of carbonate tidal flats was built on the anhydrite blanket. Rapid shifting to and fro, from hypersaline lagoons, to mudflats, and to sabkhas produced a thick intertidal-supratidal sedimentary suite. This is represented by alternating units of laminated mudstone, thick microbial films, and mosaic anhydrite.

The abrupt development of the grainstones of the Quill Lake Marker Beds may indicate physical changes in the barrier system. Transportation of the coarser carbonate grains from the near-normal marine conditions to the tidal flat complex during storms may have been through tidal channels. Although speculative, it is possible because during this time the mounds that were 60 to 70 m high were already buried, with only the very high ones still exposed. Channels could also form across the low-lying points of the high mounds. A diagram showing the inferred development of an intermound depression at this stage is illustrated in Figure 8.3.

Lateral accretion of the intertidal-supratidal sediments may have caused the regression, thus leaving behind the supratidal marshes and tidal ponds. Continued evaporation brought the brine to sulphate saturation and the laminar anhydrite of the upper part of the member was deposited. Successive thinning of the grainstone beds may indicate further retreat of the sea. A few thin mudstone beds, some with stromatolites, represent minor shifts of the subenvironments in the tidal-flat complex.
Figure 8.3 A model of the depositional environment during the deposition of the Shell Lake Member, the Prairie Evaporite Formation.
Coincident with the regression, there is an early signal of the encroaching continental influences. For the first time, brown, angular carbonate particles are found. They probably were introduced by wind or streams from the subaerially-exposed terrain to the south and southwest (Grayston et al., 1964; Holter, 1969; Meijer Drees, 1986) into the ponds that were precipitating laminar gypsum, and were, therefore, incorporated in the laminae.

The deposition of the Shell Lake Member at locations near the centre of the intermound depressions differs slightly from that of the above interpretation. At Osler and Vanscoy, the area became one of protected hypersaline ponds in which selenite (now anhydrite) grew in association with microbial mats, with little interruption until the salt-pan conditions returned. From the environmental viewpoint, these hypersaline ponds were not necessarily the single one nor the same pond that bordered the tidal flats of the Lanigan and Outlook areas. It is more likely that they were isolated brine bodies occupying the local lows of the intermound depressions.

8.5 Deposition of the Leofnard Member

8.5.1 Lower Half of the Leofnard Member

Most of the interval between the Shell Lake Member and the Marker #2 has been recrystallized, particularly in the area around Lanigan and Allan, but around Osler and Saskatoon, it is composed of translucent halite and anhydrite partings similar to those in the Whitkow Member. Given the limited evidence, it is speculated that a salt pan environment still dominated at least in the "Recrystallized Halite" and the corresponding intervals. The lack of red colouration throughout this section adds limited support to this speculation. The deposition of salt-pan halite on top of the tidal flat sediments implies farther regression.
Presumably, the pericontinental salt lake environment started above the Marker #1. An increasing contribution of sediment from the land is indicated by the generally reddish insolubles in the halite and the dominance of carbonate mud, probably of detrital or eolian origin, over anhydrite. However, periodic supply of water from the sea was still significant, judging from the aerial extent, the thickness of the salt, and the lack of any major erosional surfaces. Brines derived from continental sources alone may not be sufficient for depositing the sequence.

In more continental settings, relative humidity is usually lower than in coastal settings. Low humidity certainly promotes deposition of the highly soluble salts. As demonstrated by Kinsman (1976), only when the relative humidity is lower than 67% can the brine evaporate to the point where potash is precipitated. The primary mineralogy of potash in the Esterhazy and the White Bear Submembers is uncertain because the chemistry of the parent brines may not have been entirely marine, as traditionally viewed. It is considered likely that the brines were of mixed derivation. Furthermore, their composition could have been modified as they entered the intermound depressions (Kendall, 1989).

Considering the additional sediments from this part of the member, the topography of the area must have become almost featureless. Corrigan (1975) suggested, from his study area in northeastern Alberta, that once the mounds were buried, there was no obstruction to the eolian dust being introduced into the area from the surrounding land. Thus more dust reached the area, resulting in reddening of the salts. This suggestion probably explains the reddish colour of the salt in the Leofnard Member. Taking into account the underlying Paleozoic rocks, the dust would be dominated by carbonates, which explains the predominance of carbonate in the insolubles. The only locations with prominent relief in the study region were those to the east of Saskatoon, as reflected in the absence of the Esterhazy Submember. Figure 8.4 illustrates the inferred depositional environment of the Leofnard Member during the time of deposition of the Esterhazy Submember.
Figure 8.4 A model of the depositional environment during the deposition of the Esterhazy Submember, the Prairie Evaporite Formation.
8.5.2 Upper Half of the Leofnard Member

A notable period of brine freshening interrupted the pericontinental salt lake deposition. With reference to the study area, gypsum pools were formed in the Lanigan area above the massive halite. The resultant deposits were laminar gypsum (now anhydrite), with displacive halite of the Marker #2. Tracing westward, the corresponding unit at Allan is slightly more dolomitic, while those from Dundurn, Saskatoon, and Osler become mudstones with stromatolites, representing intertidal conditions. These rocks may not be lateral facies changes within exactly the same unit, but at least they indicate a progressively lower brine concentration in Saskatoon and the surrounding areas. Perhaps there was a better marine connection somewhere in these locations.

A pericontinental salt lake environment similar to the underlying section returned and lasted until the end of the Prairie Evaporite deposition. There must have been a significant amount of potash associated with the banded halite. Interruptions in the evaporite precipitation by dry or saline mudflat conditions (salt-pan environments) became more frequent, and a general upward increase in reddish colour became distinctive. This signifies an ever-increasing continental clastic input which may be eolian dust and/or mud in suspension. Except for a small amount of locally-derived, anhydrite intraclasts, no coarse sediments have been found. By this time, the supply of brines from the sea was probably much reduced.

Because potash, whether it was originally carnallite or sylvite, was probably precipitated in the repetitive dry-and-flood conditions, the possibilities for early diagenetic alteration are very likely. Such early changes are common in modern saline lake environments (Eugster and Hardie, 1978; Last and Schweyen, 1983; Last, 1989), and they alter the mineralogy of the deposited salts as well as the chemistry of residual or interstitial brines. The salts in the Prairie Evaporite Formation may have come under the influence of continental waters, the origins and chemistry of which are not
known at present. Rain water also entered the deposit through dissolution pits or cracks and finally merged into the shallow groundwater system. Evidence for the syndepositional dissolution of the salt flats has been recorded from mine observations in this study, and reported from many potash mines (Baar, 1974; Mossman et al., 1982).

The processes that produced the commercial potash seem to be confined to the area of banded halite which was precipitated in somewhat perennial environmental conditions. This area is, in fact, the thickest part of the formation. Such a coincidence may indicate a genetic link between greater basin subsidence in this part of the basin, the formation of the pericontinental salt lakes, and the secondary potash enrichment. The contrast is quite obvious when comparing the salt sequence in the area underlain by potash to those around the northern end of the study area, where the sequence is composed of salt-pan halite containing presumed syndepositional carnallite (see 7.3.3).

Insoluble seams could have played a key role in controlling the flow path of the brines involved in recrystallization as they usually underlie sylvinite beds, and the horizontal orientation of sylvite is common in areas adjacent to them. The importance of insoluble seams has been emphasized by Boys (1990), who proposed a "potash cycle" based on the close relationship between the two. He indicates that the reddish colour in sylvite becomes paler away from the insoluble seams. It is also important to note that even with recrystallization above and below, many insoluble seams are practically undisturbed. This fact indicates the delicate and subtle nature of the processes.

8.6 The End of the Prairie Evaporite Deposition

The banded halite at the uppermost part of the formation was exposed subaerially, as evidenced by salt polygons, dissolution pits, etc. Therefore, it was subject to dissolution by freshwater fed from the land to the south or rainwater. Temporary ponding occurred over much of the area, and the thin microbial-laminated anhydrite zones were deposited. The ponds were very patchy as indicated by two wells
in the Allan area, one showing a microbial-laminated zone whereas the other passes from banded halite to chaotic mudstone-halite, and into the overlying red dolomitic mudstone.

An unknown amount of the salts was dissolved, and the extent of the dissolution may vary from one location to the other. The insoluble residue, together with the newly-introduced fines sealed the surface of the salt. As the ponds dried up, dry mudflat conditions took over the area.
9. CONCLUSION AND DISCUSSION

9.1 Conclusion

The depositional model presented in this study is opposite to the one which advocates a progressive restriction of perennial brine body of an inland sea. Instead, it proposes the shallow water deep basin model, beginning with a sharp drop of the sea-level after the deposition of the Winnipegosis Formation. The area became a desiccated basin whose depth was about 80 to 100 m, close to the height of the carbonate mounds. Probably, the extensive mounds themselves barricaded much of the basin from the open-marine conditions. In the basin, the mounds of variable size, shape, and height created many isolated or interconnected intermound depressions.

Prairie Evaporite deposition commenced with carbonate mudflats and locally hypersaline pools, then progressed to coastal salt pan environments. Deposition of the halite and anhydrite of the Whitkow Member under these conditions filled part of the relief between the mounds. The sea-level beyond the basin margins gradually rose up to the point where transgressive pulses could overflow into the salt pans periodically, resulting in rapid migration of the subenvironments within an intertidal-supratidal complex from which the Shell Lake Member was deposited. Better communication with the sea also allowed transportation of coarse carbonate grains onto the flats during occasional storms or high tides. Infilling of the sediments in the intermound depressions and regression of the sea led to the return of a salt pan environment.

The pericontinental salt lake environment developed as the sea retreated farther. Most of the carbonate mounds were buried, and the area became featureless. Increasing influence from the land is reflected in the reddish colour of the salt and the change in mineralogy of the insolubles in the Banded Halite. A significant amount of potash started to precipitate soon after the onset of the salt lake environment and culminated when the Belle Plain and the Patience Lake units were deposited. Aridity
was probably at its peak during this time as recorded by frequent desiccation and
dissolution features within the interval. Prairie Evaporite deposition ended as the
prolonged saline and dry mudflat environments that deposited the Second Red Bed were
firmly established.

9.2 DISCUSSION ON THE IMPLICATIONS OF THE MODEL

Unlike the subaqueous deposition from an inland sea, the shallow-water deep
basin model sheds new light on several issues surrounding the Prairie Evaporite
Formation. The inferred depositional environments at different stages, according to
this model, provide a more dynamic picture of the sedimentary processes operating
during the time of deposition and shortly thereafter. Based on such a foundation, some
further thoughts and implications can be given. Basin development, the origin of salt
anomalies, and the primary mineralogy of the potash are chosen for further
discussion.

9.2.1 Basin Development

The depositional model proposed through this study does not support the
traditional inland sea model with open-marine conditions located around the
northwestern corner of Alberta and northeastern British Columbia. First, the
deposition under the inland sea conditions would not have allowed such great
lithological variations as are found in the Prairie Evaporite Formation. Due to the
hydrological characteristics of the perennial subaqueous setting, the variations should
occur basin-wide (Kendall, 1988). Second, much of the lithology and many of the
inferred environments are comparable to those along the present-day arid carbonate
shorelines, i.e., the Persian Gulf, Shark Bay of Western Australia, Baja California of
Mexico. It is difficult to visualize a long and narrow shoreline with intertidal-
supratidal zone stretching landward no less than 1,500 km away from the sea. Third, there seems to be no hydrological head that could have driven the brine across such a distance to feed the Saskatoon region. If the supply was through the Presqu’ile Reefs alone, the brine would probably have dried up soon after it had entered the basin. It would also encounter several physical obstructions along the way including the Peace River-Athabasca Arch, the Meadow Lake Escarpment (see Fig. 1.2), and the carbonate mounds themselves.

The difficulty of brine migration becomes more obvious when taking the works of Corrigan (1975) and Brodylo and Spencer (1987) in northeastern Alberta into consideration. Both have interpreted the lower part of the Muskeg Formation, which is the Prairie Evaporite Formation equivalent, as a shallow-water salt pan deposit. This conforms with the current interpretation for the Saskatoon region, and at the same time, it is apparent that a salt pan environment extended all the way from the eastern segment of Alberta, to Saskatchewan, and to the easternmost end of the formation in western Manitoba.

The source of seawater that fed Saskatoon region must, therefore, have been closer, and the most likely location is to the north and northeast of the study area. During Paleozoic time, the Hudson Bay area was a sedimentary basin where a thick carbonate sequence and small amounts of gypsum were deposited (see Norris, 1986). It is conceivable that there could have been an embayment connecting the Hudson Bay Basin with the Elk Point Basin during Middle Devonian time. If this were the case, the shoreline could have run northwesterly, probably close to the present northern edge of the Elk Point Basin (Fig. 9.1). Having the sea to the north would allow sufficient water supply in forms of seepage through the permeable carbonate mounds or fractures to feed the mudflats, hypersaline pools, and salt pans along the shoreline throughout Saskatchewan and western Manitoba.

With this picture in mind, fluctuation in environmental conditions during the deposition of any rock units in the Prairie Evaporite Formation can be explained more
Figure 9.1 A schematic diagram showing the probable shoreline during the Prairie Evaporite deposition. Arrows indicate the inferred connections with the open sea.
satisfactorily. For example, the deposition of the translucent halite and anhydrite partings could relate to periodic dry and flood due to variations of the sea-level or variations in porosity of the barrier; the alternating sequence of anhydrite and carbonate could be the result of regressive-transgressive pulses of the sea; and, with the contemporaneous rising sea-level, the carbonate grains in the grainstone could have been transported onto the area via channels cutting across the mounds during severe storms. The increasing supply of water from the land to the south and southwest is also apparent as the shoreline migrated northeastward away from the study area during the deposition of the Leofnard Member.

The idea of marine connections to the north and northeast is not new; rather, it has been overshadowed. From facies analysis of the Middle Devonian rocks, Edie (1959) suggested that during the Winnipegosis and Dawson Bay times the transgressions were from the direction of the Canadian Shield. Bassett and Stout (1967) noticed the generally higher Winnipegosis mounds along the northern edge of the Elk Point Basin, indicating a possible connection with the open sea between northeastern Alberta and Saskatchewan. Such a distribution of mound development was later confirmed by Wilson (1985). More recently, Williams (1984) pointed out several constraints in basin-wide facies correlation based on the "barred inland sea" model with the transgression from northwest. He suggested other alternatives which included the transgression from the north.

In accordance with the above, this author prefers to place the shoreline during the Prairie Evaporite Formation to the north and northeast. This does not necessarily nullify a connection with the sea to the northwest. Farther westward from the study area, particularly northwestern Alberta, the basin could still have had a supply from the sea through the Presqu'ile Reefs as indicated by several previous authors, i.e., Grayston et al. (1964), Holter (1969), and etc.. It is apparent now that the history and the development of the Elk Point Basin are more complicated than previously thought. Further investigation on the basin and its contained rock units would allow more
realistic reconstruction of the basin-wide facies distribution which, in turn, would enable delineation of the shoreline locations and the connection of the open sea to the Elk Point Basin during Middle Devonian time.

9.2.2 Origin of Salt Anomalies

One of the major problems facing potash mining is the so-called "salt anomalies". Also known as "salt horses", "anomalous ground", and "barren halite zone", the anomalies are areas where the normal ore-zone sequence is disrupted. Most anomalies are usually low ore grade, comprised predominantly of halite. However, some which are composed mostly of clear sylvite have been found in the PCS Lanigan Mine (Danyluk, pers. comm., 1990; and personal observation).

Because salt anomalies possess potential hazards and affect economic aspects of mine operations, it is beneficial to be able to predict their occurrences in advance of mining. Previous attempts in interpreting salt anomalies include those by Baar (1974), Mackintosh and McVittie (1983), and Boys (1990). Mackintosh and McVittie (1983) classified the salt anomalies into washouts, leached zones, and collapse zones, and Boys (1990) gave detailed illustrations (Fig. 9.2). The variety termed "washouts" is discussed below.

It is apparent from the illustration, coupled with mine observations during this study, that washouts are surface features produced in the depositional environment by dissolution and recrystallization of the salts. The washouts could relate to surface inflows of the less-concentrated brines formed during rainstorms and flood recharges (Baar, 1974). Naturally, the channels of surface waters in the coastal areas normally run perpendicular to the shoreline. This also probably holds true for shallow groundwater. With the depositional model and the newly-proposed shoreline in mind, the possible direction of the channels during the Prairie Evaporite deposition becomes clear - northeasterly (Fig. 9.3). It is speculated, based on this study, that this is the
Figure 9.2 A schematic diagram of salt anomalies (after Boys, 1990).
common trend of the washout anomalies around Saskatoon region.

The common trend of the salt anomalies as suggested requires verification by mapping of such features in the mines. If proved, the precise trend can be determined, and the mining plan will have to take it into account. Mining in a northeasterly direction would have a higher chance of following the trend of the washout anomalies, which is not beneficial.

From Figure 9.2, it is apparent that the leached zone and the collapse zone are post-depositional features. Nevertheless, some of them may follow the same trend of the washouts because, as pointed out by Boys (1990), some leached and the collapse zones are composite, having started to form in the depositional environment and reactivated after burial. Washouts may have acted as conduits, facilitating the flow of subsurface brines and causing disruption of the ore zone. It is appropriate to remark that the origin of salt anomalies is not fully-understood, and the problem of their genesis is far more complicated than this discussion. The suggestion here is merely to
provide a possible explanation for one of the problems in potash mining.

9.2.3 Primary Potash Mineralogy

There seems to be a consensus, from geochemical parameters, that sylvite is not expected from primary precipitation of seawater unless sulphate is removed (Stewart, 1963; Braitsch, 1971; Holser, 1979). Ironically, sylvite is perhaps the most common mineral in many potash deposits considered "marine". This has led to several attempts to explain sulphate removal prior to sylvite deposition, and the formation of sylvite after carnallite by secondary processes. To remove sulphate from the brine, Garrett (1970) suggested precipitation of magnesium and sodium sulphates (mirabilite and epsomite), while Braitsch (1971) suggested biological activity. Hite (1985), on the other hand, believed that sulphate was removed from the brine by reaction with calcium ions released from dolomitization or polyhalitization.

All of these mechanisms are tied firmly to deposition of evaporites in a perennial subaqueous setting which is not the case for the Prairie Evaporite Formation (and perhaps many others). As has been shown in the proposed model, the deposition of the Prairie Evaporite Formation took place in coastal to pericontinental environments, prone to periodic desiccation. Under such conditions, the parent brines could hardly be entirely marine. Surface runoff and groundwater must have been significant and must be taken into account. Phase diagrams on the evaporation path of seawater exclusively are, therefore, probably not applicable.

Another major factor is the role of syndepositional or very early diagenetic processes. Because of the ephemeral nature of the Prairie Evaporite sedimentation, the salt surface was subject to countless events of subaerial exposure, reworking, dissolution, and re-precipitation which led to repeated modification of the brine chemistry. Hardie (1984) indicated that dissolution of carnallite-kieserite-halite crust in salt pans would produce a new brine that, on evaporation at 25 to 40°C, should
precipitate bloedite, leonite or sylvite along with halite, depending on the original ratio of the salts.

This study strongly supports the early precipitation of sylvite. Its relationship with the zoned halite, and its occurrence as fillings in dissolution pits and pipes preclude its precipitation through secondary processes. However, this is not to argue that most of the sylvite at present is syndepositional. Rather, it argues for the existence of the "primary" sylvite in the depositional environment of the mixed brines. The different sources of the brine during potash deposition are indicated by the insolubles in the Leofnard Member (dolomite, anhydrite, clays) which are very different from those in the Whitkow Member (mostly anhydrite).

Carnallite does not have the same geochemical constraints as sylvite. Examination of cores confirms the fact that syndepositional carnallite exists locally (see Fig. 2.10). Nevertheless, like sylvite, most is secondary as it commonly occurs in interstices of the recrystallized halite.

In conclusion, this study indicates that both sylvite and carnallite in the Prairie Evaporite Formation were formed in the depositional environment, that is to say syndepositionally. They were subsequently modified by secondary processes to their present lithology.
REFERENCES


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Shearman, D.J., 1985, Syndepositional and late diagenetic alteration of primary gypsum to anhydrite: Sixth International Symposium on Salts, v.1, The Salt Institute, p.41-50.


APPENDICES
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<th>WELL</th>
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Table I A complete list of the cored wells. The italics refer to the abbreviated names used in the text.
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Table II A complete list of the wells with only geophysical logs.
Figure 1.5 Cross-section of the Prairie Duplexite Formation along line A-A'. The datum is the contact between the formation and the Lower Red Bed Member of the Dawson Bay Formation.
Figure 1.6 Cross-section of the Prairie Evaporite Formation along line B-B'. The datum is the contact between the formation and the Lower Red Bed Member of the Dawson Bay Formation.
Figure 1.7 Cross section of the Prairie Evaporite Formation along line C-C'. The datum is the contact between the formation and the Lower Red Bed Member of the Dawson Bay Formation.