THE UNIVERSITY OF MANITOBA

DEPOSITION AND DIAGENESIS
OF THE SALTER MEMBER,
LOWER MOUNT HEAD FORMATION, SOUTHWEST ALBERTA

by

Arthur Guy Masson

A thesis

Submitted to the Faculty of Graduate Studies

in partial fulfillment of the requirements for the degree

of

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ABSTRACT

The lowermost Mount Head Formation, well exposed in the easternmost Front Ranges of the southwestern Canadian Rockies, consists of a series of shallow subtidal, intertidal, and supratidal carbonate units. Detailed studies at Plateau Mountain and Mount Head indicate depositional facies ranging from thick bedded, relatively mud-free, shallow subtidal echinoderm-bryozoa packstones and grainstones through thin bedded, finely crystalline subtidal to supratidal dolomites. Conspicuous solution breccias and a number of thin carbonate-evaporite sabkha cycles are evident in the Salter Member of the formation.

Except for the supratidal deposits, the sequence contains few fabrics indicative of significant periods of subaerial exposure. The best evidence consists of a few sharp erosion surfaces, thin but laterally persistent horizons of small, irregular solution vugs, and cavities with internal vadose(?) silt. Early cementation, most obvious in the coarser grained facies, is characterized by drusy rims of equant sparry calcite and large, probably penecontemporaneous, syntaxial overgrowths. However, skeletal grains enclosed by a micritic matrix generally do not exhibit these early cements. In point of fact, this matrix, as well as horizons interpreted to have originally been primarily mudstone, has to a large extent been selectively dolomitized. Later, ferroan and non-ferroan blocky spar occludes much of the remaining pore space, but intercrystalline porosity (in the dolomitic horizons), some intraparticle space, irregular and moldic secondary vugs, and open fractures remain.

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CHAPTER 1

INTRODUCTION

Introduction

The purpose of this study is twofold. From detailed sampling of the Salter Member of the Mount Head Formation at two localities, one at Highwood River and the other at Plateau Mountain (see Figures 1 and 2), and from subsequent study of hand specimens and thin sections, this work 1) outlines the stratigraphic setting and depositional history of this Upper Mississippian Member in the study area, and 2) develops a paragenetic sequence of the diagenetic features and events that have occurred since deposition of this Member.

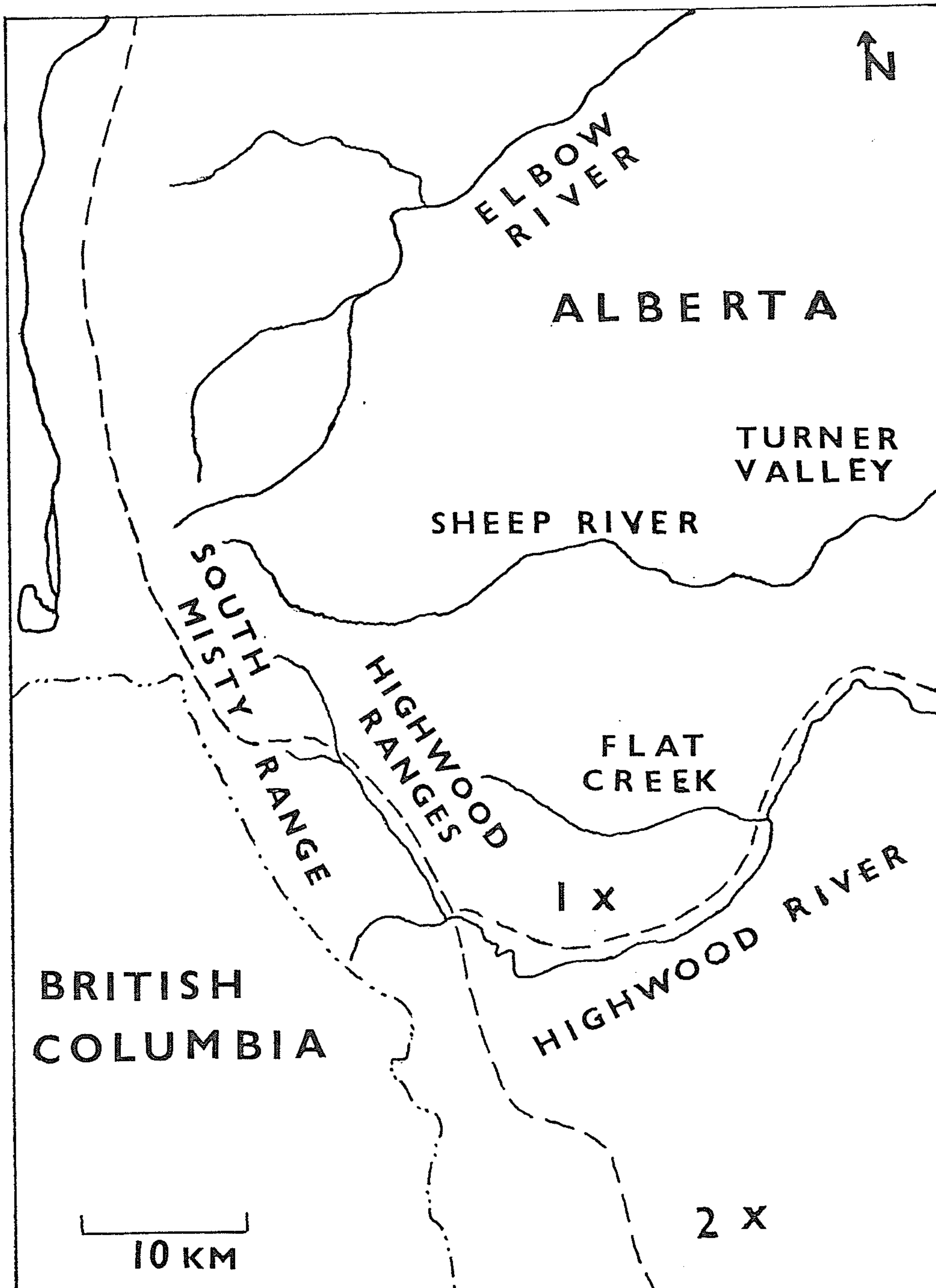
Regional geologic setting of the Mississippian, southwestern Canadian Rocky Mountains

The southern Rocky Mountains and Foothills form part of the Eastern Cordilleran Fold Belt (Wheeler, 1970), a northwesterly-trending succession of folded and thrusted rocks which borders the Interior Platform and extends from Montana, U.S.A. to the Yukon Territory of northern Canada. The Front Ranges of the southern Rocky Mountains consist of a series of west-dipping, subparallel fault slices bounded by gently-dipping thrust faults which place relatively competent Cambrian, Devonian, and Mississippian carbonate rocks over relatively incompetent Triassic, Jurassic, or Cretaceous clastic rocks. Folds are generally broad and open in Paleozoic rocks and are usually *en echelon* (more conspicuously imbricated), as are the thrusts (Price and Mountjoy, 1970; Bally et al., 1966).

Mesozoic sandstones and shales of the Foothills Belt have been deformed competently but at a scale that is at least an order of magnitude less than that of Paleozoic rocks of the Eastern Ranges of the Rocky Mountains; crumpling and minor thrusting is common. Structural

FIGURE 1

LOCATION OF MEASURED SECTIONS



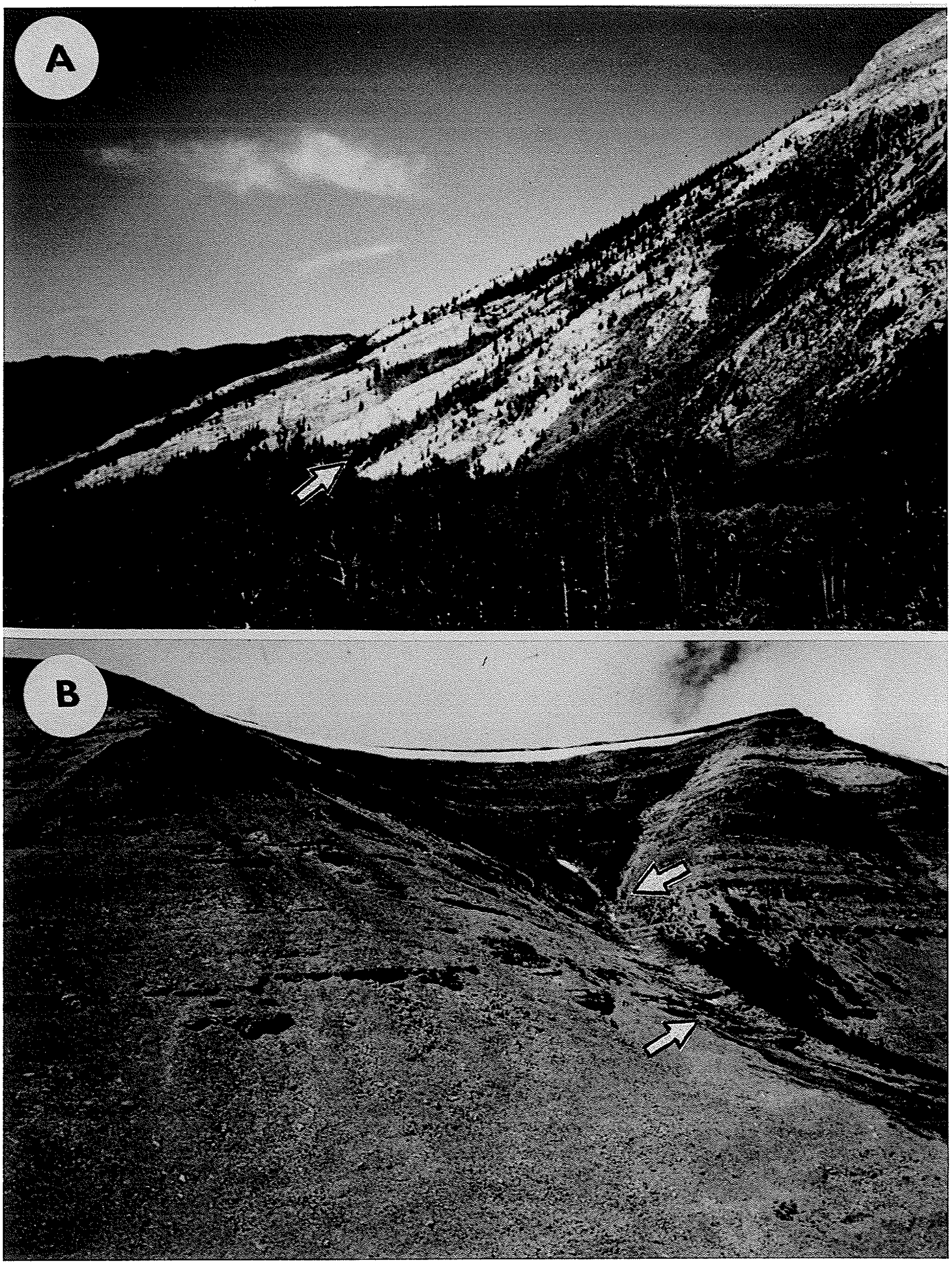
LEGEND --- FORESTRY ROAD
1_HIGHWOOD RIVER SECTION
2_PLATEAU MT SECTION

FIGURE 2

FIELD PHOTOGRAPHS OF MEASURED SECTIONS

2A. Highwood River Section: position of Salter Member, largely recessive.

2B. Plateau Mountain Section: base and top of Salter Member indicated by arrows.


A
B

culminations which expose Upper Paleozoic rocks are present locally, although the Foothills belt is dominated by the Mesozoic clastic rocks.

Regional stratigraphy, facies relationships, and sedimentology of the Mississippian, southwestern Alberta

Two widespread carbonate units characterize the Mississippian succession of southwestern Alberta: a lower, argillaceous, recessive unit [the Exshaw Formation (Warren, 1927), and the Banff Formation (Shimer, 1926)] and an upper, relatively resistant unit [the Rundle Group (Douglas, 1953, 1958)]. Table 1 illustrates these units and their regional stratigraphical subdivisions. Two laterally gradational facies belts, informally termed the eastern and western facies by Macqueen and Bamber (1967), occur within the lower part of the Banff-Rundle succession.

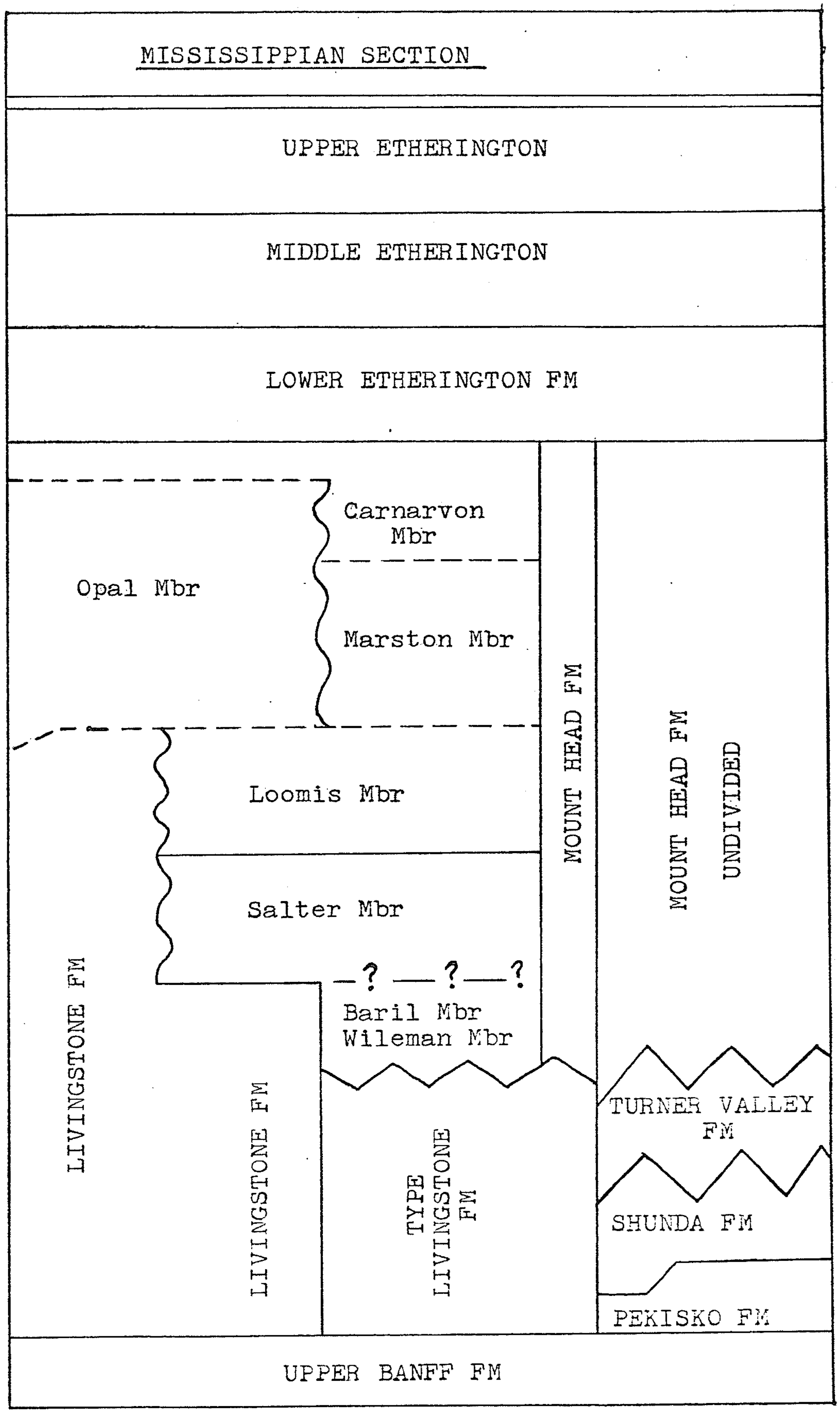
The eastern facies includes the Banff Formation and the lower Rundle Group of both the southern Alberta subsurface and the Banff-Jasper area of the Rocky Mountain Foothills and Front Ranges (Macqueen and Bamber, 1967). Included in the lower Rundle of the eastern facies are the Pekisko and Turner Valley Formations (dominantly echinoderm limestones and their dolomitized equivalents) and the intervening Shunda Formation (dominantly micritic limestone, micro to very fine crystalline dolomite, and local solution breccias or anhydrite-dolomite assemblages in the subsurface). Within the lower Rundle the western facies includes the Banff Formation and the Livingstone Formation (Table 1). The Livingstone Formation, which is widely distributed in the Rocky Mountain Front Ranges of southwestern Alberta, is composed dominantly of echinoderm limestones and their dolomitized equivalents.

TABLE 1

MISSISSIPPIAN STRATIGRAPHY,

SOUTHWESTERN ALBERTA

(Modified after Macqueen and Bamber, 1972)


MISSISSIPPIAN SECTION
UPPER ETHERINGTON
MIDDLE ETHERINGTON
LOWER ETHERINGTON FM
Carnarvon Mbr
Opal Mbr
Marston Mbr
MOUNT HEAD FM
MOUNT HEAD FM UNDIVIDED
Loomis Mbr
Salter Mbr
? ? ?
Baril Mbr
Wileman Mbr
LIVINGSTONE FM
LIVINGSTONE FM
TYPE LIVINGSTONE FM
TURNER VALLEY FM
SHUNDA FM
PEKISKO FM
UPPER BANFF FM

Overlying the Livingstone and its equivalents, in the upper part of the Rundle Group, are the Mount Head Formation and the Etherington Formation, named by Douglas (1953, 1958). The widespread Upper Mississippian Mount Head Formation (Rundle Group), which was further subdivided into six members by Douglas (1958), exhibits a complex sequence of regional facies changes (Macqueen and Bamber, 1968). It consists of approximately 150 to 300 meters of limestones and dolomites, with local shales, sandstones, siltstones (all of shallow marine origin), and of solution breccias. In the Front Ranges the formation contains six Members (Table 1) -- the Wileman, Baril, Salter, Loomis, Marston, and Carnarvon (Douglas, 1958) -- which are clearly recognizable from the southern Livingstone Range near Crowsnest Pass to the eastern Fairholme Range in the Bow Valley, north of which they lose their distinctive character (Macqueen and Bamber, 1968).

The nonskeletal limestone, solution breccia, and dolomite of the lower four Members, which accumulated in shallow shoals, lagoons, and supratidal sabkhas, change facies westward into skeletal limestones of the Livingstone Formation which were derived from widespread echinoderm-bryozoan shoals (Macqueen and Bamber, 1968). This facies change begins with the Wileman and Baril members to the east and advances westward through the overlying Salter and Loomis members. The overlying Marston and Carnarvon members, which originated in lagoons and sabkhas (Macqueen and Bamber, 1968) and are composed of dolomites and micritic limestones, pass westward into the barrier shoal, open marine skeletal, micritic limestones, and calcareous shales of the Opal Member. Only the upper part of the Carnarvon Member extends to the west, where it overlies the Opal and represents a return to widespread lagoonal conditions. The stratigraphic distribution of four assemblages of corals and brachiopods supports the correlations across these facies changes (Macqueen and Bamber, 1968).

The overlying Etherington Formation strata have been studied by Scott (1964), who recognized an eastern dolomite-shale facies in the Front Range of the Rocky Mountains south of the Bow Valley and to the west a limestone facies. The microfaunal succession of the Etherington has been outlined by Mamet (1968).

Previous work: Mount Head Formation and Salter Member

McConnell (1887) applied the names "Lower Banff Shales" and "Upper Banff Limestones" to the southwestern Alberta Mississippian carbonate rocks consisting of a lower, argillaceous, recessive unit and an upper resistant unit. Kindle (1924) named these units the Banff and Rundle formations respectively but did not describe them. Warren (1927) first described the type section of these units located on the north end of Mount Rundle. A supplementary description of the more completely exposed section along the base of Tunnel Mountain near Banff townsite was provided by Beales (1950).

Douglas's (1953, 1958) subdivision of the Rundle Formation was the first one to gain wide acceptance. From his work in the southern Foothills and Front Ranges, including the Mount Head map area (Figure 1), Douglas raised the Rundle to group status and named three new formations within it: Livingstone, Mount Head, and Etherington (Table 1). Douglas also subdivided the Mount Head Formation into the Wileman, Baril, Salter, Loomis, Marston, and Carnarvon members, in ascending order (Table 1).

The Wileman, Salter, and Marston are generally recessive and composed of yellowish-brown weathering dolomite, while the contrasting Baril, Loomis, and Carnarvon members are resistant and composed of grey weathering limestone. Type sections of these members can be observed along the Highwood River Valley, but facies changes to the north and the west of the Mount Head area greatly complicate regional recognition and correlation of the Mount Head strata away from the type sections (Douglas and Harker, 1958).

Macqueen and Bamber (1968) studied the stratigraphy and the facies relationships of the Upper Mississippian Mount Head Formation in the Rocky Mountains and Foothills of southwestern Alberta. They gave a clearer picture of the regional lithologic and faunal relationships and sedimentary environments of the Mount Head Formation, as well as clarifying the stratigraphy and depositional history of this widespread Upper Mississippian shallow marine sequence in the Rocky Mountain Foothills and Front Ranges between Crowsnest Pass and Clearwater River. In addition, they proposed a new unit within the Mount Head Formation, the Opal Member.

In their study of the Mount Head Formation, Macqueen and Bamber (1968) came to the following general conclusions:

1) All six Members of the type Mount Head Formation are clearly recognizable in a narrow belt of the Rocky Mountain Front Ranges from the southern Livingstone Range near Crowsnest Pass to the eastern Fairholme Range in the Bow Valley. Most of the members lose their distinctive character north of the Bow Valley and cannot be recognized north of the Red Deer River.

2) The lower four members of the Mount Head (Table 1), which are characterized by nonskeletal limestone, solution breccia, and dolomite,

change facies westward into the echinoderm-bryozoan limestone of the Livingstone Formation, beginning with the Wileman and Baril to the east and progressing upward through the Salter and Loomis to the west. A facies change occurs also within the upper Mount Head, where the micritic limestones and dolomites of the Marston and lower and middle Carnarvon pass westward into the skeletal limestones, argillaceous micritic limestones, and calcareous shales of the Opal Member.

3) The fauna of the Mount Head Formation contains four assemblages of Meramecian brachiopods and corals, which maintain their relative stratigraphic positions throughout the area studied and provide supporting evidence for correlations across the major facies changes previously mentioned.

4) The lower four members of the Mount Head are products of sediments accumulated in shoals, tidal flats, and shallow lagoons, which were periodically replaced by supratidal sabkhas. These evaporitic and shallow marine environments were bordered on the west by echinoderm-bryozoan shoals from which the skeletal sands of the upper Livingstone were derived. In the east during sedimentation of the Marston and lower and middle Carnarvon members, shallow marine and supratidal environments persisted (Macqueen and Bamber, 1968). To the west the Opal was deposited under barrier shoal and open marine conditions, marked by periodic influx of terrigenous clastics. This pattern of sedimentation within the upper Mount Head was followed by a return to widespread lagoonal conditions over most of the area, resulting in deposition of the micritic limestones of the upper Carnarvon.

The Salter Member

The type section of the Salter Member located in the Highwood River Valley is a 29 meters-thick recessive interval, easily recognized by the presence of distinctive yellowish-orange weathering solution breccia occurring both in outcrop and as talus boulders. This Highwood River Valley Salter Member type section is one of the two sections sampled as part of the present research. The second section studied is at Plateau Mountain and is readily accessible and provides good exposure. It is 57 meters thick.

The Salter covers a considerably greater area than the Wileman and Baril members and ranges in thickness from 29 meters at Highwood River to 67 meters at South Misty Range. In general, the Salter is thicker where it is underlain directly by the Livingstone Formation than where it is underlain by the Baril Member (Macqueen and Bamber, 1968).

The Salter forms a distinctive recessive interval and shows a greater lithic variation than any other member of the Mount Head Formation. To the east the Salter consists mainly of thin to thick bedded, finely laminated, and partly cross-bedded, partly calcareous, silty, or finely sandy microdolomite, closely similar to the Wileman. Some beds show nodules and regular stringers of chert. Others are argillaceous and grade locally to dolomitic shale (Macqueen and Bamber, 1968).

The eastern sections of the Salter have very few fossils and contain only colonial corals. Toward the west fossils become more abundant and diverse as various types of limestone appear within the Salter. In sections where it is directly underlain by the Livingstone, the Salter contains a variety of horn corals, colonial corals, and brachiopods. The Salter shows an increase in abundance of limestone and consists of recessive, finely crystalline, cherty, calcareous micritic dolomite and skeletal or oolitic limestone, commonly dolomitic. The westward increase in limestone content is accompanied by a change from micritic, skeletal-micritic, or oolitic limestones in the most easterly sections, through oolitic and echinoderm-bryozoan limestone, to dominantly echinoderm-bryozoan limestone in the most westerly sections (Macqueen and Bamber, 1968).

At the Highwood River section thin micritic limestone beds occur in the lower part of the member, and in the upper part thin discontinuous beds of solution breccia are observed, indicating the former presence of anhydrite. At the Plateau Mountain section the upper part of the Salter contains at least four cycles, ranging in thickness from 1.5 to 5 meters. Each cycle begins with a dark yellowish-brown, silty, and finely sandy micritic dolomite unit with fine cross-laminations; grades upward into microcrystalline, silty, very pale orange micritic dolomite; and culminates with sollution breccia consisting of angular microdolomite and chert fragments set in a vuggy, coarsely crystalline calcite matrix (Macqueen and Bamber, 1968).

The Baril Member, underlying the Salter Member, is commonly thick to very thick bedded and is expressed as a resistant, light grey rib between the recessive yellowish-brown weathering Wileman and Salter members. Oolitic, micritic and skeletal limestones are the dominant rock types, with regional variations produced by differences in the proportion of these limestone types. The contact between the Salter and the Baril is generally sharp and locally unconformable (Macqueen and Bamber, 1968).

The thick, resistant, limestone Loomis Member overlies the Salter. It somewhat resembles the Baril but stands out in greater relief because of its more massive character and greater thickness. It is essentially composed of thick bedded, resistant, light grey weathering, partly chert containing limestone. It contains beds of coarse to very coarse grained, echinoderm-bryozoan limestone. Oolitic limestone dominates the Loomis in the Highwood Range. In contrast with the underlying Salter, the Loomis has an abundant coral fauna. The contact with the Salter is sharp and probably conformable (Macqueen and Bamber, 1968).

Methods of study

The Salter Member was sampled in detail at two measured sections in the Mount Head map area: the type section of Highwood River Valley (29.3 meters, Figure 2A), and the Plateau Mountain section (57 meters, Figure 2B). Sampling was done on the basis of textural and lithological changes of the rocks. A total of 68 samples were collected, 26 of them from Highwood River and 42 from Plateau Mountain.

Standard-sized thin sections were made from each hand specimen and examined petrographically with respect to composition, textures, faunal elements, and sedimentologic and diagenetic features. Calcite was distinguished from dolomite by two methods: by staining with a diluted HCl solution of Alizarin red-S, as described by Dickson (1966); and by X-ray diffraction analysis of the microcrystalline fraction of 15 samples. Rocks were classified following Dunham (1962) with the addition of qualifiers to discriminate between slightly different lithofacies.

Sedimentary structures, textures, and faunas were also examined on acetate peels made for each of the 68 samples collected. The surfaces of several hand samples were polished and etched with diluted HCl to accentuate structures and compositional differences.

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CHAPTER 2

LITHOFACIES AND DEPOSITION ENVIRONMENTS OF THE SALTER MEMBER

Introduction

The study made from the hand samples and thin sections of the two measured Salter Member sections has shown that six different lithofacies are present within this Member. These facies have been named following Dunham's classification with the addition of qualifiers where necessary. These facies are listed in order of decreasing abundance in Table 2. The vertical sequence and relationships between these various lithofacies will be discussed in Chapter 3.

A close look at Table 2 reveals that most of the Salter Member is composed of calcareous to dolomitic mudstone-wackestone with varying amounts of other components. Although the general composition does not generally show great diversity, the texture, fabric, and assemblages present in each facies are sufficiently variable to justify the division of facies made.

Because of great similarities in composition and occurrence of similar features in several facies, some difficulties were encountered in trying to delineate unique and specific environments of deposition for each facies. It was found more useful and realistic to interpret each facies as belonging to a range of deposition environment (for example, low intertidal to high intertidal).

Dolomitic, Argillaceous, Mudstone-Wackestone Facies

Description

Generally the rocks of these facies are all highly dolomitic (up to 30%). Angular to subrounded silt size detrital quartz and locally dark brownish-grey clay material are also characteristic of this facies.

This facies is thin (0.5 m) to thick bedded (up to 9 m but with

TABLE-2 Lithofacies Nomenclature

Lithofacies	Highwood River Thickness		Plateau Mountain Thickness	
	Feet	Meters	Feet	Meters
Dolomitic, argillaceous, mudstone – wackestone	53	16.2	65.5	20.0
Dolomitic, quartz bearing, mudstone – wackestone	19	5.8	38.0	11.6
Evaporite solution breccia	15	4.6	13.0	4.0
Skeletal packstone to grainstone	2	0.6	18.0	5.5
Pelleted, skeletal bearing, dolomitic, mudstone – wackestone	9	2.7	6.0	1.8
Quartz siltstone	-	-	3.5	1.1

breaks) in outcrops. Flaggy weathering is generally observed on outcrops and fresh surfaces are medium to dark grey, while weathering surfaces are light grey to light orange-brown. At the two type sections, this facies generally occurs interbedded with the dolomitic, quartz-bearing, mudstone-wackestone facies and with the evaporite solution collapse breccia facies.

Laminations observable in outcrops and hand specimens range from very fine and continuous (less than 1 mm thick), to more or less well defined (a few millimeters in thickness), to being totally absent. A concentration of silt size detrital quartz fragments and silty argillaceous material, as well as horizontal iron oxide staining, accentuates the fine laminations in some samples. Occasional very fine cross-bedding and local very fine scour surfaces are also present.

The well-defined laminations are generally observed in three main forms:

1) Alternations of argillaceous material and carbonate minerals. Quartz silt and clay-rich layers grade upward into carbonate-rich layers. The carbonate-rich layers consist of dolomite crystals and sparry calcite. These laminations are 1 mm thick. An intricate, complex network of vertical microfractures cuts these cycles locally (Figure 3B).

2) Laminations consisting of alternating calcitic and dolomitic laminae. The calcite layers are thinner and they are interbedded with dolomitic thicker laminations. These cycles, although they appear to be consistently horizontal, are generally poorly defined due to dolomitization and/or recrystallization.

3) Very irregular, patchy, discontinuous horizons of subrounded oxidation spots (a few millimeters in diameter) of iron-rich black opaque

material composition.

Crystallinity in matrix ranges from fine to very fine and is well sorted (Figure 3B). Three to 10% subangular to subrounded detrital silty quartz fragments are present. The original rock is believed to have been basically calcareous mudstone that was dolomitized later on.

Pellets and pelletoids are very minor and extremely faint. Present locally are elongated and flattened (a few millimeters in length), irregular and subrounded burrows filled by microcrystalline chert, as well as a few micritic lumps filled by chert and fine grain dolomite rhombs. A few brachiopod fragments (2.5 to 0.1 mm) and 2 to 5% siliceous sponge spicule fragments (2.5 to 0.15 mm) replaced by very fine grained calcite crystals are found locally in the Highwood River section.

Euhedral to subhedral dolomite rhombs (less than 0.03 mm in diameter) compose up to 30% of the samples generally. Fifteen to 25% of all samples are composed of dolomite rhombs coarser than 0.03 mm which occur in a poorly sorted fashion in the finer grained matrix. X-ray results show that the matrix is largely dolomitic.

Porosity is less than 3% and is mainly intercrystalline in nature. Minor vug and fracture porosity is also present. Vugs vary in shape from "birdseye-like" to irregular (Figure 3C) and in size from a few millimeters to one or two centimeters in diameter. A few vugs are partially filled by equant calcite cement (Figure 3C) and iron oxides.

The presence of a great variety of microfractures is an important aspect of this facies. Intricate, irregular, complex networks as well as individual occurrences of horizontal, oblique, and vertical microfractures (Figure 3B) are found throughout this facies. Some of these microfractures are entirely or partially filled by very fine to microcrystalline calcite (Figure 3B) and/or microcrystalline chert. En echelon irregular and unfilled vertical fractures, irregular channel fracturing (1.5 to 0.5 mm wide) partially filled by microcrystalline chert, as well as vertical microfractures (less than 0.5 mm wide) filled by iron staining products and fine grain hematite grains are found locally as clusters or individually in this unit.

Cement is predominantly calcite and averages less than 15% of the total rock. It occurs essentially filling microfractures, nodules, and vugs as crystals ranging in size from 0.7 to 0.04 mm (Figure 3C) and as microcrystalline crystals in the muddy matrix. Iron oxide (hematite) also occurs as a cement.

Chert occurs extensively (10 to 50%) in some beds in various forms and shapes (Figure 3A). Dark brown to black elongated chert nodules (12 mm in length) strung out along bedding planes and lenses of black chert are common in some beds, particularly at Highwood River. Small subrounded (3 cm to 10 mm in diameter) white chert nodules, irregular greyish chert nodules, and microcrystalline quartz occurring as a mud replacement and filling in vugs and fractures (2.5 to 0.35 mm wide) are the other main forms of chert. Occasional radiating chalcedony and chert nodules (2 to 3 cm in diameter) are also found (Figure 3A).

In some locations at Highwood River, silica almost totally replaces the mud, leaving only the dolomite rhombs unreplaced. Silica also occurs as a filling of intercrystalline, interparticle, moldic, vug, and fine channel-type voids.

Various products of staining by iron oxides are an important aspect of this facies. Hematite grains (0.1 to 0.03 mm) are generally less than 2% but compose up to 5% of the samples in some Plateau Mountain localities. Blackish-red oxide material halos surrounding calcite-filled vugs and subrounded hematitic oxidation spots (1.5 to 0.5 mm in diameter) are also present at Plateau Mountain.

Interpretation

Several authors have reported modern analogs to what is believed to be the environment of deposition of this facies. Shinn (1973) reports muddy supratidal sediments in an area of longshore transport, northeast Qatar of the Persian Gulf. These sediments occur in flats up to 5 km in width and 10 km in length and have a thickness of up to 50 cm. They occur above normal high tide but within the range of spring and storm tides in a low-energy tidal area termed "coastal sabkhas." In many parts the surface material has been blown away and the underlying intertidal sediments are present beneath a salt or gypsum crust 2 to 3 cm thick; however, in other areas it is impossible to distinguish intertidal from supratidal sediments. Lags of skeletal sand 2 to 3 cm thick deposited during flooding tides are common. The muds are locally pellet-rich and are characterized by supratidal laminations, birdseye vugs, mud cracks, oxidized color, numerous iron-stained root tubes and burrows, and 10 to 20% dolomite.

Intertidal-supratidal shallow water pond sediments have been described by Shinn et al. (1969). These storm-deposited, laminated sediments contain the softest and finest grained sediments in the entire tidal-flat complex. These ponds contain only minor skeletal fragments and large quantities of siliceous or non-siliceous sponge spicules originating from an adjacent restricted platform.

Dolomitic laminated mudstone with irregular and discontinuous laminations, mud cracks, birdseye texture, scarce to very scarce fossil fragment content, burrows, and thin sandy beds from supratidal sediments of several localities of modern evaporite-carbonate shoreline sedimentation have also been reviwed by Lucia (1972).

In addition to the modern analogs, similarities in environments can be drawn from several studies made on ancient environments. Macqueen and Bamber (1967) have assigned in their description of the Mount Head Formation some occurrences of microcrystalline to very fine argillaceous dolomite as being related to restricted lagoons belonging to supratidal sabkha environments. Mamet (1977) has shown that intertidal and supratidal environments from Mississippian carbonates of the Canadian Cordillera have the following main characteristics: irregularly laminated microcrystalline dolomite, well-developed light grey and/or brown sedimentary laminations cycles, chert and calcite pseudomorphs after anhydrite and/or gypsum, mud cracks and scarcity of fossils. Armstrong (1973) has described intertidal-supratidal sediments characterized by dolomitization and dedolomitization features but showing birdseye structures, calcite and chert pseudomorphs after gypsum, cherts filling molds of algal filaments, worm burrows, and desiccation cracks, as well as pellet and mud laminae mechanically deposited by sheet flooding. McLemore (1972), Mazzullo and Friedman (1975), Schenk (1967), Friedman and Braun (1973), and Laporte (1973) have described similar intertidal-supratidal environments.

This writer believes that the following characteristics observed in the facies described here are characteristic of sediments deposited in the very shallow subtidal to low supratidal zones. Evidence for very shallow subtidal to intertidal environments includes the presence of minor skeletal debris, minor burrowing, localized pellet content, and presence in most rocks of clay minerals and detrital quartz silt, irregular and variable laminations, inorganic origin of most primary sedimentary structures still present, and extensive oxidation and iron products. Evidence for low supratidal environment includes high dolomite content in laminations and thin bedding, presence of detrital quartz silt, presence of irregular and variable vugs, and microfracturing.

The fine to very fine laminations and the fine cross-beds observed in some of the more silty rocks probably indicate transportation of carbonate sediments as debris over the tidal flats. The fine scour surfaces indicate active erosion by flood waters, along or in tidal channels.

Dolomitic, Quartz-bearing, Mudstone-Wackestone Facies

Description

This facies is predominantly dolomitic but contains variable amounts (10 to 45%) of subangular to subrounded detrital quartz silt and sand.

It occurs as thin to medium thick beds (0.5 to 4 m) which are generally weathered in outcrop. Coloration of fresh surfaces ranges from medium grey to medium light grey, while weathered surfaces are generally light grey to medium light brown. This facies generally occurs interbedded with the dolomitic, argillaceous, mudstone-wackestone facies and is overlain at several locations by the skeletal packstone to grainstone facies.

The facies contains abundant subangular to subrounded detrital quartz silt and sand (Figure 3F) and minor amounts (1 to 2%) of fine granular, randomly scattered, brownish-dark-red pyrite crystals. These grains occur in a dolomitic mud matrix. The matrix is very fine to fine crystalline (Figure 3E).

Laminations are present throughout most of this facies. Most are less than 1 mm in thickness and vary from extremely faint to well delineated (Figure 3E) and from plane parallel to locally undulating and discontinuous (Figure 3D). The well-defined laminations are the result of either variations in size and amount of dolomite crystals or differences in relative amount of detrital quartz grains and dolomite rhombs (Figure 3F). Other, often discontinuous, laminations are composed of dark grey organic-looking material (Figure 3D). Locally abundant very fine cross-beds are present (Figure 3E). These cross-beds and related minor scour surfaces, however, are in most cases faint and poorly defined and are not a major feature of this facies.

Pellets and pelloids are present locally in minor amounts and range from very well defined to extremely faint. Subspherical to spherical, 1 to 2 mm, black spheres of organic material and numerous rounded to elongated intraclasts of pale brown dolomitic mud (Figure 3E) are present but in only minor percentages. These clasts are associated with the best development of laminations and cross-beds (Figure 3E).

Extensive bioturbation has occurred in portions of this facies (Figure 3D). The burrows are irregular, predominantly vertically oriented, and filled by dolomitic micrite. Notably the detrital quartz and coarser dolomite rhombs observed in the matrix are not present in the burrow infill.

Dolomite is secondary and occurs as subhedral to euhedral rhombs, ranging in size from 0.2 to 0.002 mm. Dolomite rhombs coarser than 0.02 compose up to 30% of some samples, but the total dolomite percentage is much higher (close to 50%).

Porosity ranges from 3 to 10% and is mostly intercrystalline because of the high degree of dolomitization. There is also some minor porosity in the form of vugs and microfractures. Vugs are numerous and of irregular outline, ranging in diameter from 2.5 to 0.25 mm. Most, however, have been totally to partially filled by fine-crystalline sparry calcite (Figure 3C). This facies generally shows irregular fine vertical microfracturing partially to entirely filled by fine grain calcite sediment (0.5 to 0.1 mm) and by very finely crystalline calcite (less than 0.05 mm).

Visible cement ranges from 5 to 15% and is essentially microcrystalline dolomite and calcite, as well as minor amounts of fine grain sparry calcite filling vugs and microfractures.

Isolated grey-brown chert nodules, light grey-buff nodular chert horizons (up to 0.25 m thick), thin chert stringers 1 to 10 cm thick, and chert nodules concentrated locally along bedding planes, are present in parts of the facies. Minor iron staining is present throughout.

Interpretation

The modern and ancient environment analogs mentioned for the interpretation of the dolomitic, argillaceous, mudstone-wackestone facies as well as the comments made for the previous facies (except for the presence of quartz) can also be applied to the interpretation of this facies. Thus, the general interpretation for the dolomitic, quartz-bearing, mudstone-wackestone facies ranges from a shallow subtidal to a high intertidal-low supratidal environment.

The high detrital quartz content may have been introduced by longshore currents or by eolian transport. The occurrence of bioturbation related to vertical burrows is indicative of organisms living in very shallow subtidal to high intertidal regions (Heckel, 1972; Thompson, 1970; Mazzullo and Friedman, 1975).

Evaporite Solution Breccia Facies

Description

Although this facies is composed mainly of fragments of material from the dolomitic, argillaceous, mudstone-wackestone facies, it was decided to establish it as a specific facies because of its unique characteristics and origin. The facies differ greatly in appearance at the two sections studied. At Highwood River the facies is highly brecciated (Figure 4E); at the Plateau Mountain section the facies consists of irregular and angular fragments and very finely laminated varve-like couplets (Figure 4A).

This facies is generally recessive at the various outcrops and rocks are generally pale orange to brownish-grey on fresh surfaces, while they range from light grey to light brownish-grey on weathered surfaces. Generally speaking, in the vertical sequence at both sections this facies occurs interbedded with the dolomitic, argillaceous, mudstone-wackestone facies and is overlain at a few locations by pelleted, skeletal-bearing, dolomitic, mudstone-wackestone facies outcrops.

At Highwood River this facies is confined to a 3 meters-thick interval near the top of the section. The outcrop is medium bedded with at least four solution collapse horizons, the thickest being 20 cm and the thinnest 5 cm. These horizons are interbedded with vaguely laminated argillaceous, dolomitic mudstone horizons (Figure 4E). The breccia horizons show a vague gradation with the larger, more angular fragments at the bottom and the finer material at the top (Figure 4E).

At Plateau Mountain the middle and upper parts of the Salter contain at least five cycles, ranging in thickness from 0.5 to 2 m. Each cycle begins with a dark yellowish-brown, silty and fine dolomitic, quartz-bearing mudstone unit with fine local cross-laminations; grades upward into very pale orange fine dolomitic, argillaceous mudstone; and terminates with solution breccia consisting of angular dolomitic, argillaceous mudstone and chert fragments set in a vuggy, coarsely crystalline calcite matrix (Figure 4A). The fragments are composed of microcrystalline dolomitic mudstone with 5 to 25% detrital quartz silt and sand and/or 5 to 10% clay. The breccia fabric ranges from very coarse angular fragments (Figure 4F) to fine elongated fractures in the less brecciated samples (Figure 4B). The fragments grade upward from 3 to 15 cm at the bottom of the sequence to a few millimeters at the top of it.

These couplets at Plateau Mountain are alternations of two different sizes of calcite crystals (Figure 4D), the finer size ranging from 0.07 to 0.05 mm and the coarser one being composed of crystals greater than 0.1 mm. The coarser laminations are approximately twice as thick (1 to 2 mm) as the finer grain laminations.

Dolomite in this facies is secondary in origin, is generally less than 0.06 mm in diameter, and generally constitutes 20 to 30% of the original rock.

Porosity varies from 10 to 30% at both sections and is the result of leaching and brecciation. Good interfragmental, vuggy (Figure 4B), fracture and channel porosities, as well as intercrystalline (Figure 4C) and fenestral porosities in less brecciated portions, are present. Horizontal and vertical fractures are very extensive and link together the majority of the vugs. Most fractures, however, are partially to totally filled by fine grain calcite (Figure 4C).

Vugs are extremely variable in size and shape (Figures 4B, 4C): subspherical, birdseye, irregular-shaped vugs and cavities ranging in size from a few millimeters to several centimeters are found in almost every outcrop of this unit. Most vugs and cavities are partially to entirely filled by fine crystalline calcite cement (Figures 4B, 4C), but a great number of the cavities, especially those greater than 2.5 cm in diameter, remain at least partially open (Figure 4B). Several vugs are filled by chert and/or hematite.

Cement is essentially very fine to fine equant calcite crystals as filling in vugs and fractures (Figures 4C, 4D).

Chert is generally minor. At Plateau Mountain there are rosette-like chert nodules of chalcedony composition (Figures 4D, 9B).

Interpretation

Shearman (1963) has observed anhydrite from a modern tidal-flat environment (Trucial Coast, Persian Gulf) which occurs mainly as nodules. This nodular anhydrite forms in the sediments of the capillary zone, the first appearance being located a short distance inland of the normal high spring tide mark, and tends to increase in abundance and size inland. These anydrite nodules grow in the sediment by displacement.

Parallel laminations of calcite have been interpreted by Ogniben (1955) as varves produced by primary chemical deposition of gypsum by evaporation, and laminated calcium sulfate often alternating with very thin carbonate horizons have been interpreted by Schreiber (1976) as subaqueous to supratidal deposits. The gypsum-dolomite couplets and the normal-graded lamination of Hardie and Eugster (1971) have been interpreted as planar parallel laminations mechanically deposited by periodic storms in a manner analogous to modern tidal-flat laminations -- as in the Bahamas, for example. Cycles and partial cycles of several alternations of nodular anhydrite with thin algal mats seemingly recording minor oscillations between intertidal and supratidal conditions have also been recorded from the Persian Gulf by Shearman (1963), Kinsman (1966), and Butler (1969).

The process of removal through dissolution of anhydrite and gypsum to produce cavities, some of which collapse to produce breccias (what is believed to have happened at Highwood River), and the further filling of some of these cavities by calcite (at Plateau Mountain) has been documented by several authors from numerous ancient deposits. Lucia (1972) described a process of calcitization of gypsum and/or anhydrite and dolomite producing calcitic dolomite or limestone in place of an anhydritic or gypsiferous dolomite.

That nodular anhydrite may be of secondary origin and characteristically formed in supratidal sediments in arid coastal plains was demonstrated successfully by Kerr and Thomson (1973). Their view that nodular anhydrite of the Permian Basin northwest shelf was formed interstitially in varied coastal-plain sediments has been accepted by many researchers, including Kendall (1969) and Ball et al. (1971). The environmental significance of secondary sulfate rocks is thus well established.

Evaporite dissolution and collapse breccias present two main problems: 1) recognizing that the breccia is a product of evaporite removal, and 2) determining the nature of the removed evaporite. Criteria useful for the recognition of evaporite solution collapse breccias are given by Beales and Oldershaw (1969) and by Lucia (1972). Among their criteria the following are present at the two type sections:

- development of breccia porosity texture;
- brecciation showing vertical-size grading;

- sequence of uniform base and irregular top;
- stratigraphic conformity associated with restricted marine, very shallow water, or tidal-flat carbonates.

In their interpretation of evaporites in the Middle Devonian Elk Point Basin of Alberta, Bebout and Maiklem (1973) stated that gypsum pseudomorphs, nodular and nodular mosaic anhydrite formations were characteristic of supratidal deposits and could be compared to the anhydrite formation of the sabkhas in the Trucial Coast, while the bedded anhydrite were characteristic of shallow water deposition. Kerr and Thomson (1973) interpret nodular and bedded anhydrite in Permian shelf sediments from Texas and New Mexico as having formed in long-lived lakes or pans in which saltwater is trapped. Precipitation occurs from standing bodies of water and results in a sequence of fine laminae due to periodic supply and evaporation of water. The minor occurrence of such laminated layers suggests their origin in salt pans. The high density of gypsum crystals growing while excluding soft host sediments results in densely packed layers of anhydrite nodules.

The most likely location in which coarse gypsum (and other evaporite) crystal beds could have occurred was within an evaporitic coastal sabkha environment complex which appears to have been closely similar in type and size to the modern sabkhas of the Trucial Coast, Persian Gulf (Evans et al., 1964; Shearman, 1966). Macqueen and Bamber (1968) arrived at a similar conclusion for the Mount Head Formation.

The assemblages of primary and diagenetic sedimentary structures observed in the present facies indicate a very complex environment. The assemblages probably indicate deposition in a zone ranging from high intertidal to high supratidal flats with possible local occurrences of supratidal ponds. The cyclicity of the deposit indicates several minor relative oscillations (transgression-regression) in sea level brought by either real change in sea level, or subsidence of the shelf. It appears that the rocks were fully lithified before brecciation took place; thus brecciation and collapsing occurred at a relatively late stage in the history of this Member as a whole.

Skeletal Packstone to Grainstone Facies

Description

The outcrops of this facies are composed of coarse to medium grain skeletal fragments with a calcareous matrix. Outcrops are thinly bedded and all are massive. Except for a 1 meter-thick interval at Highwood River (Figure 7), this facies is restricted to the Plateau Mountain section. Large scale cross-bedding with overlying fine laminations is present in this facies in the lower part of the Plateau Mountain section. Generally the fresh surfaces are medium dark grey, while the weathered surfaces range from light grey to medium light brown. In vertical sequence this facies occurs in most cases overlying the dolomitic, quartz-bearing, mudstone-wackestone facies and, at one locality at Plateau Mountain, interbedded with the quartz siltstone facies.

Five to 15% of the samples are composed of detrital quartz grains (Figures 5A, 5B).

In general, laminations are absent in this facies, but some very fine, diffuse and generally faint laminations are present locally. These fine laminations are the result of variations in amount of the silt and sand size detrital quartz.

Most samples contain up to 30% pellets. Subrounded intraclasts composed of fine pale brown micrite and ranging in size from 1 millimeter to a few centimeters also occur in bedded fashion in this facies in the lower part of the Plateau Mountain section (Figure 5E). Superficial oolites are observed throughout the Plateau Mountain outcrops in amounts ranging from 3 to 10%. At the Highwood River section calcispheres compose 5 to 10% of the facies.

Skeletal fragments are an important constituent of this facies. They generally compose 30 to 60% of all rocks but only form 10 to 20% of the outcrop occurring interbedded with the quartz siltstone facies at Plateau Mountain. Generally 20 to 30% echinoid fragments (mainly plates), ranging in size from several millimeters to 0.5 mm, are found throughout the facies, but in the lower part of the Plateau Mountain section echinoid fragments compose 40 to 60% of the rocks (Figure 5D). Brachiopod fragments (ranging in size from a few millimeters to several centimeters) are abundant (20 to 40%) and 10 to 20% bryozoa, crinoid stems, ostracod and foram fragments are also present locally.

Dolomite content varies from a few scattered rhombs to as much as 25 to 35% locally. The greater percentage occurs as microcrystalline crystals, but scattered rhombs ranging from 0.5 to 0.03 mm are also present. The dolomite is believed to be of secondary origin. Porosity is generally minor, less than 3%, but locally very high (15 to 25%). It varies from interparticle, intraparticle, fenestral, to vuggy in nature. Most pores are 2 to 0.1 mm in size. Intercrystalline porosity is also observed throughout the facies. Fracturing is very minor and the few horizontal and vertical microfractures present are all filled by very fine crystalline calcite.

Cement is essentially calcite. It is mainly present as very fine

(0.3 to 0.02 mm) crystals in filling and as microcrystalline micritic cement. It is also present as overgrowth rim cements of fragmented echinoid plates (Figure 5D). The fine grain calcite occurs as interparticle, intraparticle, moldic, and other complex cementation filling. Microcrystalline and fine to medium grain chert occurs locally (essentially at Highwood River) as moldic filling of skeletal debris and in some areas as mud replacement (silicification). Chert is also present locally as dark grey nodules (up to 3 cm in diameter) and in discrete layers.

Interpretation

In their study of Khor al Bazam, Abu Dhabi, Persian Gulf, Kendall and Skipwith (1969) have shown that occurrences of ostracods, foraminifera, bryozoan, and flocculent matter are all related to the life and various deposition zones of a lagoonal environment.

In his description of carboniferous tidal-flat deposits of the North Flank, Northeastern Brooks Range, Arctic Alaska, Armstrong (1973) gives an interesting listing of the components found for several subtidal environments of this tidal flat. Tyrrell (1969), Swinchatt (1970), and Roehl (1967) have also described subtidal sediments composed of skeletal and oolitic packstones and grainstones and showing silt and sand size fecal pellets in a suspension of fine mud, and disoriented normal marine fauna skeletal debris.

The presence of pellets, abundant superficial oolites, and calcispheres, as well as extensive occurrence of gravel size to fine sand size disarticulated marine fauna skeletal fragments, is indicative of a subtidal deposition on an open, at times more restricted, subtidal marine platform.

Micrite content indicates that most deposition occurred under relatively quiet conditions, and the degree of skeletal debris sorting (poor to high, depending on the locality) suggests that the currents were persistent over at least short periods and that at times they were quite strong, as witnessed by the presence of some cross-beds and scour surfaces locally.

This top part of the Plateau Mountain section is believed to represent deeper water sediment, as suggested by the predominance of oolites in the sediments of the overlying Loomis (Figure 5F). The subtidal nature of this facies is confirmed by its relation to overlying and underlying facies.

In summary, we can say that generally speaking the skeletal packstone to grainstone facies is the result of an open subtidal shelf deposit of variable energy conditions.

Pelleted, Skeletal, Dolomitic, Mudstone-Wackestone Facies

Description

This variable skeletal facies is calcareous and dolomitic, mudstone-wackestone occurring in thinly bedded (0.5 to 1 m) outcrops. Fresh surface colors are medium grey to dark grey and weathered surfaces are light grey to brownish-grey. This facies occurs essentially interbedded with the dolomitic, argillaceous, mudstone-wackestone facies.

This facies is generally moderately well sorted, and has a very fine to fine crystallinity range with slight coarsening to medium-coarse crystals locally. Three to 15% subrounded to subangular detrital quartz sand and silt are also present.

The facies is thin bedded with thin to thick laminations. Almost all types, sizes, and shapes are present (Figures 6A, 6B, 6E). In some areas laminations are totally absent. The better defined laminations are the result of alternations of slightly recrystallized micrite, medium crystalline dolomite crystals, and some quartz detrital fragments (Figure 6A). Thin laminations (a few millimeters thick) composed of fine crystalline dolomite rhombs and gypsum crystal ghosts partially to totally filled by fine grain calcite (Figures 6A, 6C) alternating with thicker, poorly outlined laminations composed of pellets, pelloids, and skeletal debris (Figure 6D) are present locally. Inclusions of micritic elongated intraclasts (1.5 mm long) occur intermixed with the gypsum ghosts in the thinner laminae.

Besides showing a great variety of laminae, this unit also has a great variety of components. Well-defined to faint pellets are found throughout the facies and vary in amount from 2 to 25% (Figure 6F). Vertical and horizontal burrows (0.5 to 4 mm long) filled by a microcrystalline material (Figure 6E) and containing detrital quartz and coarse dolomite rhombs occur with and are related to the highly pelleted areas. Rounded, subrounded, and irregular pelloids are present but generally are very minor (less than 3%). Round to subrounded composite grains, small oncolites, oolites and micritic lumps, as well as algal lamination-like features, superficial oolites and calcispheres are also found scattered in minor amounts.

Occurrence of vadose silt sediment occupying the lowest part of secondary cavities is an additional feature of this facies. The vadose silt crystals are more or less equigranular calcite mosaics with median crystal diameters less than 0.02 mm, very well sorted, with no visible sand-grade or clay-grade particles and no recognizable skeletal material.

They always overlie some early calcite cement and are covered in some cases by later calcite cement.

Skeletal debris constitutes 3 to 10% of this facies and is composed of brachiopod fragments (0.5 to 2.5 mm), crinoid stems, encrusted algal and foram fragments, coralline algae fragments (2 mm in diameter) as well as 2 to 3% unidentified debris (possibly spicules or echinoid fragments). These are found scattered in the muddy fraction and as debris in the algal laminations (Figures 6B, 6D).

The matrix in which this mixture of pellets, pelletoids, and skeletal fragments occurs has undergone dolomitization and replacement, as well as some recrystallization.

Dolomite occurs mainly as microcrystalline crystals but also as well-defined subhedral to euhedral rhombs (0.4 to 0.03 mm), with some of them showing zoning. The percentage of dolomite with crystallinity larger than 0.02 mm ranges from 5 to 25% of all samples.

Porosity is generally less than 5% in all the unit, but it can reach 25% locally. Several types of porosity are observed, including: minor intercrystalline, good fenestral, fracture, moldic, channel, and vuggy (irregular to tiny birdseye). Sizes and amounts of the vugs vary locally. Most vugs show total to partial filling by fine grain to blocky sparry calcite and pyrite. In many cases the vugs are linked by microfractures. Calcite-filled dolomite rhombs and gypsum ghost molds also show a good amount of porosity. The microfractures present are numerous and vary greatly in size and direction.

Cement is principally microcrystalline dolomite and fine grain to sparry calcite. Cement content ranges from 10 to 30%. Some minor interstitial clay is also present in the muddy fraction.

Chert occurs as small lenses and stringers parallel to bedding, as void-fill and as microcrystalline crystals in some of the smaller vugs present. Iron staining occurs along most of the fractures and very minor (less than 1%) pyrite opaque grains are present in the mud matrix.

Interpretation

It is well documented from numerous modern environments that stromatolites, algal mats, and associated structures are features of the intertidal zones. But because of the diversity of forms that these can take in response to differences in environmental location, exposure, and tidal amplitude (Logan et al., 1964), and because of diagenetic changes, it is very difficult to define the exact type and environment of occurrence which a deposit of this type represents. However, the presence of oncolites in this unit is a good indicator of low intertidal areas exposed to waves and agitated shallow water. Oncolites, as defined and described by Logan et al. (1964), are a category of stromatolitic structures that may be formed by detachment from the substrate and overturning or rolling of the original head, or by growth of the laminated structure about a shell of lithic fragment that is rolled about by the intervention of mechanical forces in the environment. Mechanical tidal forces would provide sufficient agitation to wash the various debris, including the oncolite fragments, into the binding layers of the mats.

One of the most diagnostic characteristics for environment interpretation of this facies is the presence of layers of gypsum crystal growth. Evans et al. (1969) described a fossil algal mat from the Abu Dhabi sabkha with a maximum thickness of 0.3 mm and made up of numerous thin algal mats interlaminated with grey muddy bioclastic to pelletal carbonate sand and mud. The fauna indicated a restricted environment.

As a result of secondary gypsum crystal growth, the general algal-laminated structure is destroyed. The authors believe these algal-laminated structures to be of intertidal to supratidal origin. Masson (1973) describes similar occurrences in algal mats from southern Texas, and Shinn et al. (1969) describe the occurrence of mushy gypsum laminations a few centimeters below algal-mat surfaces on a carbonate tidal flat of Andros Island, the Bahamas.

Many intertidal tidal-flat deposits from ancient environments having characteristics somewhat similar to those of modern environments and of the present facies have been described by Tyrrell (1969) and by Friedman and Braun (1973). Other similar observations from restricted shallow water-intertidal tidal-flat deposits have been made by Laporte (1973), Matter (1968), Lucia (1972), Shinn (1968), Schenk (1967), and Roehl (1967).

From the characteristics observed and described in this facies there is good evidence to show that the present facies ranges from subtidal shallow water through intertidal. High pellets content and the low amount of varying skeletal fragments characterize shallow water (restricted?) environment, while vertical cracks, randomly scattered birdseye vugs and burrowed and churned mud sediments are more characteristic of the low intertidal environment. The great variety of laminations present, as well as their characteristics, is believed to be a product of deposition in an intertidal algal-mat environment where binding by the sticky-mucilage of the algal mats has played a major role.

Quartz Siltstone Facies

Description

Detrital quartz silt and sand grains dominate this facies, which is only present at one location in the upper part of the Plateau Mountain section in the form of two thin beds (0.5 m) interbedded with the skeletal packstone to grainstone facies. The fresh surfaces are light to medium grey to pale green-grey and the weathered surfaces are medium greyish-brown to orange-brown with flaggy recessive weathering.

Very fine to silt size detrital quartz grains constitute 50 to 90% of the facies. Terrigeneous argillaceous silty mud and calcareous and dolomitic mud compose the remainder (Figure 5A).

Fine laminations are present (Figures 5A, 5B). Most laminations are irregular and discontinuous with some very fine cross-beds. Changes in amount and size of quartz (from silt to very fine sand), change in content of interstitial brownish to greenish-grey, argillaceous material and iron staining of some laminations help to define the laminations.

Very good but highly localized porosity reaching 5 to 10% is present, but generally it is less than 2% of the rock, primarily fenestral to round vugs and minor fractures. Microfractures are both vertical and horizontal.

Interpretation

In modern sabkha environments (Bush, 1973; Irwin, 1965; Kinsman, 1969; and Lucia, 1972) the reach of the highest tides generally approximates the boundary line between the carbonate and detrital quartz sedimentation. It is a transitional zone between the predominant carbonate supratidal-intertidal coastal sabkha and the detrital quartz continental sabkha. With regressive sedimentation, the horizontal and vertical sequence of facies from marine carbonate sediment landward to the detrital quartz of the sabkha results in a stratigraphic sequence of carbonate rock conformably overlain by detrital quartz rock. In light of this, a similar mechanism can perhaps explain the occurrence of the quartz siltstone facies at Plateau Mountain.

Although this interpretation is questionable, it is sufficient to state here that the present facies accumulated in a coastal-plain environment and that most sediments were water laid probably by long-shore currents or storm deposition. Addition of silt size quartz detrital grains by eolian means is not ruled out.

FIGURE 3

LITHOFACIES

3A. Irregular to subrounded clusters of whitish-grey chert nodules of the dolomitic, argillaceous mudstone facies. Scale bar 1 cm.

3B. Fine crystalline equant calcite partially cementing vertical microfractures in the very fine crystalline dolomitic, argillaceous, mudstone-wackestone facies. Thin section, plane polarized light. Scale bar .25 mm.

3C. Vaguely pelleted dolomitic (and also quartz-bearing), mudstone-wackestone facies with large vugs cemented by sparry calcite cement. Thin section, plane polarized light. Scale bar .25 mm.

3D. Dolomitic, quartz-bearing, mudstone-wackestone facies with bioturbation and disruption of fine to irregular laminations by vertical-type burrowing. Scale bar 1 cm.

3E. Dolomitic, quartz-bearing, mudstone-wackestone facies with laminations, cross-bedding and intraclasts. Scale bar 1 cm.

3F. Microscopic view of the fine laminations observed in 3E. These fine laminations are composed of alternations between fine sandy-silty detrital quartz and microsparite dolomite. Thin section, plane polarized light. Scale bar .25 mm.

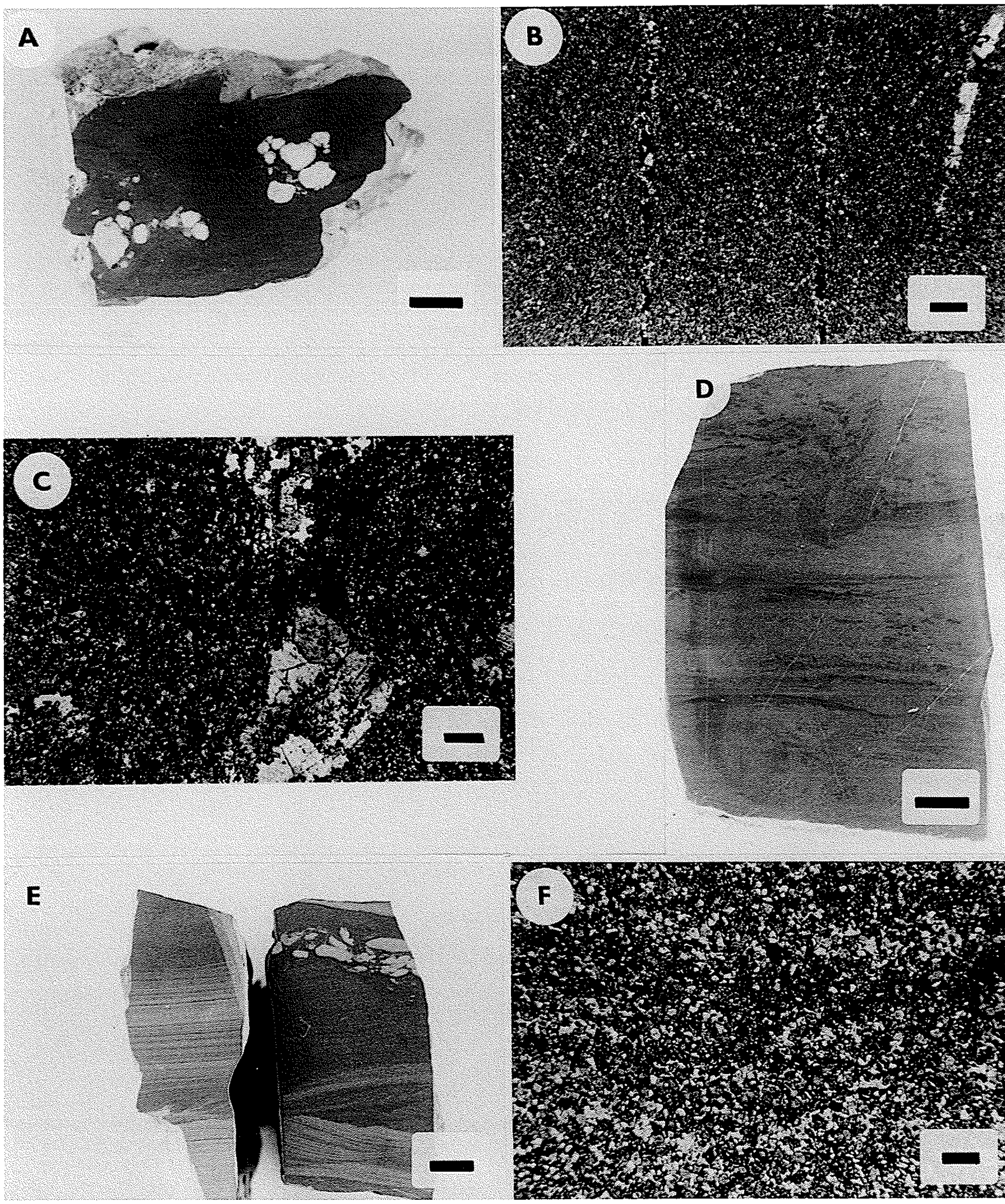
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FIGURE 4

LITHOFACIES

4A. Evaporite solution breccia facies. Field photograph of the Plateau Mountain section sabkha cycles.

4B. Evaporite solution breccia facies from Plateau Mountain section showing great variety of vug shapes and sizes. Vugs are partially to entirely filled by fine to coarse crystalline equant and bladed sparry calcite cements. Scale bar 1 cm.

4C. Microscopic view of the smaller filled vugs in 4B. Equant granular calcite cement is rimming and completely filling pores. Scale bar .25 mm.

4D. Varve-like couplets observed in Plateau Mountain section locally, part of the sabkha cycles. Laminations represent the alternation of two different sizes of granular calcite cement. Scale bar 1 cm.

4E. Field photograph of evaporite solution breccia facies from the Highwood River section showing collapsing. Collapsed fragments and more uniform beds are composed of dolomitic, argillaceous, mudstone-wackestone facies.

4F. Very coarse breccia within the evaporite solution collapse breccia facies from Highwood River. Scale bar 1 cm.

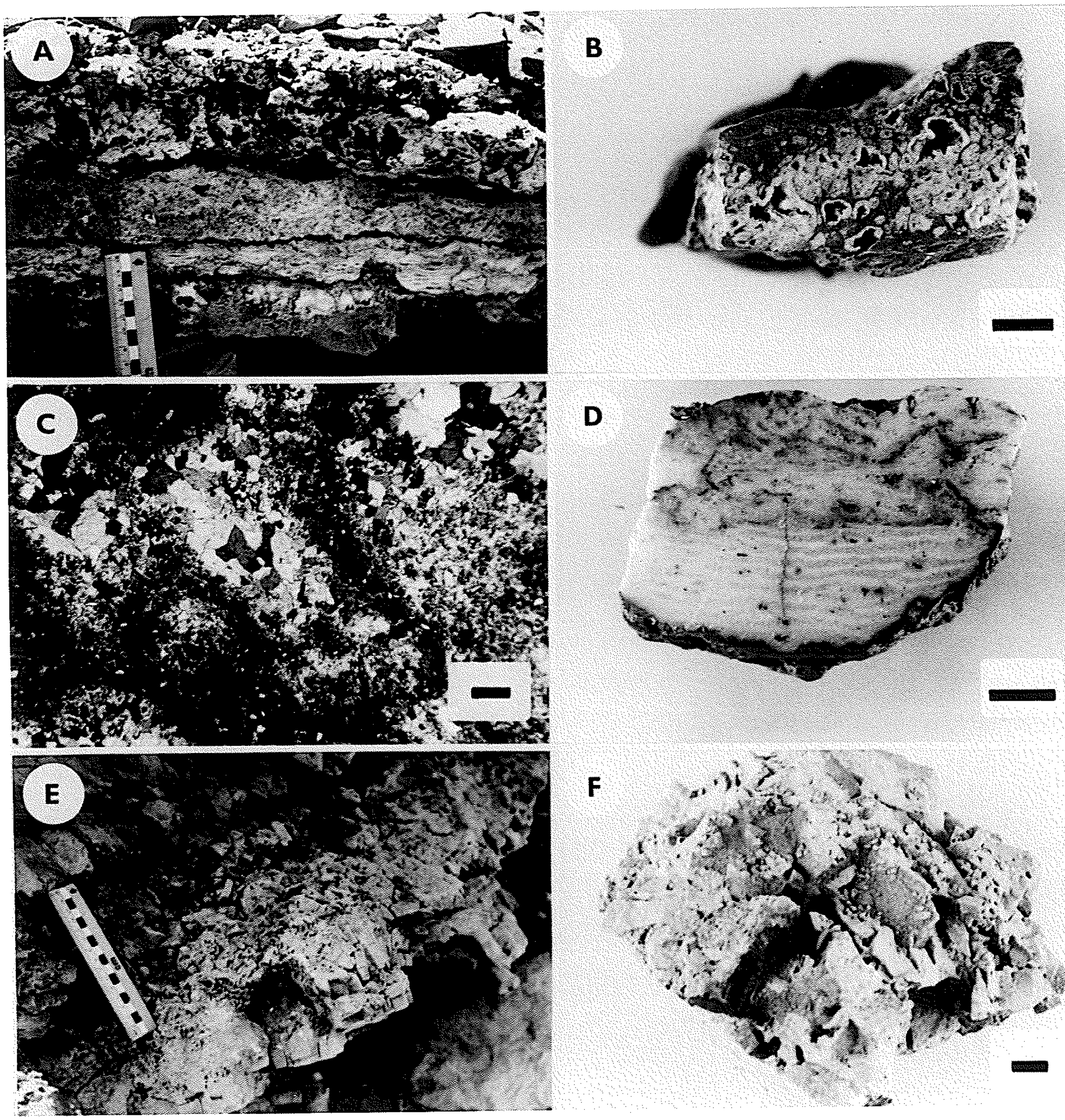
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FIGURE 5

LITHOFACIES

5A. Sample from quartz siltstone facies exhibiting sharp contact (erosional surface?) between lower yellowish-brown dolomitic material and upper argillaceous, silty detrital quartz-rich material. Scale bar 1 cm.

5B. Lamination of sandy echinoid fragments in an iron oxide-stained quartz siltstone matrix. Thin section plane polarized light. Scale bar .25 mm.

5C. Highly silicified skeletal grainstone sample from skeletal packstone to grainstone facies. Both brachiopods and coarser skeletal fragments, as well as finer matrix, are silicified. Scale bar 1 cm.

5D. Skeletal packstone exhibiting syntaxial overgrowth calcite cement on crinoid debris. Thin section plane polarized light. Scale bar .25 mm.

5E. Pelleted, skeletal grainstone exhibiting poorly sorted, nonoriented skeletal fragments and mud intraclasts occurring in organic-rich micrite mud. Scale bar 1 cm.

5F. Oolitic, skeletal packstone to wackestone material believed to be basal typical Loomis Member overlying Salter. Thin section plane polarized light. Scale bar .25 mm.

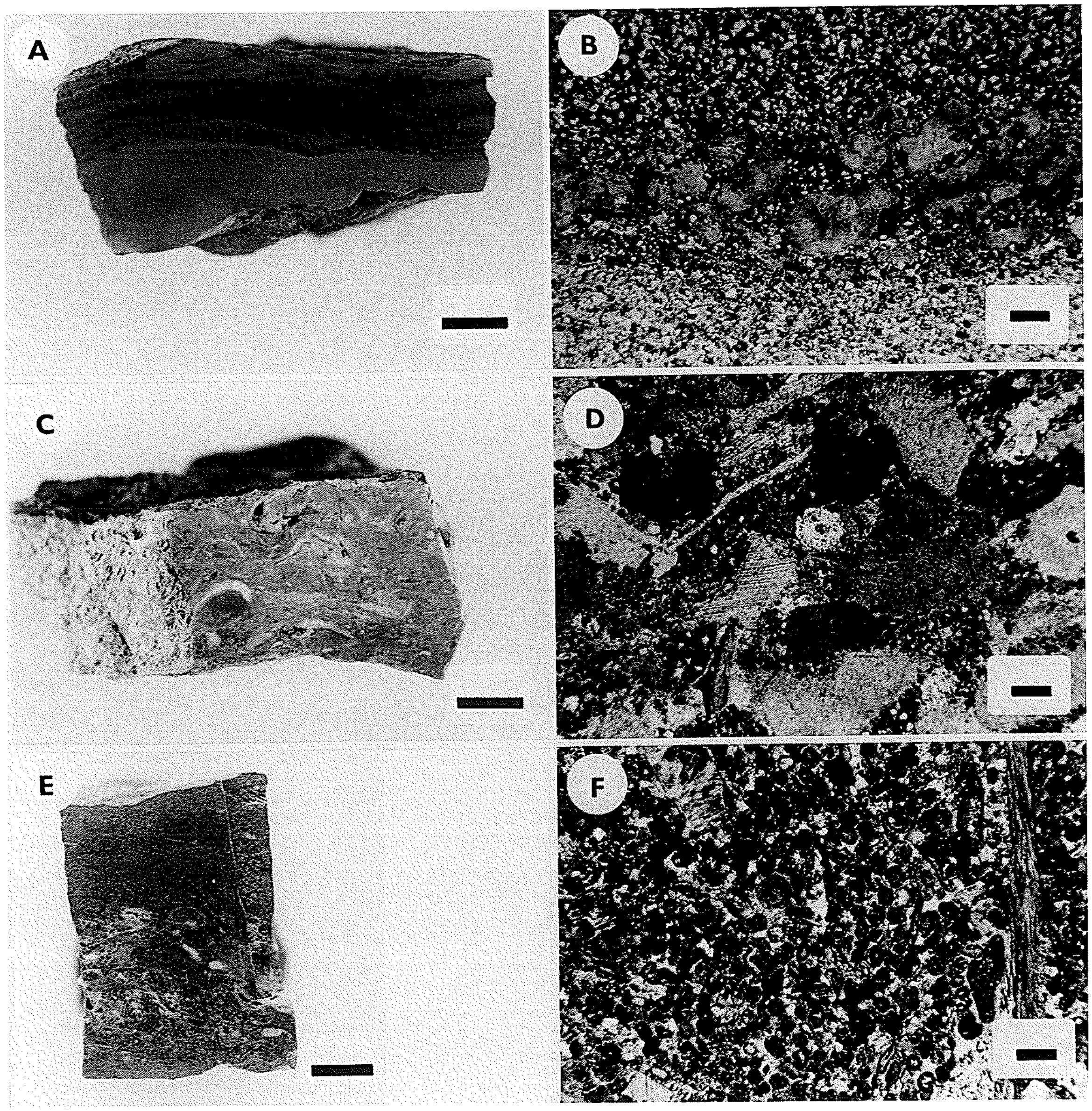
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FIGURE 6

LITHOFACIES

6A. Pelleted, skeletal-bearing, dolomitic, mudstone-wackestone facies with laminations including those of calcite-filled gypsum ghosts. Scale bar 1 cm.

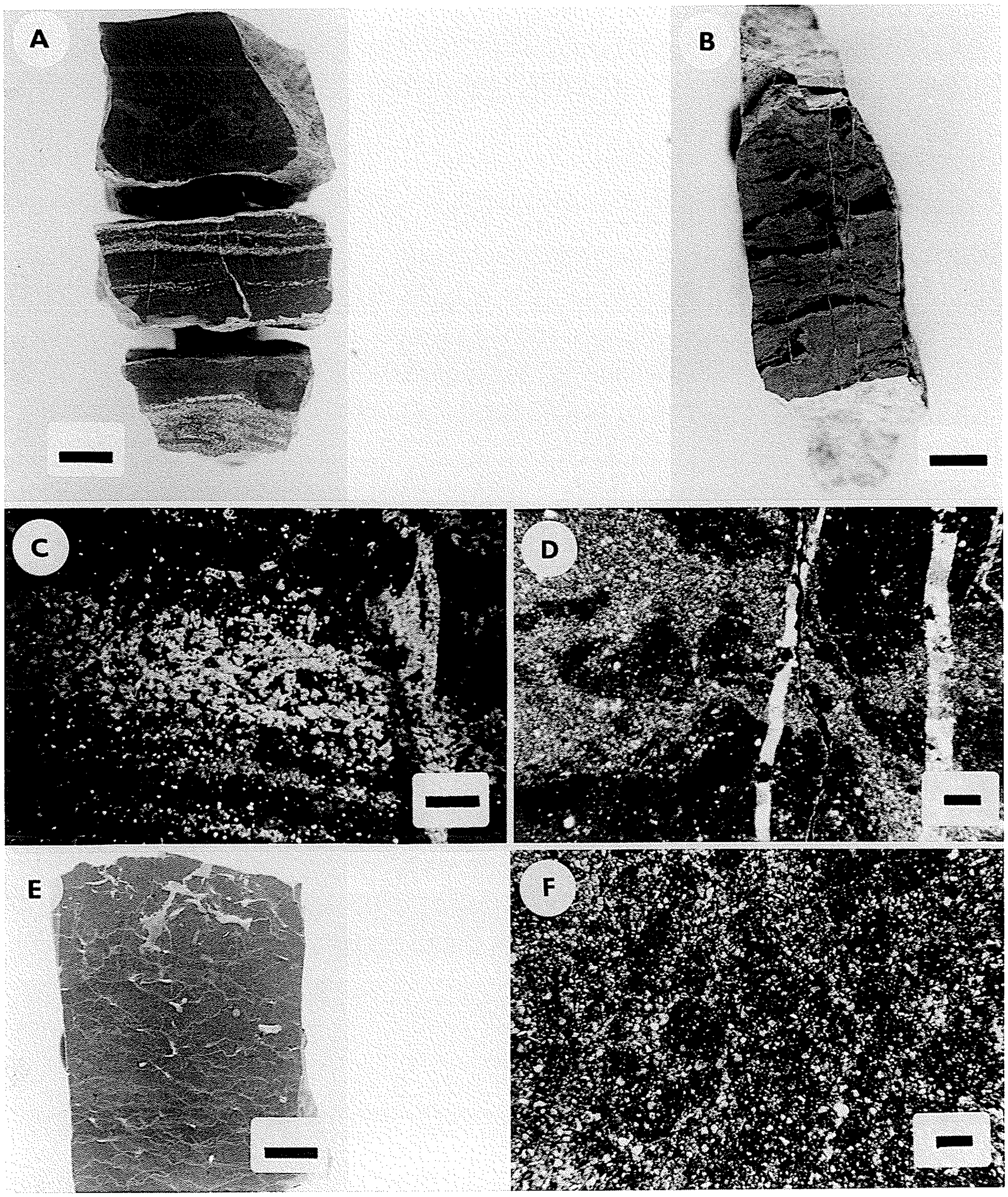
6B. Pelleted, skeletal-bearing, dolomitic, mudstone-wackestone facies showing irregular laminations from algal-mat environment. Scale bar 1 cm.

6C. Microscopic view of the white laminations observed in middle sample from 5A. Laminations exhibit fine granular cementation of dolomite rhombs, gypsum ghosts, and vertical microfracture. Thin section plane polarized light. Scale bar 1 mm.

6D. Microscopic view of algal laminations observed in 5B. Microspar calcite recrystallization, composite mud grains, irregular muddy intraclasts, granular calcite filling of fractures, as well as refracturing, are observed. Thin section plane polarized light. Scale bar .25 mm.

6E. Pelleted, skeletal-bearing, dolomitic, mudstone-wackestone facies exhibiting irregular filaments of microsparite dolomite. Scale bar 1 cm.

6F. Highly pelleted sample from the pelleted, skeletal-bearing, dolomitic, mudstone-wackestone facies exhibiting interparticle (interpellet) microsparite calcite and dolomite. Thin section plane polarized light. Scale bar .25 mm.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CHAPTER 3

GENERAL DEPOSITIONAL MODEL

Introduction

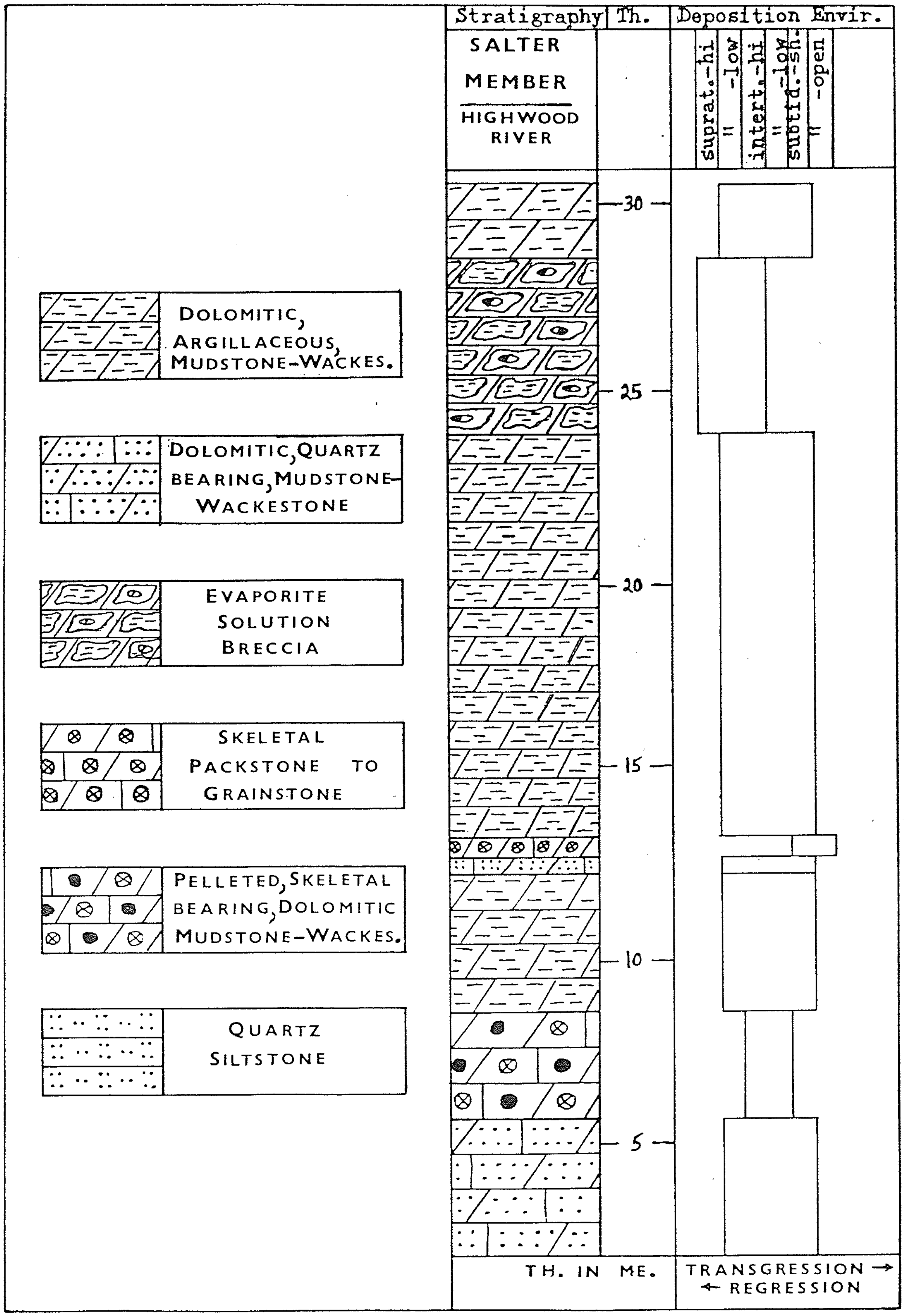
Broadly speaking, the Salter Member is the result of very sudden flooding and slow sea regression occurring at variable intervals and to a great extent being cyclical. It is a very shallow subtidal to supratidal, offlap carbonate, now extensively dolomitized. Local deposition by storms, high tides, and wind have left a particular characteristic to the member. The general picture is that of a generally prograding supratidal environment (Figures 7 and 8). Supratidal sediments prograde over the intertidal stromatolitic lime muds, which in turn prograde over the shallow marine beds alternating or interrupted by several episodes of sea transgression. Varying rates of carbonate production, sea level instability, variation of distance of shore lines, changes of water depths, shifting environments, and terrigeneous influx are a few of the numerous contributing factors. These may be either highly varied cycles or monotonous repetitions.

Several sedimentation energy levels are represented within the Salter Member model: 1) higher energy accumulated fine to coarse grained skeletal sands as shoals and as subtidal deposits especially where wave and current actions are strongest, mainly as the product of the reworking of various debris such as echinoderm and bryozoan; 2) mudstones and very fine grained terrigeneous detrital material in a low energy environment; 3) dolomitized lime muds and sands and microcrystalline dolomite muds (once evaporitic) accumulating within shallow supratidal ponds and intertidal to supratidal environments. These energy levels are very similar to those described by Macqueen and Bamber (1968) for all of the Mount Head.

FIGURE 7

STRATIGRAPHIC COLUMN

HIGHWOOD RIVER SECTION

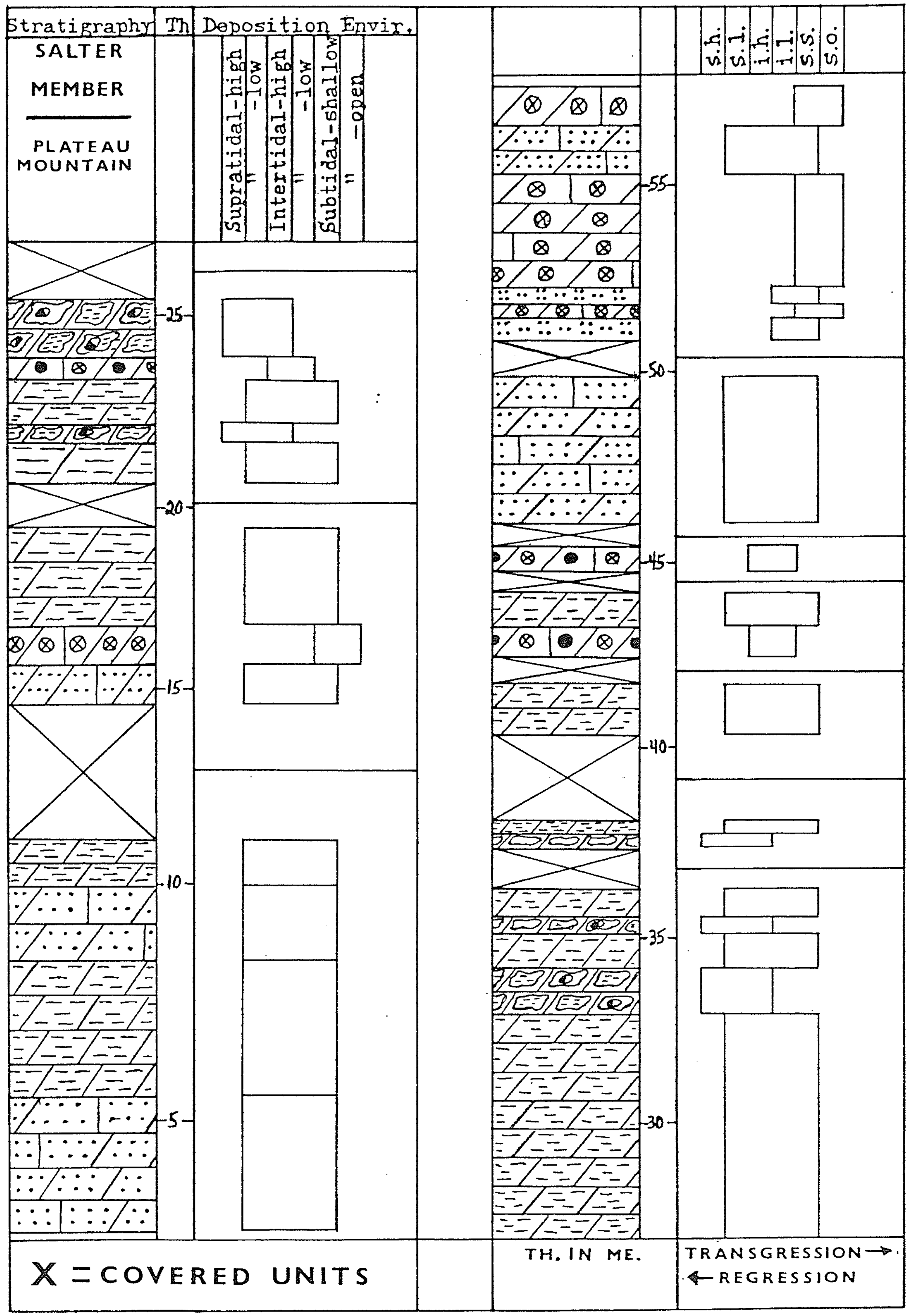


Stratigraphy
Th.
Deposition Envir.
SALTER MEMBER
HIGHWOOD RIVER
suprat.-hi
" -low
intert.-hi
" -low
subtid.-sh.
" -open
30
25
20
15
10
5
TH. IN ME.
TRANSGRESSION →
← REGRESSION
DOLOMITIC, ARGILLACEOUS, MUDSTONE-WACKES.
DOLOMITIC, QUARTZ BEARING, MUDSTONE-WACKESTONE
EVAPORITE SOLUTION BRECCIA
SKELETAL PACKSTONE TO GRAINSTONE
PELLETED, SKELETAL BEARING, DOLOMITIC MUDSTONE-WACKES.
QUARTZ SILTSTONE

FIGURE 8

STRATIGRAPHIC COLUMN

PLATEAU MOUNTAIN SECTION


Stratigraphy
SALTER MEMBER
PLATEAU MOUNTAIN
Th
Deposition Envir.
Supratidal-high
" -low
Intertidal-high
" -low
Subtidal-shallow
" -open
s.h.
s.l.
i.h.
i.l.
s.s.
s.o.
5
10
15
20
25
30
35
40
45
50
55
X = COVERED UNITS
TH. IN ME.
TRANSGRESSION →
← REGRESSION

Concept of Epeiric Sea Sedimentation

Shaw (1964) and Irwin (1965) both dealt with a general theoretical model for carbonate sedimentation within a broad shallow (Epeiric) sea. This model can help to illustrate the mechanisms operating during deposition of the Salter Member. Such Epeiric seas would have depositional slopes of very low angle, on the order of less than one meter per mile. Given such widespread relatively shallow seas with such low depositional slopes, a necessary consequence would be sharp variations in water circulation and agitation across this shallow sea. Different sedimentary environments would be forming, oriented approximately parallel to the strand-line and reflecting equilibrium conditions between the ambient hydrographic conditions and the associated carbonate sediments and fossil organisms. With transgression and regression of the sea, these environmental belts would migrate, accordingly building up a vertical stratigraphic record and locally recording the marine transgression or regression.

The Epeiric sea environment is essentially differentiated into three major belts: an offshore area where the sea bottom lies below the zone of wave and current action and where little sediment forms; a second belt where waves and currents touch bottom, characterized by the presence of sediments that are basically biogenic; and a third, landward belt where wave and current agitation, having been dissipated across the second belt, are virtually absent, except for storms, even though in this environment the water is very shallow and consequently becomes the natural site for the deposition of sediments basically of chemical origin. On this landward type of shelf, salinities (in restricted areas) increase shoreward as there is progressively less introduction of fresh seawater, so that a regular pattern of facies from dolomite, through anhydrite or gypsum, to salt and other evaporites is established. The individual width of these three belts depends, of course, upon the sea floor's depositional slope and the magnitude of wave and current agitation.

The general model for the Salter Member is believed to correspond to the one proposed by Macqueen and Bamber (1968), where the concidence of favorable climatic and physiographic factors, although achieved on a large scale in very few places, is more common on a small scale in the form of lagoons, pans, and exposed salt-flat areas during processes of nearshore sedimentation. This environmental model is fairly well represented today in the Persian Gulf as described by Kinsman (1969, 1971), Evans et al. (1964), and Illing et al. (1965). It consists basically of an unrestricted marine basin with unrestricted normal or near normal marine peripheral lagoons; marginal accumulations of normal marine sediments ultimately forming exposed supratidal surfaces and marginal evaporitic environments; and brines developing interstitially within the sediments. Incomplete sedimentation may locally isolate shallow depressions, which may carry semipermanent bodies of brine, or minor variable supratidal ponds.

Highwood River Section

Deposition (illustrated in Figure 7) begins with a 10.3 meter unit of dolomitic, quartz-bearing, mudstone-wackestone deposited in environments ranging from nearshore shallow subtidal to low supratidal.

This initially deposited unit is overlain by 2.7 m of pelleted, skeletal-bearing, dolomitic, mudstone-wackestone facies (intertidally deposited). The lower contact is sharp and shows some local relief, possibly indicating a break in sedimentation(?). One of the main features of this unit is the presence of algal mat-related-features. This new intertidal area (ranging from low to high intertidal) was then colonized by algal mat.

Progressive transgression occurred with the successive deposition of 3.7 m of dolomitic, argillaceous, mudstone-wackestone (very shallow subtidal to high intertidal); 0.4 m of dolomitic, quartz-bearing, mudstone-wackestone (shallow subtidal to high intertidal); and 0.6 m of skeletal packstone to grainstone (open, high subtidal shelf with variable energy conditions).

Following this transgression is a regressive sequence, marked by the deposition of a 10.7 m unit of dolomitic, argillaceous, mudstone-wackestone.

This unit is then capped by a 4.6 m unit of evaporite solution collapse breccia composed of fragments and thin beds of dolomitic, argillaceous, mudstone-wackestone. This evaporite solution collapse breccia is of high intertidal to high supratidal origin and thus a good indicator of the continuation of regressive conditions.

The section is terminated by a 2.0 m occurrence of dolomitic, argillaceous, mudstone-wackestone, indicating a return to very shallow subtidal to high intertidal conditions.

Plateau Mountain Section

The vertical depositional sequence at the Plateau Mountain section is illustrated in Figure 8. Two repeated alternations of deposition between underlying dolomitic, quartz-bearing, mudstone-wackestone (3.7

and 1.8 m) and overlying dolomitic, argillaceous, mudstone-wackestone (3.8 and 1.2 m) begin the Plateau Mountain deposition sequence. Both lithofacies represent very shallow subtidal to high intertidal-low supratidal deposits. This sequence is overlain by a 3.6 m covered section.

A brief transgression-regression episode then follows. In this sequence, a 1.1 m unit of dolomitic, quartz-bearing, mudstone-wackestone is overlain by a 3 m unit of skeletal packstone to grainstone. The sequence is capped by 2.6 m of dolomitic, argillaceous, mudstone-wackestone. Laminations, cross-beds, scour channel surfaces, and rip-up clasts of the lower unit, overlain by the highly diversified skeletal content (high echinoid fragment content with brachiopods, crinoids, bryozoas, forams, and pellets) suggest transgression from shallow subtidal-low supratidal to an open, subtidal shelf environment. The occurrence of dolomitic, argillaceous, mudstone-wackestone is interpreted as a return to a more restricted environment of the very shallow subtidal-low supratidal type. Again a covered unit (1.2 m thick) overlies the sequence.

The transgression-regression sequence is then overlain by a thick cyclic unit (totalling 17.7 m) of five cyclical transgression-regression episodes. These cycles are obscured locally by covered intervals. Each cyclical episode is believed to represent a sequence of fluctuation (relative transgression-regression and/or progradation) between very shallow subtidal-high intertidal (dolomitic, argillaceous, mudstone-wackestone) to high intertidal-high supratidal (evaporate solution breccia). The occurrence of a pelleted, skeletal-bearing, dolomitic, mudstone-wackestone interbed in one cycle represents a former algal-mat-bearing low to high intertidal environment.

Local changes in the rate of subsidence or emergence in relation to the rate of deposition as well as regional "kickback" (as described by Irwin, 1965) brought about by regional transgressions and regressions are possible mechanisms by which cyclicity at Plateau Mountain might have originated. However, it is impossible to discriminate between these two possibilities.

Mossop (1973) and Havard and Oldershaw (1976) advocate a mechanism for the accumulation of thin repetitive carbonate sequences based on a model of progradation superimposed on a steady subsidence rate. If the sedimentation rate slightly exceeds the subsidence rate, the accumulation of sediment is likely to be greater in the subtidal areas, with some accumulation in intertidal areas and very little in supratidal regions. Sediment accumulation at one point in the intertidal zone eventually will cause elevation of this point into the supratidal realm. Then sedimentation will decrease at this point and the intertidal environment will shift slightly seaward. The subsidence rate would then be greater than the sedimentation rate for the geographic point that became slightly emergent. According to the authors, progradation of the intertidal zone could continue until the margin of the island approached the reef or shelf margin, at which time sedimentation would virtually cease. A return to subtidal conditions over the emergence areas could occur as subsidence caused relative deepening water conditions. Whether this model may be used to explain cyclicity at Plateau Mountain remains uncertain, but it is useful to understand mechanisms explaining repetitive characteristics of a shallowing sequence.

Overlying the thick cyclical sequences is an interval characterized by 1.5 m of dolomitic, argillaceous, mudstone-wackestone (very shallow subtidal to high intertidal). This in turn is overlain by 0.6 m of covered, unexposed outcrops and 0.7 m of pelleted, skeletal-bearing, dolomitic, mudstone-wackestone (low to high intertidal). This type of deposition sequence is repeated twice. The interval is capped by 0.5 m of covered outcrop. The overlying sediments from this point on are of a different assemblage and represent mostly subtidal deposition environments.

The next sequence begins with a thick unit (4.0 m) of dolomitic, quartz-bearing, mudstone-wackestone (shallow subtidal-low supratidal) overlain by a covered interval 1 m thick. The contact between these two units suggests a possible erosional surface(?). Above the covered interval the sequence continues with a thin (1.5 m) unit of quartz siltstone exhibiting a 0.3 m interbed of skeletal packstone to grainstone. These sediments are believed to be part of a transgressive, partly clastic sequence. Although many of the silt to sand size quartz grains probably have undergone phases of eolian accumulation, it is believed that most were water laid. A less probable but still possible alternative origin of this quartz siltstone unit is the subaerial exposure(?) of a supratidal pond with the addition of silt size quartz material by eolian means or by storm tides (water-laid) on the newly exposed surface.

A slight transgression is then believed to have occurred, bringing about deposition of a 3 m-thick unit of subtidally deposited skeletal packstone to grainstone sediments. This unit is overlain by a 2.4 m-thick unit of dolomitic, quartz-bearing, mudstone-wackestone (shallow subtidal-low supratidal) and by a 2.3 m-thick unit of subtidally deposited skeletal packstone to grainstone. This slight transgression terminates the sequence of the Salter Member at Plateau Mountain.

A deepening of the water and an increase in energy in the lowermost unit of the overlying Loomis Member are indicated by the high percentage of oolites and foraminiferas, and by the substantial amount of echinoderms, brachiopods and bryozoas.

Correlation problems between the two sections of the Salter Member

Correlation between the two Salter Member sections studied can be done only at a general level. The only possibility of a general lithologic correlation observed occurs between the four cycles of formation of collapsed rocks at Highwood River and the five cycles of formation of the evaporite solution breccia observed at Plateau Mountain. This correlation can be made only on a general basis; it is not possible on a cycle-to-cycle basis.

However, the greater thickness of the Plateau Mountain section, the more numerous occurrences of various skeletal facies, the better defined and fewer leached and collapsed cycles seem to indicate very strongly a thickening of the sediment from Highwood River to Plateau Mountain. This greater in situ sediment accumulation at Plateau Mountain suggests a possible gap in the depositional time line or a different rate of deposition at each section. In addition to events correlation, lithofacies correlation as well remains highly speculative in the Salter Member.

To summarize, the Plateau Mountain section was probably located in a more seaward direction than the Highwood River section on the Epeiric Sea model. Correlation between the two sections, whether on a lithofacies or an events basis, remains highly speculative and somewhat unrealistic.

CHAPTER 4

DIAGENESIS

Introduction

The actual processes leading to diagenetic alterations and modifications of limestones have been divided by Chilingar et al. (1967) into: (1) physicochemical processes, (2) biochemical processes, and (3) physical processes. The writer has employed the term "diagenesis" to include all processes that affect a sediment between the time of deposition and metamorphism, including postlithification processes.

The phases of diagenesis used are those defined by Schmidt (1965): "early diagenesis" refers to diagenetic changes which were influenced by the physicochemical environment and the biologic activity at the site of deposition; "late diagenesis" refers to diagenetic changes not influenced by the depositional environment or by the physiochemical conditions of the water. The phases of late diagenesis directly following early diagenesis will be referred to as "intermediate diagenesis" (Schmidt, 1965).

Cementation

Cementation is one of the major processes that contributed to the lithification of carbonate sediments and thus is the principal factor of porosity reduction in the Salter Member.

The fabric criteria employed to differentiate between cement mineral and neomorphic/recrystallized minerals are those of Bathurst (1975, pp. 417-419) and Chilingar et al. (1967). The descriptive and genetic nomenclature of Chilingar et al. (1967) is used to indicate size. Thus, whether being equant or bladed, sparite will be defined as being greater than .02 mm and microsparite ranging in size from .005 to .02 mm. Micrite (also called cryptocrystalline calcite) will be cement smaller than .005 mm, generally too small to be distinguished under the microscope.

The terminology for cement morphology classification is adapted from Folk (1965) and Milliman (1974). Calcite is the dominant cementing mineral in the Salter Member, but silica and iron oxides have also been observed as cement. The Salter Member cement fabrics have been examined in thin sections and the following types identified (listed in order of decreasing abundance and discussed in that order):

A) Calcite cements:

1. Equant (blocky and granular); 2. bladed (drusy and fringing); 3. syntaxial overgrowth.

B) Other cementing minerals -- silica and iron oxides.

A) Calcite cements

1. Equant cements: These sparry calcite cements exhibit mostly equant but also slightly irregularly shaped crystals of various sizes, ranging from 0.03 to 5 mm (Figure 9D). Equant cement composes from 3 to 30% of the samples studied, depending on the facies and the pre-existing pore space available. The larger crystals show irregular boundaries and somewhat undulatory extinction. These crystals are also zoned; i.e., showing transitions from iron-poor to iron-rich calcite, as tested by staining.

In general, the equant calcite cement occurs mainly as finely crystalline to coarsely crystalline equant crystals mosaics partially to completely filling vugs (Figures 4C, 9C, 9E) and vertical fractures (Figure 9E). Inclusion content is generally low but some of the coarser granular blocky crystals contain darker specks of iron oxide. Equant calcite cement also occurs in many chert nodules.

Fine to coarse granular equant intercrystalline and interparticle calcite mosaic also occurs around grain clusters and between pellets and skeletal debris not already filled by bladed, overgrowth, or other cements. Equigranular mosaics of sparry calcite serve also as a very good intraparticle and moldic cement by filling chambers of foraminifers, spaces between shells, zooecial openings in bryozoa, spicule fragments, growth framework of coralline algae, and gypsum and dolomite rhomb ghosts (Figures 6C, 10B). In general it shows good cementation of those fabric-controlled features, indicating that the good porosity the rock had at one time is now mostly plugged.

The varve-couplet laminations (Figure 9B) interpretation is believed to be similar to the one given by Fuller and Porter (1969) for varved aragonite mud from a sabkha setting from an environment similar to the Salter and where the final product is similar to the calcite couplets shown in Figure 9B. The basic materials from which the observed lamination varieties were derived by diagenesis might have been varved aragonite mud and clay material. These materials are believed to have undergone the following sequence of diagenetic changes:

a) Aragonite mud is recrystallized to calcite, producing fine granular calcite laminite.

b) Aragonite mud is dolomitized, producing microdolomite laminite.

c) Microdolomite laminite and the fine granular calcite laminite are locally invaded by nodular anhydrite, which disrupts the laminar structures.

d) Microdolomite-anhydrite laminite are then converted to coarse granular calcite laminite. These first three "stages" may all be contemporaneous since aragonite, dolomite, and evaporites occur together in the Persian Gulf today. The varve-couplet laminations in the evaporite solution breccia facies of the Salter are also invaded locally by growths of nodular anhydrite (now replaced by microcrystalline chert) which have partially disrupted the original laminite structures.

The equant calcite cement is the most abundant cement present in the Salter Member and is found in all facies with the exception of the two quartz-rich facies: the dolomitic, quartz-bearing, mudstone-wackestone facies and the quartz siltstone facies. This probably reflects the unavailability of nucleons or the lack of sufficient time to grow and/or the difficulty for the cement solution to travel through these two facies.

Most of the equant calcite cement was probably introduced by migrating or circulating formation water which used, among other means, tectonic fractures as pathways. All of this cement is believed to be "late" in origin. Although the presence of fine equant calcite cement as intraparticle filling of skeletal fragments suggests an early diagenetic origin, the fact that it overlies bladed and overgrowth cement indicates that it formed later than the other two types of cements and that it is of late diagenetic origin.

2. Bladed cements: Bladed cement in the Salter generally occurs as a mosaic of elongated crystals (2:1 to less than 6:1 ratio of width to length) often rimming rather than totally filling voids (Figure 4B). In many cases there is an increase in crystal size away from the wall and the crystals normally show a preferred orientation of the longest grain axis normal to the surface of the host particle.

The more drusy bladed sparry calcite cement occurs as crystals ranging from very fine-medium sized to coarse elongated (0.1 to 5 mm) lining and fringing the pore walls of vugs to which they are oriented perpendicularly (Figure 9A). The thickness of the cement crusts ranges from 0.1 to 10 mm. Most vugs are only partially cemented but many are completely cemented, especially those with diameters smaller than 1 mm. The larger vugs (a few millimeters to several centimeters) vary from irregular to subrounded in shape and the calcite cement in some of these shows elongated coarse bladed calcite crystals in the interior overlain and surrounded by a rim of later finer grain and more equant cement at the periphery (Figure 9A). The rim thickness is usually less than 1 to 2 mm and is unevenly distributed. Staining reveals that calcite, in most cases, has a low iron content.

This type of cement occurs mostly in the evaporite solution breccia facies of Plateau Mountain. This cement is also observed in lesser amounts in the evaporite solution collapse breccia facies at Highwood River and as a filling in some large vugs in the dolomitic, argillaceous, mudstone-wackestone and the pelleted, skeletal-bearing, dolomitic, mudstone-wackestone facies. This is probably a good reflection of the ease of circulation of the cement solution and the availability of sufficient space and time to grow crystals, especially inside the leached vugs.

This cementation by bladed calcite cement is probably the most important episode following and showing association with solution of the allochems, in the present case the leaching of gypsum or anhydrite to form collapse breccias.

Because the bladed cement underlays the equant cement and also because of its predominance as rimming in vugs, the deposition and formation of bladed calcite cement in the Salter Member is believed to be an early diagenetic event preceding, at least in the early stage, the formation of overgrowth and equant calcite cement. Since several leaching episodes are observed, the writer feels that some of the cement could also be intermediate diagenetic.

3. Syntaxial overgrowth cements: Syntaxial overgrowth cement, according to Bathurst (1975), refers to the overgrowth on a crystal such that the original crystal and the overgrowth form a single larger crystal sharing the same crystallographic axis. Commonly and more generally the overgrowths fill all available pore space, extending up to the surface of polycrystalline grains or to the fringe of bladed cements that surrounds them. In the Salter it is generally greater than 0.5 mm but can reach several millimeters in thickness. Where extensively developed, the outer rim boundaries of syntaxial overgrowths come in contact with other rims from surrounding overgrowths and enclose polycrystalline grains, dolomite rhombs (Figure 9F), or detrital particles.

Syntaxial overgrowth cement is confined to the skeletal packstone to grainstone facies of the upper part of the Plateau Mountain section. It forms the dominant cement in samples with highly fragmented crinoid and echinoid plates and ossicles, echinoid stems, and several highly fragmented (unidentified) skeletal remnants (Figures 5D, 9F).

Syntaxial overgrowth cement is believed to have formed later than the bladed cement but probably also early in the diagenetic sequence. Other authors -- for example, Evamy and Shearman (1965), Purser (1969), Young and Greggs (1975) -- have presented evidence that the overgrowth cement on echinoderm grains which they studied was synsedimentary (early diagenetic) in origin. Folk (1965) noted that overgrowths on echinoderm grains tend to fill all available pore spaces and suggested that the overgrowths formed earlier and faster than the other types of spar cement. The excellent development of syntaxial overgrowth cement in the skeletal facies of the Plateau Mountain section could be explained by a combination of great availability of calcite-bearing water and early and rapid growth of the syntaxial cement.

Timing and environment of calcite cementation: Because of the characteristics of the various calcite cements and their relation to what has been stated previously on the general depositional model, the writer believes that the bladed cement occurred slightly earlier than the syntaxial overgrowth cement, and that the equant cement is a later diagenetic event. However, the difference in timing between the bladed and syntaxial cements still remains uncertain regarding how much earlier the bladed cement was deposited. It is probably more realistic to consider both of them as early diagenetic events. The later origin for the equant cement is believed to have been well established by the relationship with the other two types of cement.

Since there is no good evidence for cementation in subaerial (vadose or phreatic) and submarine environments, it is proposed that calcite cementation in the Salter took place mostly in the subsurface environment. However, it is extremely difficult (if not impossible) to specify whether this subsurface cementation was of a shallow or a deep nature.

B) Other cementing minerals

The silica and iron cements found in the Salter are essentially of microcrystalline sizes and originate mainly from calcite micrite mud cementation and leaching.

Microcrystalline silica cement occurring primarily as replacement of calcite micrite mud and acting as interparticle cement of detrital quartz grains and highly fragmented skeletal debris is present in the quartz siltstone facies and, to a lesser extent, in the dolomitic, quartz-bearing, mudstone-wackestone and the skeletal packstone to grainstone facies. In the latter two facies, occurrences are very localized and sporadic. In the quartz siltstone facies, microcrystalline silica cement ranges from thin film on detrital quartz grains to interparticle cements between these same grains.

Microcrystalline opaque iron oxide cement is observed predominantly in the evaporite solution collapse breccia facies of the Highwood River section. It occurs as partial filling of fractures of variable sizes resulting from brecciation and is essentially a deposition product from leaching of water loaded with iron content, following the brecciation episode (Figures 12D, 12E).

Both types of cements are believed to be late diagenetic events.

Vadose Silt Sediments

Generally speaking, vadose silt sediments are known (Dunham, 1969; Bathurst, 1975) to have peculiar textures which are different from their host rocks and different from associated diagenetic sediments or cements of intertidal and subtidal origin. This is certainly true for those present in the Salter.

The Vadose silt sediments present in the Salter are more or less equigranular calcite mosaics with calcite crystals of silt grade, extraordinarily well sorted, with virtually no sand-grade or clay-grade particles and no recognizable skeletal material. They occur as internal sediments in secondary voids. They are geopetal and always occupy the lowest part of cavities. They produce inclined floors or complete fillings indicative of current transport.

In the Salter Member, vadose silt sediments are observed at the

Highwood River section in part of a unit of the pelleted, skeletal-bearing, dolomitic, mudstone-wackestone facies showing several remnants of algal-mat features. This unit is overlain by dolomitic, argillaceous, mudstone-wackestone. Most occurrences are observed at the bottom of cavities and are overlain and underlain by different types of calcitic diagenetic cements (Figure 11F). Where the sequence is complete, from the vug border to the center, it appears as:

1) micrite-microspar calcite mud (host sediment rock) surrounding the cavity;
2) rimming of pore walls by fine bladed calcite cement or by fine to medium equant granular calcite cement;
3) vadose silt sediment;
4) coarser granular equant calcite cement completing the filling of the vugs; this phase only occurs in some of the larger vugs.

This sequence can be incomplete and/or interrupted and can vary greatly with shape and sizes of the vugs.

Dunham (1969), who made extensive studies of vadose silt cements, concluded that the silts must have been deposited in the vadose zone from meteoric water in voids formed by leaching and fracturing. Dunham notes that gravity transport must have been greatly aided by movement of the pore water itself. Voids completely filled with silt are strongly indicative of strong current movement. The currents moved fast enough to pick up silt size sediment and carry it in suspension or traction. The calcite source is unsure but Dunham supposed that the vadose silt crystals were winnowed from the primary sediment by moving groundwater, the sand-grade particles being mechanically trapped in the pore system and unable to move. The clay-grade particles, he suggested, succumbed to "chemical attack by vadose water" on their large surface area.

A similar deposition mechanism is believed to have taken place in the Salter Member. The writer also believes that even if the calcite source remains uncertain, the overlying and possibly adjacent (now highly dolomitized) beds could have been a good source of material for the vadose silt cement observed.

The Salter Member vadose silt is believed to be diagenetic sediment deposited during the early stages of calcite cementation; i.e., after the beginning of cementation but before its completion, and after the formation of secondary voids. This is strongly supported by the fact that it is underlain, overlain, and interlayered with calcite cement and that it floors secondary voids whose existence implies prior leaching. This diagenetic sediment predates equant cement and postdates (overlies) early bladed calcite cement.

Neomorphism

Neomorphism (Folk, 1965) is "a comprehensive term of ignorance embracing all transformations between one mineral and itself or a polymorph, whether the new crystals are larger or smaller or simply differ in shape from the previous ones." The term, as redefined by Bathurst (1975), in fact embraces three in situ processes: 1) polymorphic transformation, 2) recrystallization, and 3) aggrading neomorphism, all three as part of a new definition of "neomorphism."

The fine grain carbonates of the Salter Member consist primarily of dolomitic micrite mud with extensive patches of calcite micrite and microspar. The original composition of the mud is unknown, but it was possibly originally composed of a mixture of aragonite, calcite derived from skeletal debris and silici-clastic grains reduced to minute particles.

Bathurst (1975) has demonstrated that crystals released by the breakdown of many types of skeletal debris are smaller than the crystals in microspar -- i.e., are less than 0.005 mm. The small particle size, and the resultant small size of interparticle pores, renders the lime muds particularly susceptible to diagenesis, especially pressure-solution and simple interparticle cementation. According to Bathurst (1975), it is also these same characteristics that make the lime micrite so amenable to dolomitization early in the sediment history, as witnessed by the high content of dolomitic micrite mud observed in variable concentrations in most Salter Member facies.

A good portion of the Salter Member fine grain carbonates consists of microspar calcite crystals of equidimensional uniform size (0.02 to 0.005 mm in diameter) which may have originated through neoorphism of the carbonate micrite muds. Although found in all facies of the Salter, they are more prominent in the more calcareous and skeletal facies, suggesting that the growth of neomorphic spar in these facies was favored by their less compacted or partially consolidated nature at that time. The process might have involved also, in its earlier stages, the wet transformation of aragonite to calcite and some passive dissolution-precipitation (Bathurst, 1975) which might have been more prominent in these facies. These microspar calcite crystals are generally arranged in interlocking mosaics in which dispersed and scattered patches of micrite, pellets, or fossil fragments appear to float. The general texture gives the impression of "grain growth" from the finer micrite material. This increase in grain size is irregular and patchy. The patchy sparry replacement of micrite by microspar is masked in the highly dolomitized samples.

Microspar is commonly concentrated around allochems (Figure 6F) and detrital grain clusters such as detrital quartz clusters in the quartz siltstone facies and in the evaporite solution breccia facies. In this latter facies, most of the micritic mud has been recrystallized and only a few ridges of mud material have remained unaltered by neomorphism.

The time at which the various neomorphic changes occurred in sediments of the Salter Member is impossible to determine accurately on the basis of the observations made. Bathurst (1975) suggests that the growth of neomorphic sparry calcite begins in partly consolidated sediments. Inversion of aragonite to calcite has been observed in the recent carbonate sediments (Evamy, 1973; Purser and Loreau, 1973; Shinn, 1973; Matthews, 1968; Kinsman et al., 1971). It is possible that the development of neomorphic sparry calcite in the Salter Member was a relatively early diagenetic event.

Whereas neomorphism is used as transformation of mud to neomorphic spar, recrystallization comprises, in this discussion, any change in the fabric of a monomineralic sediment such as fragments or individual grains. Some of the pellets-pelletoids embedded in microsparite in the pelleted, skeletal-bearing, dolomitic, mudstone-wackestone facies have been recrystallized by identical microspar, so that the only remaining evidence of their existence is an elliptical brown organic-iron stain and slight color differences within them. Perhaps the most spectacular and interesting occurrence of recrystallization is as interparticle and intraparticle microsparite surrounding and filling highly fragmented skeletal debris (Figure 12C) such as the walls of mollusks, forams, brachiopods skeletal fragments, ostracods, spines, bryozoa internal features, and coralline algae radiating features. This type of recrystallization is particularly abundant in the pelleted, skeletal-bearing, dolomitic, mudstone-wackestone and the skeletal packstone to grainstone facies.

Secondary Porosity

The processes used to describe creation and modification of pore spaces and the zones in which they operate for the Salter Member are those defined by Choquette and Pray (1970). The traditional time terms related to the various basic porosity types in carbonates are "primary" and "secondary." As used in most of the literature and defined by Choquette and Pray (1970), "primary porosity" includes all pore space present immediately after final deposition; "secondary porosity" any pore space created after final deposition.

Diagenetic processes that created porosity in the Salter Member

Dissolution appears to be the most important process contributing to the origin of porosity in the Salter Member. It may occur on a large scale, as in the evaporite solution breccia facies; or on a smaller scale, as in the finer muddy fraction of the other facies. Dissolution in the Salter is mainly selective but is also nonselective. Dissolution effects are evident in the Salter Member as: (1) irregular leaching of original mud (Figures 10E, 10F), and (2) extensive leaching of gypsum, anhydrite and dolomite rhombs by fresh water producing molds of gypsum and anhydrite and dolomite ghosts, as well as extensive cavities, some of them large enough to allow the formation of collapse breccias. Dissolution is very minor and highly localized in the skeletal packstone to grainstone facies.

The vug types found in the Salter and their distribution in each facies are given in Table 3. As can be seen from this table, vugs show a great variety of occurrence, size, and shape. Fractures are abundant and predominantly fine, thin and vertical in orientation, although horizontal, oblique and branching types are also present. In general, the fractures in the Salter show a great variety of thicknesses ranging from 0.07 mm to several millimeters wide. Approximately 75% of the fractures observed exhibit some degree of porosity, ranging from being completely open to partially filled (Figure 3B), with a few of them showing cement crystal size increases away from the walls. These fractures, when combined with intercrystalline porosity in the matrix and interconnecting vugs, form systems that greatly increase the rock porosity. Fracturing is particularly extensive in the various mudstone facies and in the brecciated facies. Two of the more prominent types of fracturing observed in the Salter are: (1) irregular fracturing developing into channel fracturing (Figures 10C, 10E), and (2) modifications and enlargement of fractures by later dissolution of the walls.

A second episode of fracturing (i.e., refracturing of previous fractures) now filled by calcite cements (Figure 6D) is also observed locally.

<u>Origin and nature of porosity in the Salter Member</u>

The writer believes that, during deposition, sediments of the Salter Member probably had intergranular, intragranular, and intraskeletal microporosity, as well as intraskeletal and possibly biologically induced macroporosity. However, through diagenetic processes this primary porosity has been completely destroyed. Therefore the porosity now observed in the Salter Member is essentially secondary porosity.

The various porosity types observed in the Salter Member and the

Table-3 Porosity of the Salter Member.

Lithofacies	Porosity types
Dolomitic, argillaceous, mudstone — wackestone	Total less 3%. Mainly intercrystalline with very minor vuggy porosity (i.e. irregular shaped and sizes ---1 to 10 cm, birdseye to subrounded and few large vugs greater than few cm); very minor fracture porosity.
Dolomitic, quartz bearing, mudstone — wackestone	Total 3 to 10%. Essentially good intercrystalline and minor vuggy porosity (i.e. irregular shaped and sizes vugs--0.25 to 2.5 mm, tiny eye to subrounded).
Evaporite solution breccia	Total 5 to 30%. Very good vuggy, irregular, fracture, channel, interfragmental, intraparticle porosities with good intercrystalline porosity in mud material. Vuggy porosity is extensive and of variable sizes--few mm to several cm-- and shapes--eye, large subspherical, subrounded, elongated, flattened and irregular.
Skeletal packstone to grainstone	Total 5 to 10%. Good interparticle, intraparticle, intercrystalline and fenestral porosities. Very minor vuggy porosity (i.e. tiny eye) is present.
Pelleted, skeletal bearing, dolomitic, mudstone — wackestone	Total 3 to 10%. Mostly intercrystalline porosity with good interparticle, intraparticle and moldic porosities as well as minor irregular, vuggy (tiny eyes), fenestral and fracture porosities.
Quartz siltstone	Total less 3%. Mainly intercrystalline and minor fracture porosities.

total porosity percentage for each facies are listed in Table 3. In general, porosity is more important in the evaporite sollution breccia facies. Lesser but still good porosity is observed in the skeletal packstone to grainstone and in the pelleted, skeletal-bearing, dolomitic, mudstone-wackestone facies. Otherwise, porosity is very minor and mainly intercrystalline.

The most common porosity present in the Salter is the intercrystalline type (Figure 10A). It is observed in all facies in varying degrees and is mainly concentrated in the finer fraction muddy material, as a result of dolomitization and extensive dissolution.

Vuggy porosity occurring in hollow to partially cemented vugs (Figure 9A) of various sizes and types, and ranging from irregular to subrounded in shapes (Figures 10E, 10F), is present in variable amounts (3 to 25%) in a majority of the facies. However, it is more predominant in the evaporite solution facies which are the most porous rocks in the Salter Member. Some porosity is also observed in small partially cemented voids and birdseye vugs in the dolomitic, argillaceous, mudstone-wackestone facies and in the pelleted, skeletal-bearing, dolomitic, mudstone-wackestone facies. Spectacular but minor amounts of moldic porosities are observed in hollow to partially cemented dolomite rhomb ghosts (Figures 10B, 10C) in the pelleted, skeletal-bearing, dolomitic, mudstone-wackestone facies and in the centers of large bryozoa fragments in the skeletal packstone to grainstone facies.

Fracture porosity is present in all facies in variable amounts, except in the skeletal packstone to grainstone facies where it is virtually absent. It is most prominent in the brecciated facies where it is grading to channel and good interfragmental porosity (Figure 12D), and to a lesser extent in the pelleted, skeletal-bearing, dolomitic, mudstone-wackestone facies as partially filled vertical fractures related to algal mat-features. In the remaining facies it is generally minor (less than 3%), appearing as partially filled thin vertical fractures.

Factors that reduced porosity in the Salter

Calcite cement is the most common cause of diminished primary and secondary porosity in the Salter Member rocks. Other materials that have acted as cementing agents at one time or another in the Salter are dolomite, silica (detrital quartz and chert), authigenic clay and iron oxide products. It is estimated that all of the original primary porosity, as well as more than half of the secondary porosity, has been destroyed by these various cements.

Sediment compaction is another process that is believed to have played a major role in porosity reduction in the Salter Member. Choquette and Pray (1970) noted that compaction of carbonate sediments leads to water expulsion and volume reduction. They also noted that fine grain sediments undergo enormous losses of porosity and moisture content in the first few feet of burial, whereas medium sand size and coarser sediments are subject to slow continuous compaction with burial. Because of the generally fine grain characteristics of most Salter facies, it is believed that this process was very important in early reduction of primary porosity.

Stylolites and microstylolites are common and well developed in the Salter Member (Figure 12F). They are present to various degrees in all the other facies, with the exception of the quartz siltstone and the skeletal packstone to grainstone facies. They are particularly important in the finer grain facies, such as the dolomitic mudstones. Bathurst

(1975) believes that stylolitization begins early in the diagenetic history of a sediment and is important in promoting induration by supplying cement. Park and Schot (1968) advocate that stylolitization in carbonate rocks usually begins during the deposition of the early bladed cement and ends concordantly with the virtually complete cementation of pore space by late bladed calcite mosaic. So, stylolitization in the Salter is believed to have extended from early to late in the diagenetic history of these sediments.

Dolomitization

In the Salter Member, evidence of selective dolomitization is generally found in the more calcareous and less thoroughly dolomitized facies. Fine grained carbonate is dolomitized in preference to coarser material and, as a result, in the partially dolomitized skeletal mudstone-packstone and packstone to grainstone facies the matrix always shows dolomitization, whereas the skeletal fragments remain unaltered (by dolomitization).

Dolomite in the Salter Member occurs in three size ranges: (1) microcrystalline dolomite (less than 0.005 mm); (2) microspar size dolomite crystals (0.005 to 0.02 mm); and (3) fine to medium crystalline rhombs (larger than 0.02 mm). Dolomite distribution, percentage, and sizes are given in Table 4.

The dolomitic micrite is present in all facies with the exception of quartz siltstone facies. It is particularly abundant as an alteration of the matrix in the various dolomitic mudstone facies. This main micrite is generally darkish brown and is locally extremely dense (finer fraction of Figure 11A). It is extremely equigranular and has very

Table- 4 Dolomitization characteristics of the Salter Member.

Lithofacies	%,sizes and types of dolomite
Dolomitic,argillaceous,mudstone — wackestone	Abundance:10 to 40%,most common 25 to 35%; Size range:0.1to 0.03mm but mostly 0.06mm, micrite > microsparite > fine granular.
Dolomitic,quartz bearing,mudstone — wackestone	Abundance: 25 to 40%,most common 25 to 30%; Size range: 0.2 to 0.02mm but mostly 0.07mm, micrite > microsparite > fine granular.
Evaporite solution breccia	Abundance: 10 to 30%; Size range: less than 0.06mm, micrite ≫ microsparite ≫ fine granular.
Skeletal packstone to grainstone	Abundance: 10 to 35% but mostly 5 to 10%; Size range: 0.3 to 0.02mm mostly 0.07mm, micrite > microsparite.
Pelleted,skeletal bearing,dolomitic mudstone — wackestone	Abundance: 10 to 30% but mostly 15 to 20%; Size range: 0.4 to 0.03mm but mostly 0.07mm, micrite ≃ microsparite+fine granular.
Quartz siltstone	Abundance: less than 1%;only few scattered fine granular rhombs present.

*-----% only include fraction greater than 0.02mm, to obtain total % of dolomite add 25 to 40% for the microsparite-micrite fraction (less than 0.02mm in diameter rhombs).

little "visible" porosity. Murray (1960), Lucia (1972) and Murray and Lucia (1967) have demonstrated that dolomite distribution is generally controlled by the distribution of lime mud, and they concluded that the type of rocks most susceptible to dolomitization were originally lime mud with scattered fossil fragments or lime sand with all the interparticle area filled with lime mud. This interpretation can be applied to the origin of the dolomitic micrite of the Salter.

Dolomitic microsparite is present in the same facies as the dolomitic micrite. However, its occurrence is greater in the various dolomitic mudstone-wackestone facies. Several of the coarser rhombs exhibit opaque core with clear margins. This dolomitic microsparite may be the result of selective recrystallization (aggrading neomorphism) of dolomitic micrite material. This selectivity is believed to be due to permeability differences or to greater reactivity to dolomitizing water of fine grained sediment.

As in the previous two types, the fine-medium crystalline rhombs also occur in most facies of the Salter Member (see Table 4). Most rhombs are subhedral ranging to anhedral and they appear to be cloudier and dirtier looking than the microsparite dolomite (Figure 11C). Most rhombs show more or less well-defined rusty or opaque cores with clear overgrowths (Figure 11C). These rhombs generally have very-well defined borders and very well-developed rhombic shape. A few of the larger rhombs enclose finer, earlier dolomite rhombs.

Dolomitization in the Salter has created and altered several fabrics. Laminations caused by amount and size variations of dolomitic microsparite have been observed in a few facies but are particularly important in the dolomitic, argillaceous, mudstone-wackestone facies. In these laminations (of variable thicknesses) fine detrital quartz sand occurs in greater quantity with the coarser dolomite material (Figure 3F). Relics of algal laminations observed in the pelleted, skeletal-bearing, dolomitic, mudstone-wackestone facies also show this differential size occurrence of dolomitic material. These laminated fabrics probably simply reflect original laminations. In some facies original textures are vaguely indicated by shadowy allochem ghosts (Figure 11B). In some cases, pellets are progressively obscured as the percentage of dolomitization increases (Figure 9C), while in other instances microsparite dolomite concentration suggests the former presence of burrows, pelletoids, or other primary features now unrecognizable as a result of dolomitization (Figure 11B).

Porosity as a result of dolomitization is very difficult to evaluate visually in the Salter and therefore remains an unknown. The only sure way to resolve this dilemma would be to measure it by mechanical-fluidal methods, since visual evaluation is totally inaccurate.

It is suggested that, in the Salter, the thickness of the dolomitization zones may have been controlled by the original porosity, permeability, and environmental position on the model. The dolomitization of strata in the Salter Member is believed to have taken place by seepage refluxion of hypersaline brine during deposition. The close association of the dolomites with supratidal sediments and the presence of evaporite mineral molds in such dolomites imply that these were dolomitized by downward-seeping magnesium-rich brines formed in a supratidal environment. Dolomitization by seepage refluxion of hypersaline brine in modern environments has been documented by Buller (1973), Illing et al. (1965), Bush (1973), Atwood and Bubb (1970), and Deffeyes et al. (1965).

Although the reflux brine theory does not explain the associated dolomitized subtidal and marine echinoderm-bryozoan carbonate rocks (Kinsman and Patterson, 1973) similar to those found in some sections of the Salter, the reflux brine theory of dolomitization explains the close stratigraphic relation of intertidal microdolomite and adjacent dolomitized bryozoan-echinoderm wackestones and packstones that are observed locally in the Salter. This theory is believed to be generally satisfactory for the dolomitization in the Salter. This theoretical carbonate depositional model illustrates very well the close interplay of subsidence and carbonate production, development of hypersaline brines in the offlap intertidal-supratidal environments, and reflux dolomitization and porosity development very similar to the Salter.

The characteristics and distribution of the three types of dolomites provide evidence for an early stage of penecontemporaneous dolomitization associated with shifting supratidal environments. Although there is little evidence for it, it is possible that a later continuing stage of post-depositional dolomitization, possibly by Mg-rich ground water associated with migration of the saltwater-freshwater interface, took place in the Salter.

Silicification

Silification is a common feature in all facies of the Salter Member as indicated by the abundance of chert nodules, areas of partially silicified dolomite and limestone, and the presence of chert-replaced fossil fragments.

Microcrystalline silica is observed locally as partial replacement of calcareous and/or dolomitic mud in the dolomitic, argillaceous and the dolomitic, quartz-bearing, mudstone-wackestone facies. Microcrystalline silica is also observed as intercrystalline and interparticle replacement around pellets and other muddy features in the pelleted, skeletal-bearing, dolomitic, mudstone-wackestone facies and as filling in some fractures and centers of large vugs partially cemented by calcite in the evaporite solution breccia facies. In the skeletal packstone to grainstone facies, silica occurs as intraparticle and moldic replacement in fossil fragments (Figures 12B, 12C). Silicification of spicules, crinoids, brachiopods, ostracods, and foram fragments (Figure 12C) is also observed in general in the Salter in minor amounts. Fossil fragments always show better silicification than the carbonate mud matrix (Figure 12B).

The writer believes that two generations of chert have taken place in the Salter Member. One of these was an early chert formed during deposition and early compaction and the other one was a later chert formed during and after lithification of the carbonate but prior to or during dissolution leading to brecciation and collapsing.

Chert occurring lining or filling fractures and carbonate laminations terminating abruptly against chert nodules are good indicators of early chert. Chert material with microsparite calcite inclusion, chert crystals filling centers of partially calcite-cemented vugs, fracturing and shattering of calcite material in contact with chert material, and inclusions of dolomite rhombs in chert crystals all show that silicification came after most of the calcite cementation and are good indicators of the later chert.

Although there is little direct evidence, detrital silt and sandy quartz (probably from eolian but also marine origin) appear to be the most probable source of silica for the early chert. Silica produced by reactions between clay minerals and water could also have been a source of silica to early chert. Variation in pH may have been the main control for the silica redistribution. According to Banks (1970), a pH of 10.2 causes dissolution of detrital silica; lowering of the pH and evaporation of the precipitation waters could have caused precipitation of the chert. Possible(?) sources of silica for the late chert might have been: (1) silica from leached silicious tests (i.e., sponge spicules); (2) detrital quartz; (3) silica derived from reactions between clay mineral and water, or (4) extra-formational silica. Whatever the source, silica was deposited as amorphous silica probably from atmospheric access to the ground water, resulting in supersaturation of amorphous silica by evaporation at the water-air interface (Banks, 1970).

The relation of the various chert occurrences to the sediments of the Salter indicates that the silica is diagenetic in origin and that some of it was precipitated during the early burial stage. Many chalcedony crystals were checked optically to see if they were of a length-slow nature. Unfortunately, these observations were not definitely conclusive, since some crystals showed some of the optical characteristics of length-slow chalcedony while others did not. Sulphate replacement by chalcedony suggests, however, that this chalcedonic silica precipitated in an evaporitic environment or during later removal of evaporites.

Time relationships of diagenetic processes and products

The relative time relationships of the diagenetic processes and products observed in the various Salter Member facies are summarized in

Table 5. Because of the great difficulties encountered in interpreting the occurrence of each diagenetic process individually, environmental boundaries between the various stages of diagenesis have not been attempted.

The considerable overlapping of the processes shown in Table 5 reflects well the complexities of the environmental model we are dealing with in the Salter. In most cases bed-to-bed or regional differences at the time diagenetic changes took place show extensive overlapping and simultaneous activities of two or more diagenetic processes. The termination of one process indicating the beginning of a new process and/or independent alteration showing no overlapping are clearly indicated only in a few cases.

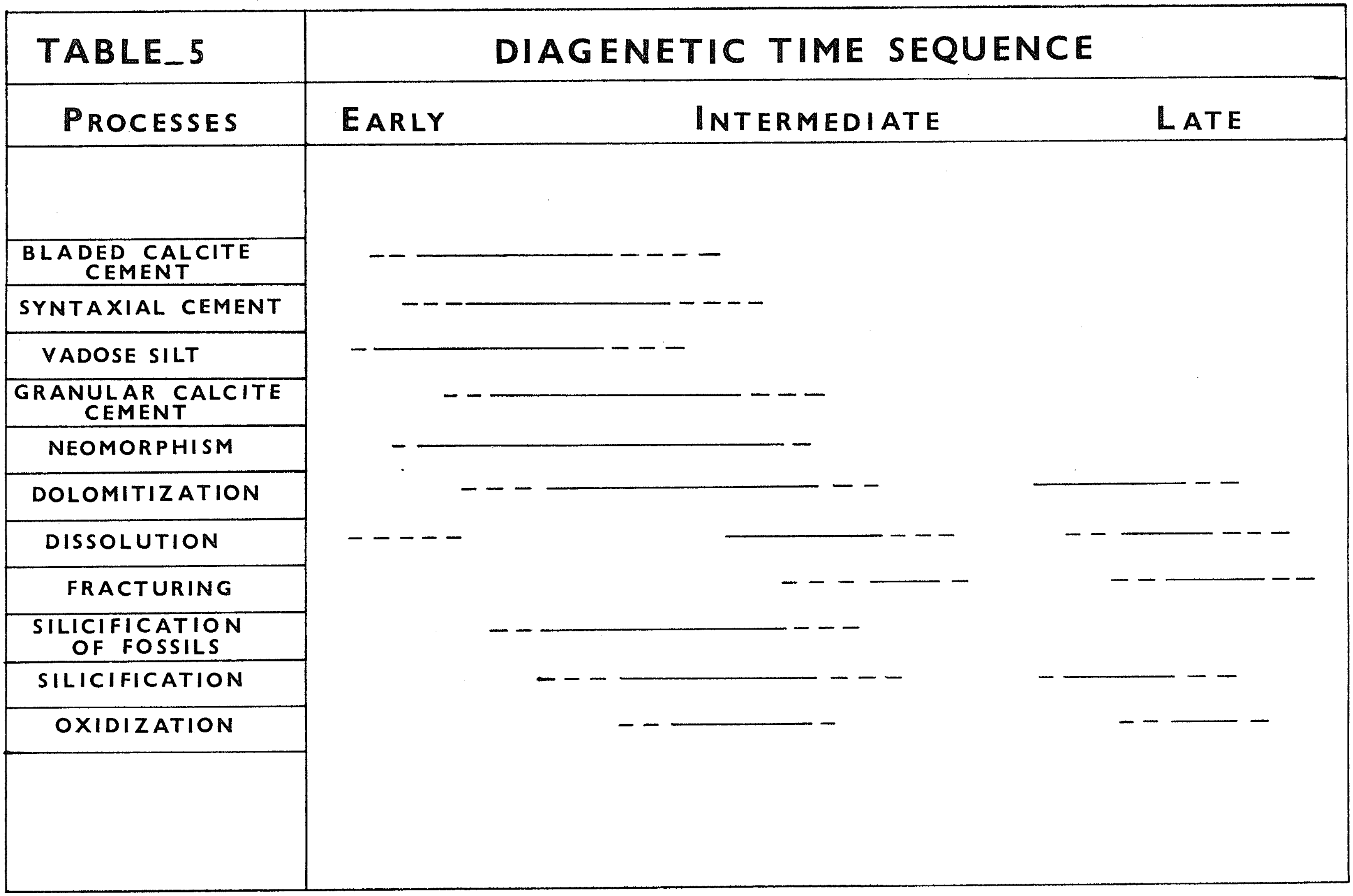


TABLE_5
DIAGENETIC TIME SEQUENCE
PROCESSES
EARLY
INTERMEDIATE
LATE
BLADED CALCITE CEMENT
SYNTAXIAL CEMENT
VADOSE SILT
GRANULAR CALCITE CEMENT
NEOMORPHISM
DOLOMITIZATION
DISSOLUTION
FRACTURING
SILICIFICATION OF FOSSILS
SILICIFICATION
OXIDIZATION

FIGURE 9

Diagenesis: Cementation

9A. Fringing equant granular and bladed calcite cement rimming and partially filling vugs. Good porosity occurs in vug centers. Scale bar .25 mm.

9B. Microscopic view of sabkha cycle "varve-like" couplets of 5D. Laminations are composed of alternating coarse granular and very fine granular equant sparry calcite cements. Rosette-shaped greyish chert nodules invade and disrupt laminations. Scale bar 1 mm.

9C. Equant calcite cement filling birdseye vugs. Pelleted micrite inferred from occurrence of interparticle microsparite dolomite rhombs. Scale bar .25 mm.

9D. Fringing equant granular and bladed calcite cements totally filling large vugs. Scale bar .25 mm.

9E. Subrounded vugs and related vertical microfractures showing complete cementation by fine equant calcite cement. Micritic mud material exhibits good irregular fracture porosity developing into channel porosity. Scale bar 1 mm.

9F. Syntaxial overgrowth calcite cement surrounding echinoid stem. The syntaxial cement shows dolomite rhomb inclusion. Scale bar .1 mm.

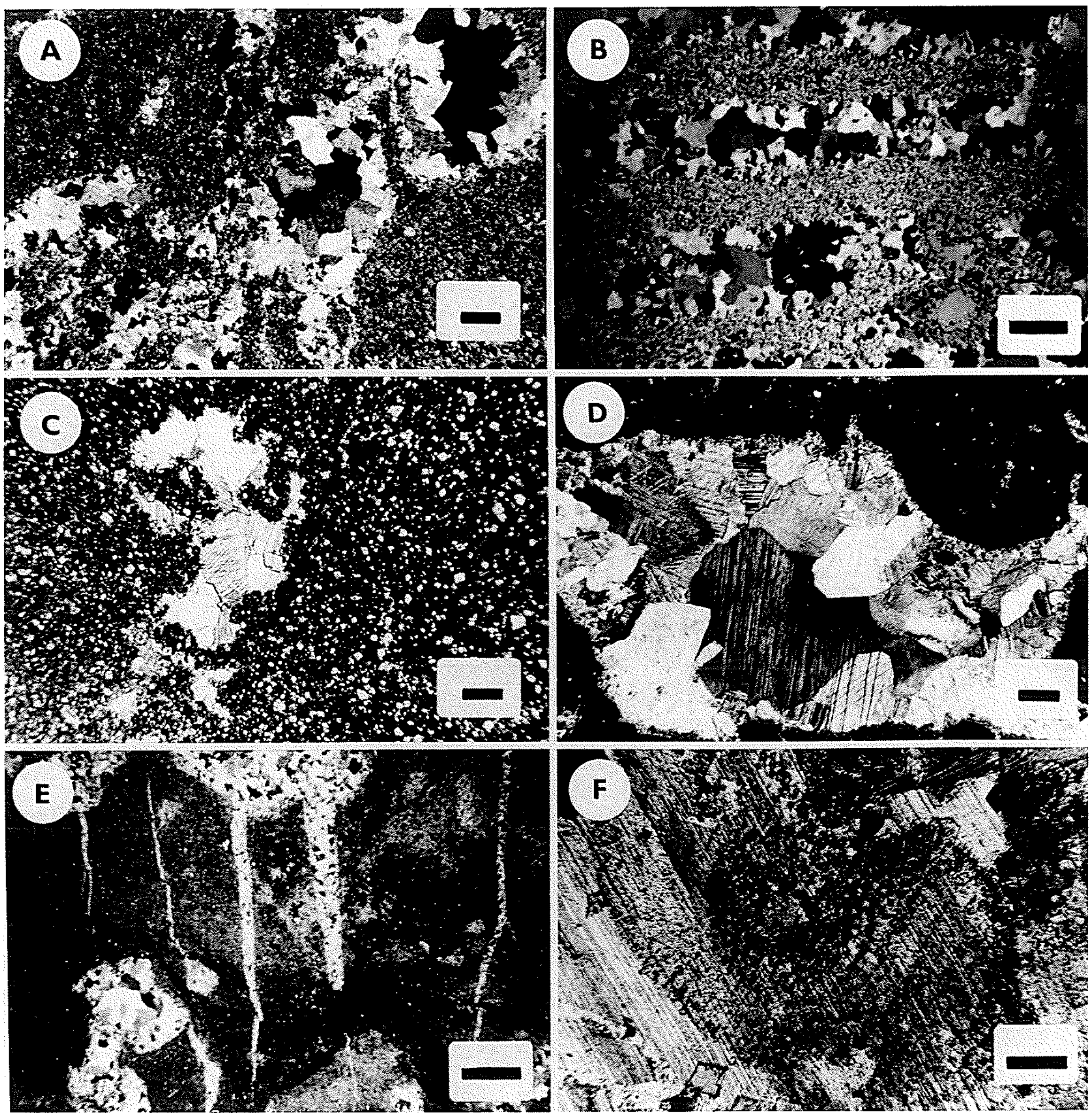

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FIGURE 10

Diagenesis: Secondary porosity

10A. Euhedral to subhedral fine to coarse microsparite and fine to medium granular dolomite rhombs occurring in a mosaic exhibiting good intercrystalline porosity originating from dolomitization. Scale bar .1 mm.

10B. Intraparticle and moldic porosities in partially cemented dolomite rhombs and gypsum ghosts. Scale bar .25 mm.

10C. Minor intraparticle and moldic porosities in partially cemented and hematite-stained gypsum ghosts occurring in fractured mud ridges surrounding several calcite cemented vugs. Scale bar .25 mm.

10D. Intercrystalline and interfragmental porosities in mud micrite as a result of dissolution and brecciation. Scale bar .25 mm.

10E. Intercrystalline, fracture, channel, and vuggy (in partially filled vugs) porosities resulting from extensive dissolution and brecciation. Scale bar .25 mm.

10F. Good vuggy porosity in hollow vugs. Cement is essentially fine equant granular calcite cement rimming pores. Scale bar .25 mm.

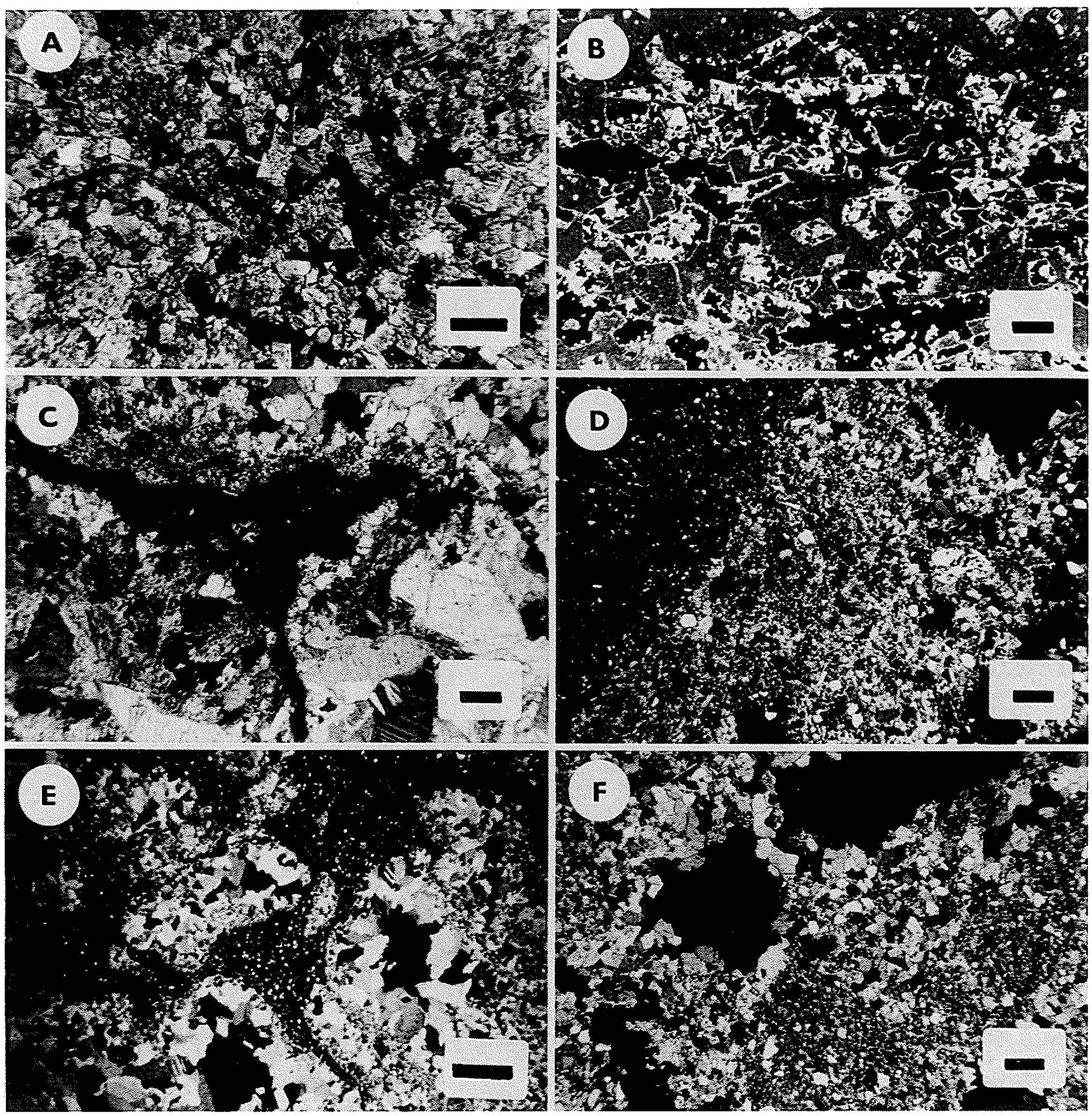
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FIGURE 11

Diagenesis:

Dolomitization, Neomorphism, Vadose Silt

11A. Euhedral to subhedral fine to coarse microsparite dolomite rhombs and crystals floating in a denser finer dolomitic micrite. Scale bar .1 mm.

11B. Euhedral to subhedral fine to coarse microsparite dolomite. Dolomitization has destroyed primary features; some remnants of original textures are vaguely indicated by shadowy allochem ghosts. Scale bar .1 mm.

11C. Euhedral to anhedral fine to medium granular dolomite rhombs, some having opaque and/or dirty cloudy cores with clear overgrowths, floating in a finer grained (mostly micritic) muddy dolomitic matrix. Scale bar .1 mm.

11D. Neomorphism of calcitic micritic mud to calcite microsparite mosaic. Scale bar .1 mm.

11E. Burrowing resulting in micritization. Scale bar .25 mm.

11F. Vadose silt sediment at the bottom of vug. The silt is underlain and overlain by different generations of calcite cements. Scale bar .1 mm.

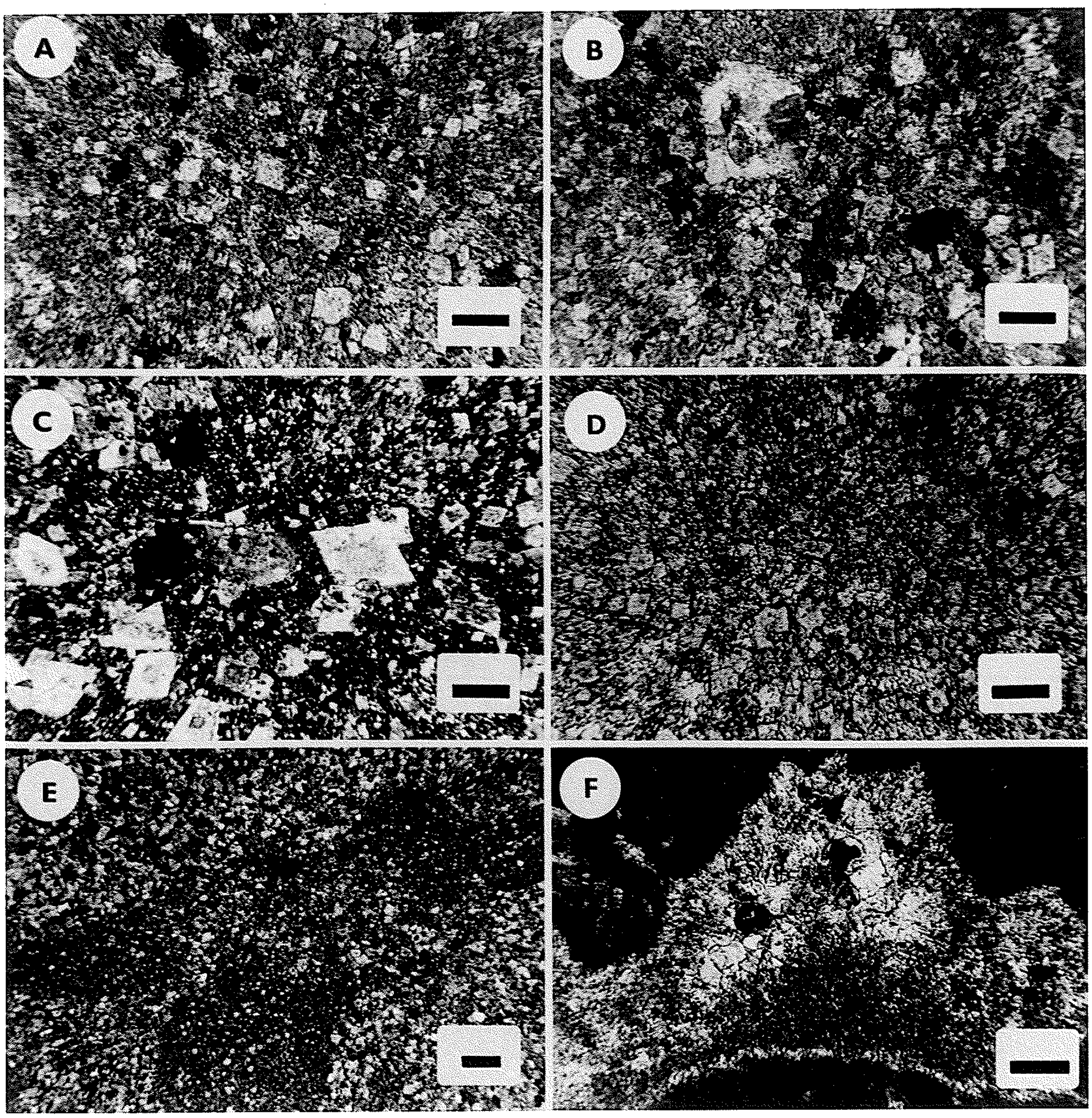
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FIGURE 12

Diagenesis:

Silicification, Oxidation/Pyritization

12A. Rosette-shaped chert nodules (of 11B) having inclusion of very fine subrounded pyrite grains. Grains are also observed in the surrounding granular calcite cement. Scale bar .25 mm.

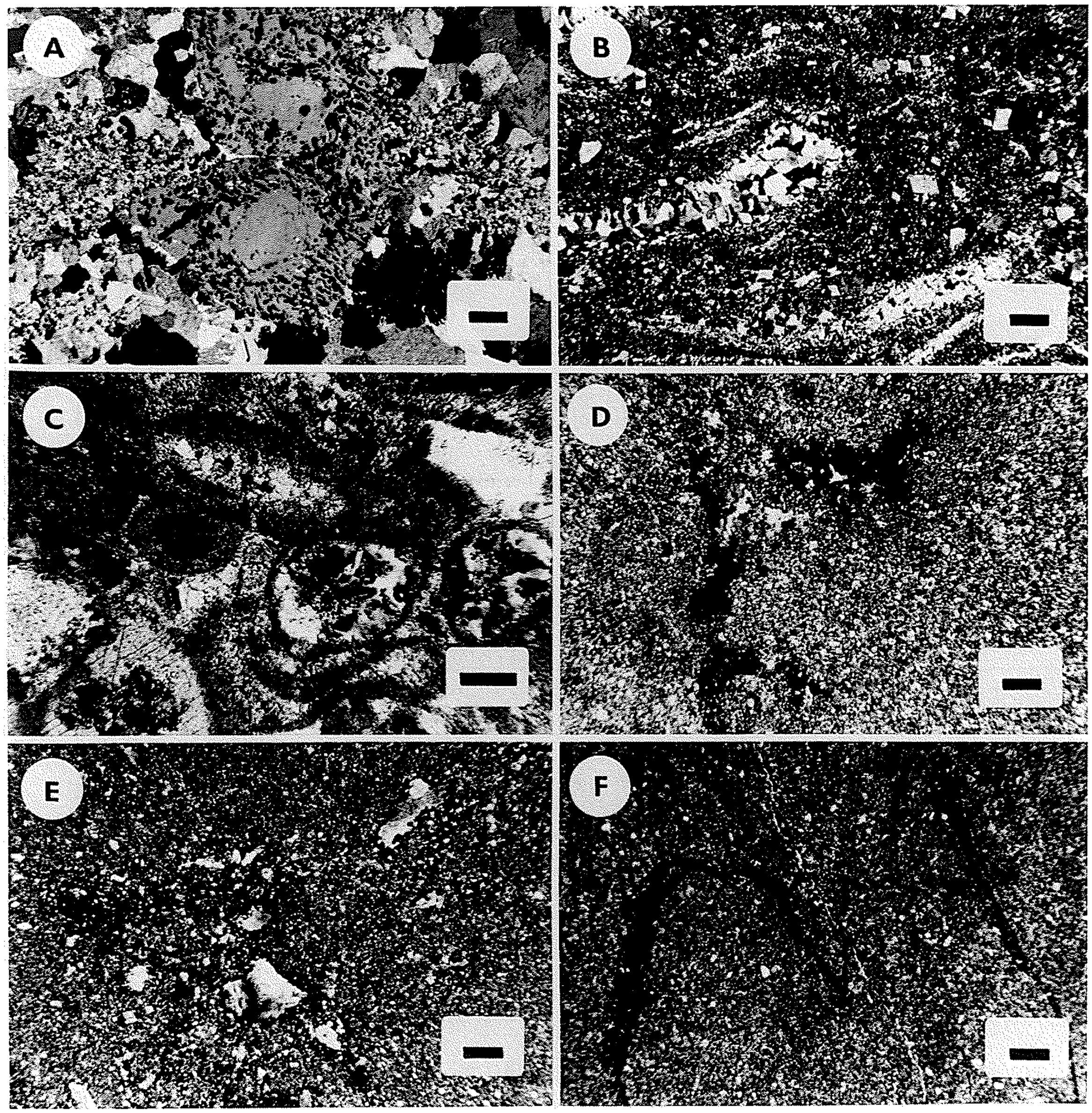
12B. Intraparticle and moldic silica cement (chalcedonic quartz) in brachiopods and other unidentified skeletal fragments. Micrite matrix has also been heavily silicified by microcrystalline silica. Scale bar .25 mm.

12C. Intraparticle and moldic replacement of various skeletal debris (crinoids, forams) by microcrystalline silica and neomorphic calcite microsparite. The calcite microsparite also occurs as interparticle cement between debris material. Scale bar .1 mm.

12D. Scattering of silt size iron oxide grains in dolomitic micrite and fillings of fractures and birdseye vugs by iron oxide staining. Scale bar .25 mm.

12E. Scattering of silt size pyrite grains in dolomite micrite and iron oxide staining cementation surrounding calcite-filled micro-vugs or interstitial leaching. Scale bar .25 mm.

12F. Iron oxide staining totally occluding a horizontal (parallel to bedding) seismogram type microstylolite. Scale bar .25 mm.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CHAPTER 5

CONCLUSION

Detailed studies at the Highwood River and Plateau Mountain sections of the Salter Member can be summarized as follows.

1) The lithofacies present are, in order of decreasing abundance:

- dolomitic, argillaceous, mudstone-wackestone;
- dolomitic, quartz-bearing, mudstone-wackestone;
- evaporite solution breccia;
- skeletal packstone to grainstone;
- pelleted, skeletal-bearing, dolomitic, mudstone-wackestone;
- quartz siltstone.

2) The depositional facies represented in the Salter Member exhibit several relative transgression-regression and/or progradation episodes ranging from subtidal to intertidal to supratidal environments. Carbonates accumulation conditions are those of an Epeiric Sea model. Modern counterparts are believed to be sabkha environments from the Persian Gulf.

Depositional facies ranging from thickly bedded, relatively mud-free, shallow subtidal echinoderm-bryozoa skeletal packstones and grainstones through thinly bedded, extremely extensive, finely crystalline subtidal to supratidal dolomitic mudstone-wackestone showing algal-mat textures and thin units of quartz siltstone facies are also observed. Conspicuous sollution breccias and a number of thin carbonate-evaporite sabkha cycles are evident at Highwood River and at Plateau Mountain respectively.

3) The greater sediments thickness at the Plateau Mountain section, as well as the more numerous occurrences of various skeletal facies, the better defined and fewer leached and collapsed cycles observed in this section seem to indicate a thickening of the sediment deposition from

Highwood River to Plateau Mountain. This greater in situ sediment accumulation suggests a possible gap in the depositional time line or a different rate of deposition at each section. The Plateau Mountain section was probably located in a more seaward direction than the Highwood River section on the Epeiric Sea environment. Correlation between the two sections whether on a lithofacies or an events basis remains highly speculative.

4) The sequence of sedimentation in the Salter contains few fabrics indicative of significant periods of subaerial exposure. Evidences consist of a few sharp erosion surfaces, thin but laterally persistent horizons of small, irregular solution vugs, and cacities with internal vadose silt(?) sediment.

5) Early cementation, most obvious in the coarser grained facies, is characterized by drusy rims of equant sparry calcite and large, probably penecontemporaneous, syntaxial overgrowths. However, skeletal grains enclosed by a micritic matrix generally do not exhibit these early cements. This matrix, as well as horizons interpreted to have originally been primarily mudstone, has to a large extent been selectively dolomitized. Later, ferroan and non-ferroan blocky granular calcite spar occluded much of the remaining pore space.

6) Intercrystalline porosity, mainly in the dolomitic horizons, some intraparticle, irregular, and moldic secondary vug porosities, and open fractures developing locally into partial to hollow channels give locally good porosity to the Salter Member.

BIBLIOGRAPHY

Armstrong, A. K., 1973, Carboniferous tidal flat deposits of the North Flank, Northeastern Brooks Range, Arctic Alaska; Tidal Deposits, N. James ed., pp. 106-110.

____, 1973, Mississippian tidal deposits North-Central New Mexico; Tidal Deposits, N. James ed., pp. 100-105.

Atwood, D. K., and Bubb, J. N., 1970, Distribution of dolomite in a tidal flat environment, Sugarloaf Key, Florida: Jour. Geol., v. 78, pp. 499-505.

Ball, S. M., Roberts, J.W., Norton, J.A., and Pollard, W. D., 1971, Queen Formation (Guadalupian, Permian) outcrops of Eddy County, New Mexico, and their bearing on recently proposed depositional models: Am. Assoc. Petroleum Geologists, Bull., v. 55, no. 8, pp. 1348-1355.

Bally, A. W., Gordy, P. L., and Stewart, G. A., 1966, Structure, seismic data, and orogenic evolution of the southern Canadian Rocky Mountains: Bull. Can. Petrol. Geol., v. 14, no. 3, pp. 337-381.

Banks, N. G., 1970, Nature and origin of early and late cherts in the Leadville Limestone, Colorado: Geol. Soc. Amer., Bull., v. 81, pp. 3033-3048.

Bathurst, R. G. C., 1975, Carbonate sediments and their diagenesis: Developments in Sedimentology 12, Elsevier Publ. Co., N. Y., 658 pp.

Beales, F. W., 1965, Diagenesis in pelleted limestones: Dolomitization and limestone diagenesis, a symposium; L. C. Pray and R. C. Murray eds., Soc. Econ. Paleontol., and Min., Spec. Pub. no. 13, pp. 49-70.

____, and Oldershaw, A. E., 1969, Evaporite-solution brecciation and Devonian Carbonate reservoir porosity in Western Canada: Carbonate Rocks 2, Porosity and Classification of reservoir rocks, Am. Assoc. Petroleum Geologists, Repr. Ser., no. 5, pp. 134-143.

Bebout, D. G., and Maiklem, W. R., 1973, Ancient anhydrite facies and environments; their role in reconstructing geologic history of the middle Devonian Elk Point Basin, Alberta (abstr.): Am. Assoc. Petroleum Geologists, Bull., v. 57, no. 4, pp. 769-770.

Bush, P., 1973, Some aspects of the diagenetic history of the Sabkha in Abu Dhabi, Persian Gulf: The Persian Gulf, B. H. Purser ed., Springer-Verlag, N. Y., pp. 395-407.

Butler, G. P., 1969, Modern evaporite deposition and geochemistry of co-existing brines, the sabkha, Trucial Coast, Abrian Gulf: Journ. Sed. Petrology, v. 39, pp. 70-89.

Chilingar, G. V., Bissell, H. J., and Wolf, K. H. eds., 1967, Diagenesis in Carbonate Rocks, Development in Sedimentology, no. 8, Diagenesis in Sediments, Elsevier Publ. Co., pp. 179-321.

Choquette, P. W., and Pray, L. C., 1970, Geologic nomenclature and classification of porosity in carbonate sediments: Am. Assoc. Petroleum Geologists, Bull., v. 54, pp. 207-250.

Deffeyes, K. S., Lucia, J., and Weyl, P. K., 1965, Dolomitization of Recent and Plio-Pleistocene sediments by marine evaporite waters on Bonaire, Netherlands Antilles: Dolomitization and limestone diagenesis, a symposium; L. C. Pray and R. C. Murray eds., Soc. Econ. Paleontol., and Min., Spec. Pub. no. 13, pp. 71-88.

Dickson, J. A. D., 1966, Carbonate identification and genesis as revealed by staining: Journ. Sed. Petrology, v. 36, pp. 491-505.

Douglas, R. J. W., 1953, Carboniferous stratigraphy in the southern foothills of Alberta: Alberta Soc. Petroleum Geologists, Guide Book, Third Ann. Field Conf., pp. 68-88.

____, 1958, Mount Head map area, Alberta: Geol. Surv. Can., Mem. 291.

____, and Harker, P., 1958, Mississippian succession in Mount Head area, Alberta: Jurassic and Carboniferous of western Canada, Am. Assoc. Petroleum Geologists, Bull., v. 42, pp. 177-189.

Dunham, R. J., 1962, Classification of carbonate rocks according to depositional texture: Classification of carbonate rocks, a symposium; W. E. Ham ed., Am. Assoc. Petroleum Geologists, Mem. no. 1, pp. 108-121.

____, 1969, Early vadose silt in Townsend Mound (Reef) New Mexico: Depositional environments in carbonate rocks, G. M. Friedman ed., Soc. Econ. Paleontol., and Min., Spec. Pub., no. 14, pp. 139-181.

Evamy, B. D., 1973, The precipitation of aragonite and its alteration to calcite on the Trucial Coast of the Persian Gulf: The Persian Gulf, B. H. Purser ed., Springer-Verlag, N. Y., pp. 329-341.

____, and Shearman, D. J., 1965, The development of overgrowths from echinoderm fragments: Sedimentology, v. 5, pp. 211-233.

Evans, G., Schmidt, V., Bush, P., Nelson, H., 1969, Stratigraphy and geologic history of the sabkha, Abu Dhabi, Persian Gulf: Sedimentology, v. 12, pp. 145-159.

Folk, R. L., 1965, Some aspects of recrystallization in ancient limestones: Dolomitization and limestone diagenesis, a symposium; L. C. Pray and R. C. Murray eds., Soc. Econ. Paleontol., and Min., Spec. Pub., no. 13, pp. 14-49.

____, and Pittman, J. S., 1971, Length-slow chalcedony; a new testament for vanished evaporites: Journ. Sed. Petrology, v. 41, pp. 1045-1058.

Friedman, G. M., and Braun, M., 1973, Tidal origin of the Tribes Hill Formation (Lower Ord.) of the Mohawk Valley, New York: Tidal Deposits, N. James ed., pp. 37-42.

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

Gebelein, C. D., 1969, Distribution, morphology, and accretion rate of recent subtidal algal stromatolites, Bermuda: Journ. Sed. Petrology, v. 39, pp. 49-69.

Hardie, L. A., and Eugster, H. P., 1971, The depositional environment of marine evaporites; a case for shallow, clastic accumulation: Sedimentology, v. 16, pp. 187-220.

Havard, C., and Oldershaw, A., 1976, Early diagenesis in back-reef sedimentary cycles, Snipe Lake Reef Complex, Alberta: Bull. Can. Petrol. Geol., v. 24, pp. 27-69.

Heckel, P. H., 1972, Recognition of ancient shallow marine environments: Recognition of Ancient Sedimentary Environments, J. K. Rigby and W. K. Hamblin eds., Soc. Econ. Paleontol., and Min., Spec. Pub., no. 16, pp. 226-286.

Illing, L. V., Wells, A. J., and Taylor, J. C. M., 1965, Penecontemporaneous dolomite in the Persian Gulf: Dolomitization and limestone diagenesis, a symposium; L. C. Pray and R. C. Murray eds., Soc. Econ. Paleontol., and Min., Spec. Pub., no. 13, pp. 89-111.

Irwin, M. L., 1965, General theory of epeiric clear water sedimentation: Am. Assoc. Petroleum Geologists, Bull., v. 49, pp. 445-459.

Kendall, C.G.S.C., 1969, An environmental reinterpretation of the Permian evaporite/carbonate shelf sediments of the Guadalupe Mountains: Geol. Soc. Amer., Bull., v. 80, pp. 2503-2526.

____, and Skipwith, Sir P. A., 1969, Holocene shallow-water carbonate and evaporite sediments of Khor al Bazam, Abu Dhabi, southwest Persian Gulf: Am. Assoc. Petroleum Geologists, Bull., v. 53, pp. 841-869.

Kerr, S. D., and Thomson, A., 1973, Origin of nodular and bedded anhydrite in Permian shelf sediments, Texas and New Mexico: Marine-Evaporites-origin, diagenesis and geochemistry; D. W. Kirkland and R. Evans, D. H. and R. Pub., pp. 51-57.

Kindle, E. M., 1924, Standard Paleozoic section of the Rocky Mountains near Banff, Alberta: Pan-Am. Geol., v. 42, pp. 113-124.

Kinsman, D. J. J., 1971, Diagenetic history of limestones determined from Sr distribution: Carbonate Cements, O. P. Bricker ed., John Hopkins Pub., pp. 259-263.

____, 1966, Gypsum and anhydrite of recent age, Trucial Coast, Persian Gulf: Second Symposium on Salt, 1, J. L. Rau ed., Northern Ohio Geol. Soc., Cleveland, Ohio, pp. 302-326.

____, 1969, Modes of formation, sedimentary association, and diagnostic features of shallow-water and supratidal evaporites: Am. Assoc. Petroleum Geologists, Bull., v. 53, pp. 830-840.

____, 1964, The recent carbonate sediments near Halat el Bahrani, Trucial Coast, Persian Gulf: Deltaic and shallow marine deposits, L.M.J.U. Van Straaten ed., Elsevier Pub., Amsterdam, pp. 185-192.

____, Park, R. K., and Patterson, R. J., 1971, Sabkhas; studies in recent carbonate sedimentation and diagenesis, Persian Gulf (abstr.): Geol. Soc. Amer., Abstr., v. 3, pp. 772-774.

____, and Patterson, R. J., 1973, Dolomitization process in sabkha environment (abstr.): Am. Assoc. Petroleum Geologists, Bull., v. 57, pp. 788-789.

Land, L. S., Salini, M. R. S., and Marron, D. W., 1975, Paleohydrology of ancient dolomites--geochemical evidence: Am. Assoc. Petroleum Geologists, Bull., v. 59, pp. 1602-1625.

Laporte, L. F., 1973, Carbonate tidal flat deposits of the Early Devonian Manlius Formation of New York State: Tidal Deposits, N. James ed., pp. 67-72.

Logan, B. W., Rezak, R., and Ginsburg, R. N., 1964, Classification and environmental significance of algal stromatolites: Jour. Geol., v. 72, pp. 68-83.

Lucia, F. J., 1972, Recognition of evaporite-carbonate shoreline sedimentation: Recognition of ancient sedimentary environments, J. K. Rigby and W. K. Hamblin eds., Soc. Econ. Paleontol., and Min., Spec. Pub., no. 16, pp. 160-191.

Macqueen, R. W., and Bamber, E. W., 1968, Stratigraphy and facies relationships of the upper Mississippian Mount Head Formation, Rocky Mountains and Foothills, Southwestern Alberta: Bull. Can. Petrol. Geol., v. 16, pp. 225-287.

____, 1967, Stratigraphy of Banff Formation and lower Rundle Group (Mississippian), southwestern Alberta: Geol. Surv. Can., Paper 67-47.

____, and Mamet, B. L., 1972, Lower Carboniferous stratigraphy and sedimentology of the southern Canadian Rocky Mountains: 24th Int. Geol. Congr., Montreal Excursion Book C 17, 62 pp.

Maiklem, W. R., Bebout, D. G., and Glaister, R. P., 1969, Classification of anhydrite; a practical approach: Bull. Can. Petrol. Geol., v. 17, pp. 194-233.

Mamet, B. L., 1977, An Atlas of microfacies in Carboniferous Carbonates of the Canadian Cordillera: Geol. Soc. Can., Memoir 255.

____, 1968, Foraminifera, Etherington Formation (Carboniferous), Alberta, Canada: Bull. Can. Petrol. Geol., v. 16, pp. 167-179.

Masson, P. H., 1973, An occurrence of gypsum in Southwest Texas: Marine Evaporites, D. W. Kirkland and R. Evans eds., D. H. and R. Pub., pp. 45-50.

Matter, A., 1968, Tidal flat deposits in the Ordovician of Western Maryland: Recent developments in carbonate sedimentology in central Europe, Springer-Verlag Pub., N. Y., pp. 172-174.

Matthews, R. K., 1968, Carbonate diagenesis: equilibration of sedimentary mineralogy to the subaerial environment, Coral Cap of Barbados, West Indies: Jour. Sed. Petr., v. 38, pp. 1110-1119.

Mazzullo, S. J., and Friedman, G. M., 1975, Conceptual Model of Tidally influenced Deposition on Margins of Epeiric Seas: Lower Ordovician (Canadian) of Eastern New York and Southwestern Vermont: Am. Assoc. Petroleum Geologists, Bull., v. 59, Op. 2123-2141.

McConnell, R. G., 1887, Report on the geological structure of a portion of the Rocky Mountains: Geol. Surv. Can., Ann. Rept., New Series, v. 11, pt. D, pp. 1-41.

McLemore, W. H., 1972, Depositional environments of Mississippian carbonates in Northwest Georgia and Southeast Tennessee: Geol. Soc. Amer., Abstr., v. 4, p. 91.

Mossop, G. D., 1973, Sabkha cycles in the Ordovician of the Canadian Arctic: Geol. Soc. Amer., Abstr., v. 6, no. 7, pp. 879, 1974.

Murray, R. C., 1964, Origin and diagenesis of gypsum and anhydrite: Journ. Sed. Petrology, v. 34, pp. 512-523.

____, 1960, Origin of porosity in carbonate rocks: Journ. Sed. Petrology, v. 30, pp. 59-84.

____, and Lucia, F. J., 1967, Cause and control of dolomite distribution by rock selectivity: Geol. Soc. Amer., Bull., v. 78, pp. 21-36.

Ogniben, L., 1955, Inverse graded bedding in primary gypsum of chemical deposition: Journ. Sed. Petrology, v. 25, pp. 273-281.

Park, W., and Schot, E. H., 1968, Stylolitization in carbonate rocks: Recent developments in carbonate sedimentology in central Europe, G. Muller and G. M. Friedman eds., Springer-Verlag, N. Y., pp. 66-74.

Price, and Mountjoy, E. W., 1970, Geologic structure of the Canadian Rocky Mountains between Bow and Athabasca rivers; a progress report: Structure of the southern Canadian Cordillera, Geol. Assoc. Can., Spec. Paper, no. 6, pp. 7-25.

Purser, B. H., 1969, Syn-sedimentary marine lithification of Middle Jurassic limestones in the Paris Basin: Sedimentology, v. 12, pp. 205-230.

____, and Loreau, J. P., 1973, Aragonitic, supratidal encrustations on the Trucial Coast, Persian Gulf: The Persian Gulf, B. H. Purser ed., Springer-Verlag, N. Y., pp. 374-376.

Roehl, P. O., 1967, Stony Mountain (Ordovician) and Interlake (Silurian) facies analogs of recent low-energy marine and subaerial carbonates, Bahamas: Am. Assoc. Petroleum Geologists, Bull., pp. 1979-2032.

Schenk, P. E., 1967, The Macumber Formation of the Maritime Provinces, Canada--a Mississippian analogue to recent strand-line carbonates of the Persian Gulf: Journ. Sed. Petrology, v. 37, no. 2, pp. 365-376.

Schmidt, V., 1965, Facies, diagenesis, and related reservoir properties in the Gigas Beds (Upper Jurassic), Northwestern Germany: Dolomitization and limestone diagenesis, a symposium; L. C. Pray and R. C. Murray eds., Soc. Econ. Paleontol. and Min., Spec. Pub., no. 13, pp. 124-166.

Schreiber, B. C., 1976, Evaporitic lithofacies and their depositional environments (abstr.): Can. Soc. Petroleum Geologists, Reservoir, pp. 1-2.

Scott, D. L., 1964, Pennsylvanian stratigraphy: Alta. Soc. Petrol. Geol., Guidebook, Fourteenth Ann. Field Conf.: Bull. Can. Petrol. Geol., v. 12, pp. 460-493.

Shaw, A. B., 1964, Time in stratigraphy, McGraw-Hill, N. Y., 365 pp.

Shearman, D. J., 1966, Origin of marine evaporites by diagenesis: Trans. Inst. Mining Met., v. 75, pp. 208-215.

____, 1973, Origin of marine evaporites by diagenesis: Marine Evaporites, D. W. Kirkland and R. Evans eds., D. H. and R. Pub., pp. 61-68.

____, 1963, Recent anhydrite, gypsum, dolomite and halite from the coastal flats of the Arabian shore of the Persian Gulf (abstr.): Geol. Soc. London Proc. 1607, pp. 63-64.

Shimer, H. W., 1926, Upper Paleozoic faunas of the Lake Minnewanka section, near Banff, Alberta: Geol. Surv. Can., Mus. Bull. 42, pp. 1-84.

Shinn, E. A., 1968, Practical significance of birdseye structures in carbonate rocks: Journ. Sed. Petr., v. 38, pp. 215-223.

____, 1968, Selective dolomitization of recent sedimentary structures: Journ. Sed. Petr., v. 38, pp. 612-616.

____, 1973, Recent intertidal and nearshore carbonate sedimentation around rock highs, E. Qatar, Persian Gulf: The Persian Gulf, B. H. Purser ed., pp. 193-198.

____, Lloyd, R. M., and Ginsburg, R. N., 1969, Anatomy of a modern carbonate tidal-flat, Andros Island, Bahamas: Journ. Sed. Petrology, v. 39, pp. 1202-1228.

Smith, D. B., 1974, Sedimentation of Upper Artesia (Guadalupian) Cyclic Shelf Deposits of Northern Guadalupe Mountains, New Mexico: Am. Assoc. Petroleum Geologists, Bull., v. 58, pp. 1699-1730.

Swinchatt, J. P., 1970, Mississippian carbonate facies in northeastern Kentucky; tidal-flat-island complexes on a terrigenous-carbonate shelf (abstr.): Geol. Soc. Amer., v. 2, p. 243.

Thomas, G. E., and Glaister, R. P., 1960, Facies and porosity relationships in some Mississippian carbonate cycles of Western Canada Basin: Am. Assoc. Petroleum Geologists, Bull., v. 44, pp. 569-588.

Thompson, A. M., 1970, Tidal-flat deposition and early dolomitization in upper Ordovician rocks of southern Appalachian Valley and Ridge: Journ. Sed. Petrology, v. 40, pp. 1271-1286.

Tyrrell, W. W., Jr., 1969, Criteria useful in interpreting environments of unlike but time-equivalent carbonate units (Tansill-Capitan-Lamar), Capitan Reef Complex, West Texas and New Mexico: Depositional environments in carbonate rocks, G. M. Friedman ed., Soc. Econ. Paleontol. and Min., Spec. Pub., no. 14, pp. 80-97.

Warren, P. S., 1927, Banff area, Alberta: Geol. Surv. Can., Mem. 153.

Wheeler, J. O., 1970, Introduction in structure of the southern Canadian Cordillera: Geol. Assoc. Can., Spec. Paper no. 6, pp. 1-5.

Young, J. R., and Greggs, R. G., 1975, Diagenesis in Lodgepole Limestones, Southwestern Manitoba: Bull. of Can. Petr. Geology, v. 23, pp. 201-223.