DEPOSITION AND DIAGENESIS OF THE UPPER MOUNT HEAD FORMATION (MISSISSIPPIAN), HIGHWOOD RIVER, ALBERTA

A Thesis

Submitted to

The Faculty of Graduate Studies

The University of Manitoba

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

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by

Keith Stuart Glenday

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ABSTRACT

The Loomis, Marston, and Carnarvon Members of the upper Mount Head Formation were studied at the Highwood River in southwestern Alberta. A single section was measured and sampled in detail. A petrographic study was then done to determine the environment in which these rocks were deposited and their subsequent diagenetic history.

The upper three members of the Mount Head Formation were deposited in a coastal barrier complex ranging from the open marine to the supratidal environment. The Loomis Member was depostied in a high energy barrier complex and consists of oolitic, skeletal, echinoderm, and pelloidal skeletal grainstones.

The Marston Member consists of sediments deposited in an alternating lagoon-intertidal-supratidal setting. The lagoonal rocks of this member are wackestones and mudtones containing abundant ostracodes, algae, and pelloids. The intertidal to supratidal rocks are mud-rich and contain oncolites, evaporites, and fenestral structures.

The Carnarvon Member was deposited predominantly within a lagoonal environment alternating with the intertidal environment. Lagoonal sediments consist

mainly of ostracode algal wackestones and intertidal sediments consist mainly of fenestral mudstones and vertically burrowed mudstones.

Biological alteration is the earliest form of diagenesis in these rocks and began as soon as the sediment was deposited. Burrowing and pellet formation occur within the mud-rich sediments of the Marston and Carnarvon Members. Intense burrowing within the Loomis Member may account for the lack of primary sedimentary structures in that member. Micritization caused by boring algae and fungi occurs predominantly with the grainstones of the Loomis Member.

Both marine and freshwater cements are present. Marine cements observed are acicular isopachous, syntaxial overgrowth, and cloudy blocky. They occur within the grainstones of the Loomis Member and begin precipitating soon after deposition of the sediments. Freshwater cements are clear isopachous and clear blocky and form in the phreatic environment. Alteration of the sediments from high magnesium calcite and aragonite to low magnesium calcite occurs at this time because of the change in pore fluid composition from marine to non-marine.

Dolomitization caused by hypersaline brines begins in the sabkha sediments of the Marston Member and continues after burial in the shallow subsurface during mixing of marine and freshwater pore fluids.

Cementation and dolomitization destroyed all primary and most secondary porosity. Only minor vuggy porosity remains within the Loomis and Marston Members.

Tension fractures associated with thrust faulting have been cemented tight by clear blocky cement.

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INTRODUCTION

INTRODUCTION

Within the Western Canada Sedimentary Basin, carbonate rocks contain important accumulations of hydrocarbons. Because of the unstable nature of carbonate sediments outside of the normal marine environment, they are very susceptible to diagenetic alteration. These diagenetic alterations more often than not reduce the porosity and permeability during lithification and greatly influence the quality of potential reservoirs. However, relatively few studies have been conducted which concern themselves with the diagenesis of the Mississippian rocks in Western Canada.

The study area is located 84 kilometres southwest of Calgary in the Highwood Range. Access is by hard top and gravel road for 28 kilometres west of Longview, Alberta on secondary road 541 (see Figure 1).

The 130 metre section includes the Middle to Late Visean Loomis, Marston, and Carnarvon Members of the Mount Head Formation, Rundle Group (see Figure 2). The section was measured on the cliff-forming, leading edge of a thrust sheet at Douglas' (1958) type section of the Wileman, Baril, Salter, and Loomis Members of the

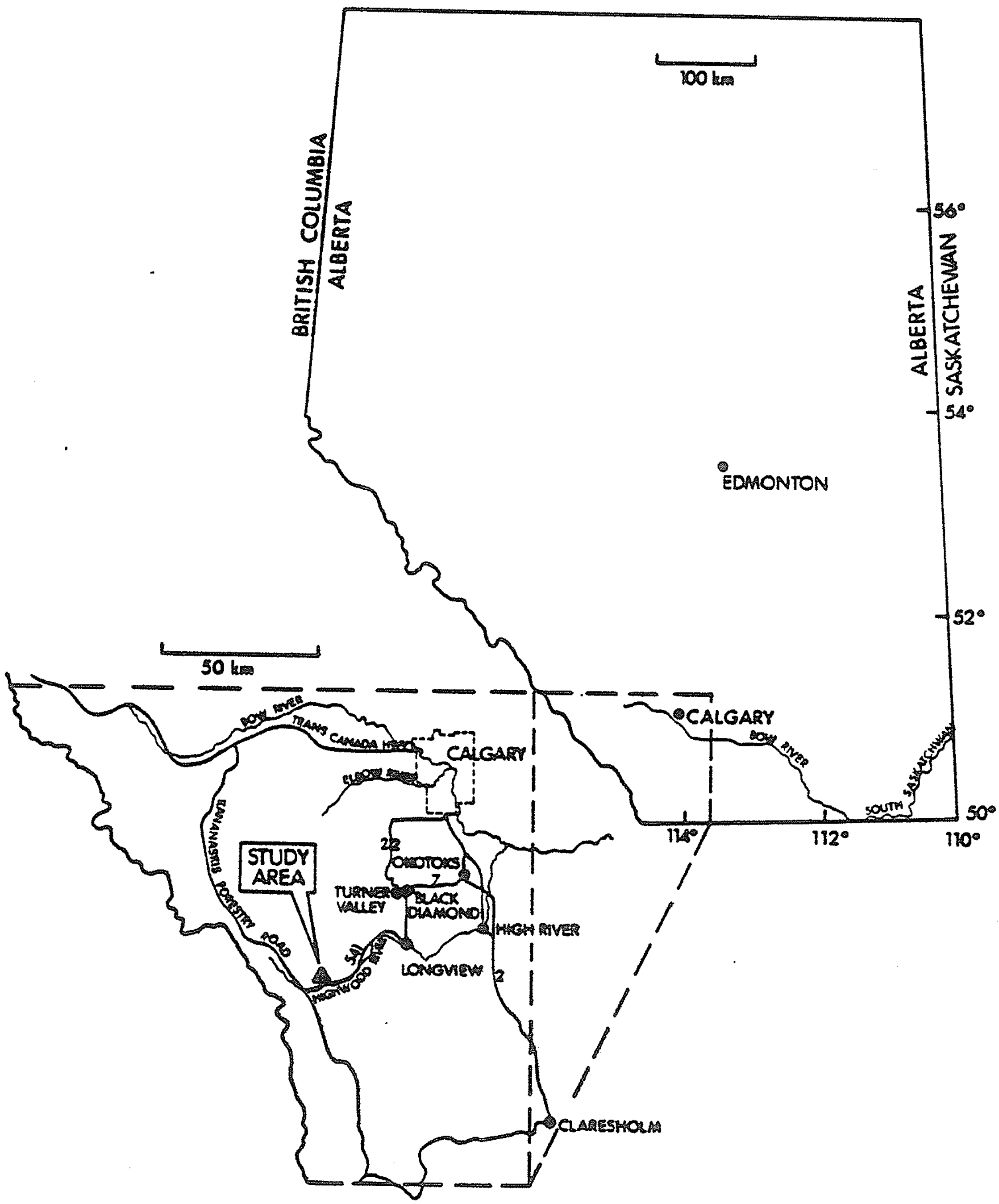

FIGURE 1 LOCATION MAP

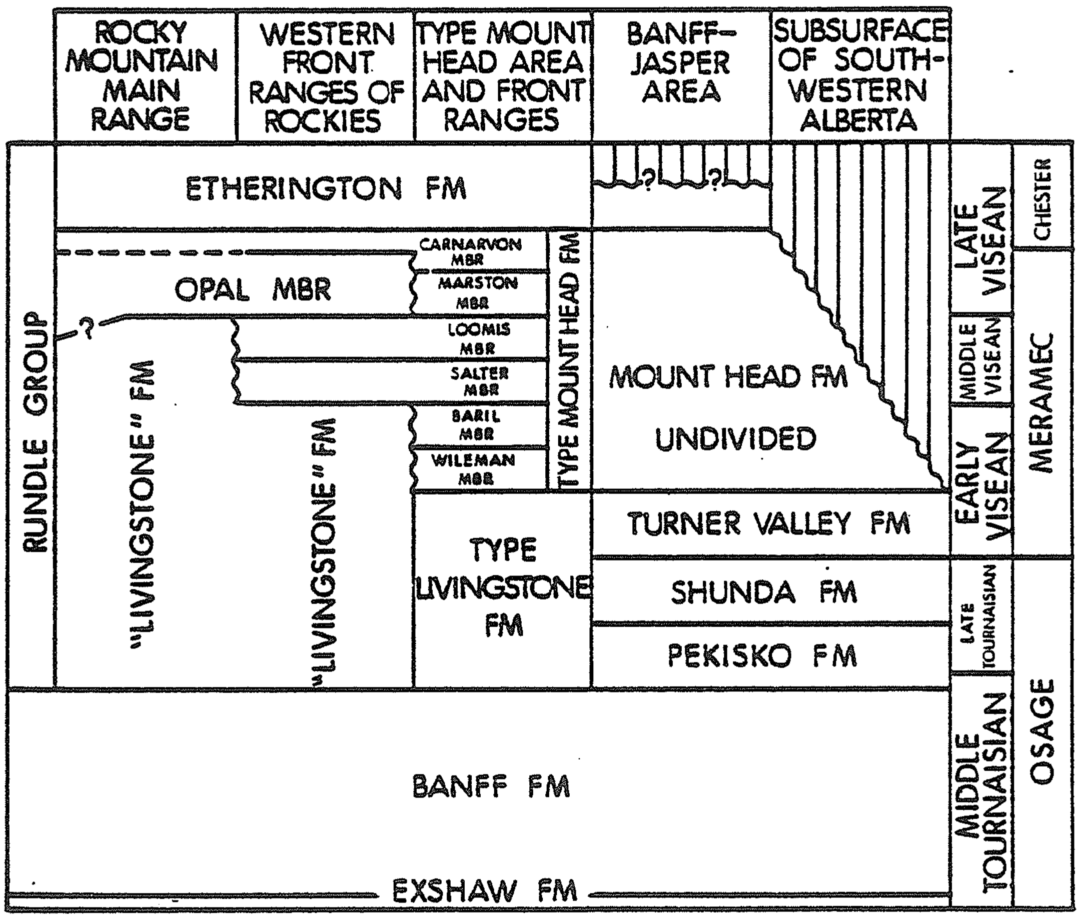

FIGURE 2 REGIONAL MISSISSIPPIAN STRATIGRAPHY (MODIFIED AFTER MACQUEEN ET AL, 1972)

Mount Head Formation. The rocks here are predominantly limestones and dolostones with very minor occurrences of evaporites and siliciclastic rocks.

Most of the previous work concerned with the Mount Head Formation has dealt with stratigraphy and sedimentation and has dealt only slightly with the diagenetic history of the rocks. Those that do, are concerned with the Turner Valley Formation; for example: Goodman (1945), Murray and Lucia (1967), and Stein (1977). Illing (1959) studied the deposition and diagenesis of the Banff, Shunda, Pekisko, and Turner Valley Formations.

Douglas (1958) raised the Rundle Formation to Group status and subdivided it into the presently used formations and members. Macqueen and Bamber (1968) and Macqueen *et al* (1972) studied the facies relationships and depositional environments of the Mount Head Formation in the Rocky Mountains and foothills of southwestern Alberta.

REGIONAL AND LOCAL STRATIGRAPHY

Regional stratigraphy of the Mount Head area is summarized in Douglas (1958) and more detailed studies of the Mississippian stratigraphy have been done by Macqueen and Bamber (1968) and Macqueen *et al* (1972). The following is summarized from Macqueen *et al* (1972).

The Front Ranges of the southern Rocky Mountains consist of a series of west-dipping thrust sheets which displace relatively competent Cambrian, Devonian, and Mississippian carbonate rocks over relatively incompetent Mesozoic clastic rocks. Mississippian stratigraphy in southwestern Alberta consists of two main carbonate units: the lower, recessive Exshaw and Banff Formations, and the upper, generally resistant Rundle Group (see Figure 2).

The Exshaw Formation consists of a lower black shale approximately 6 metres thick overlain by a siltstone-limestone unit ranging from 1 to 30 metres in thickness. The Devonian-Mississippian contact is believed to occur at about the middle of the black shale unit. The shale unit is interpreted as having been deposited within a euxinic lagoon while the siltstone-limestone unit originated in a well-oxygenated tidal flat.

Overlying the Exshaw is the Banff Formation which ranges in thickness from 280 to 430 metres. It may be informally divided into three units: a lower, well-laminated, evenly bedded, unfossiliferous dolomitic and calcareous shale and argillaceous limestone; a middle, resistant argillaceous and dolomitic echinoderm limestone with rare brachiopods and bryozoans; and an upper, recessive argillaceous and dolomitic echinoderm limestone, with abundant brachiopods. The Banff Formation is interpreted as being of open-marine origin with sediments accumulating at or below wave base.

The Rundle Group overlies the Banff Formation and comprises three formations: the Livingstone, Mount Head, and Etherington Formations. The oldest of the three, the Livingstone, forms gray-weathering resistant cliffs. It is composed of alternations of medium to coarse grained echinoderm-bryozoan limestone, medium crystalline porous dolomite, fine grained argillaceous dolomitic or cherty limestone, and fine crystalline dolomite. The Livingstone is about 340 metres thick in the Mount Head area and the sediments of this formation represent the first regional development of shallow-water echinoderm banks. In the Banff-Jasper area and subsurface of southern and central Alberta, the Livingstone Formation is absent. In its place are the Pekisko, Shunda, and Turner Valley Formations (Macqueen and Bamber, 1968).

The Pekisko ranges in thickness from 30 to 90 metres and is composed of skeletal grainstones and packstones, oolitic grainstones, micritic limestone and microdolomite. Depositional environments range from high energy shoals to semi-restricted lagoons.

The Shunda Formation is an approximately 70 metre thick, thin to thick bedded recessive unit dominated by pelleted micritic limestone with microcrystalline dolomites, minor skeletal limestone, solution breccia, and fine to medium crystalline dolomites. Shunda sediments were deposited in an extensive lagoon-tidal flat-sabkha complex.

The Turner Valley Formation is a 30 to 150 metre thick resistant, gray weathering, commonly dolomitized sequence of beds which were originally deposited as resistant, light gray weathering, oolitic limestone of shallow marine and shoal origin. The Marston Member measured 32.3 metres thick at the study locality but elsewhere, it may range in thickness from as little as 18 metres to as much as 68 metres. It is a recessive, brownish weathering unit composed predominantly of microcrystalline dolostone with lesser amounts of micritic limestone. Shale is present as thin partings and as beds up to 30 centimetres in thickness. Macqueen and Bamber (1968) interpret it to consist of cycles of alternating lagoon and sabkha sequences.

The Carnarvon Member measured 45.6 metres thick but ranges from 23 to 64 metres at other localities. It was divided by Douglas (1958) into the lower, middle, and upper units. The lower unit is dominated by micrites and fine grained skeletal limestone separated by thin beds of calcareous shale. The middle unit consists of micrite alternating with thin, dark gray, calcareous shale beds while the upper unit is characterized by skeletal limestones and lesser amounts of micritic limestones interbedded with thin greenish or gray calcareous shales. Sediment types indicate that the Carnarvon Member was deposited in an extensive lagoon system.

The Marston and Carnarvon Members grade westward into the Opal Member which is greater than 300 metres in thickness. At its base, the Opal consists of a resistant, thick bedded succession of grain-supported skeletal and oolitic limestones with minor amounts of micritic limestone and finely crystalline dolostone. This grades upward to a succession of very thin bedded to thick bedded argillaceous, micritic limestone and dolomitic and calcareous shale with minor amounts of skeletal limestone.

The youngest Mississippian rocks in the area belong to the 60 to 450 metre thick Etherington Formation. Douglas (1958) divided it into three units: a lower, recessive, green shale interbedded with micritic and fine grained limestones and dolostones; a middle fine grained arenaceous, cherty limestone and medium crystalline dolostone; and an upper, microcrystalline to finely crystalline, sandy dolostone. The depositional environments of the Etherington range from sabkha to open-marine with influxes of terrigenous material.

OBJECTIVES OF STUDY

The purpose of this study is twofold. The first objective is to interpret the depositional environments of the upper three members of the Mount Head Formation on a more detailed scale than previous authors, and secondly to document and interpret their diagenetic history.

METHOD OF STUDY

Field work was carried out in September, 1975 during which time the Highwood River section (see Figure 3 and Plate 1) was measured and sampled. The section was measured with a Jacob's staff and an attempt was made to sample each bed. A total of 150 samples were taken from the 130 metre thick, essentially continuous section. One hundred fifteen thin sections were made and most were stained. Generally only half of the thin section was stained in order to preserve an unetched

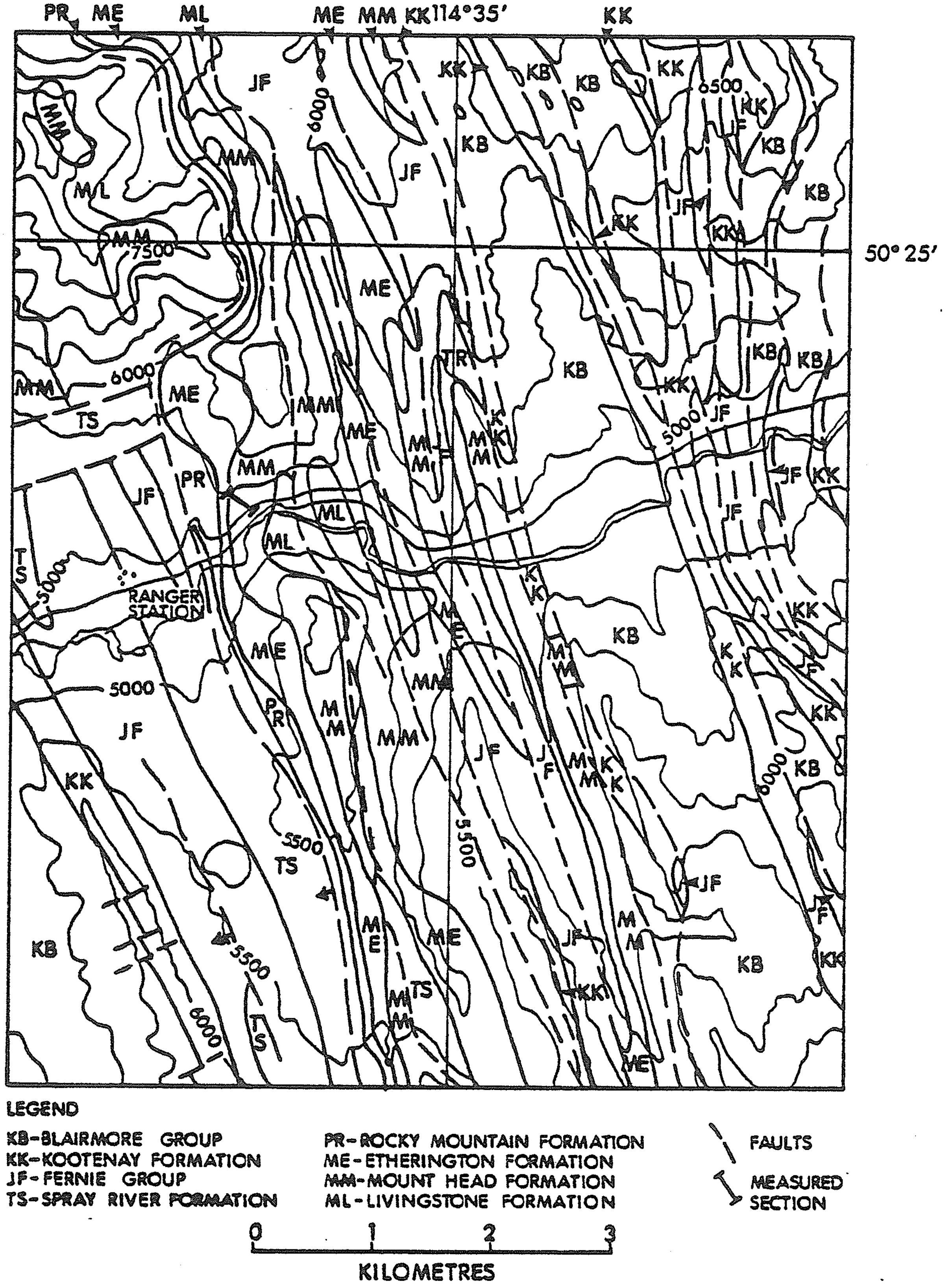

FIGURE 3 SURFACE GEOLOGY AND LOCATION OF MEASURED SECTION AT HIGHWOOD RIVER, SOUTHWESTERN ALBERTA. (BASE MAP BY DEPARTMENT OF ENERGY, MINES AND RESOURCES, 1976. GEOLOGY BY R.J.W. DOUGLAS, 1947, 1948)

and unstained portion. Staining was done using Dickson's (1965) technique which employs alizarin red S solution and potassium ferricyanide to distinguish between calcite, dolomite, and any iron-rich horizons. With this technique calcite stains pink while dolomite shows no colour change. Ferroan calcite and ferroan dolomite both stain various shades of blue but may be distinquished by the degree of etching undergone in the first stage of the procedure which consists of an acid bath.

The rocks were classified according to Dunham's (1962) classification of carbonate rocks and void spaces were classified according to Choquette and Pray's (1970) nomenclature.

ACKNOWLEDGEMENTS

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CHAPTER 2

FACIES AND THEIR ENVIRONMENTAL INTERPRETATION

INTRODUCTION

The upper three members of the Mount Head Formation, namely the Loomis, Marston, and Carnarvon, are composed mainly of limestones and dolostones, with lesser amounts of shales, siltstones, cherts, and evaporites. In general, the Loomis and Carnarvon are limestones and the Marston is dolostone.

The carbonate rocks were classified according to Dunham's (1962) classification. This classification is based on depositional textures which are an important factor in determining the environment in which the sediment was deposited. In all cases, an attempt was made to determine the facies which existed prior to dolomitization and classify the rock on the basis of its original texture. Besides original texture, depositional environments were interpreted on the basis of fossils, mineralogy, and associated sediments.

Fifteen facies were recognized within the carbonates of the upper three members of the Mount Head Formation. These are listed in Figure 4 with their interpreted depositional environments. The facies were differentiated on the basis of texture, faunal and floral assemblages, and, in the case of the evaporitic mudstone, mineralogy.

GRAIN SUPPORTED FACIES AND INTERPRETATION

The grain supported facies were divided into eight separate facies; four of these were grainstones and four packstones. The dominant components of these rocks are echinoderm grains, oolites, pelloids, and unidentifiable fossil fragments. Present in lesser amounts are bryozoans, forams, bivalves, ostracodes, algal thalli, and oncolites. The grain sizes of these components range from very fine to coarse but is predominantly medium to coarse.

GRAINSTONES

As defined by Dunham (1962), a grainstone is a rock that is grain supported and lacks lime mud in the interstices. These rocks are generally interpreted as having been deposited in a high energy environment in which all lime mud was winnowed out.

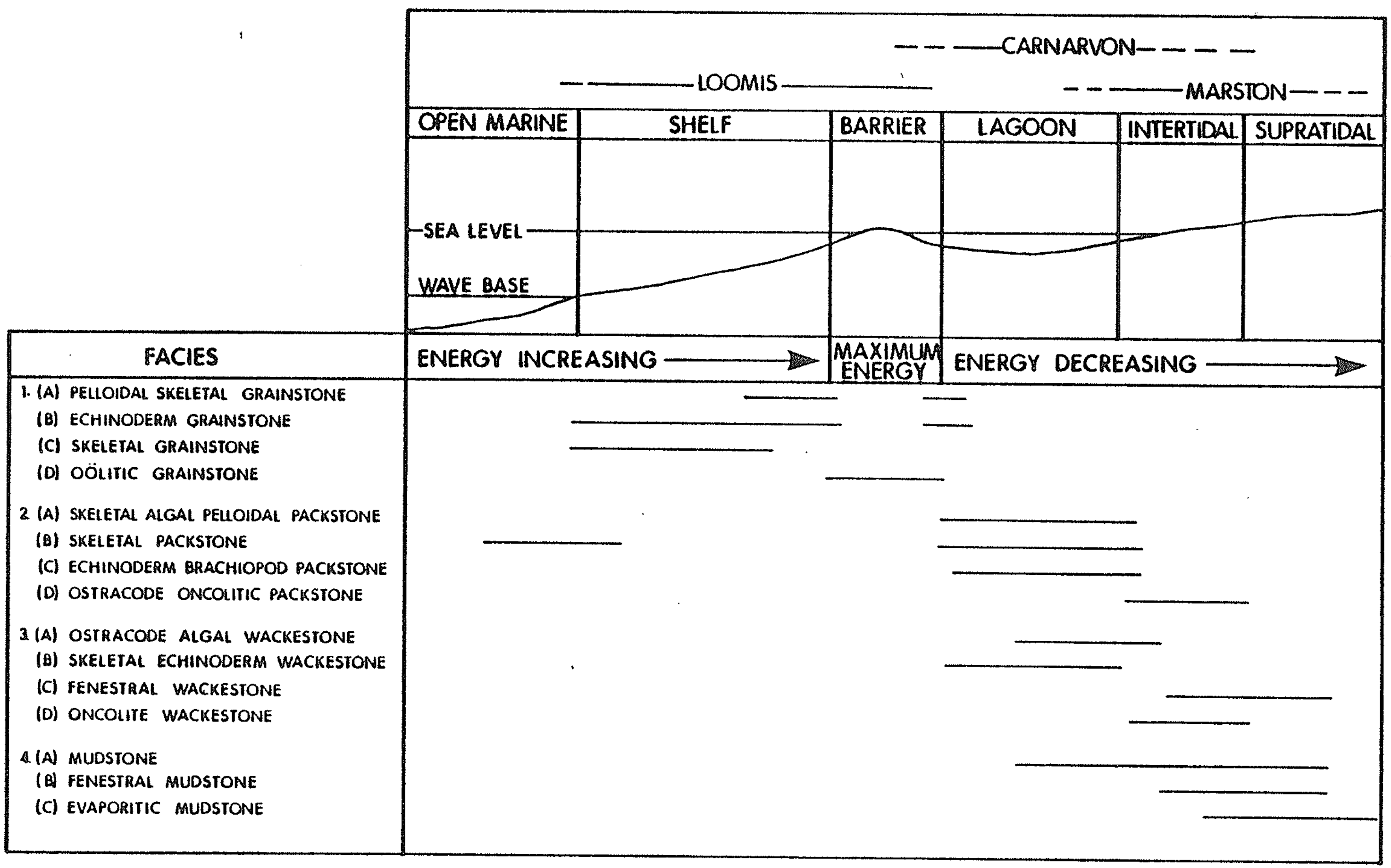

FIGURE 4 FACIES OF THE UPPER MOUNT HEAD FORMATION AND THEIR DEPOSITIONAL ENVIRONMENTS (MODIFIED AFTER MACQUEEN AND BAMBER, 1968)

At the Highwood River section, four grainstone facies have been identified and described (see Figures 5-7). These are:

1(a) pelloidal skeletal grainstone facies

1(b) echinoderm grainstone facies

1(c) skeletal grainstone facies

1(d) oolitic grainstone facies.

1(a) Pelloidal skeletal grainstone facies

This facies is part of the gray-weathering, resistant, cliff-forming limestones of the Loomis Member (see Figure 5). It is generally massive but may be laminated or thinly bedded and often displays cross-bedding (Plate 2a). Four beds ranging from 2.5 to 6 metres in thickness were observed within the Loomis for a cumulative thickness of 14 metres.

This facies, except in one case, always occurs in contact with other grainstones, both above and below. It is most commonly associated with the oolitic grainstone facies. Both the upper and lower contacts may be sharp but are generally gradational over a short interval. The one case where this facies comes in contact with a rock type other than a grainstone occurs approximately in the middle of the Loomis Member. Here, the pelloidal skeletal grainstone overlies a dolomitized mudstone. The lower 1 to 2 metres of this grainstone bed contains thin stringers of dolomite (Place 2c, d).

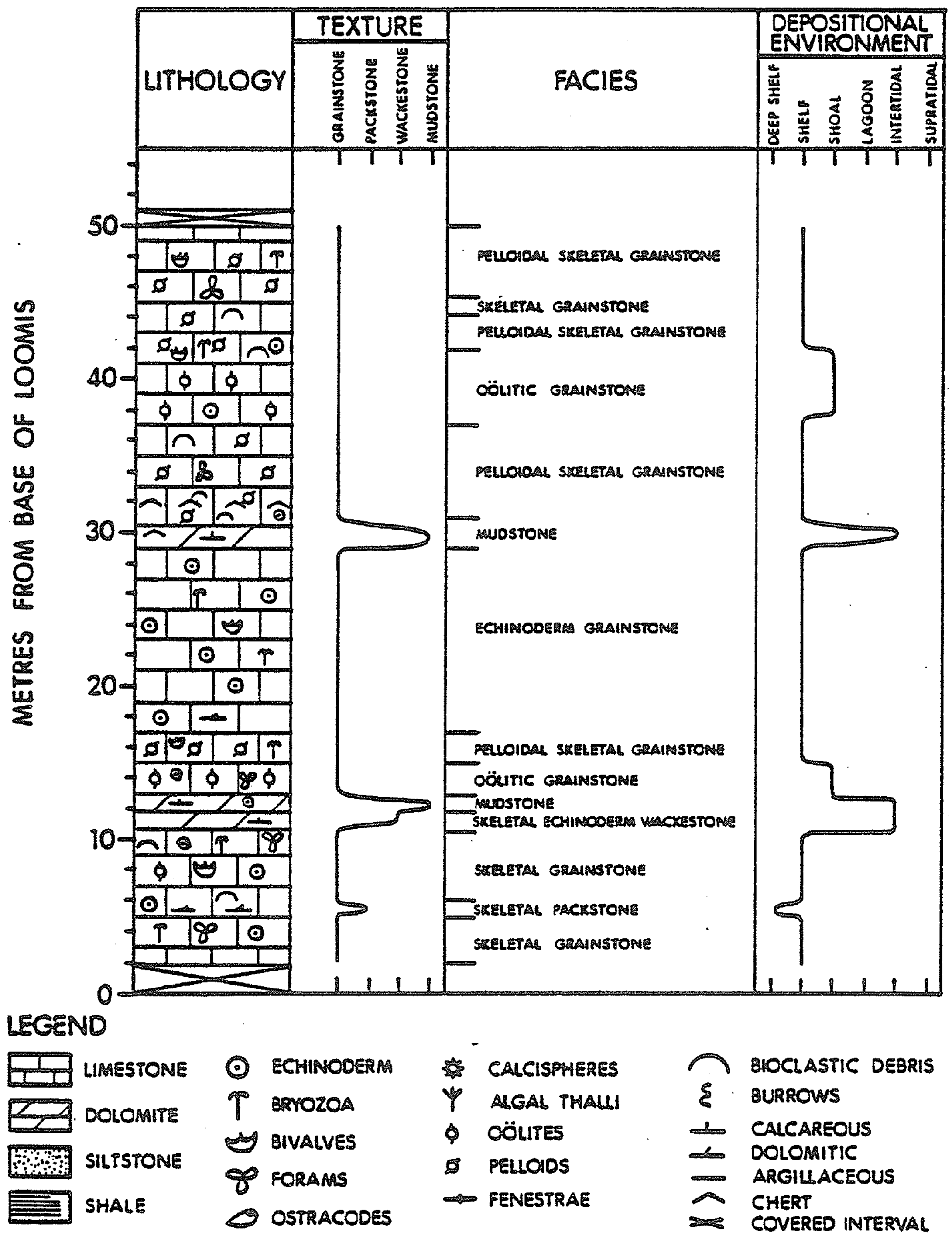

FIGURE 5 STRATIGRAPHIC SECTION OF THE LOOMIS MEMBER, MOUNT HEAD FORMATION, HIGHWOOD RIVER SECTION.

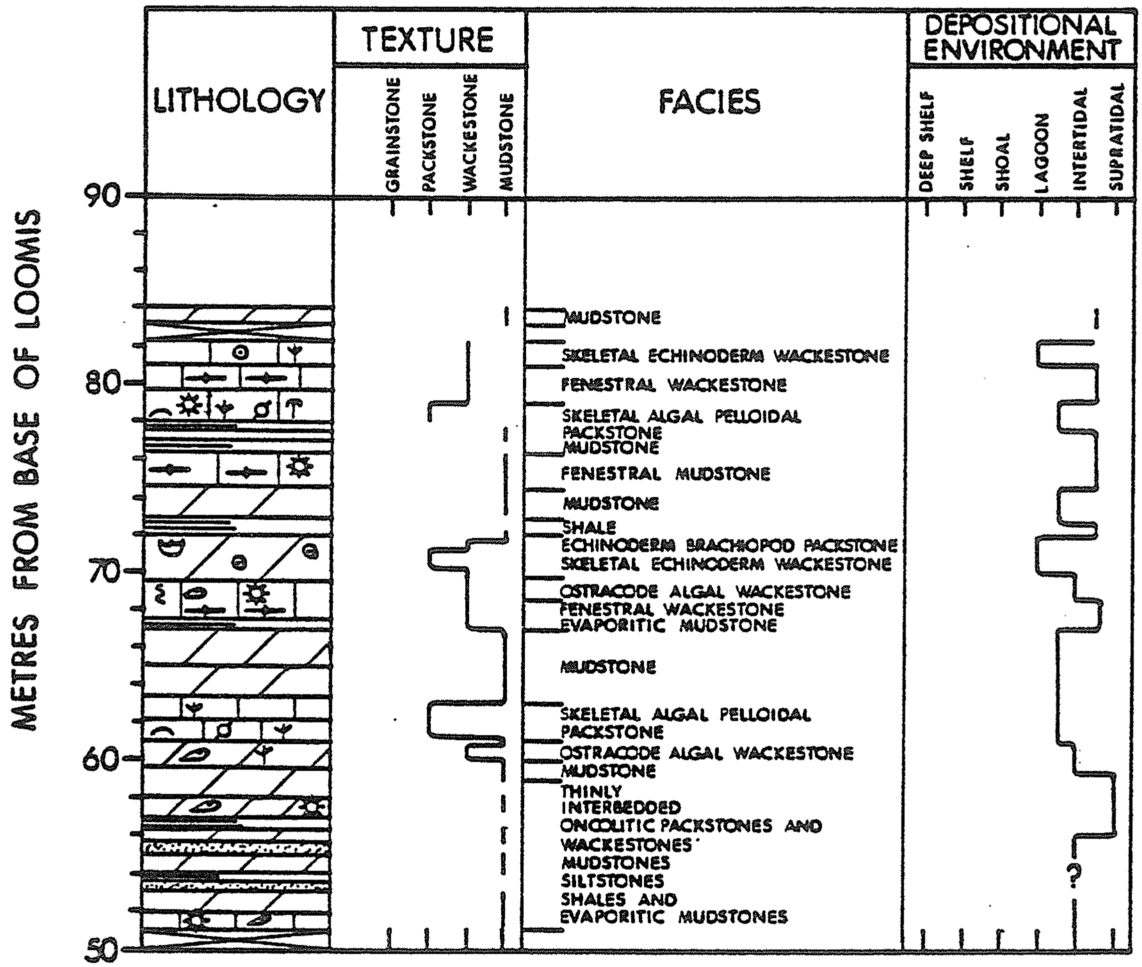

FIGURE 6 STRATIGRAPHIC SECTION OF THE MARSTON MEMBER, MOUNT HEAD FORMATION, HIGHWOOD RIVER SECTION. SEE FIGURE 5 FOR EXPLANATION OF SYMBOLS.

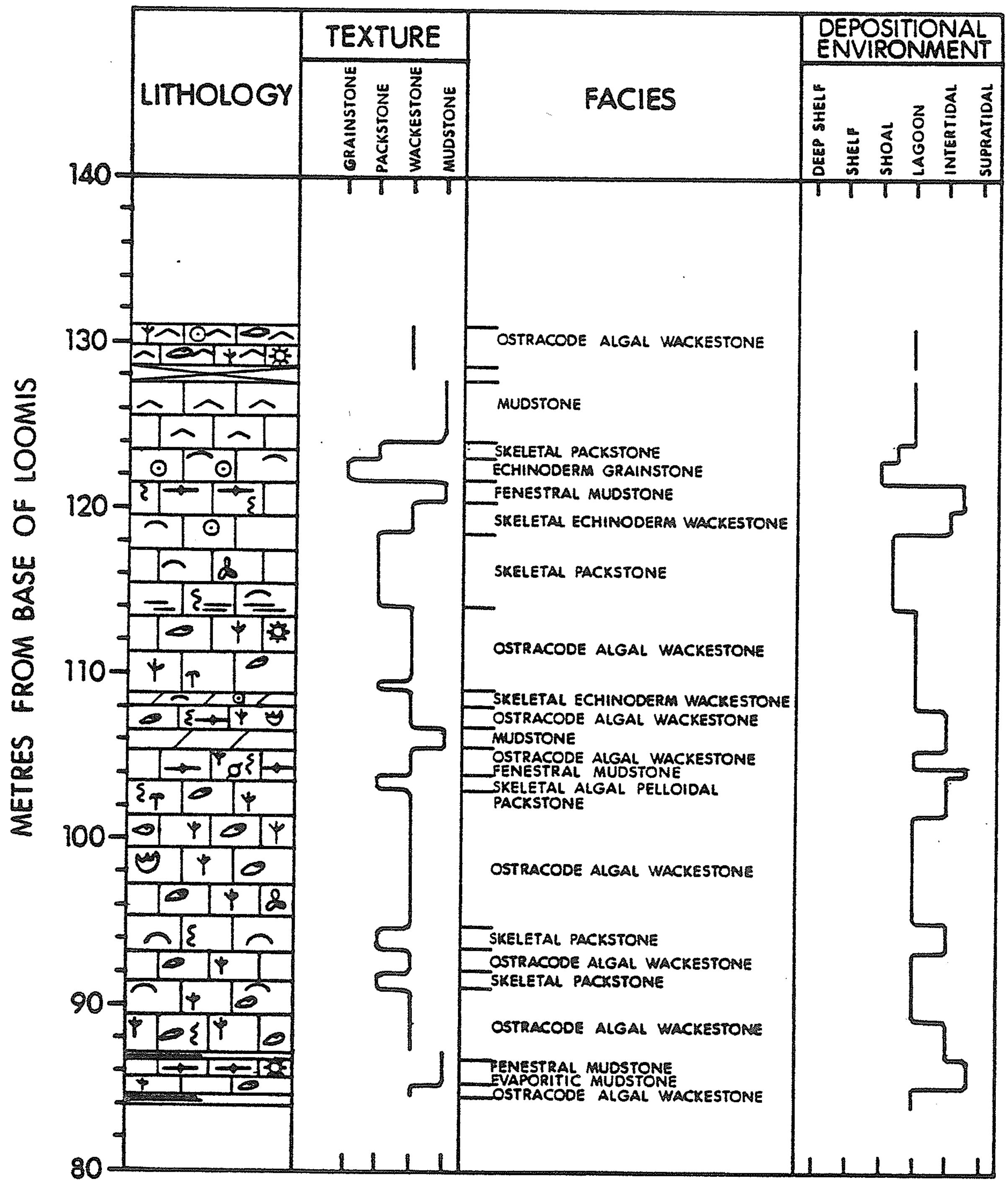

FIGURE 7 STRATIGRAPHIC SECTION OF THE CARNARVON MEMBER, MOUNT HEAD FORMATION, HIGHWOOD RIVER SECTION. SEE FIGURE 5 FOR EXPLANATION OF SYMBOLS.

Grain size ranges from medium to coarse but may locally be fine. The rocks are composed predominatly of pelloids (60-80 percent, visual estimate) with lesser amounts of echinoderm, bryozoan, foram, and brachiopod fragments. (Plate 2b). Oolites occasionally are present in trace amounts. Changes in grain size and grain type give rise to the small scale bedding features within these beds.

The pelloids occurring in this facies are interpreted as being the result of total micritization of skeletal fragments by boring algae and are not of faecal origin. Many of the pelloids have a single oolitic coating (Plate 2c) up to 0.25 millimetres thick. This single oolitic layer consists of acicular to bladed calcite crystals oriented normal to the grain boundary. Bathurst (1967) described oolitic films forming on fine sand grains in the low energy environment of the Bimini Lagoon. However, these films consisted of a mosaic of crystals unlike the elongated crystals of the present study. Newell et al (1960) described single layer "oolites" in the oolitic sands of the Bahamas and interpreted them as being the first stage of oolite formation. These "proto" - oolites were then stabilised, stopping subsequent growth of concentric rings.

In the Loomis Member of the Mount Head Formation the presence of these single layer oolites indicates that the rocks of this facies were deposited adjacent to oolite shoals in a transition zone between the shoals and the open marine shelf or the lagoon (see Figure 4). The single layer oolites were probably washed out of the oolite-forming environment into adjacent environments. The presence of oolites in small amounts and the close association of this facies with oolitic grainstones supports this conclusion.

1(b) Echinoderm Grainstone Facies

This facies occurs as a single 12.2 metre thick limestone within the middle of the Loomis Member (Figure 5) and as a 1.5 metre thick limestone bed near the top of the Carnarvon Member (Figure 7). These rocks are light gray-weathering, resistant, and cliff-forming.

The echinoderm grainstone facies within the Loomis is underlain by pelloidal skeletal grainstones and is overlain by a mudstone. The upper contact is sharp. Within the Carnarvon Member this facies overlies a mudstone and is overlain by a packstone.

This facies is generally thinly bedded or laminated. The laminations are due to changes in the grain size which ranges from medium to very coarse (Plate 3a). Echinoderm fragments are the principle component of this facies (70-75 percent, visual estimate) with lesser amounts of bryozoa, forams, and brachiopods (Plate 3b). Oolites are present in trace amounts. Many of the grains have been highly micritized by algae. This process will be discussed in a later section dealing with biological diagenesis.

The echinoderm grainstones of the Loomis Member were probably deposited in a moderate to high energy subtidal environment in which echinoderms flourished and formed extensive biogenic banks. The moderate to high energy resulted from wave action and tidal induced currents.

The echinoderm grainstone of the Carnarvon Member was probably deposited on a small biogenic bank within the lagoon. The association with quiet water, muddy sediments supports this interpretation.

1(c) Skeletal Grainstone Facies

This facies occurs as three beds within the Loomis (Figure 5), with two beds at the base and one near the top.

Beds range in thickness from 1 to 3.5 metres and are light to medium gray weathering, resistant cliff-forming units similar to the other grainstone facies. The facies is generally massively bedded but may have even, horizontal beds on the order of 10 centimetres thick.

The two lower beds of this facies are separated by a skeletal packstone and overlain by a mudstone. The contacts here are abrupt and may be slightly undulatory. The upper bed of this facies is sandwiched between two pelloidal skeletal grainstones and has gradational contacts.

The rocks are predominantly medium to coarse grained and are composed mainly of echinoderms, bryozoan, and foram fragments (Plate 3c). Echinoderm clasts range in abundance from 15 to 45 percent, foram from 2 to 30 percent, and bryozoans from 5 to 15 percent (all based on visual estimates). Other skeletal debris, generally unidentifiable, occurs in lesser amounts. A high percentage of the skeletal components have been totally micritized or have thick micrite rinds.

These sediments were probably deposited on the moderate to high energy, subtidal shelf (Figure 4). The total lack of oolites indicates an environment somewhat removed from the oolite shoals. Also, the association of this facies with muddy sediments indicates its proximity to quieter water conditions such as the deeper shelf or the open marine environment. However, the skeletal grainstone facies associated with the pelloidal skeletal grainstones may have been deposited on the shallower portion of the shelf.

1(d) Oolitic Grainstone Facies

Two beds of oolitic grainstones are found within the Loomis Member (Figure 5). The lower one is 2 metres thick and occurs 14 metres from the base. It has a very sharp lower contact and overlies a dolomite mudstone. The upper contact is gradational over a short distance and the oolite grades into a pelloidal skeletal grainstone. The upper oolite bed is 5 metres thick and occurs 40 metres from the base of the Loomis. Both contacts are gradational into pelloidal skeletal grainstones. Both beds are resistant, gray weathering, cliff-forming limestones typical of the grainstones in the Loomis.

These rocks are predominantly composed of medium to very coarse grained oolites with minor amounts of skeletal debris, especially echinoderm plates, ossicles and spines (Plate 3d). The nuclei of the ooids are mainly pelloids and unidentifiable skeletal debris.

Plate 3d exhibits a thin micritic horizon which is interpreted as being the initial stage in the formation of a type of submarine hardground initiated by algal activity. In Plate 3d the micritized horizon is only one ooid layer thick and in some instances affects only the upper surface of the ooid. Dravis (1979) has documented these types of crusts from the active oolite shoals of Schooner Cays, Bahamas.

The oolitic grainstone facies is interpreted as having been deposited on widespread, high energy shoals which occur in belts parallel to the shoreline and act as partial barriers between the open shelf environment and the lagoon (Figure 4). Oolites and the environments in which they are formed and deposited have been extensively studied by Ball (1967), Gebelein (1974, pp. 38-43), and Newell et al (1960).

Because of our ability to associate a specific environment with this facies, we are greatly assisted in interpreting the depositional environments of the rocks which are associated with the oolitic facies, especially the pelloidal skeletal grainstone facies.

PACKSTONES

According to Dunham's (1962) classification, a packstone is a grain supported rock which has some lime mud in the interstices. The presence of lime mud in these sediments indicates that they were deposited in a low to moderate energy environment with prolific production of carbonate grains.

Four major types of packstones were encountered in the thesis area.

They are: 2(a) skeletal algal pelloidal packstone
2(b) skeletal packstone
2(c) echinoderm brachiopod packstone
2(d) ostracode oncolite packstone.

2(a) Skeletal Algal Pelloidal Packstone Facies

This facies occurs in four beds. Two beds are in the Marston Member and two are in the Carnarvon Member (Figures 6 and 7). These rocks are generally recessive, brownish weathering limestones but they may be slightly dolomitic. They are thinly bedded or laminated, rarely massive, and are closely associated with mudstones and wackestones. The contacts with the other rocks are gradational and the two beds within the Carnarvon are separated from the beds above and below by shale breaks (0.5 - 1.0 centimetre thick). The argillaceous content of these rocks increases gradually toward these shale breaks.

Grain size ranges from very fine to fine. The main components are pellets and skeletal debris with minor amounts of algal thalli (5-10 percent based on visual estimates). The dominant alga was determined to be Proninella sp. (Mamet, 1976) with minor amounts of Girvanella sp. (Petryk and Mamet, 1972). Other skeletal components present in minor amounts are brachiopods, ostracodes, echinoderms, forams, calcispheres, and bryozoans (Plate 4a).

These rocks were probably deposited in the quiet, restricted waters of a lagoon protected from open marine conditions by oolite shoals (Figure 4). According to Milliman (1974, p. 38) pellets must undergo early intragranular lithification to be preserved. This is best accomplished in low energy, shallow waters supersaturated with respect to calcium carbonate. Also indicative of deposition within a lagoonal environment is the occurrence of calcispheres (Murray, 1966; Petryk and Mamet, 1972) and algal thalli. Burrows can be present in both deep water muds and lagoonal muds (Jamieson, 1969) but in the presence of the above indicators, they support deposition within a lagoonal environment.

2(b) Skeletal Packstone Facies

This facies occurs in five beds. One bed occurs within the lower Loomis Member (Figure 5) and is one metre thick. The other four beds occur within the Carnarvon Member (Figure 7). Three of these are one metre thick and the fourth is 4.4 metres thick. The skeletal packstone within the Loomis Member is a brownish-weathering, slightly dolomitic, thinly bedded to laminated limestone (Plate 4b). This bed is bounded on both top and bottom by skeletal grainstones. The four beds within the Carnarvon Member are medium gray-weathering, massive limestones and are closely associated with mudstones and wackestones. Often they are separated from these facies by thin shale breaks.

These rocks are predominantly medium grained. The skeletal packstone of the Loomis Member contains mostly echinoderms and forams while the beds within the Carnarvon contain abundant brachiopods and other bivalves as well as minor amounts of calcispheres, ostracodes, bryozoans, and algae (Plate 4c). The skeletal packstone of the Loomis, because of its faunal assemblage and association with skeletal grainstones is interpreted as having been deposited on the deeper reaches of the shelf or the open marine environment at or below wave base where energy ranges from low to moderate (Figure 4).

Within the Carnarvon Member, because of the close association of this facies with muddy, lagoonal sediments, it is interpreted as having been deposited in the quieter waters of the lagoon. The abundant fossil debris indicates that it may have been deposited on or near a biostrome within the lagoon.

2(c) Echinoderm Brachiopod Packstone Facies

This facies is minor but distinctive and occurs as a 1.5 metre thick bed in the middle of the Marston Member (Figure 6). Lithologically it is a silica-rich, highly dolomitic, recessive limestone with light brown, weathering. The lower contact is gradational with the underlying skeletal echinoderm wackestone whereas the contact with the overlying shale is abrupt. The rocks are very coarse grained and consist predominantly of echinoderms and brachiopods (Plate 4d, e).

Based on its association with lagoonal and intertidal sediments, this facies is interpreted as having been deposited in a quiet water lagoonal setting, perhaps in a biostrome in which brachiopods flourished.

2(d) Ostracode Oncolite Packstone Facies

This facies is minor in terms of volume, but it is very significant as an environmental indicator and acts as a datum from which depositional environments of nearby facies may be interpreted.

The facies occurs as a single, thin, 0.15 metre bed in the lower Marston Member in a complex sequence of thinly bedded oncolitic packstones and wackestones, mudstones, siltstones, shales, and evaporitic mudstones (Figure 6). Lithologically this facies is a slightly dolomitic limestone which weathers light gray. The rock is composed mainly of medium to very coarse grained oncolites with cores of ostracodes, either whole or fragmented, and calcispheres. Trace amounts of echinoderm fragments and *Girvanella* thalli are also present (Plate 4f).

Hofmann (1969) defines oncolites as stromatolites with centripetal growth vectors, and encapsulating laminae formed around an intermittently mobile nucleus. In this case, the nucleii are fragments of ostracode tests and calcispheres. Bathurst (1971 pp. 131, 135) and Laporte (1967) interpreted oncolites as forming in the moderate energy intertidal environment, on the floors of tidal channels, or just below the level of low tide.

MUD SUPPORTED FACIES AND INTERPRETATION

WACKESTONES

A wackestone, as defined by Dunham (1962), is a mud supported sediment with greater than 10 percent grains. The abundance of mud within these rocks as well as the faunal and floral assemblages indicates that some were deposited within a low energy, somewhat restricted, lagoon, and some within a low to moderate energy intertidal to supratidal setting.

Three major and one minor facies of wackestone were recognized in the thesis area. They are, in order of decreasing abundance:

3(a) ostracode algal wackestone

3(b) skeletal echinoderm wackestone

3(c) fenestral wackestone

3(d) oncolitic wackestone.

3(a) Ostracode Algal Wackestone Facies

This facies is relatively abundant and has a total thickness of 24 metres with individual beds ranging in thickness from one metre to almost 6 metres. Two beds of one metre thickness each are present in the Marston Member (Figure 6) and six beds are present within the Carnarvon Member (Figure 7).

The beds are closely associated with other wackestone and mudstone facies as well as thin shale beds and partings. Contacts may be gradational or very sharp especially in cases where the beds are separated by shale partings.

Lithologically, the rocks are mostly limestone but often have trace amounts of dolomite rhombs replacing micrite. Occasionally all of the lime mud matrix has been dolomitized. The limestones weather light gray while the dolostones weather buff brown. These beds are generally massively bedded and have no internal structures except for the rare occurrence of vertical burrows.

Skeletal debris in the wackestones has grain sizes ranging from very fine to medium, with the most abundant grain size being fine. The dominant skeletal types are algal thalli (Kamaena and minor Proninella) and ostracodes which each make up 5 to 10 percent of the rock (Plate 5a). Calcispheres are relatively abundant (5 percent) with trace amounts of echinoderm and bivalve fragments also present.

These sediments were deposited in a quiet, low energy, lime mud-rich environment. A lagoonal environment (Figure 4) is supported by the presence of abundant algae and calcispheres (Mamet, 1976). Further evidence for this depositional environment is the close association of this facies with other low energy, shallow water facies such as mudstones and fenestral mudstones and wackestones. Fenestrae are voids within the rock which are larger than the framework grains. They may be horizontal laminar, tubular, or irregular.

3(b) Skeletal Echinoderm Wackestone Facies

This facies occurs as a single one-metre-thick bed in the upper Marston Member (Figure 6) and in two beds within the upper half of the Carnarvon Member. Here, the beds are 1 and 2 metres thick respectively. Within the Marston, this unit is underlain by a fenestral wackestone while the upper contact is covered. The lowermost bed of the facies within the Carnarvon is bounded by ostracode algal wackestones. The upper bed is resting on a skeletal packstone and overlain by a fenestral mudstone.

Lithologically, the rocks are dolostone and limestone, and weather light gray to buff. The beds are usually massive but may be finely laminated.

The most abundant skeletal component is medium to coarse grained echinoderm fragments with lesser amounts of brachiopods, ostracodes, algal thalli, and gastropods (Plate 5b). Bioclastic debris accounts for 15 to 25 percent of these rocks.

There are few environmental indicators within these rocks. However, the abundance of echinoderm grains and the relation to other facies indicates proximity to a biogenic bank or biostrome within a low energy lagoon (Figure 4).

3(c) Fenestral Wackestone Facies

This facies occurs as two beds within the Marston Member (Figure 6). The lower bed is 1.4 metres thick and the upper is 2.2 metres thick. The beds weather a light buff brown and are recessive. The rocks are limestone with varying amounts of dolomite rhombs replacing micrite.

These beds are associated with mudstones, wackestones, and packstones. Contacts are quite sharp, and occasionally are shale partings. Internal structures consist of very fine laminations and fenestral structures (Plate 5 c, d). A thin intraclastic breccia occurs at the top of the lower bed and consists of sub-rounded clasts 1 to 5 centimetres in size (Plate 5e).

Very fine grained skeletal debris is present in amounts from 10 to 20 percent. Fossils are mainly ostracodes, calcispheres and algal thalli (Plate 5d). Algae appear to be both *Proninella* and *Stacheoides*.

The fenestral voids may remain open or be occluded by calcite, dolomite, or gypsum as in Plate 11e. The fenestrae found within the Marston Member are horizontal laminar and are believed to have been formed through dessication of the sediment and/or gas expansion bubbles formed by decay of organic material, especially algal mats.

Fenestral textures indicate deposition in the high intertidal to supratidal environment (Figure 4). Supporting this is the presence of gypsum which, if penecontemporaneous, indicates deposition in an evaporitic environment. Also, the presence of the intraclastic breccia indicates a dessicating environment which is necessary to form mudcracks and rip-up clasts.

3(d) Oncolitic Wackestone Facies

Rocks of this facies are minor volumetrically but are important as environmental indicators. This facies occurs in a 10 centimetre-thick bed near the base of the Marston Member (Figure 6). This rock is recessive and weathers light buff brown. It is quite vuggy (5-10 percent) with vugs ranging in size from 3 millimetres to 3 by 17 millimetres.

This facies occurs within a complex assemblage of thinly bedded wackestones, mudstones, shales, silts, and evaporitic rocks. Lithologically it is a limestone and consists of 25 to 30 percent medium to very coarse grained oncolites (Plate 5f). Minor skeletal debris, especially ostracodes, are also present. The facies was probably deposited in a moderate energy intertidal environment (Figure 4).

MUDSTONES

As defined by Dunham (1962), a mudstone is a mud supported rock with less than 10 percent constituent grains. Like wackestones, they are deposited in low energy environments.

Mudstones account for approximately 22 metres of the section and were divided into the following three facies:

4(a) Mudstone

4(b) Fenestral Mudstone

4(c) Evaporitic Mudstone.

4(a) Mudstone Facies

This facies is the most abundant of the mudstones and has a total thickness of approximatley 20 metres.

A two-metre-thick mudstone is present in the middle of the Loomis Member (Figure 5) and two mudstone beds (1 and 3.7 metres thick) are present within the Carnarvon Member (Figure 7). The Marston, however, contains the bulk of this facies, which occurs in five beds ranging from a few centimetres thick to 4 metres thick.

These rocks weather light gray to buff brown depending on the lithology, which can be either limestone or dolostone or gradational between these.

Except for one bed which occurs in the Loomis and is associated with grainstones, all these rocks are associated with other muddy sediments. The beds are generally massive but may be finely laminated. The laminations are often accentuated by dolomite. Skeletal debris is scarce, less than 10 percent of the total rock, and consists of fine fragments of ostracodes, algae, and calcispheres.

Some of these sediments may have been deposited in the quiet, intertidal zone fringing a restricted or semi-restricted lagoon as suggested by fine laminations, the faunal assemblage, and association with fenestral mudstones and wackestones. Some of these mudstones are associated with evaporitic mudstones, lack any fossil remains, and are predominantly or totally dolomite.

These dolostones consist of inclusion-rich microcrystalline to fine grained dolomite and may have been deposited in hypersaline, supratidal pools similar to those described by Folk and Land (1975) (see Figure 4).

4(b) Fenestral Mudstone Facies

This facies was observed in one two metre bed within the Marston Member (Figure 6) and in three beds one metre thick or less within the Carnarvon (Figure 7).

These rocks weather light gray and lithologically they are limestones although, they may contain a few percent of euhedral dolomite rhombs. Beds of this facies are associated with other muddy sediments and may have sharp or gradational contacts. The fenestrae are horizontal laminar, and show up as 2 to 15 millimetre lenses filled with blocky calcite (Plate 6a,b). Up to 5 percent fine skeletal debris may be present and include ostracodes, calcispheres, and algae. One sample from near the top of the Carnarvon is a highly pelleted fenestral mudstone which has a very finely laminated micritic encrustation on the floor of a fenstral void. This appears to be the result of algal mat formation. Other thin, dense micritic beds also indicate the presence of algal mats.

These sediments were deposited in a high supratidal and intertidal environment (see discussion of fenestral wackestone facies).

4(c) Evaporitic Mudstone Facies

This facies is restricted to the Marston Member (See Figure 6) and one occurrence at the base of the Carnarvon (Figure 7) and accounts for only one metre of section. Four beds are present and range in thickness from 0.2 to 0.4 metres.

These evaporitic rocks occur mainly in a completely interbedded sequence composed of mudstones, wackestones, silts, and shales in the lower Marston Member, but elsewhere are associated with fenestral wackestones and mudstones. The types of evaporites present are gypsum and celestite. The gypsum occurs in both dolostones and limestones (Plate 10a) while the single occurrence of celestite is in a micritic limestone (Plate 10 b, c, d). The rocks may be massive with scattered euhedra of gypsum throughout (Plate 6d), finely laminated, or thinly bedded as in Plate 6c.

These sediments were probably deposited in a high intertidal to supratidal environment where rates of evaporation were high. Fairly common occurrences of celestite have been reported by Evans and Shearman (1964) and Kinsman (1969) in sediments of the Persian Gulf sabkhas. Shearman (1966) described gypsum crystals from less than one millimetre up to one centimetre in size in the intertidal zone of the Persian Gulf which locally are abundant enough to form a crystal "mush" several inches thick. Butler (1969), in his study of the Persian Gulf, reports that gypsum precipitation and dolomitization are limited to a 3 to 5-kilometre-wide belt adjacent to the lagoon margin in an area which is subject to frequent flooding. Butler (1969) also reports a crystal "mush" of gypsum up to twelve inches thick. These crystal mushes consist of randomly oriented gypsum crystals ranging in size from 4 to 20 millimetres. Evaporitic mudstones shown in Plates 6c and 10a have a similar morphology to those described by Butler (1969) from the Persian Gulf.

SILTSTONE AND SHALE FACIES

Two minor beds of siltstone are present in the lower part of the Marston Member. The lower bed has a thickness of 0.1 metres and the upper has a thickness of 0.45 metres.

These rocks consist of approximately 70 percent silt-size, angular quartz grains and 30 percent clay minerals. Silt sized quartz grains are also present in trace amounts within some of the carbonate rocks of the lower Marston Member as well.

Shales occur frequently in the Marston and Carnarvon Members and usually occur as thin, less than one centimetre partings between carbonate beds. Thicker beds up to 0.8 metres but generally 0.2 to 0.3 metres occur sporadically throughout the upper two members.

These rocks are associated with all types of lime mud-rich sediments within the Marston and Carnarvon Members. They probably originated from the northeast (Macqueen *et al* 1972), were carried south by longshore currents, and deposited in and around, quiet, low energy lagoons.

SUMMARY

In this section, the data and interpretations of this chapter will be summarized, a depositional model for each of the three members will be developed, and their relationships to one another will be discussed. Figure 4 is a summary of the sedimentary facies and the environmental interpretations of the various rock types present and the Highwood River section. Fifteen carbonate sedimentary facies were recognized within the section and represent deposition within high energy shoals, moderate to high energy open shelf environments, quiet water lagoons, and the intertidal to supratidal environment.

General depositional models for the Mississippian of southern Alberta have been constructed by Mamet (1976), Macqueen *et al* (1972), Macqueen and Bamber (1968), and Illing (1959). The present study will attempt to detail the vertical variations in depositional environments at the Highwood River section.

DEPOSITIONAL MODEL

Deposition of Mount Head sediments occurred adjacent to the Canadian Shield on a slowly subsiding, broad, shallow marine shelf within the Middle to Late Visean epicontinental sea (Macqueen and Bamber, 1968). The geologic setting during this time is somewhat analogous to the modern-day Persian Gulf with its supratidal sabkhas, broad tidal flats, low energy, sheltered lagoons, oolite shoals, and extensive calcarenite banks and blanket deposits.

Figure 8, is a diagrammatic interpretation of Mississippian depositional environments in southwestern Alberta modified after Macqueen and Bamber (1968). It shows the relative positions of the Loomis, Marston, and Carnarvon Members with respect to their depositional environments.

Within this model, the highest energy environment is the oolite shoals which form linear bars parallel to the shoreline and create a barrier complex of shoals, tidal flats, and channels. Because of shallowing conditions on the landward side of the lagoon, moderate wave activity and energy conditions occasionally develop and, combined with tidal activity make the intertidal

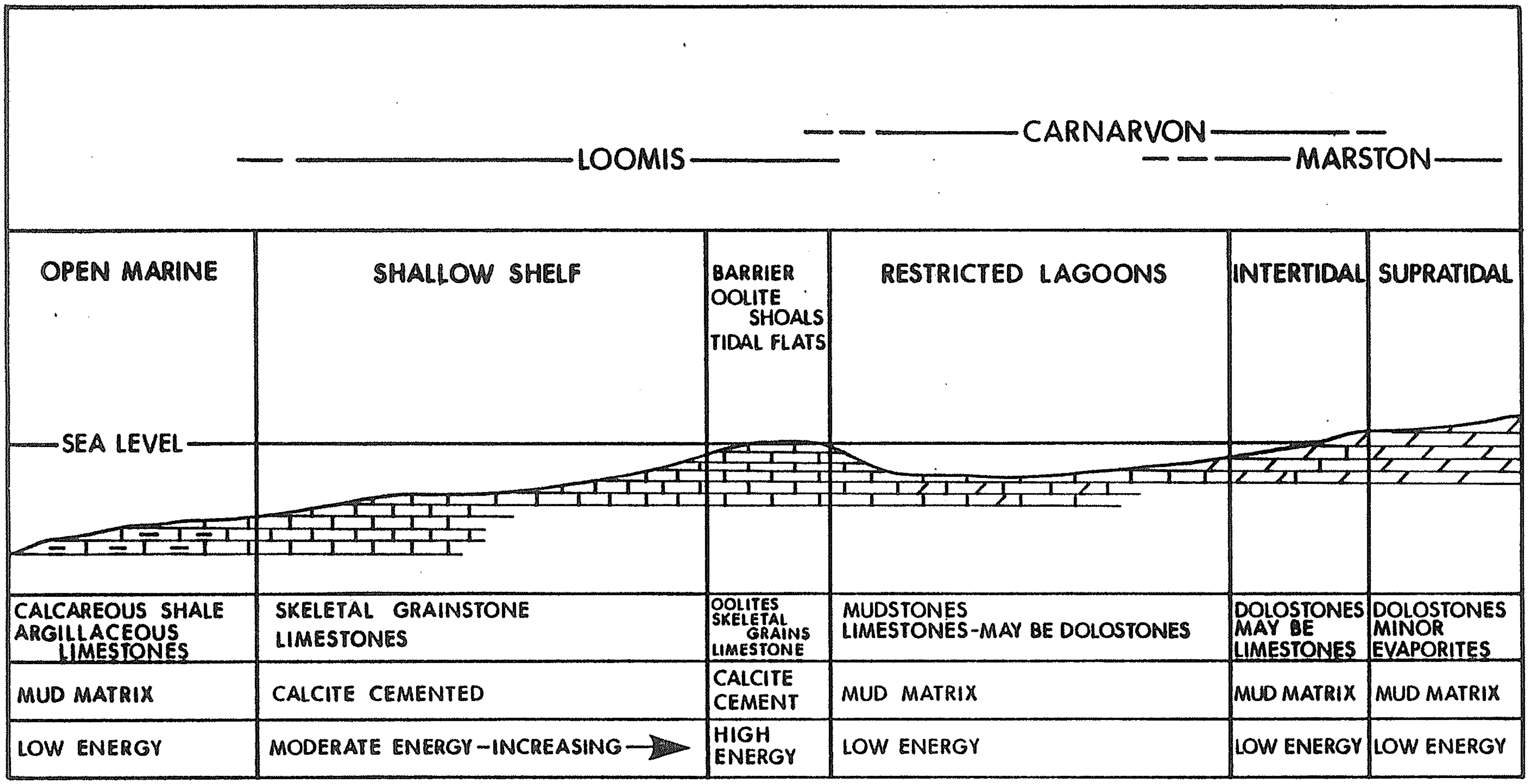

FIGURE 8 DEPOSITIONAL MODEL FOR THE UPPER MOUNT HEAD (MODIFIED AFTER MACQUEEN AND BAMBER, 1968)

zone one of moderate energy. Overall, however, wave and current energy levels generally decrease away from the barrier complex towards the open marine and towards the shoreline with most environments having a low energy setting.

Loomis Member

The massively bedded Loomis Member is 50 metres thick at the Highwood River section and stands out as a resistant, gray weathering cliff. The individual beds range in thickness from 0.5 metres to 12 metres. Lithologically, it is a limestone except for 3.3 metres of calcitic dolostone. The Loomis Member conformably overlies the Salter Member of the Mount Head Formation (see Figure 9).

As can be seen in Figure 5, the Loomis is predominantly shallow shelf deposits with minor shoal, intertidal, and deeper water deposits. In general, these are the result of a major transgression of the sea at the end of Salter deposition (Macqueen and Bamber, 1968).

The dominant facies present within the Loomis Member are skeletal grainstones, echinoderm grainstones, and oolitic grainstones. These three facies account for 99 percent of the Loomis section. The skeletal and echinoderm grainstones are characteristic of moderate to high energy shallow shelf deposits (Macqueen and Bamber, 1968). Oolite grainstones were deposited in a high energy shoal environment at or above wave base and may actually build up to sea level.

A skeletal packstone near the base of the Loomis is interpreted as having been deposited in quiet waters of the shelf below wave base. Mudstones and echinoderm wackestones are interpreted as having accumulated on tidal flats which form on emergent shoals within the barrier complex. Figure 9 shows schematically the relationship of the Loomis Member with the other members of the Mount Head Formation and the Livingstone Formation. Here, the Loomis is shown as the lateral equivalent of the Livingstone and was deposited as the transgressive Visean sea moved eastward over the lagoonal to supratidal sediments of the Salter Member.

Marston Member

The Marston Member is 34 metres thick at the Highwood River section. It is a recessive unit, weathers buff brown, and consists roughly of 50 percent dolostone,

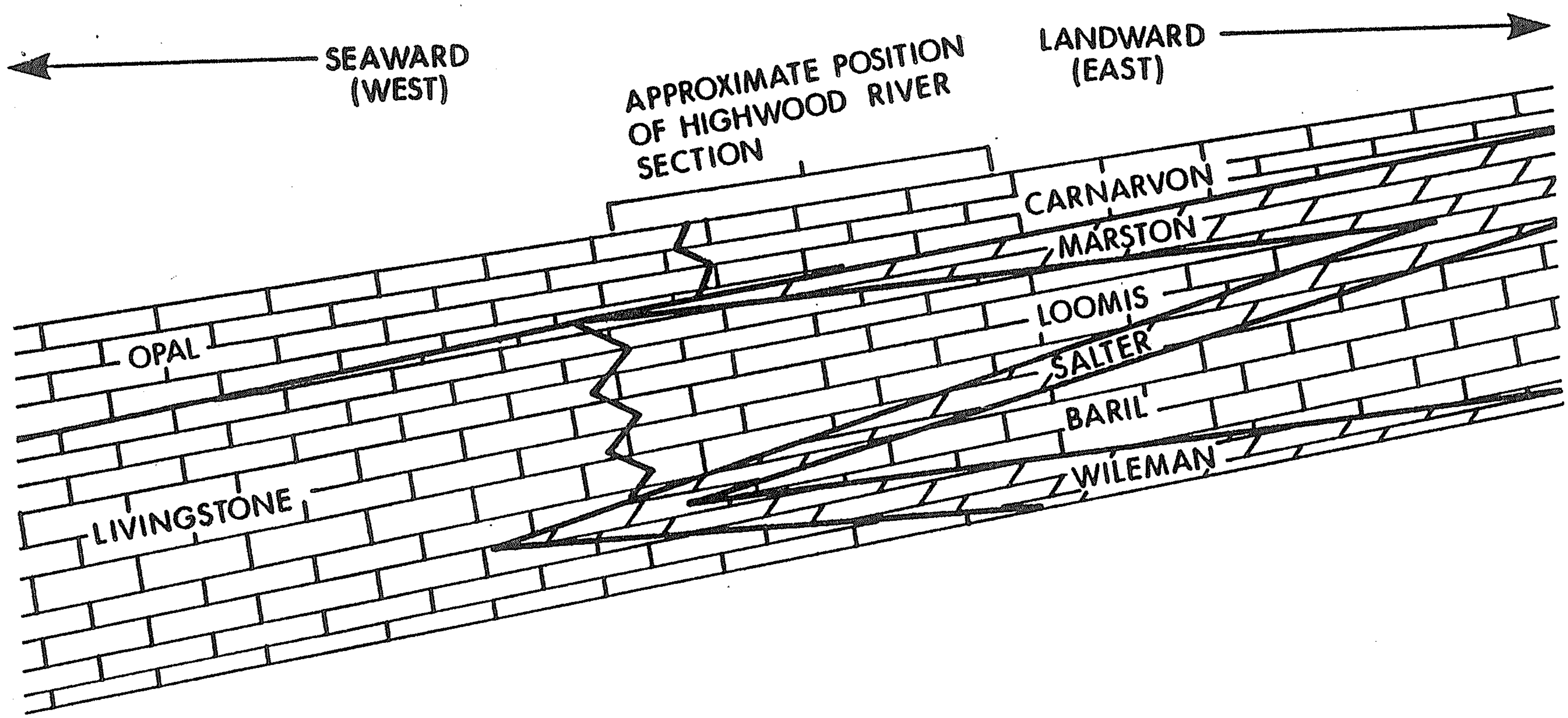

FIGURE 9 GENERALIZED CROSS-SECTION SHOWING THE RELATIONSHIP BETWEEN THE MOUNT HEAD FORMATION (WILEMAN, BARIL, SALTER, LOOMIS, MARSTON, AND CARNARVON MEMBERS) AND THE LIVINGSTONE FORMATION AND OPAL MEMBER TO THE WEST (MODIFIED AFTER MACQUEEN ET AL 1972)

35 percent limestone, 9 percent shale and siltstone, and the remaining 6 percent is covered.

Figure 6 shows the vertical variations in depositional environments within the Marston, along with the lithologies and facies types present. It is dominated by intertidal to supratidal sediments as well as sediments which could not be interpreted with any degree of confidence except to say they are of lagoonal to intertidal origin. Strictly lagoonal sediments account for only 2 to 3 metres of the Marston. Dominant facies present include fenestral wackestones and mudstones, evaporitic mudstone, ostracode algal wackestones, oncolitic packstones and wackestones, and mudstones.

Abundant shale partings less than one centimetre thick commonly occur between beds in the upper Marston and represent short breaks in the carbonate sedimentation due to an influx of terrigenous material.

Carnarvon Member

The Carnarvon Member is 47 metres thick at the Highwood River section and is the thickest of the three members studied. It is predominantly limestone with only 2 metres of dolostone. Shale partings between beds are quite common.

Figure 7 shows the vertical variation in depositional environments along with lithology and facies changes. The dominant facies present is an ostracode algal wackestone characteristic of lagoonal deposits. Many of the facies which occur within the Carnarvon Member contain vertical burrows. According to Rodriguez and Gutschick (1970) these are found only in sediments of intertidal origin. Fenestral wackestones and mudstones with evidence of algal mats are also present in lesser amounts. These sediments are interpreted as being intertidal to supratidal in origin. The beds of skeletal packstones and skeletal algal pelloidal packstones are derived from biostromes which have developed within the lagoon. The presence of an echinoderm grainstone near the top of the Carnarvon could possibly be the result of a biostrome building upwards to the surface of the water forming a small shoal with sufficient energy to wash the sediments of lime mud.

In general, the Carnarvon was deposited within a large, quiet water lagoon with short episodes of regression or progradation resulting in intertidal to supratidal conditions developing. The lagoon was sheltered from the open marine conditions to the west by the oolitic and echinoderm grainstone barrier complex of the Opal Member, Mount Head Formation (see Figure 9).

CHAPTER 3

DIAGENESIS

INTRODUCTION

Diagenesis refers to all processes which result in the alteration, cementation, and lithification of sediments during the interval of time between deposition and the elevated temperatures and pressures of metamorphism (Blatt et al, 1972 p. 456). Carbonate sediments and rocks are relatively unstable chemically and are therefore subject to more profound and rapid diagenetic modifications than are siliciclastic sediments. As mentioned in Chapter 1, this instability of carbonates has a significant effect on the preservation and/or development of porosity and permeability. Thus, an understanding of the diagenetic history of a rock sequence has an important economic significance in the search for and development of hydrocarbon reservoirs.

Major diagenetic processes which have affected the carbonate rocks studied are: biological diagenesis, neomorphism, cementation, and dolomitization. Neomorphism, as defined by Bathurst (1971, p. 475) consists of two *in situ* processes: 1) polymorphic transformation, and 2) recrystallization. Bathurst goes on to say that it is a useful term to use when it is known that an *in situ* fabric change has occurred but it is not clear which of the above two phenomena, or both has been active. Diagenetic processes of lesser importance include silicification, pyritization, solution, and evaporite mineral formation. Each of these processes will be dealt with in detail in the following sections.

BIOLOGICAL DIAGENESIS

Biological diagenesis refers to those processes which, through the activity of various organisms, alter the nature of the original sediments and/or their component grains. This can occur in the form of burrowing or bioturbation which can range from minor disruption of sedimentary structures to the complete destruction of structures and textures through homogenization of the sediments. Another form of biological diagenesis is pelletization which occurs when a fine grained sediment or mud is passed through the digestive tract of certain organisms. Another type of biological diagenesis results in the modification of individual carbonate grains through the process of microboring and micritization.

BURROWING AND PELLET FORMATION

Burrowing and pellet formation both result in the reworking of sediments and the destruction of primary sedimentary structures. Within sediments of Holocene age, both burrows and pellets are produced by polychaete worms, gastropods, and crustaceans, especially crabs (Shinn *et al*., 1969). Evidence for burrowing by ostracodes is present in some of the wackestones of the Carnarvon Member but these small organisms probably do not account for many of the larger burrows. In Place 7c, numerous ostracodes are present within a large burrow and appear to be burrowing into the sides. It is not possible to tell if they are responsible for the large burrow or not, but this photograph indicates that they were probably responsible for some burrowing.

Evidence of burrowing is restricted almost totally to the Carnarvon Member with the exception of a single burrowed bed in the middle of the Marston. The burrows range in size from 4 to 10 millimetres long and from less than 1 millimetre to 4 millimetres in width (see Plates 7a, b). They are generally filled with sparry calcite but may be filled with pellets or gypsum. Plate 7d shows pellets within a void cemented by sparry calcite. One sparry calcite-filled burrow has a lining of sediment along the inside of the burrow wall. This structure may be a "dwelling tube" as described by Frey (1973) in which the organism secretes a sticky substance to stabilize the burrow and prevent it from collapsing (Plate 7b).

Most of the burrows are vertical i.e. normal to the bedding plane or nearly so, but a few are horizontal. Vertical burrows are restricted to the intertidal zone (Rodriguez and Gutschik, 1970). Generally, they have a regular shape such as those in Plates 7a, b, and d, but they may be highly irregular and indistinct. Intensive burrowing probably accounts for the lack of primary structures such as bedding and cross-bedding within the grainstones of the Loomis Member. This phenomenon has been observed by Handford (1978) in similar facies within the Mississippian Monteagle Limestone of Alabama.

Pellets interpreted as faecal in origin are generally associated with burrowing within muddy sediments, and are restricted to the Marston and Carnarvon Members. These pellets are fine grained and range in size from 0.15 to 0.20 millimetres.

MICROBORING AND MICRITIZATION

Microborings are caused by endolithic algae and/or fungi which bore into the surface of carbonate grains to live. These organisms, through this process, result in the widespread and abundant destruction of carbonate skeletal grains, oolites, and faecal pellets (Bathurst, 1971, p. 381). According to Bathurst (1971), micritization occurs by infilling of the microbores with micritic carbonate. This mechanism causes the grains to be centripetally replaced. In addition to this mechanism, algal filaments, protruding from the surface of the grain may become calcified. When these filaments coalesce they form micritic envelopes on the grains. This is a constructive process and results in grain accretion (Kobluk and Risk, 1977). Recent studies indicate that infestation and boring occur very rapidly, on the order of days to weeks (Kobluk and Kahle, 1978; and Perkins and Tsentas, 1976).

Microboring is ubiquitous throughout the section, occurs in all depositional environments except supratidal, and is observable in all types of carbonate grains. It may result in the formation of a simple micrite rind or in the complete micritization of the grain (Plate 7e).

NEOMORPHISM

The bulk of carbonate sediments, both bioclastic fragments and lime mud, were probably deposited as high magnesium calcite or aragonite (Lowenstam, 1963), however, as pointed out by Bathurst (1971 p. 58), there is at present no way of determining the original mineralogy of the fossils.

The original sediments, then, composed of high magnesium calcite and aragonite subsequently undergo inversion and recrystallization (Folk, 1965) to produce the low magnesium calcite, which is the mineralogy of almost all ancient limestones. Because of mineral stabilities, these neomorphic changes will not occur in normal seawater (Winland, 1969) but occur during lithification of the sediments (Friedman, 1964, and Cotter, 1966), when non-marine waters circulate through the sediments. Besides changing the mineralogy of the original components of the sediment, neomorphism also results in microscopic textural changes. Examples of textural changes due to neomorphism include the alteration of micrite, which by definition consists of particles 1 to 4 microns in size, to microspar 4 to 10 microns in size (Folk, 1965). This phenomenon occurs in all lime mud-bearing facies throughout the section. Another example includes the recrystallization of molluscan tests in which the shells have been recrystallized to coarse, bladed calcite crystals oriented perpendicular to the shell margins.

CEMENTATION

Cementation of carbonate sediments, both modern and ancient, has justly received much attention in the modern literature (for example, Bricker, 1971; James et al, 1976; Lindholm, 1974, and Cussey and Friedman, 1977). It is the main cause of lithification in carbonate rocks and results in a major reduction of primary pore spaces.

Three morphological types of cements are present in the Highwood River section. These are isopachous, syntaxial, and blocky.

ISOPACHOUS CEMENTS

Isopachous cement refers to thin, even crusts of cement which line the interior of voids or occur as coatings on grains (Plate 8a). Isopachous cement crystals may occur in three different morphologies, namely acicular, bladed, and equant. Although not abundant, isopachous cements occur in all three members of the section with equant isopachous cement being the most common of the three morphologies. Mineralogically, these cements are predominantly calcite but locally within the Marston Member, dolomite may occur as subhedral equant isopachous cement lining fenestral voids (Plate 8c). Bladed and equant isopachous calcite occurs in interparticle and intraparticle voids. It is clear and free of inclusions, and may be earlier than or contemporaneous with syntaxial overgrowth cement. For example, in Plate 8d, it appears that either an incomplete isopachous cement was formed with subsequent filling of the void by syntaxial cement, or the development of the isopachous cement was interrupted and halted by the more rapidly forming syntaxial cement. Notably, isopachous cement forms on micritized portions of echinoderm fragments and syntaxial overgrowths on nonmicritized or lightly micritized parts.

Within a few of the grainstones of the Loomis Member, the first generation of cement often occurs as 100 to 200 micron thick fringes composed of acicular crystals oriented normal to the grain boundaries (Plate 8b). Acicular cement crystals are defined by Milliman (1974, p. 271) as "long, thin crystals, usually oriented normal to the grain surface" and are equivalent to Havard and Oldershaw's (1976) fibrous cement in which the crystals have a length to width ratio of greater than 6:1. In modern environments acicular fringes consist of much smaller crytals than do those of the Mount Head. Also, mineralogically they are composed of aragonite or high magnesium calcite. In these ancient rocks, neomorphism has resulted in crystal enlargement and inversion to low magnesium calcite but has preserved the original morphology. This phenomenon has been observed by Burgess (1979) in Jurassic carbonates of Morocco and by Mazzullo et al. (1978) in Lower Ordovician carbonates in New York. Like the other isopachous cements, the acicular variety occurs only on the micritized portions of echinoderm fragments and on other skeletal grains not prone to syntaxial overgrowths.

In some instances due to their fragility, the acicular fringes have been spalled off by grain movement or compaction (Plate 9b). This is evidence for precipitation soon after deposition because the fringe precedes any substantial burial or grain to grain movement caused by shifting of unstable sand bodies. The morphology of the crystals, that is, their acicular nature, is indicative of Mg^{++} "poisoning" (Folk, 1974). This occurs when the smaller Mg^{++} ion substitutes for the Ca^{++} ion causing the crystal lattice to distort. This distortion terminates further growth along that crystallographic plane which in the case of calcite is the plane defined by the a and b axes. The overall effect is to produce a calcite crystal much elongated in the c direction. Thus, these acicular isopachous cements indicate formation in a magnesium-rich environment such as in beaches or marine bottoms (Folk, 1974). Present-day seawater has approximately five times as much Mg^{++} as Ca^{++} while freshwater systems such as rivers contain approximately twice as much Ca^{++} as Mg^{++} (Weyl, 1970, p. 324). Many authors have observed and described the occurrence of acicular calcite and aragonite sediments in the modern marine environment (Cotter, 1966; Purser, 1971; Burgess, 1979; and Hattin and Dodd, 1978).

SYNTAXIAL CEMENTS

Syntaxial refers to an optically oriented crystal overgrowth developed on a detrital grain and indicates lattice continuity between overgrowth and grain. Syntaxial overgrowth cement occurs on monocrystalline echinoderm grains and grows in optical continuity with them. This cement type occurs in all grainstones and most packstones which contain echinoderm debris. However, because of the high degree of micritization of the grains, this cement type is not abundant. Micritization prevents the formation of syntaxial cements by preventing the nucleating calcite from coming in direct contact with the echinoderm fragment itself (Gorur, 1979; Evamy and Shearman, 1965). Instead, the substrate on which the cement nucleates is composed of many randomly oriented microcrystals and results in randomly oriented multicrystal cements.

Several recent studies describe syntaxial overgrowth cement which has formed early in the history of the sediments within the marine environment (Gorur, 1979; Burgess, 1979; Friedman, 1975; Young and Greggs, 1975; Evamy and Shearman, 1965, 1969). Evidence for marine formation of these cements within the rocks at the Highwood River section may be seen in Plates 7e, and 8e. In Plate 7e, syntaxial overgrowths have developed only on the echinoderm grains where the fungi and algae have not had sufficient time to completely micritize the grain surface. The overgrowth, then, has a substrate on which to nucleate. As mentioned early, micritization of grains can occur soon after deposition and the presence of syntaxial overgrowths in a sediment that has been highly micritized indicates that perhaps the overgrowth as well occurred soon after deposition. Also, in some instances, boring has been observed within the overgrowths themselves.

In Plate 8e, many of the grains exhibit pressure welding and solution along grain to grain boundaries. However, the large echinoderm grains with syntaxial overgrowths have resisted this pressure solution indicating that they were cemented prior to burial.

Some of the observed syntaxial cements are believed to have formed later in the sediment's history, possibly in a freshwater phreatic environment. Evidence for this is shown in Plate 8d. Here the syntaxial cement post-dates or is at least penecontemporaneous with the formation of a clear equant druse which is interpreted as having formed in the freshwater phreatic environment. Also, none of the criteria listed above to suggest precipitation in the marin environment are present in these particular syntaxial cements.

BLOCKY CEMENTS

Blocky calcite cement is the most common and abundant cement type observed in the rocks of the Highwood River section. It consists of massive, equant calcite crystals filling void spaces within the sediment. It occurs in all rock types from all depositional environments and occludes all void types.

Within the Loomis Member, blocky cements may be very cloudy and full of inclusions (Plate 8b). These inclusions are believed to be impurities which were present in the pore fluids and subsequently entrapped during crystallization of the cement. Marine pore fluids contain more impurities in the form of minute particulate matter and foreign ions than do meteoric waters (Cotter, 1966; Meyers, 1974). Therefore, these cloudy blocky cements are interpreted as having formed in the marine environment but post-dating the acicular isopachous fringing cements described earlier (Plate 8b). The change in cement morphologies from acicular to blocky may be due to a reduction in Mg^{++} ions in the pore fluids as a result of formation of the acicular cements. An alternate explanation is that the crystal growth was slow enough to expel the foreign ions from the lattice during crystallization.

More abundant than the cloudy blocky cements are clear, relatively inclusion-free blocky cements (Plate 8a, f). This cement type consists of equant calcite crystals ranging in size from fine to coarse. Often the crystal sizes within a single void increase in size from the grain boundaries to the centre of the void (Plate 8f). The clarity, coarseness, and equant nature of these cements suggest precipitation within a freshwater phreatic environment for the following reasons: (1) the clarity of the cement crystals indicates that the pore fluids were relatively free of impurities which are common in the marine environment (Cotter, 1966), (2) coarseness of the cements indicates slow crystallization in the absence of Mg^{++} and Na^{++} in an environment uninfluenced by organic reactions (Folk, 1974), (3) the equant nature of the calcite also indicates the absence of Mg^{++} and Na^{++} in the pore fluids because the crystal is able to grow in all three crystallographic directions without interference from impurities (Folk, 1974).

SUMMARY

In summary, the earliest precipitated cements are believed to have been formed within the marine environment and occur as thin acicular isopachous fringes. The isopachous fringes were followed by cloudy, inclusion-rich blocky cements also interpreted as marine in origin. These blocky cements, however, may occur without the earlier fringing isopachous cements.

Two generations of syntaxial cements occur. The earlier one was precipitated within the marine environment. However, no evidence was observed to allow a determination of the relationships between the syntaxial cements and the other marine cements. The second generation of syntaxial cement was deposited within the freshwater phreatic environment and post dates the precipitation of clear equant drusy calcite.

The final generation of cement was precipitated in a freshwater environment and resulted in the occlusion of almost all remaining void space. It is a fine to coarsely crystalline, clear, blocky calcite cement.

DOLOMITIZATION

DESCRIPTION

Dolostone accounts for approximately 18 metres of the 130 metre Highwood River section. Of this, 15 metres occur within the Marston Member with only 2 metres and 1 metre in the Loomis and Carnarvon Members, respectively.

In the field, dolostone is fairly easily distinguished from limestone because of its distinctive yellowish brown weathering. Sedimentary structures, such as very fine laminations and burrows are preserved.

Although dolomite is present predominantly in mudstones and wackestones, it occasionally is found in all facies within the section. It occurs in all stages of development from a few scattered euhedral rhombs (Plate 9a) to selective dolomitization of the micrite matrix of wackestones and packstones (Plate 9b, c) to complete dolomitization of mudstones (Plate 9d).

Crystal size of the dolostones ranges from microcrystalline to medium grained although the finer grain sizes predominate. The average crystal size is 60 microns but all sizes may be found in a single sample. The finest dolomite crystals are anhedral and contain abundant inclusions giving them a dusty or cloudy appearance. The coarser crystals are commonly euhedral or subhedral and free of impurities. Often, the core of the dolomite crystals contain abundant inclusions but become clearer and impurity-free towards the edges.

Staining with potassium ferricyanide (Dickson, 1965) identified substantial amounts of ferroan dolomite ($Ca(Mg, Fe)(CO_3)_2$). The iron may have been derived from iron-bearing clay minerals within the shales of the Marston and Carnarvon Members or from subsurface waters. With the exception of two beds, all of the dolostones are calcitic to some degree. The calcite occurs either as undolomitized skeletal debris or is intercrystalline to the dolomite. This intercrystalline calcite may be either a remnant of the original micrite material which escaped dolomitization or post-dolomitization additions.

Selective dolomitization within the upper Mount Head rocks is quite common and has been described by Douglas (1958). It may be observed on a microscale as in the micro-fabric of the rock (Plate 10b, c) or on a macroscale such as the selective dolomitization of the mud-supported beds within the Loomis Member. Lime muds are selectively dolomitized because of their original high porosity and high surface area. These properties result in greater reactivity to dolomitizing solutions (Murray and Lucia, 1967).

Within the Marston, which is approximately half dolostone, much of the dolomite is associated with gypsum. This association has been described in the Persian Gulf by Purser (1973) and indicates a similarity between the depositional environments of the Marston Member and the sabkha of the Persian Gulf.

DISTRIBUTION

There are two beds of dolostone within the Loomis Member. Each is approximately one metre thick. One occurs roughly 12 metres above the Salter-Loomis contact while the other occurs approximately in the middle of the Loomis Member (see Figure 5). Both beds were originally mud-supported sediments and are in contact with undolomitized grainstones both above and below. Both the upper and lower contacts are sharp.

The Marston Member contains 15 metres of dolostone, which is approximately half of its total thickness (see Figure 6). Dolomitization occurs randomly within this member. Even though the Marston consists of almost wholly mud supported sediments, only 50 percent of the rocks have been dolomitized. The contacts between dolostone and limestone commonly are sharp, but are more likely to be gradual over 30 to 60 centimetres. Although the dolomitization has preferentially altered the lime muds it does not appear to be wholly influenced by depositional environment. That is, within the Marston, rocks interpreted as being from the same depositional environment and in contact with each other stratigraphically may be either limestone or dolostone.

Only two half-metre-thick beds of dolostone occur within the Carnarvon Member. These beds occur approximately mid-way between the upper and lower contacts of the Carnarvon. The lower bed was originally a lime mudstone while the upper bed was a skeletal echinoderm mudstone. Contacts between the dolostones and limestones are quite sharp and in some cases are shale partings.

DOLOMITIZATION MODELS

The occurrence of large amounts of dolomite within ancient carbonate rocks has been a problem to geologists because of: 1) the rarity of dolomite in carbonate sediments of Holocene and Pleistocene age, and 2) the inability to synthesize it at temperatures and pressures characteristic of the sedimentary cycle (Lippman, 1973, p. 48).

Although some dolomite is found in most of the modern-day carbonate depocentres, it only occurs in relatively small amounts within areally restricted environments.

Because of the general absence of active dolomite producing areas today and because of its observed relationships to other carbonate sediments, it is presently believed that most dolomite is secondary in origin (Milliman, 1974, p. 304). That is, it is a replacement of previously existing $CaCO_3$ sediments. Evidence to support this conclusion is the presence of preserved primary structures and textures, relict grains, and the occurrence of dolomite cross-cutting bedding planes. Evidence for the primary precipitation of dolomite is rare in the geologic literature and much confusion has resulted over the controversy between primary and secondary dolomite formation (Milliman, 1974, p. 309). Several models have been developed in the past twenty years to explain the occurrence of dolomite within modern and Pleistocene sediments and relate these mechanisms to ancient rocks.

Adams and Rhodes (1960) proposed the seepage refluxion theory to explain the occurrence of dolomite in sediments of the Permian Basin of Texas and also the pre-Pleistocene carbonates of the Bahamas and Florida. The mechanism involves evaporation of seawater in a coastal lagoon to form heavy, warm brines which percolate downward through underlying sediments causing dolomitization and deposition of evaporite minerals. Evaporative reflux, a modification of this theory was proposed by Deffeyes _et al_ (1965) as a mechanism for the formation of dolomite on the island of Bonaire, Netherlands Antilles. This theory calls for evaporation of seawater in supratidal lakes and ponds with resultant dolomitizing brines flowing downward through the underlying permeable sediments. Murray and Lucia (1967) appealed to a similar mechanism to explain dolomitization of the Mississippian Turner Valley Formation in western Canada. Here, brines were formed in the supratidal and tidal flats of the Mound Head Formation and percolated downwards into the Turner Valley sediments altering limestone to dolostone. Von der Borch and Lock (1979) attributed the formation of dolomitizing brines to evaporation in ephemeral lakes in the Coorong area of southern Australia.

Another mechanism believed to be operating in sediments of the Bahamas and the Persian Gulf is evaporative pumping. This involves pore fluids being drawn laterally from the marine environment and vertically to the sediment-air interface through evaporation. In the Bahamas, Shinn _et al_ (1965) described this phenomena occurring on supratidal mud flats of Andros Island and forming hardened crusts with up to 80 percent dolomite.

Illing _et al_ (1965) described the same process occurring on the sabkhas of the Persian Gulf where the dolomite is replacing aragonite mud.

A more recent theory for the formation of dolomite within Holocene sediments, proposed by Hanshaw _et al_ (1971), requires the mixing of meteoric groundwater with marine pore fluids. Folk and Land (1975) theorized on the mechanics and chemistry of dolomite formation due to the mixing of freshwater and marine water. They proposed that although a reduction in salinity results from mixing, the Mg/Ca ratio remains quite high and dolomite is able to form due to a slow-down of the crystallization rate and a reduction in the concentrations of interfering foreign ions. Because of dolomite's relatively complex and ordered structure (as compared to aragonite and high-magnesium calcite), it's development is favoured if crystallization occurs slowly and concentrations of competing ions are low enough that they don't disrupt the precise ordering of the lattice.

Badiozamani (1973) proposed the Dorag dolomitization model to explain dolomitization within the Ordovician sediments of Wisconsin. Here, the dolomitized zone is associated with structural highs and subaerial exposure resulting in the formation of freshwater lenses. The zone of mixing between the fresh and saline waters is where dolomitization takes place. Land (1973) also described a process in northern Jamaica whereby meteoric water flowing towards the sea mixes with marine pore fluids and results in dolomitization.

Some of the above mentioned theories explain very well the occurrences of some dolomite within the Holocene and Pleistocene, but, they still do not account for the very large volumes present within ancient carbonate rocks. Perhaps, to explain these large quantities, we must appeal to deep subsurface and possibly low temperature hydrothermal mechanisms about which very little is known.

Land _et al_ (1975), Morrow (1979), and Randazzo _et al_ (1977) invoke combinations or stages of dolomitization such as dolomite forming from early saline brines, followed by enlargement of dolomite rhombs during meteoric diagenesis, and finally, subsurface diagenetic processes, possibly with elevated temperatures. This theory suggests that dolomite crystals which form early in the history of the sediment act as nucleii which make further dolomite crystal growth possible.

It is likely that some dolostones occurring in the geologic record may be the result of a single-step, post-depositional event but the author feels that such a mechanism would result in more wholesale dolomitization than is encountered within Mount Head Formation sediments.

Other considerations which help to explain the abundance of dolomite within the geologic record are the former abundance of shallow, epeiric seas which covered the continents at intervals throughout geologic time. These seas were characterized by warm waters which were probably more saline than our present-day oceans and by gently sloping shorelines resulting in very extensive supratidal and tidal flat zones (Zenger, 1972). This would greatly effect the extent of influence of tides and other relative changes in sea level resulting in larger areas of potential dolomitization.

DIAGENETIC ORIGIN OF THE MOUNT HEAD DOLOSTONES

As mentioned in a previous section, most of the dolostone occurs within the Marston Member and may be interpreted as being at least partially dependent upon depositional environment. Sediments of the Marston Member were deposited wholly within lagoonal, intertidal, or supratidal environments and may locally contain evaporite mineralization, particularly gypsum. Dolomitization here may have begun in a supratidal sabkha setting characterized by high rates of evaporation. In contrast, the other members of the Mount Head Formation were deposited predominantly in environments in which water salinities and compositions were normal marine. These rocks contain very little dolomite and what is present occurs only locally or in thin beds which were interpreted as being deposited in an intertidal to supratidal setting.

Microcrystalline and very fine grained, inclusion-rich dolomite described earlier probably formed in a supratidal environment were pore fluids are highly saline, resulting in impure, poorly developed crystals.

Either an evaporative pumping mechanism or an evaporative reflux mechanism or both may have initiated early dolomitzation. Purser (1973) described dolomite associated with evaporite minerals similar to those observed in the Marston Member forming on the sabkhas of the Persian Gulf. Dolostones petrographically similar to those discussed above but containing no evaporite minerals may have developed in a similar environment except that saline and sulphate evaporite minerals were subsequently flushed out of the system by meteoric water in a manner similar to that described by Von de Borch and Lock (1979).

Continued dolomitization in the shallow subsurface environment resulted in enlargement of the early, penecon-temporaneous dolomite crystals and often complete dolomitization of the sediment. This process may have occurred in an environment where marine pore fluids came into contact with and mixed with freshwater. This interpretation is supported by the observation that a large percentage of the dolomite crystals have dusty or inclusion-rich cores but become clear towards the edges. This indicates a change in pore fluid chemistry and as described in the section on dolomitization models, indicates a reduction in salinity. The resultant solution, having a relatively high Mg/Ca ratio but low salinity, promoted the growth of subhedral to euhedral, inclusion-free dolomite crystals. Further crystal growth may have occurred at greater depths accompanied by elevated temperatures as postulated elsewhere by Land *et al* (1975) and Randazzo *et al* (1977).

EVAPORITES

Gypsum ($CaSO_4 \cdot 2H_2O$) and celestite ($SrSO_4$) are present in small amounts within the lower half of the Marston Member. These evaporites occur within isolated beds and make up only a minor part of the rock. Gypsum is the most abundant of the two evaporite minerals present in this member and occurs predominantly within very finely crystalline dolostones. It may occur as a fenestral void filling where it forms coarse mosaics of anhedral crystals, (Plate 10e) or in thin beds of pure gypsum up to 20 millimetres thick (Plates 6c, 10a) consisting of anhedral to euhedral crystals.

No evaporite mineralization is present within the Loomis Member. In the Carnarvon Member, gypsum occurs only within a single mudstone bed at the base of this member. The gypsum occurs as isolated, subhedral to euhedral crystals and comprises less than 1 percent of the rock (Plate 6d).

Kinsman (1969) indicated that evaporite mineralization of the types described above is an early diagenetic process, is restricted to the upper layers of the sediment, and is often related to dolomitization. Roehl (1967), Mukherji (1969), Kinsman (1969), Butler (1969), Cook (1973), and Levy (1977) all discussed Holocene occurrences of gypsum similar to that described here for the Mount Head Formation. Gavish (1974) described gypsum forming by "evaporative pumping" in the upper 30 to 40 centimetres of a sabkha along the Gulf of Suez.

For the types of gypsum found within the Mount Head Formation, the consensus of opinion favours deposition within a supratidal environment. Shearman (1966), however, reported abundant gypsum crystals, often forming crystal mushes several inches thick, associated with algal mats and occurring in intertidal sediments. Von der Borch _et al_ (1977) described gypsum, associated with stromatolites, forming in 2 to 3 metres of water in ephemeral lakes in South Australia. However, only localized evidence for the occurrence of algal mats has been observed within upper Mount Head sediments at the Highwood River section and none has been associated with evaporite mineralization.

The thin beds of gypsum crystals found within the Marston Member (Plates 6c and 10a) are similar to those described by Butler (1969) as occurring on the sabkha of the Trucial Coast. These beds are formed as crystal "mushes" at the surface of the sabkha from standing brines and are primary precipitates.

Void filling gypsum precipitates from hypersaline pore fluids and forms beneath the surface of the sediment. The brine solutions are caused by evaporation of normal seawater and are moved through the sabkha sediments either by evaporative pumping or seepage refluxion. The gypsum which fills the fenestral voids of the Marston Member was probably precipitated from brines formed in the above fashion. It is not possible to deduce which of the above mechanisms circulated the brines.

Celestite has also been mentioned in the literature as occurring in supratidal sabkhas along with other evaporite minerals (Shearman, 1966, Mukherji, 1969, and Kinsman, 1969). The celestite occurs within a single bed 0.15 metres thick near the base of the Marston Member. This bed consists of 40 to 60 percent celestite in a micrite matrix (Plate 10b, c, d). Plates 10b and c show large optically continuous crystals replacing micrite in a poikilotopic manner. Thin haloes rim the celestite as in Plate 11d and is probably a replacement "front" which was preserved after celestite replacement was halted.

SILICIFICATION

Silicification is minor in the rocks of the upper Mount Head at the Highwood River section, but, it is present in all three members and is most common in the Loomis Member. Silicification is present in two forms; chert nodules and thin, discontinuous beds, and silica replacement of fossils.

Chert nodules and thin beds occur in all three members. Microscopically, the nodules are generally structureless, however, they may contain relict patches of the host rock. The nodules may be linked laterally in varying degrees or be completely discontinuous. They average 10 centimetres in diameter but they may range from less than 1 centimetre up to 30 centimetres.

Beds of cherts such as those in Plate 11a may be up to 30 centimetres thick and in the limestones just below the Carnarvon-Etherington contact, make up about 40 percent of the rock. Locally within the Loomis, chert may account for up to 25 percent of the rock.

Silicification of fossil debris occurs locally and seemingly at random throughout the section within grainstones and packstones, but is most abundant in the Loomis Member. It has an affinity for skeletal calcarenites because it replaces skeletal fragments, especially echinoderms (Plate 11b).

Chert formation may be either an early or late diagenetic event dependent upon certain physicochemical properties in which carbonate becomes more soluble and silica less soluble. According to Siever (1962), early diagenetic chert requires bacterial action and organic decay to lower the pH. As a result, carbonate dissolves and organically complexed silica precipitates. These same conditions are produced by highly saline brines found in sabkha environments or in the deep subsurface (Siever, 1962).

Little evidence is present to determine the diagenetic timing of the silicification, however, with those grainstones of the Loomis Member which have been partially silicified, the silicification of the echinoderm grains appears to have occurred subsequent to the precipitation of syntaxial overgrowth cement. Plate 11b shows a silicified echinoderm fragment in direct contact with syntaxial overgrowth cement which could not have formed unless the grain was calcite during precipitation of the cement.

The source of the silica may have been siliceous organisms such as sponges and radiolaria which occupied the open marine environment in Mississippian seas (Mamet, 1976). However, none were observed in the sediments studied. A second source of silica may have been siliciclastic sediments such as the quartz siltstones found at the base of the Marston Member.

PYRITIZATION

Pyrite or hematite replacement of pyrite is present throughout the section in quantities up to 5 percent, but usually constitutes less than 1 percent. It may occur as: (1) microcrystalline flecks scattered throughout the rock, (2) euhedral cubes up to 0.5 millimetres (Plate 11c), (3) as large aggregates up to 1.5 centimetres in size, or (4) as partial replacement of fossils (Plate 11a).

Pyrite is especially common in fine grained dolostones and may have been emplaced during the final stages of dolomitization. Replacement pyrite as observed in Plate 11d appears to have pre-dated the precipitation of the blocky calcite cement.

SOLUTION AND SECONDARY POROSITY

Solution is a minor phenomenon within the rocks of the upper Mount Head Formation at the Highwood River. Solution is manifest in the following three ways: (1) stylolite development, (2) pressure solution along grain contacts, and (3) secondary porosity development.

Stylolites are quite rare within the section but occur in all three members. They are of low amplitude which suggests relatively little pressure solution, however, this is by no means a definitive indication (Bathurst, 1971, p. 471). The stylolites consist of brownish-black or yellow-brown insoluble residue and occasionally contain ten to fifteen percent finely disseminated pyrite. Stylolitization occurred after lithification of the rock and probably at depths (or overburden equivalents) of 600-900 metres (Dunnington, 1967).

Pressure solution grain boundaries are present in up to 5 percent of the grains in most of the grainstones of the Loomis Member. This observation indicates that the calcarenite sediments were unlithified or only partly lithified before burial (Cussy and Friedman, 1977).

Primary porosity has been completely destroyed within the rocks of the upper Mount Head Formation by the various processes of diagenesis. Also, most of the secondary porosity, which was produced through solution, has been destroyed by cementation. These secondary voids occur as vugs 1 to 10 centimetres in size and are present in thin, isolated beds within some of the mud-rich beds of the Loomis and Marston Members. Within these isolated beds, vuggy porosity may be as high as 3 to 4 percent.

FRACTURING

Post-lithification, tectonically produced tension fractures occur throughout the section. Densities vary from one or two fractures per metre in most parts of the section to several tens of fractures per metre within the Carnarvon Member. These fractures are generally straight and may be up to one to two metres in length. They range in width from hairline to 2 millimetres. Their attitudes range from vertical to horizontal but the majority by far are vertical.

Almost all the fractures are cemented tight with blocky calcite, but a few retain traces of porosity.

CHAPTER 4

SUMMARY AND CONCLUSIONS

DEPOSITIONAL ENVIRONMENTS

The upper three members of the Mount Head Formation at the Highwood River were deposited in a coastal barrier complex ranging from the open marine to the supratidal environment.

Sediments of the Loomis Member were deposited on a barrier bar complex composed of oolite shoals and shallow, high energy, open marine shelves. The facies within this member consist primarily of oolitic, skeletal, echinoderm, and pelloidal skeletal grainstones.

The Marston Member consists of sediments which were deposited in a quiet water lagoonal environment and the intertidal to supratidal environment. Lagoonal facies consist primarily of skeletal echinoderm wackestones, skeletal algal pelloidal packstones, ostracode algal wackestones, and some mudstones. Intertidal to supratidal facies consist of oncolitic packstones and wackestones, fenestral wackestones and mudstones, evaporitic mudstones, and mudstones.

Sediments of the Carnarvon Member were deposited primarily within the quiet water lagoon and consist mainly of ostracode algal wackestones with lesser amounts of skeletal packstones, skeletal echinoderm wackestones, skeletal algal pelloidal packstones, and mudstones. Interbedded with the lagoonal deposits are intertidal sediments characterized by fenestral mudstones and vertically burrowed mudstones. Associated with some of the intertidal sediments are minor evaporitic mudstones which indicate supratidal deposition.

DIAGENESIS

The relative timing of the various diagenetic processes which affected the sediments of the upper Mount Head Formation is shown in Figure 10. Below is a summary of the diagenetic history of these rocks and the conclusions regarding diagenetic timing and origin.

1) Biological diagenesis begins as soon as the sediments are deposited. The types of biological processes involved are burrowing, pellet formation, microboring, and micritization. Burrowing and pellet formation occur in close proximity to the sediment surface and are present within the mud-rich sediments

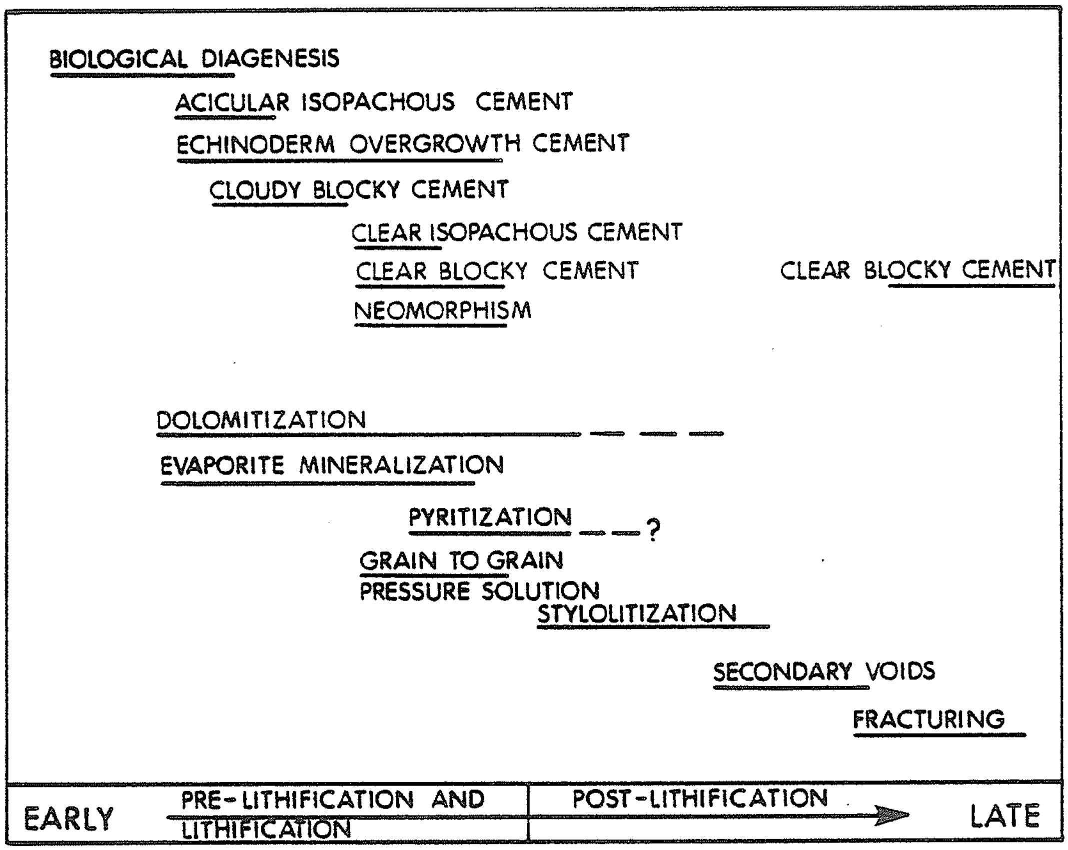

FIGURE 10 RELATIVE TIMING OF DIAGENETIC PROCESSES IN THE UPPER MOUNT HEAD FORMATION, HIGHWOOD RIVER, ALBERTA

of the Marston and Carnarvon Members. Intensive burrowing and bioturbation may account for the lack of primary sedimentary structures within the grainstones of the Loomis Member.

Microboring and micritization by algae and fungi is present throughout the section and occurs in all depositional environments except the supratidal. However, it is most prevalent in the grainstones of the Loomis Member.

2) Cements found in these sediments can be divided into marine and freshwater varieties. Marine varieties include acicular isopachous, syntaxial overgrowth, and cloudy blocky cements. The marine cements are present within the grainstones of the Loomis Member. Freshwater cements include clear isopachous and clear blocky cement and were precipitated in the shallow subsurface phreatic environment. Neomorphism, the alteration from high magnesium calcite and aragonite to low magnesium calcite, occurred at the same time as the formation of the freshwater cements.

3) Dolomitization has been interpreted to occur in two stages. Early, penecontemporaneous dolomitization occurs within the mud-rich sediments of the supratidal sabkha environment of the Marston Member. It forms from hypersaline brines and is often accompanied by the

precipitation of evaporite minerals. Dolomitization continues after burial in the shallow subsurface during mixing of marine and meteoric pore fluids.

4) Silicification is most common within the rocks of the Loomis Member and occurs as silicification of fossil debris and as chert nodules and discontinuous beds.

Pyrite or hematite replacement of pyrite is most common within the Marston Member and may occur as microcrystalline flecks, euhedral cubes, small nodules, or fossil replacement.

5) Solution occurs as grain-to-grain pressure solution, stylolitization, and formation of secondary voids. Grain-to-grain pressure solution is found within the grainstones of the Loomis Member and occurrred before the sediments were lithified. Stylolitization occurs at any level within the section but is not common. Low amplitudes on the stylolites indicate that little material has been dissolved and lost.

Solution has resulted in the formation of vugs within isolated beds of the Loomis and Marston Members. These vugs were formed after lithification of the rocks and most of them were subsequently occluded by clear blocky calcite cement.

6) Tension fractures, tectonically produced, occurred after lithification. Most of these fractures are cemented tight with clear blocky calcite cement.

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PLATES

Plate 1 HIGHWOOD RIVER SECTION

Highwood River section looking northward. Note the resistant, light gray, massive bedded Loomis Member in the centre of the photo. Overlying the Loomis is the thinner bedded, recessive, gray-brown weathering Marston Member. Above the Marston is the well-bedded, resistant, gray weathering Carnarvon Member. The line shows approximately the route taken when measuring and sampling. The Marston measures 32.3 metres thick at this locality.

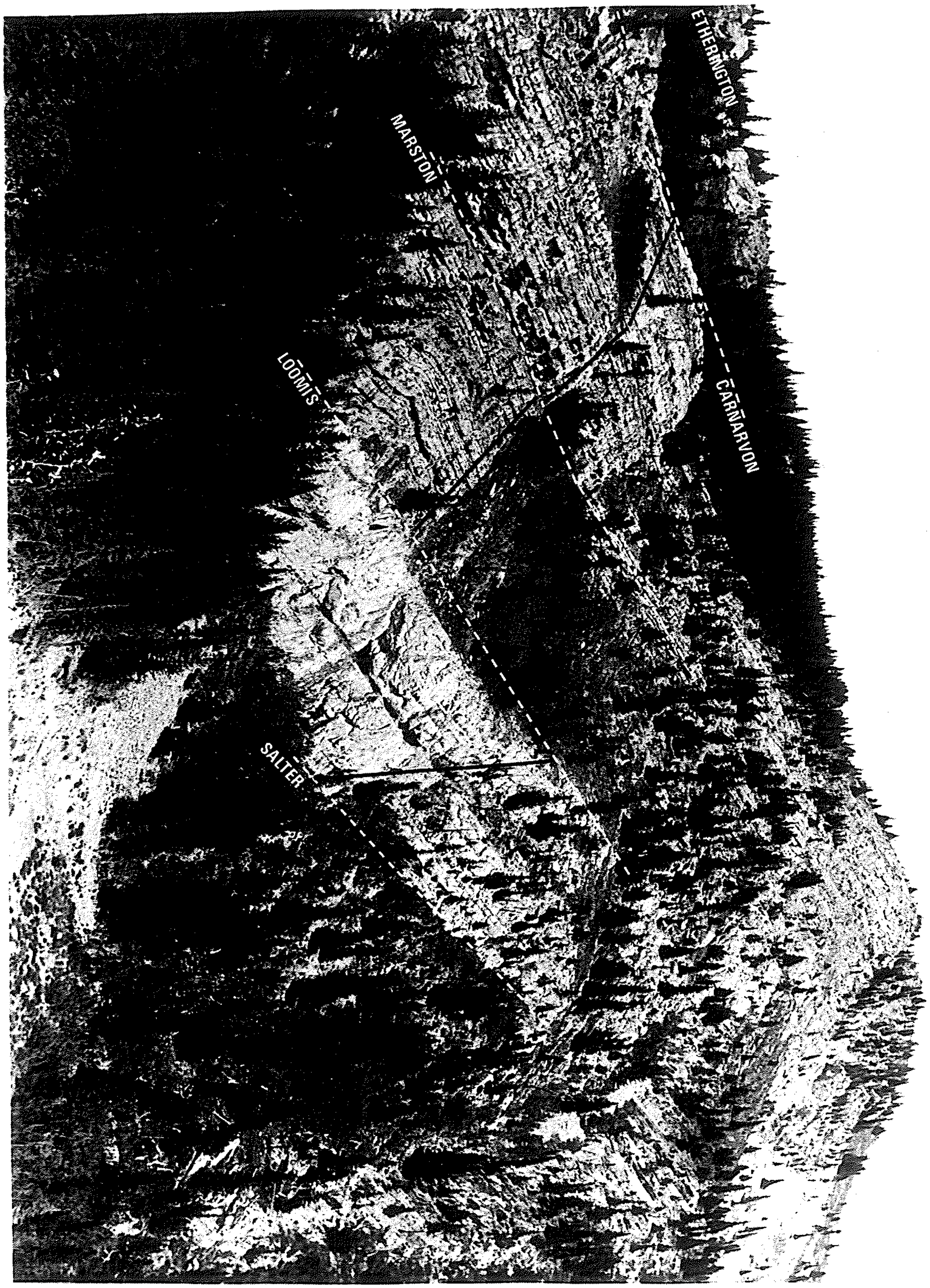
ETHERINGTON
MARSTON
LOOMIS
CARNARVON
SALTER

Plate 2 GRAINSTONE FACIES

(a) Hand sample of a pelloidal skeletal grainstone displaying laminations and crossbedding. The bedding in these rocks is accentuated by changes in grain size and type. (Sample K31, Loomis Member.)

(b) Coarse grained pelloidal skeletal grainstone showing abundant pelloids with lesser amounts of skeletal debris. These pelloids are interpreted as being the result of algal boring, and not of faecal origin. (Sample K32, Loomis Member, plane light.)

(c) Hand sample of a pelloidal skeletal grainstone. Light coloured beds and laminations are dolomite while the rest of the rock is limestone. Note the convolute bedding within the dolomite stringers indicated that dolomitization predated lithification. (Sample K26, Loomis Member.)

(d) Coarse to very coarse grained pelloidal skeletal grainstone with thin stringers of dolomite. Dolomite probably replaced the matrix of lime mud-rich laminations. (Sample K26, Loomis Member, plane light.)

(e) Higher magnification view of pelloidal skeletal grainstone shown in Plate 2b, showing superficial oolitic coats, a, surrounding many of the micritized fragments. (Sample K32, Loomis Member, plane light.)

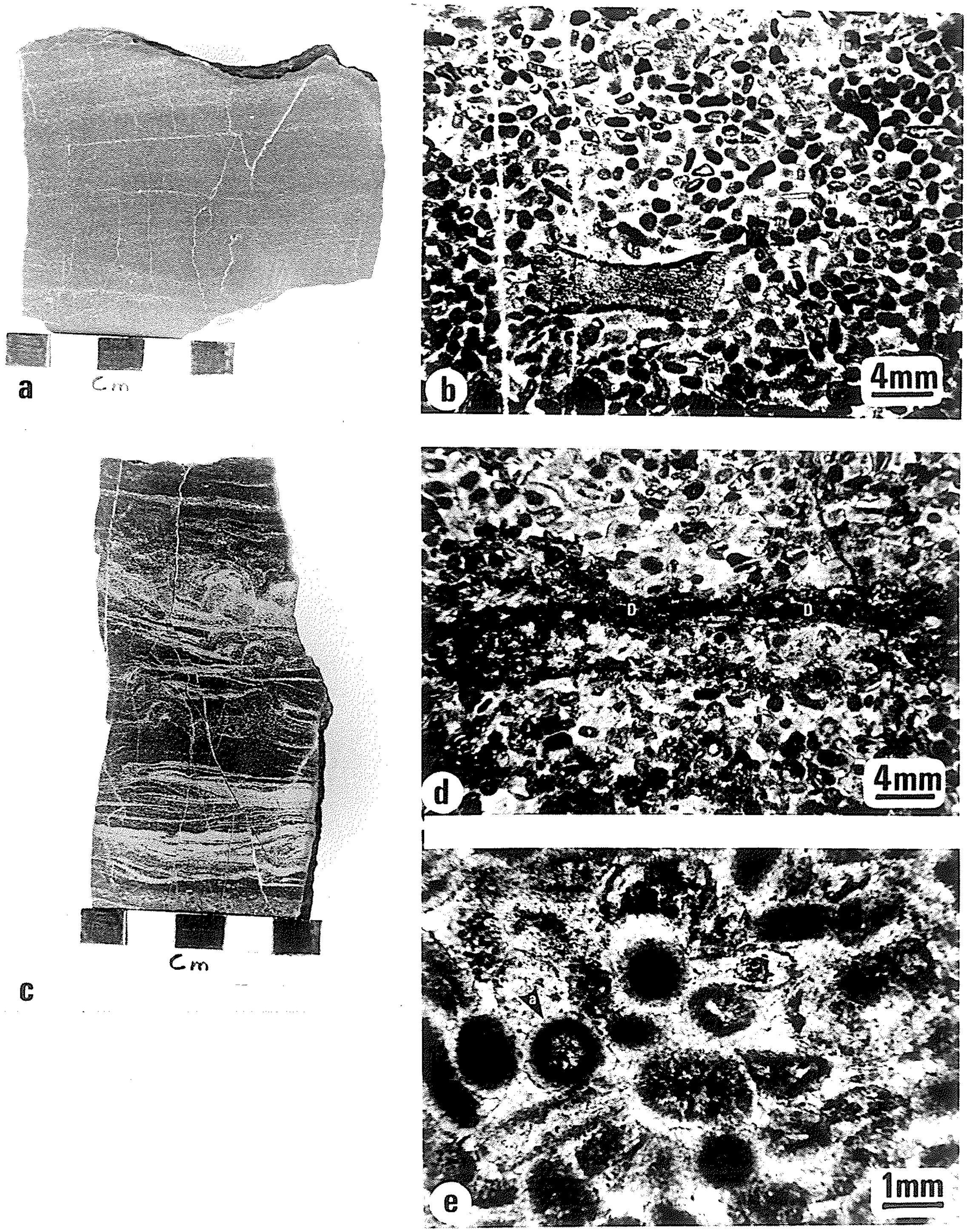
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Plate 3 GRAINSTONE FACIES

(a) Hand sample of very coarse grained echinoderm grainstone. Highly porous zone is due to very late leaching by groundwater. (Sample K33, Loomis Member.)

(b) Very coarse echinoderm grainstone showing abundant echinoderms most of which are probably crinoids. Many of the fragments have partial, a, or complete, b. micrite rinds and many have been completely micritized, c. (Sample K22, Loomis Member, plane light.)

(c) Very coarse grained skeletal grainstone composed of echinoderm, foraminifera, and bryozoa fragments. (Sample K8, Loomis Member, plane light.)

(d) Very coarse grained oolitic grainstone. Note the thin micritic horizon across the centre of the photograph. This horizon consists of a single layer of micritized or partially micritized ooids. Notice that on some of the ooids, the micritization occurs only on the upper surfaces (arrow). This horizon probably represents the initial stage in the formation of the "algal scum mats" described by Dravis (1979) from the Schooner Cays, Bahamas. (Sample K28, Loomis Member, plane light.)

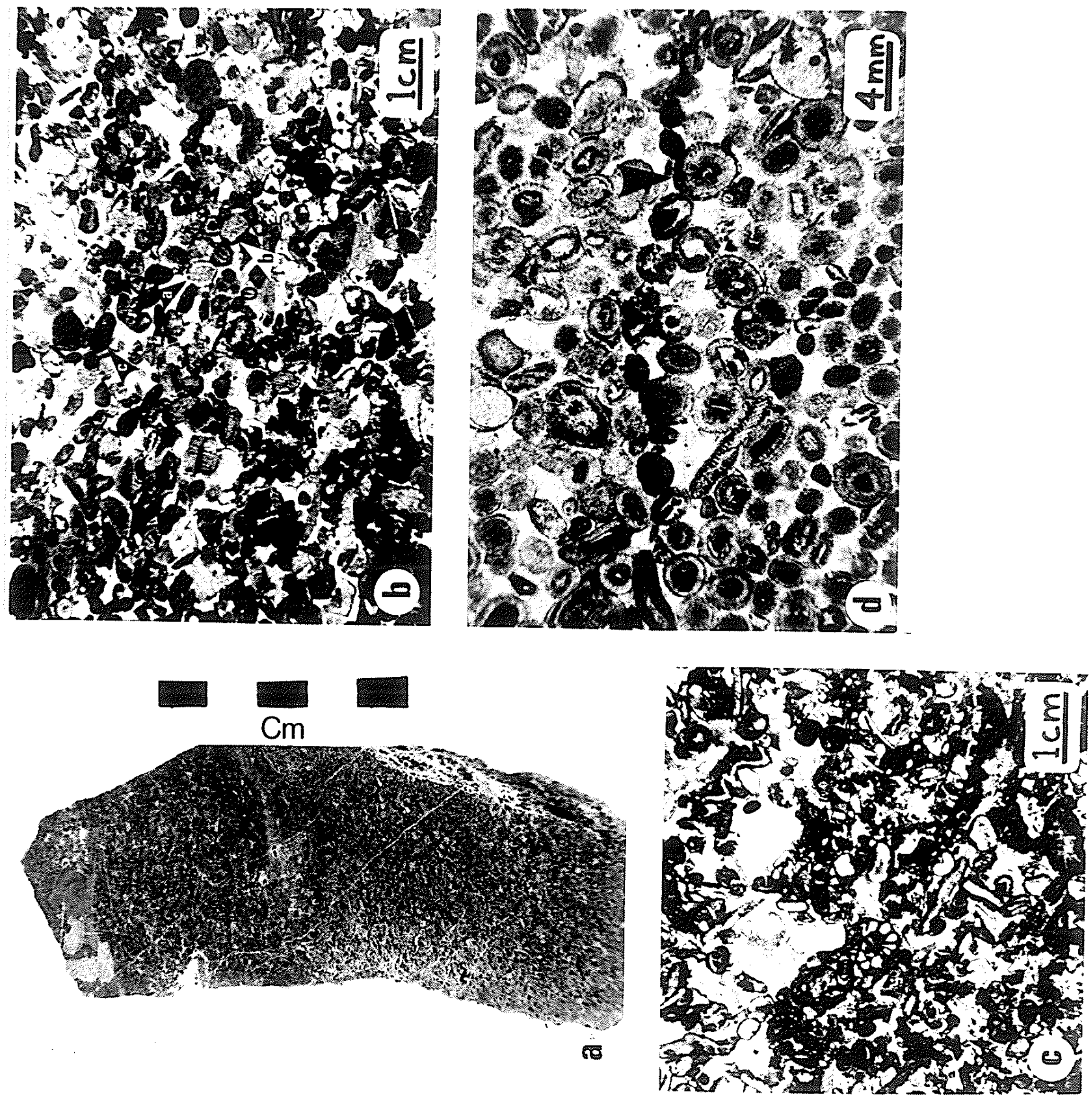

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Plate 4   PACKSTONE FACIES

(a) Fine grained skeletal algal pelloidal packstone. (Sample K123, Carnarvon Member, plane light.)

(b) Hand sample of laminated skeletal packstone facies. Laminations are due to varying micrite content. (Sample K114, Carnarvon Member.)

(c) Medium to coarse grained skeletal packstone showing wide variety of skeletal debris. (Sample K110, Carnarvon Member, plane light.)

(d) Hand sample of echinoderm brachiopod packstone. Lithic frament, a, is a chip of dolomitized mudstone. (Sample K77, Marston Member.)

(e) Very coarse grained echinoderm brachiopod packstone. The micrite matrix has been altered to finely crystalline dolomite and locally the dolomitization has affected the edges of skeletal fragments as at a. (Sample K74, Marston Member, plane light.)

(f) Ostracode oncolite packstone showing abundant oncolites and disarticulated ostracode tests. Note incorporation of skeletal debris into the oncolites as at a. Also note calcispheres as cores of oncolites, b. (Sample K62, Marston Member, plane light.)

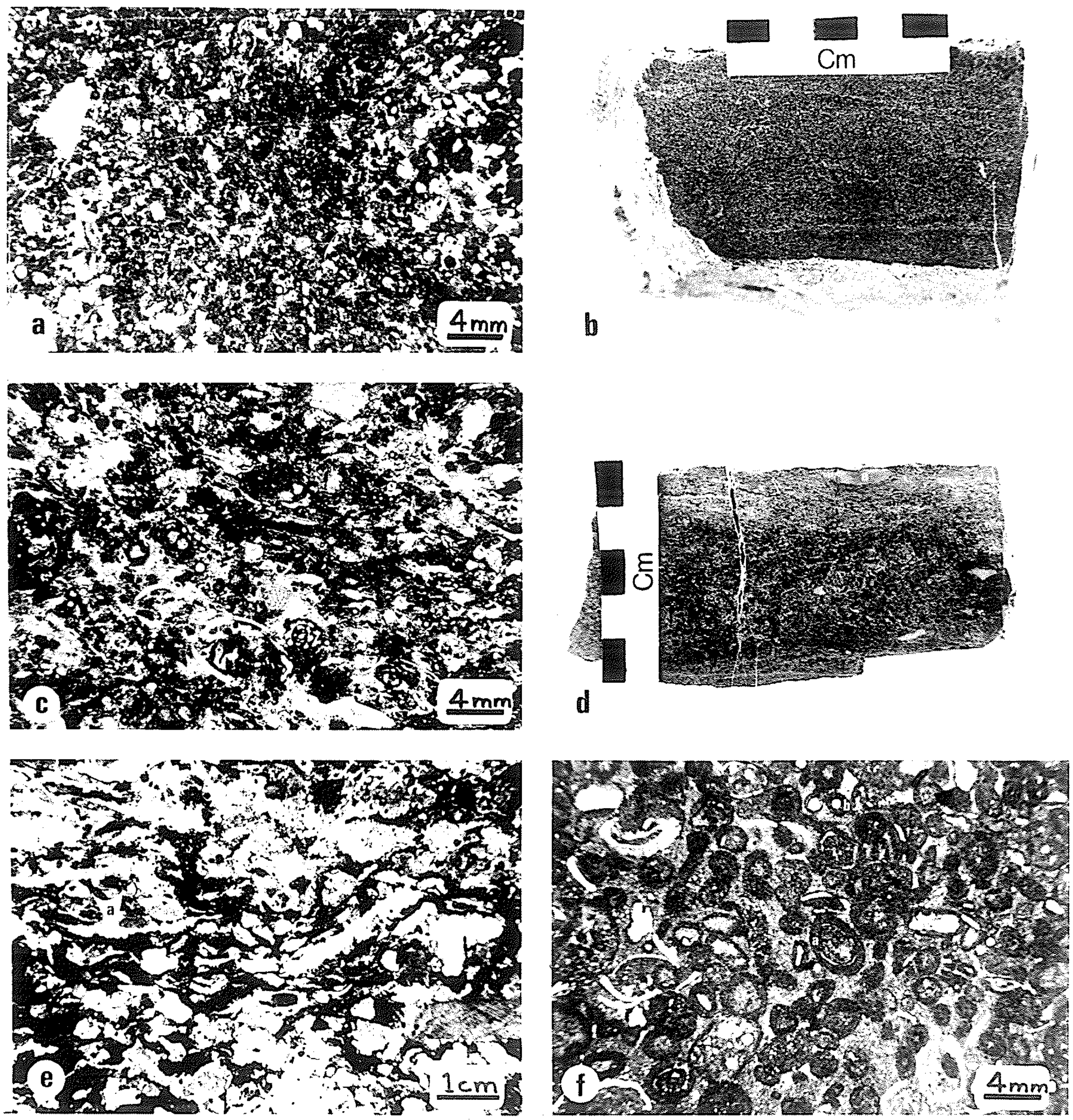
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Plate 5 WACKESTONE FACIES

(a) Medium to very coarse ostracode algal wackestone with articulated and disarticulated ostracodes. Abundant very fine algal filaments scattered throughout, a, as well as minor amounts of calcispheres. (Sample K119, Carnarvon Member, plane light.)

(b) Coarse grained skeletal echinoderm wackestone with coarse grained echinoderm fragments in a matrix which has largely been altered to dolomite. Fine network of lines on photo are cracks in the thin section lacquer. (Sample K15, Loomis Member, crossed nicols.)

(c) Fenestral wackestone showing large fenestral voids in which most of the cement has been leached out. A thin section of this sample revealed that the cement in the fenestral voids was gypsum. (Sample K68, Marston Member.)

(d) Fenestral wackestone showing large fenestral voids filled with blocky, sparry calcite cement. Most common fossils are algae and calcispheres. (Sample K89, Marston Member, crossed nicols.)

(e) Intraclastic breccia composed of clasts of calcisphere wackestone. This facies is very closely associated with the fenestral wackestone facies. (Sample K70, Marston Member, plane light.)

(f) Oncolitic wackestone with abundant ostracode fragments. Ostracode fragments often form the nuclei of oncolites. (Sample K57, Marston Member, plane light.)

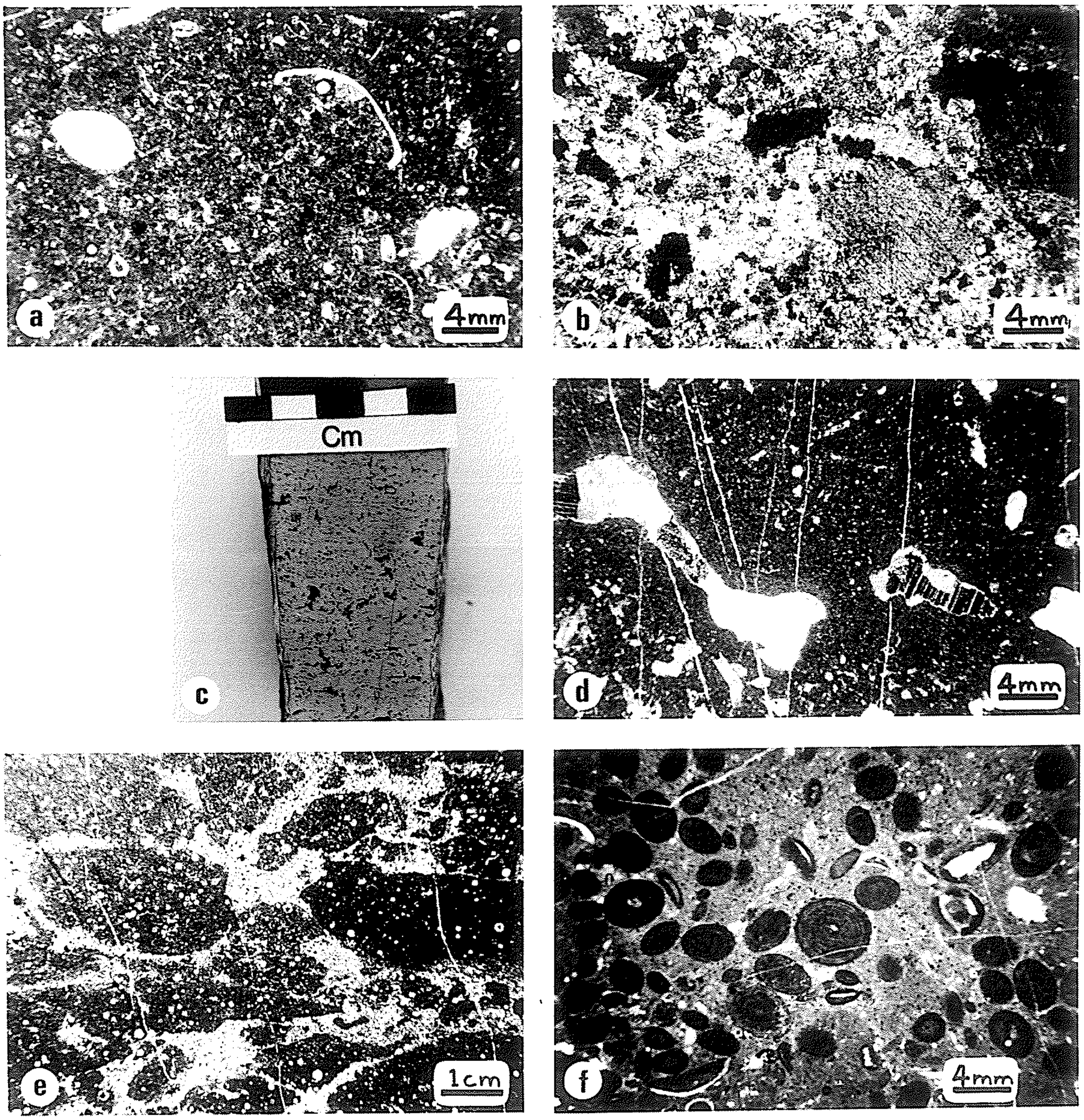
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PLATE 6 MUDSTONE FACIES

(a) Hand sample of fenestral mudstone with calcite cemented fenestral voids and fractures. (Sample K124, Carnarvon Member.)

(b) Fenestral mudstone with abundant large fenestral voids occluded by calcite. (Sample K83, Marston Member, plane light.)

(c) Hand sample of laminated evaporitic mudstone with 1 to 1.5 cm thick beds (lenses?) of gypsum, a. (Sample K54, Marston Member.)

(d) Evaporitic mudstone with very fine laths of gypsum (or pseudomorphs after gypsum) in a micrite matrix. (Sample K100, plane light.)

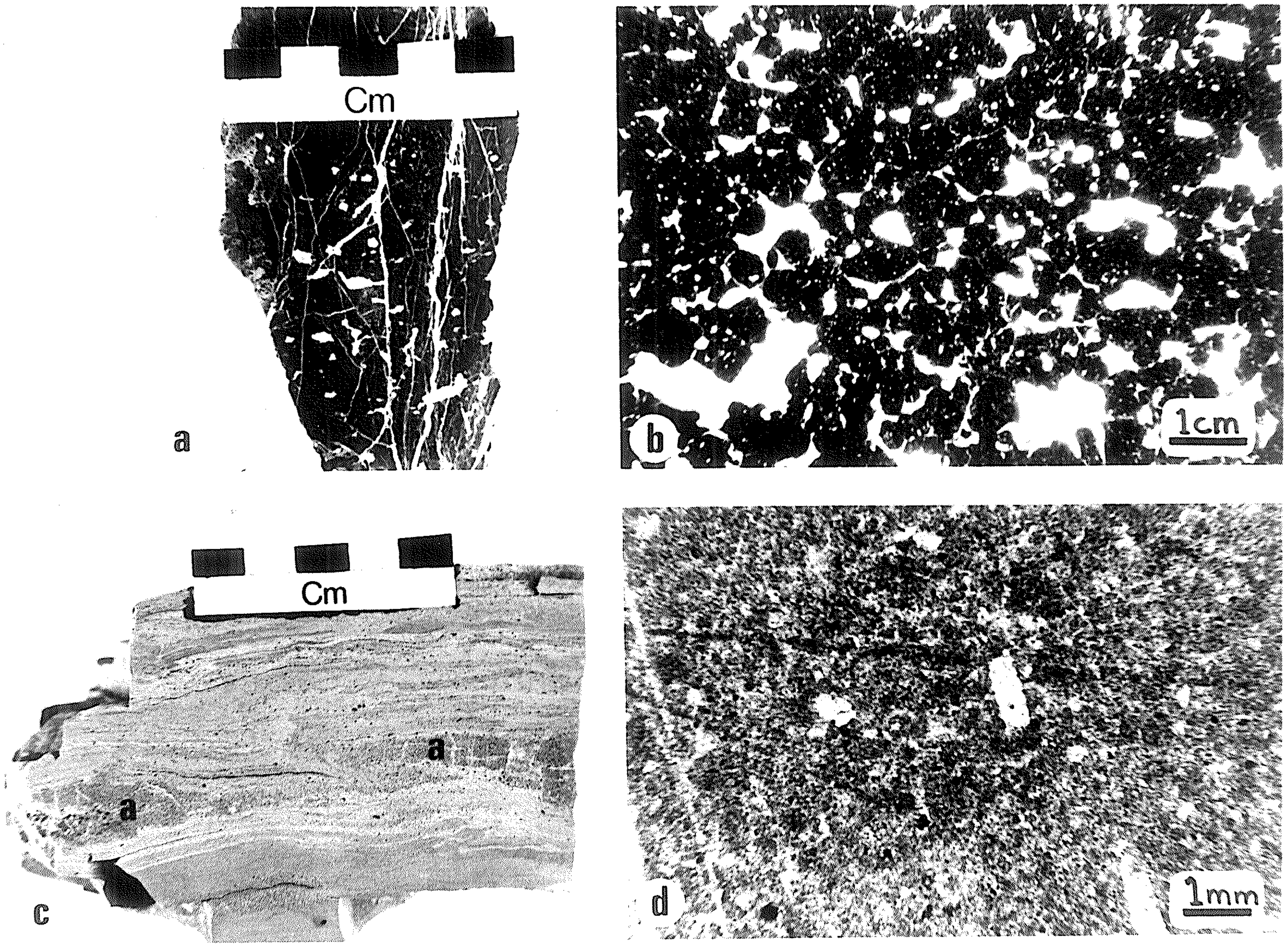
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PLATE 7   BIOLOGICAL DIAGENESIS

(a) Hand specimen showing vertical burrows filled or partially filled with gypsum and calcite. (Sample K72, Marston Member.)

(b) Vertical, calcite-filled burrow in a laminated sediment. Note the burrow walls which have a sediment lining, a. This may have resulted from the burrowing organism secreting a sticky substance in order to stabilize the burrow walls. (Sample K130, Carnarvon Member, crossed nicols.)

(c) Calcite-filled burrow with numerous articulated ostracodes within. The fact that the ostracodes are articulated and locally appear to have been burrowing(?) into the burrow walls, a, indicate that they may have been responsible for the formation of the burrow. (Sample K14, Carnarvon Member, plane light.)

(d) Burrow filled with faecal pellets cemented by sparry calcite. (Sample K124, Carnarvon Member, plane light.)

(e) Thick micritic envelopes, a. and completely micritized skeletal fragment, b. caused by endolithic algae.
Note echinoderm grain at c, with thin micrite rind and syntaxial cement, d. (Sample K8, Loomis Member, plane light.)

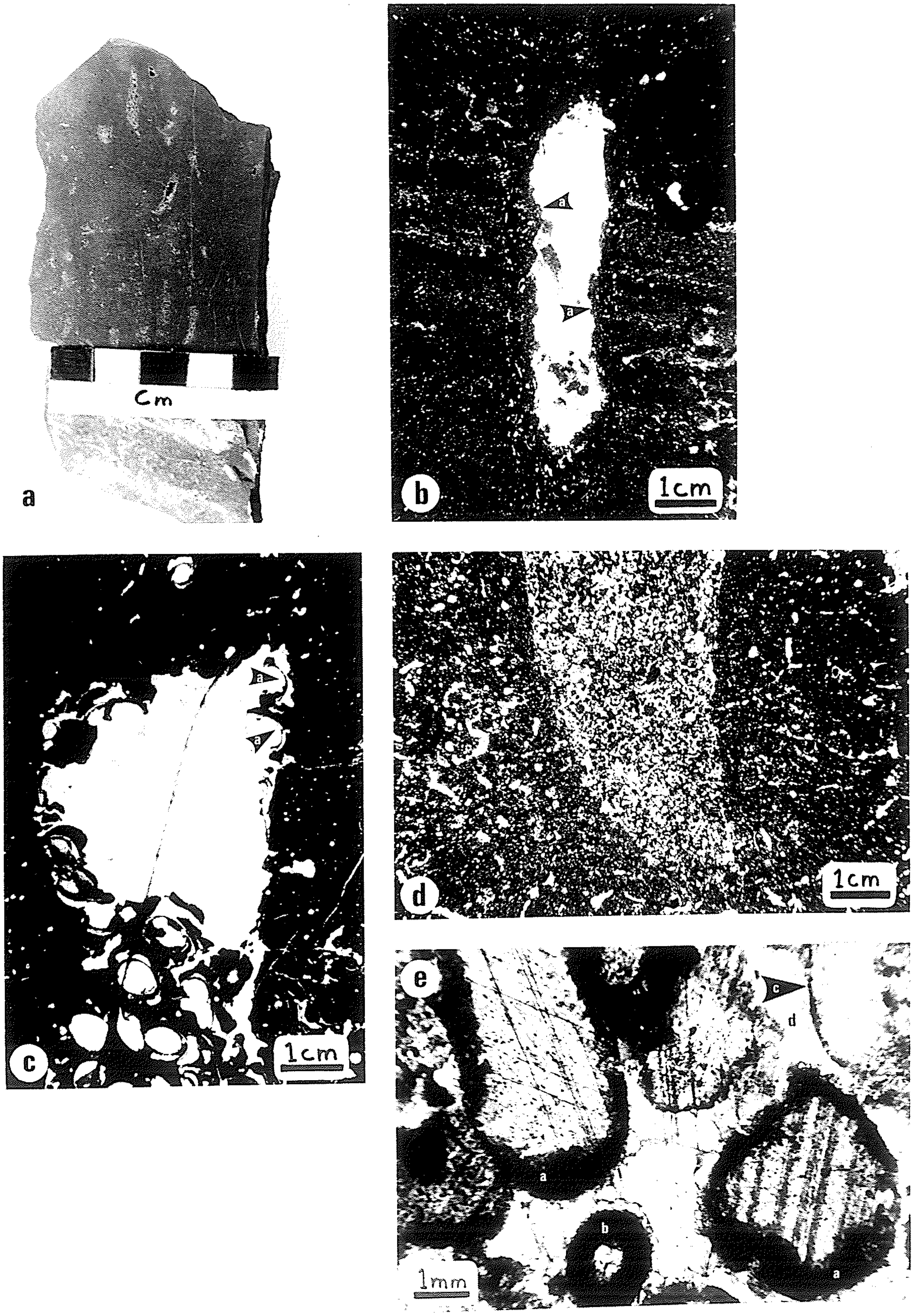

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PLATE 8 CEMENTATION

(a) Equant calcite isopachous cement lining a void which has subsequently been occluded by blocky calcite cement. (Sample K114, Carnarvon Member, plane light.)

(b) The interparticle voids are lined with acicular, isopachous calcite cement, a. In this particular example, this fringing cement has locally been spalled off the grain into the adjacent pore space and later preserved by subsequent cementation, b. This may have resulted through grain movement during compaction, and is evidence for early cementation. (Sample K20B, Loomis Member, plane light.)

(c) Equant dolomite isopachous cement lining a fenestral void. (Sample K68, Marston Member, crossed nicols.)

(d) Equant calcite isopachous cement (arrow) lining an interparticle void followed, essentially contemporaneously, by syntaxial cement. Note echinoderm grain with thin micrite envelope which was not thick enough to prevent development of syntaxial cement, a. (Sample K23, Loomis Member, plane light.)

(e) Syntaxial cements, a. filling interparticle voids in an echinoderm grainstone. Note interpenetration of many of the grains, b. except those grains in contact with the syntaxial cements. (Sample K23, Loomis Member, plane light.)

(f) Equant, blocky calcite cement filling interparticle void. Note increasing crystal size toward the centre of the pore. This cement type is the most commonly observed in the rocks studied. Note also that although this is an echinoderm grainstone, the complete micritization of the grains has prevented the development of syntaxial overgrowths. (Sample K10, Loomis Member, plane light.)

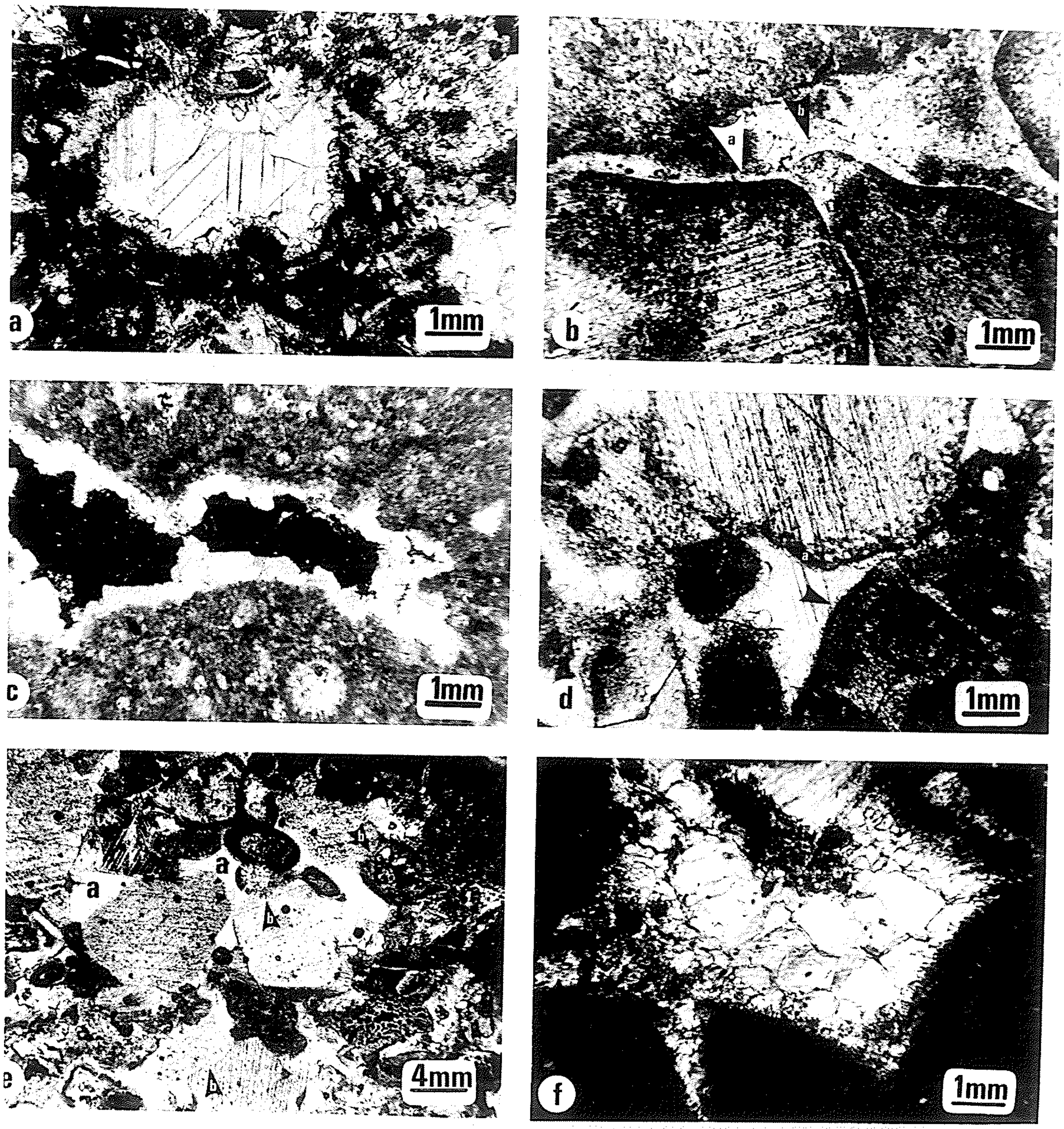
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Plate 9 DOLOMITIZATION

(a) Euhedral dolomite rhombs, a. replacing micrite. (Sample K12, Loomis Member, plane light.)

(b) Selective dolomitization of an echinoderm wackestone showing complete dolomitization of the mud component of the rock. This slide has been strongly etched in HCl resulting in almost complete removal the calcite grains. (Sample K15, Loomis Member, plane light.)

(c) Selective dolomitization of a brachiopod wackestone showing preferential dolomitization of the micrite. The dolomite is ferroan. (Sample K77, Marston Member, plane light.)

(d) Total dolomitization of a sediment which was probably originally a lime mud with little or no fossil debris. (Sample K94, Marston Member, plane light.)

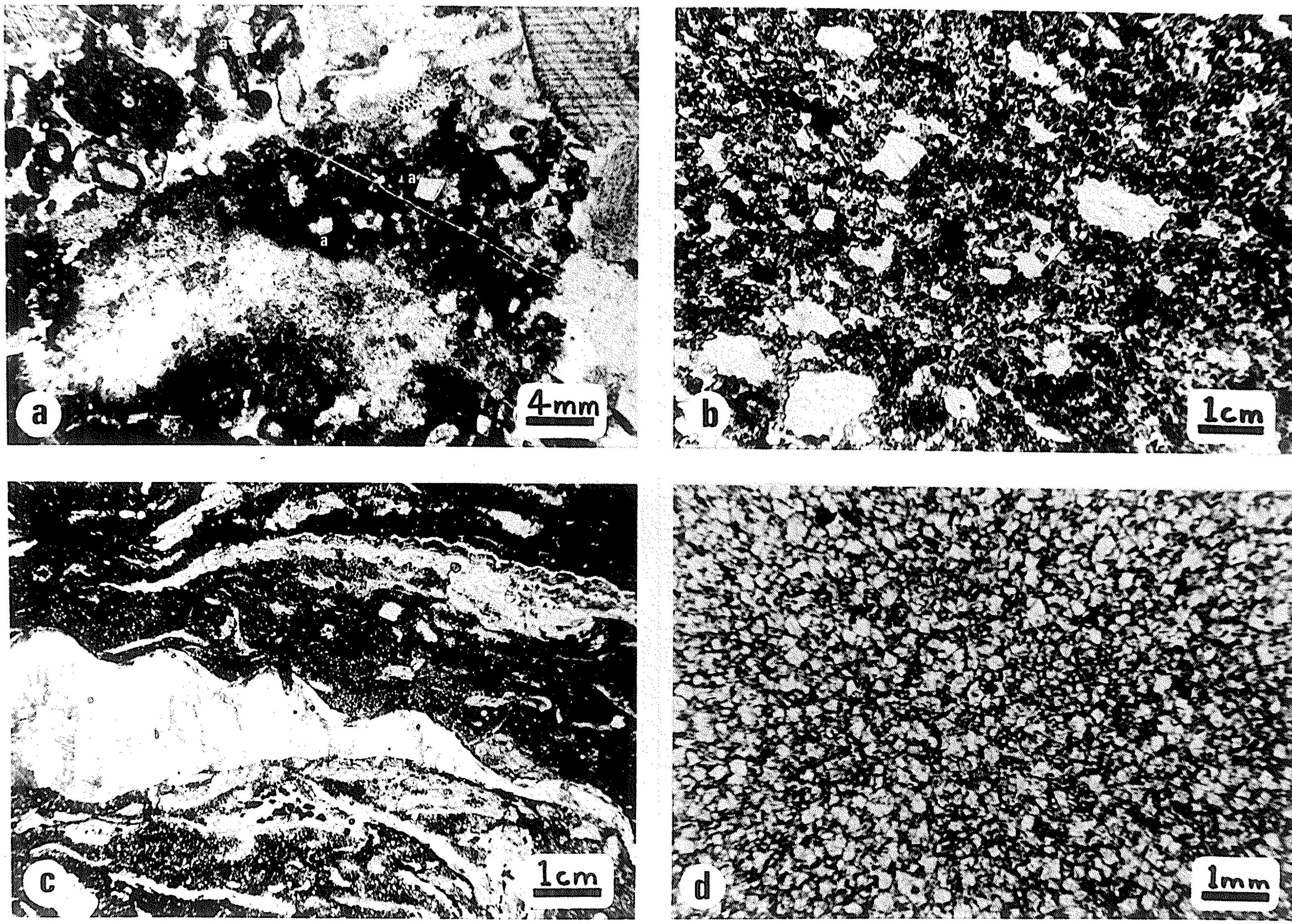

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Plate 10 EVAPORITIC ROCKS

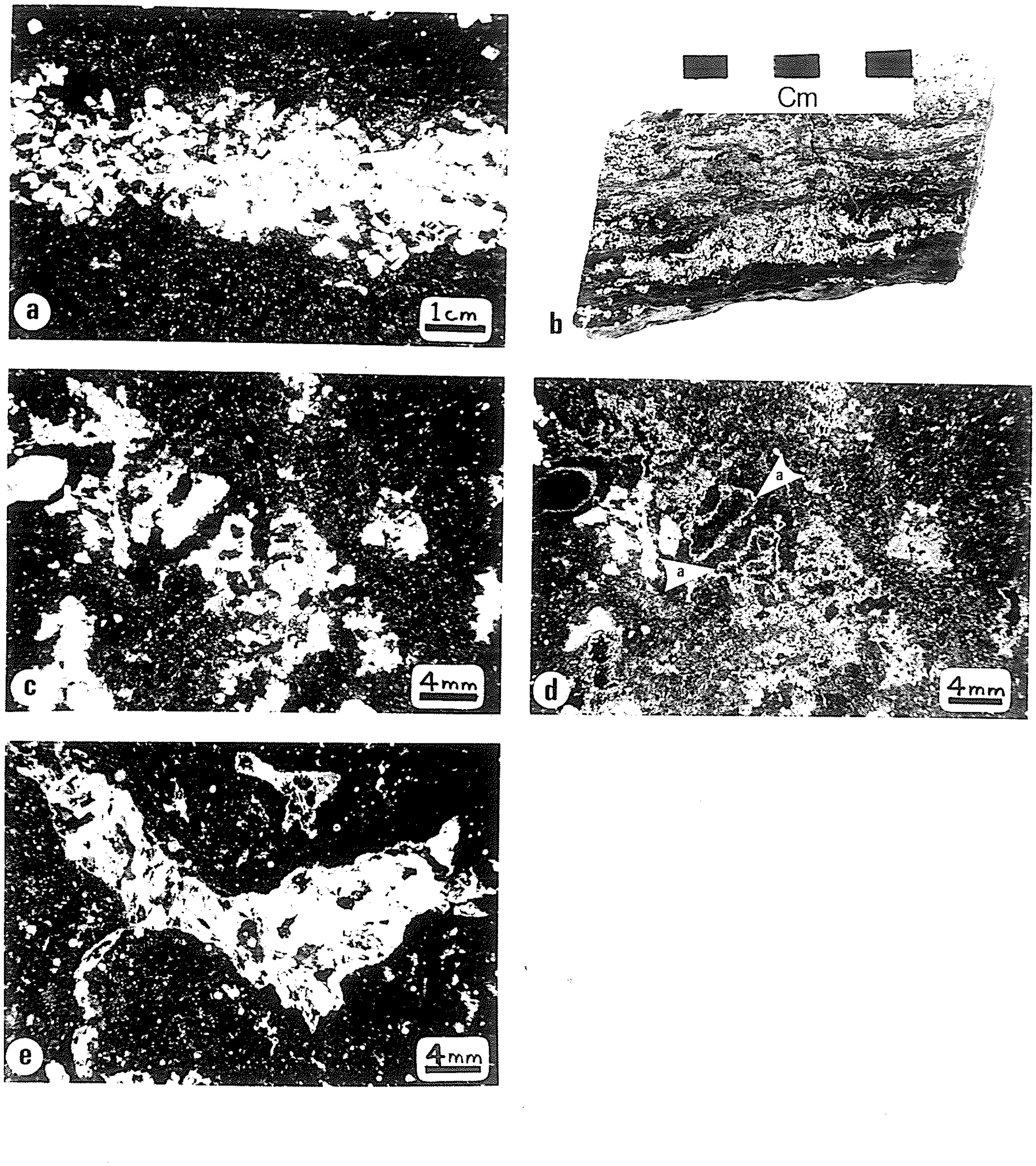
(a) Two centimetre thick bed of euhedral and subhedral gypsum crystals in mudstone. See Plate 6c for hand specimen of this rock. (Sample K54, Marston Member, plane light.)

(b) Hand sample showing interbeds of micrite and celestite. Celestite is the light coloured mineral. (Sample K61, Marston Member.)

(c) Thin section of rock in Plate 11b showing large patches of poikilotopic celestite replacing micrite. (Sample K61, Marston Member, plane light.)

(d) Same as Plate 11c but with crossed nicols to show apparent optical continuity of celestite over a large area. The light rims around much of the celestite, a. may be reaction "fronts" as the micrite is being replaced. (Sample K61, Marston Member, crossed nicols.)

(e) Coarse crystalline mosaic of gypsum cement filling a fenestral void. See Plate 5c for hand specimen of this rock. (Sample K68, Marston Member, crossed nicols.)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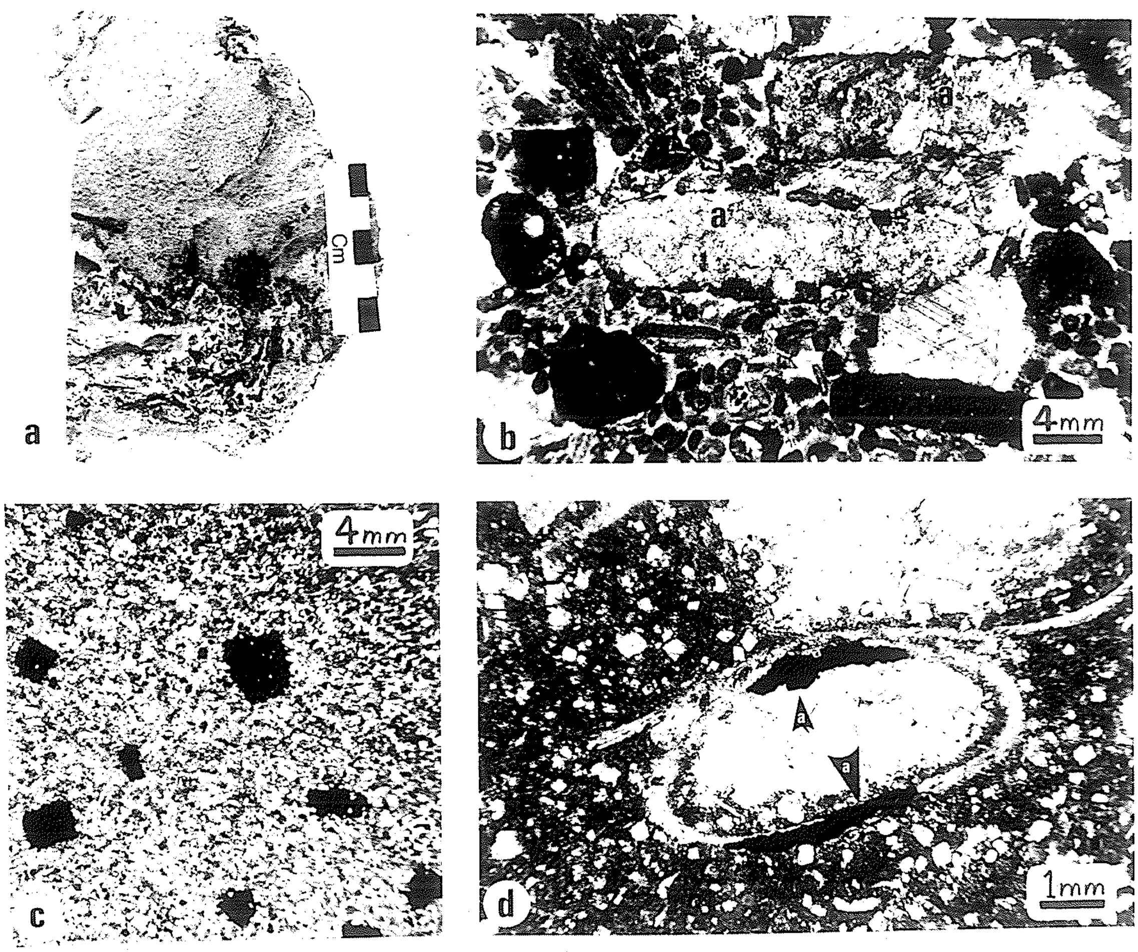
<u>Plate 11</u> SILICIFICATION AND PYRITIZATION

(a) Five centimetre thick chert bed within a limestone. Chert beds compose approximately 40% of this bed within the Carnarvon Member. (Sample K155, Carnarvon Member.)

(b) Silica, <u>a</u>. replacing bioclastic grains. (Sample K33A, Loomis Member, plane light.)

(c) Euhedral and subhedral cubes of pyrite within a highly dolomitic mudstone. (Sample K51A, Marston Member, crossed nicols.)

(d) Pyrite partially replacing the test of a gastropod, <u>a</u>. Also note abundant subhedral dolomite rhombs replacing micrite matrix. (Sample K86, Marston Member, plane light.)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APPENDIX

APPENDIX I

Description of the upper three members of the Mount Head Formation measured at the Highwood River section. Description from the first exposed unit of the Loomis upward.

Unit	Lithology	Thickness (Metres)
	Loomis Member	
1	Limestone; medium gray, weathers light gray; medium grained, skeletal fragments, possible oolites, crystalline appearance; bedded; samples K8, 9 and 10. Petrographic name: echinoderm skeletal grainstone. Trace interparticle, vuggy and fracture porosity.	2.9
2	Limestone; medium gray weathers buff; skeletal material, bryozoans and rugose corals; bedded chert nodules; thinly bedded, upper and lower contacts sharp; samples K11, 11A and K12. Petrographic name: highly dolomitic foram echinoderm packstone. Trace fracture porosity.	2.6
3	Limestone; coarsely crystalline; medium gray, weathers light gray; massive, homogeneous throughout; porous on weathered surface, in places has 1 cm sized vugs; lower contact sharp and undulating; sample K13. Petrographic name: skeletal echinoderm grainstone. Trace interparticle and vuggy porosity.	3.3
4	Dolostone, highly calcitic; light brownish gray, weaters buff; fine grained, sucrosic, some solitary corals; locally finely laminated, generally massively bedded; porous on weathered surface; lower contact sharp and undulating; samples K14 and K15. Petrographic name: echinoderm wackestone (dolomitized). Trace fracture porosity.	1.6
5	Dolostone; weathers light brown, light brownish gray on fresh surface; massive; lower contact gradational; sample K16. Petrographic name: slightly calcitic dolostone; was originally a mudstone.	0.6

Unit	Lithology	Thickness (Metres)
6	Limestone; medium gray, weathers gray; composed of rounded clasts, medium gray; massively bedded; lower contact sharp and undulating; porous on weathered surface; sample K17. Petrographic name: oolitic grainstone. Trace fracture porosity.	2.2
7	Limestone; medium gray, weathers brownish gray; composed of rounded clasts, fine grained; massive, locally thinly bedded; sample K18. Petrographic name: pelloidal grainstone.	1.7
8	Limestone; coarse grained; composed of echinoderm (crinoid) ossicles; excellent interparticle porosity; sample K19 and K20B. Petrographic name: echinoderm grainstone.	0.3
9	Limestone; light gray; coarse grained; composed of echinoderm fragments; massively bedded with laminated central zone contains chert modules along bedding plane; samples K19, K20B, K21, K22 and K23. Petrographic name: echinoderm grainstone. Trace fracture porosity.	11.9
10	Dolostone; light brownish gray; very fine grained; recessive weathering; highly fractured with calcite along fractures; band of nodular chert 4 cm thick approximately 10 cm from the upper contact; upper and lower contacts sharp; samples K24 and K25. Petrographic name: calcitic dolostone. Originally was probably a lime mudstone.	1.1
11	Limestone; medium gray; medium grained skeletal limestone; finely laminated; brown to black banded chert comprises approximately 20% of this unit; samples K36 and K26A. Petrographic name: dolomitic skeletal pelloidal grainstone.	2.8

Unit	Lithology	Thickness (Metres)
12	Limestone; medium gray, weathers light gray and brownish gray; massively bedded; medium grained; sample K27. Petrographic name: skeletal pelloidal packstone to grainstone.	2.7
13	Limestone; weathers buff brown; medium grained; rough weathered surface; gradational contacts; cross-bedding in lower part of unit; vugs up to 8 cm present as well as 0.5mm surface porosity (weathering product not detected in thin section); sample K28. Petrographic name: oolitic grainstone.	1.9
14	Limestone; medium gray, weathers light gray; medium grained; surficial porosity not detected in thin section; sample K29. Petrographic name: skeletal pelloidal grainstone.	2.5
15	Limestone; weathers mottled buff brown and gray; medium grained crinoid and oolite clasts; gradational contacts; vuggy; sample K30. Petrographic name: echinoderm oolitic grainstone.	1.0
16	Limestone; gray; coarse grained crinoid and brachiopod fragments; stylolitic contacts; samples K31, 32. Petrographic name: oolitic skeletal pelloidal grainstone.	6.0
17	Limestone; gray; coarse grained; 20 cm thick highly porous horizon within this unit; this unit forms the top resistant layer of the cliff forming Loomis Member; samples K33, 33A. Petrogrpahic name: echinoderm pelloidal grainstone.	0.5
	<u>Marston Member</u>	
	Covered	1.0
18	Argillaceous limestone; weathers light brown; very crumbly and fissile; increasingly argillaceous upward; samples K35, K36.	0.65

Unit	Lithology	Thickness (Metres)
19	Argillaceous limestone; weathers light brown; very crumbly and fissile; increasingly argillaceous upward; samples K35, K36.	0.65
20	Dolostone; dark gray, weathers light brown; fine grained; finely laminated; upper contact grades into overlying limestone; lower contact gradational, samples K37, 38. Petrographic name: ferroan dolostone.	0.28
21	Limestone; dark gray; finely laminated; pyritic; vugs to 4 cm; pyrite increases upward; sample K39. Petrographic name: slightly fossiliferous dolomitic mudstone.	0.15
22	Calcitic dolostone; light brown; thin discontinuous bed which pinches out; massive; lower contact sharp; upper contact gradational into overlying shale; sample K40. Petrographic name: very fine calcitic dolostone.	0.1
23	Dolomitic shale; very fissile and crumbly greenish gray; weathers light light brown.	0.2
24	Argillaceous siltstone; massive; light brown; pyritic; fine grained; samples K41, 42. Petrographic name: argillaceous quartzose siltstone.	0.2
25	Calcitic dolostone; dark gray, weathers light brown; very fine grained; weakly laminated; abundant 1 to 10 mm thick calcite-filled vertical veins; sample K43. Petrographic name: calcitic ferroan dolostone.	0.65
26	Argillaceous siltstone; light brown, weathers light brown; 5% pyrite which on the surface has been oxidized; contacts are shalier than the middle of the bed; sample K44 (from the middle of the bed). Petrographic name: argillaceous siltstone.	0.45

Unit	Lithology	Thickness (Metres)
27	Dolostone; weathers light brown; dark gray on fresh surface; is generally massive but locally is finely laminated; very fine grained; abundant pyrite; sample K45. Petrographic name: gypsiferous ferroan dolostone.	0.3
28	Dolomitic shale; weathers light brown, light brown on fresh surface; undulating contacts made bed thickness vary from 0.15 to 0.25 metres in thickness; sample K46.	0.2
29	Dolomitic limestone; weathers light brown, dark gray on fresh surface; very fine grained; finely laminated near base becoming more massive upwards; band of coarse pyrite cubes through centre of bed; pyrite scattered throughout; calcite filled fractures; samples K47, 47A. Petrographic name: skeletal gypsiferous calcite ferroan microdolostone. Laminations due to changes in evaporite content.	0.38
30	Limestone; light brown weathering; dark gray on fresh surface; massive; minor pyrite; sample K49. Petrographic name: calcitic ferroan dolostone.	0.1
31	Dolomitic shale; weathers light brown, light brown on fresh surface, no sample.	0.1
32	Dolostone; weathers light brown, dark gray on fresh surface; massive; sample K50. Petrographic name: ferroan dolostone.	0.3
33	Limestone; weathers dark gray-brown, dark gray on fresh surface; fine grained; finely laminated, may be algal; abundant blebs and cubes of pyrite; contacts are both gradational and abrupt; samples K51, 51A, 52. Petrographic name: slightly gypsiferous dolomitic mudstone.	0.07

Unit	Lithology	Thickness (Metres)
34	Dolomitic shale; weakly calcareous; no sample.	0.15
35	Dolostone; weathers light brown, dark gray on fresh surface; massive; sample K53. Petrographic name: ferroan dolostone.	0.2
36	Dolostone; weathers medium grained, dark gray on fresh surface; fine grained; finely laminated; pyrite present along some laminations; sample K54. Petrographic name: calcitic gypsiferous ferroan dolostone.	0.2
37	Dolostone and shale interbeds; roughly 4 cm thick interbeds of dolostone similar to that described above on a shale; samples K55, 56.	0.55
38	Limestone; weathers light brown, dark brownish gray on fresh surface; very fine grained; vuggy; highly fractured with calcite veining; sample K57. Petrographic name: skeletal oncolitic wackestone.	0.1
39	Limestone; similar to 38; very fine grained; massive, almost lithographic; highly fractured with calcite veinings; sample K58. Petrographic name: dolomitic skeletal algal wackestone.	0.6
40	Dolostone; weathers medium and light gray, dark gray on fresh; very finely laminated; minor pyrite present; sample K59. Petrographic name: calcitic dolostone.	0.7
41	Limestone; weathers medium gray, dark gray on fresh surface; fine grained; massive; sample K60. Petrographic name: dolomitic ostracode mudstone.	0.6
42	Limestone; as above but is laminated; highly fractured; sample K61. Petrographic name: slightly dolomitic celestitic mudstone.	0.15

Unit	Lithology	Thickness (Metres)
43	Limestone; same as 41; sample K62. Petrographic name: slightly dolomitic ostracode oncolitic packstone.	0.15
44	Limestone; same as 41; sample K63. Petrographic name: dolomitized ostracode wackestone.	1.7
45	Dolostone; weathers light brown, dark gray on fresh surface; slightly calcareous; fine grained; massive; abundant pyrite; sample K64A. Petrographic name: slightly calcitic ferroan dolostone.	0.02
46	Dolomitic shale; slightly calcareous; weathers light brown; no sample.	0.02
47	Limestone; weathers light brown, dark gray on fresh surface; 30 cm thick massive beds interbedded with argillaceous units of approximately same thickness; a few large (30cm) chert nodules are present; samples K64, 65. Petrographic name (K64): pelloidal packstone.	2.11
48	Dolostone; weathers light brown, gray on fresh surface; massive; fine grained; sample K66. Petrographic name: calcitic ferroan dolostone.	2.0
49	Calcitic shale; weathers light brown; undulating; no sample.	0.04
50	Dolostone; as above but finely laminated; sample K67. Petrographic name: slightly calcitic ferroan dolostone.	1.78
51	Limestone; light grayish brown on weathered surface, light to medium gray on fresh surface, 15% fenestral porosity; sample K68. Petrographic name: fenestral calcisphere wackestone.	0.5
52	Shale; weathers light brown; undulating contacts; no sample.	0.04

Unit	Lithology	Thickness (Metres)
53	Limestone; weathers dark gray, dark gray on fresh surface; minor small chert nodules; sample K69.	0.3
54	Dolostone; weathers light brown, medium gray on fresh surface; minor fenestral porosity; sample K70. Petrographic name: fenestral calcisphere wackestone.	0.4
55	Shale; slightly calcareous; weathers light brown; no sample.	0.05
56	Limestone; weathers light brown, dark gray on fresh surface; massive; fine grained; sample K71.	0.2
57	Green shale, waxy; no sample.	0.2
58	Limestone; weathers dark and light gray, dark gray on fresh surface; fine grained with small (4 x 1 cm) lenses which are slightly coarser; massively bedded; worm burrowed (burrows 0.5 to 1.5 cm in length); stylolitic; calcite filled fractures; sample K72. Petrographic name: burrowed ostracode wackestone.	1.0
59	Calcitic dolostone; weathers brown, dark gray on fresh surface; abundant solitary corals; medium grained clasts in very fine grained matrix; sample K73. Petrographic name: dolomitized coral echinoderm wackestone.	0.7
60	Calcitic dolostone; weathers light brown, dark brown on fresh surface; coarse grained; abundant brachiopods; brachiopods most abundant at base of bed; sample K74. Petrographic name: dolomitized echinoderm brachiopod packstone.	0.5
61	Calcitic dolostone; weathers brown, dark gray on fresh surface; highly fossiliferous at base grading upward into fossiliferous finely laminated and massive; samples K75, 76, 77. Petrographic name: dolomitized brachiopod wackestone grading upwards into slightly calcitic ferroan dolostone.	1.0

Unit	Lithology	Thickness (Metres)
62	Argillaceous limestone; medium gray weathering, medium gray on fresh surface; flaggy cleavage; sample K78.	0.8
63	Calcitic dolostone; weathers brown, dark brownish gray on fresh surface; abundant skeletal debris; vuggy with calcite linings; calcite filled fractures; sample K79. Petrographic name: dolomitized brachiopod echinoderm wackestone.	0.7
64	Shale; highly recessive unit composed only of small broken chips; very fissile; no sample.	0.04
65	Calcitic dolostone; weathers light brown, dark gray on fresh surface; fine grained; massive on fresh surface but weathering brings out fine laminations; sample K80. Petrographic name: ferroan dolostone.	0.45
66	Black shale; very fissile, very crumbly; no sample.	0.5
67	Dolostone; weathers light brown, dark gray on fresh surface; very fine grained; massive; minor pyrite; sample K81. Petrographic name: ferroan dolostone	0.5
68	Green shale; waxy, no sample	0.03
69	Limestone; weathers medium gray, dark gray on fresh surface; abundant coarse calcite crystals; massive; minor pyrite; sample K82. Petrographic name: fenestral mudstone.	0.5
70	Green shale; waxy; no sample.	0.03
71	Limestone; weathers light gray, gray on fresh surface; birds-eyes; sample K83. Petrographic name: fenestral mudstone.	0.6
72	Shale; weathers light gray; no sample.	0.03

Unit	Lithology	Thickness (Metres)
73	Limestone; weathers light brownish dark gray on fresh surface; massive; vuggy on weathered surface; sample K84. Petrographic name: fossiliferous birds-eye mudstone.	0.9
74	Limestone; weathers light brownish gray, dark gray on fresh; fenestral porosity; calcite filled fractures; sample K85. Petrographic name: fenestral mudstone.	0.2
75	Shale; weathers light gray; no sample.	0.3
76	Limestone; brownish gray weathering, medium gray on fresh surface; fine grained; sample K86. Petrographic name: dolomitic ostracode mudstone.	0.5
77	Shale; weathers light gray; no sample.	0.25
78	Limestone; light brown weathering, dark gray on fresh surface; finely laminated; dense; sample K87.	1.0
79	Shale; weathers light gray; no sample.	
80	Limestone; same as 78; sample K88. Petrographic name: skeletal algal pelloidal wackestone to packstone.	0.5
81	Shale; weathers light gray; no sample.	0.03
82	Limestone; weathers medium gray, medium gray on fresh surface; massive; sample K89. Petrographic name: fenestral algal mudstone.	0.8
83	Limestone; as above; K90. Petrographic name: fenestral ostracode wackestone.	0.7
84	Dolomitic limestone; weathers brown, dark gray on fresh surface; finely laminated; sample K91.	0.5
85	Argillaceous limestone; weathers brown, light brown on fresh surface; well laminated; sample K92.	0.2

Unit	Lithology	Thickness (Metres)
86	Dolomitic limestone; weathers light brown, dark gray on fresh surface; finely laminated: Sample K93. Petrographic name: dolomitic algal echinoderm wackestone.	1.4
	Covered	1.0
87	Shale; weathers light gray;no sample.	0.05
88	Dolostone; weathers medium gray, dark gray on fresh surface; very fine grained; massive; sample K94. Petrographic name: dolostone.	0.04
	Carnarvon Member	
89	Black shale; weathers medium gray; very fissile; sample K95.	0.15
90	Limestone; weathers light-medium gray, medium gray on fresh surface; massive; lower contact gradational; abundant pyrite in lower 10 cm; samples K96, 97. Petrographic name: foram calcisphere wackestone.	0.6
91	Argillaceous limestone; very argillaceous at upper and lower contacts, dense in the middle; sample K98.	0.08
92	Limestone; weathers light brown, dark gray on fresh surface; massive; sharp contacts, sample K99. Petrographic name: dolomitic foram calcisphere wackestone.	0.45
93	Shale; very fissile; crumbly; green; sharp contacts; no sample.	0.05
94	Limestone; weathers light gray, dark gray on fresh surface; sharp contacts; birds-eyes; sample K100. Petrographic name: fenestral calcisphere mudstone.	1.1

Unit	Lithology	Thickness (Metres)
95	Shale; very recessive; sharp contacts; no sample.	0.15
96	Limestone; as above; highly fractured; sample K101.	0.63
97	Black shale; calcitic; upper contact gradational; sample K102.	0.23
98	Limestone; as above; lower contact gradational; sample K103. Petrographic name: highly fossiliferous ostracode skeletal wackestone.	0.2
99	Shale; same as unit 91; sample K104.	0.1
100	Limestone; same as unit 98; sample K105. Petrographic name: highly fossiliferous calcisphere algal wackestone.	0.85
101	Limestone; same as above; lower contact based only on shale parting; sample K106.	0.75
102	Limestone; as above; stylolitic; contacts based on shale parting; sample K107.	1.8
103	Limestone; as above; contacts based on shale parting; sample K107.	1.8
103	Limestone; as above; contacts based on shale parting; sample K108.	0.65
104	Limestone; weathers medium gray, dark gray on fresh surface; coarse fossil content increases upwards; abundant brachiopods; samples K109, 110. Petrographic name: brachiopod packstone.	1.15
105	Argillaceous limestone; 1 cm thick shale stringers at upper and lower contact; fossiliferous with abundant brachiopods; sample K111. Petrographic name: argillaceous skeletal wackestone.	0.06
106	Limestone; same as unit 104; sample K112.	0.5

Unit	Lithology	Thickness (Metres)
107	Limestone; same as unit 94; burrowed; upper contact grades into a shale; sample K113. Petrographic name: burrowed intraclastic wackestone.	1.6
108	Shale; lower contact gradational, upper contact abrupt, no sample.	0.02
109	Limestone; medium gray weathering, dark gray on fresh surface; stylolitic; sample K114. Petrographic name: foram brachiopod skeletal packstone.	1.5
110	Limestone; weathers medium gray, light gray on fresh surface; trace pyrite; sparry calcite blebs present; a few braciopods present; sample K115. Petrographic name: ostracode wackestone.	1.4
111	Shale; lower contact gradational, upper contact sharp; no sample.	0.02
112	Limestone; same as unit 110; sample K116.	0.8
113	Shale; weathers light gray; sharp contacts; no sample.	0.04
114	Limestone; weathers medium gray, dark gray on fresh surface; abundant fine skeletal debris present; thin discontinuous shale stringers present; sample K117. Petrographic name: foram ostracode calcisphere wackestone.	1.2
115	Shale; calcareous; more massive in centre and more argillaceous towards the contacts, no sample.	0.03
116	Limestone; weathers light gray, dark gray on fresh surface; stylolitic; no sample.	1.2
117	Limestone; as above; sample K119. Petrographic name: ostracode bioclastic wackestone.	0.6
118	Very argillaceous limestone; weathers light brown; sample K120.	0.25

Unit	Lithology	Thickness (Metres)
119	Limestone weathers light gray, dark gray on fresh surface; possible burrows near top; birds-eyes; sample K121. Petrographic name: highly fossiliferous algal bioclastic wackestone.	1.01
120	Limestone; weathers medium gray, dark gray on fresh surface; highly burrowed; burrows filled with calcite, burrows increase in abundance upward; very fine grained, micritic; sample K122.	0.75
121	Argillaceous limestone; more argillaceous at the top and bottom of this unit and more massive in the middle; very fine grained; upper contact gradational; sample K123 (from the middle, massive zone). Petrographic name: burrowed pelleted bioclastic packstone.	1.0
122	Limestone; weathers light gray, dark gray on fresh surface; abundant burrows throughout filled with sparry calcite; upper contact is a 1 cm shale parting; sample K124. Petrographic name: fenestral burrowed fossiliferous mudstone.	0.25
123	Limestone; as above; upper contact is very thin shale parting; sample K125.	
124	Limestone; as above but lacks burrows; very fine grained; upper contact is very thin shale parting; sample K126. Petrographic name: bioclastic wackestone.	0.35
125	Calcitic dolostone; weathers medium gray, dark gray on fresh surface; medium grained with thin interbeds of very fine limestone; sample K127. Petrographic name: dolomitized echinoderm packstone with interbeds of dolomotized wackestone.	0.2
126	Dolostone; weathers buff brown; light brownish gray of fresh surface; trace amounts of pyrite; very fine grained; sample K128. Petrographic name: ferroan dolostone.	0.5

Unit	Lithology	Thickness (Metres)
127	Interbedded limestone and dolostone; very fine grained; interbeds of finely laminated limestone and massive dolostone; grades upwards into 2 cm shale parting; samples K129-132. Petrographic name: fossiliferous burrowed laminated mudstone and burrowed algal fenestral wackestone.	0.6
128	Limestone; weathers light gray, dark gray on fresh surface; fine grained; grades upward into a 1-2 cm shale parting; sample K133. Petrographic name: bioclastic packstone.	0.15
129	Limestone; weathers medium gray, black on fresh surface; massive very fine grained; upper contact grades into 4 cm thick shale; sample K134.	1.05
130	Limestone; as above; grades into 1 cm shale parting; sample K135. Petrographic name: bioclastic wackestone.	0.3
131	Limestone; finely laminated very fine grained limestone grading upwards into a medium grained fossiliferous limestone; a few large brachiopods present in the upper part of this bed; samples K136 and 137. Petrographic name: echinoderm bioclastic packstone.	0.6
132	Argillaceous limestone; argillaceous content increases upward; fine to medium grained; sample K138. Petrographic name: ostracode foram wackestone.	0.32
133	Limestone; weathers light gray, dark brownish gray on fresh surface; massive; two stylolites; minor sparry calcite blebs; sample K139.	1.9
134	Limestone; as above; sample K140. Petrographic name: bioclastic foram wackestone.	1.4

Unit	Lithology	Thickness (Metres)
135	Limestone; weathers light gray, dark gray on fresh surface; fine grained; massive at the bottom with calcite filled burrows increasing in abundance upwards; sample K141.	0.8
136	Shale; black; lower contact gradational, upper contact sharp; no sample.	0.1
137	Limestone; weathers light gray, dark brownish gray on fresh surface; coarse grained with abundant brachiopod and crinoid fragments; samples K142 and 143. Petrographic name: foram brachiopod echinoderm packstone with some thin interbeds of grainstone.	3.1
138	Limestone; weathers medium gray, dark brownish gray on fresh surface; abundant skeletal fragments; fine grained; sample K144. Petrographic name: dolomitic bioclastic packstone.	1.3
139	Shale; same as unit 136; sample K146.	0.09
140	Limestone; weathers medium gray, dark brownish gray on fresh surface; medium grained skeletal debris and very fine grained matrix; sample K146. Petrographic name: echinoderm wackestone.	0.45
141	Limestone; light gray weathering, dark gray on fresh surface; massive; trace pyrite; upper contact is shale parting; sample K147. Petrogrpahic name: echinoderm wackestone.	0.2
142	Limestone; as above; sample K148.	0.5
143	Limestone; weathers light gray, medium gray on fresh surface; burrows abundant; sample K149. Petrographic name: burrowed ostracode wackestone.	0.95
144	Limestone; light gray weathering, medium gray on fresh surface; finely laminated; abundant calcite filled laminar fenestral voids; sample K150. Petrographic name: fenestral pelleted grainstone with minor interbeds of mudstone.	1.25

Unit	Lithology	Thickness (Metres)
145	Limestone; weathers light gray, medium gray on fresh surface; a bed of 10 cm size chert nodules is present in the middle of this unit; birds-eye structure present; highly fractured; sample K151.	0.7
146	Limestone; weathers light gray medium gray on fresh surface; coarse grained; minor beds of fine grained sediment; upper contact gradational; minor solitary corals present; samples K152 and 153. Petrographic name: echinoderm grainstone.	1.5
147	Limestone; light gray weathering, medium gray on fresh surface; coarse grained; a few brachiopods present; sample K154. Petrographic name: echinoderm pellet packstone.	1.15
148	Cherty limestone; interbeds of chert and limestone; approximatley 40% of this unit is chart in beds up to 30 cm thick; chert weathers light pink; limestone weathers medium gray, medium gray on fresh; highly fractured; sample K155. Petrographic name: pelleted grainstone.	2.4
	Covered	1.2
149	Cherty limestone; as above; samples K156, 157, 158. Petrographic name: bioclastic wackestone.	2.5