THE UNIVERSITY OF MANITOBA

ALLOCHTHONOUS CARBONATE DEBRIS DEPOSITS ADJACENT TO THE SOUTHESK-CAIRN CARBONATE COMPLEX (UPPER DEVONIAN), WAPIABI GAP, ALBERTA

by

Peter Forrest Cameron

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Allochthonous Carbonate Debris Deposits Adjacent to the Southesk-Cairn Carbonate Complex (Upper Devonian), Wapiabi Gap, Alberta.

by Peter F. Cameron

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

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ABSTRACT

Basinal sediments of the lower part of the Mount Hawk Formation adjacent to the Upper Devonian Southesk-Cairn carbonate complex in the Big Horn Mountain Range at Wapiabi Gap, Alberta, contain seven allochthonous carbonate debris deposits. The lowermost debris deposit which occurs near the base of the Mount Hawk Formation is a rudstone of unknown thickness consisting of buildup-derived skeletal debris. The debris clasts increase in size up to small boulder dimensions towards the carbonate complex. The allochthonous debris consists of skeletal remains of Thamnopora, echinoderms, inarticulate and articulate brachiopods, bryozoans, and peloids of microcrystalline calcite. The second debris deposit, which has different petrographic characteristics than the lowermost debris interval, is about 0.5 meters thick and is a rudstone consisting of well-rounded lenticular-shaped clasts (pebble to small boulders in size) of carbonate mud and cemented calcarenite, within a fine sand-sized matrix.

The five allochthonous carbonate debris sheets that occur higher in the Mount Hawk sequence are much thinner (about 15 centimeters thick) than the lower debris intervals and maintain a constant thickness laterally, over a distance of 1 kilometer. Each debris sheet has a basal portion of carbonate mud and an upper portion which has a floatstone texture consisting of irregular and lenticular-shaped lutite clasts embedded in a matrix of echinoderm sand and carbonate mud.

There are two generations of carbonate cement (blocky mosaic and ferroan calcite) found in all deposits. An earlier generation (bladed fringing and echinoderm rim cement) is found in the two lowermost debris intervals and this generation is believed to be a product of

early submarine lithification.

It is inferred that debris material in the lowermost deposit was derived from the lower part of the Peechee Member of the Southesk Formation, probably originating on a forereef or bank margin position. It is believed that the second debris deposit is the result of a sediment mass flow that eroded material as it moved downslope, from the underlying, already lithified, lowermost debris interval. The echinoderm sand material in the upper allochthonous debris sheets probably originated from the middle portion of the Peechee Member, which is believed to have originally been a carbonate bank deposit.

The mode of transport of the buildup-derived material for all of the debris deposits is thought to have been grain flow and/or turbidity flow types of sediment gravity flows.

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CHAPTER 1

INTRODUCTION

Introduction

In the past decade a number of workers (eg. MacKenzie, 1965; Noble, 1970) have contributed to the knowledge of Upper Devonian carbonate complexes in Western Canada (Figure 1). However, relatively few studies have been concerned with reef to off reef facies transitions.

At Wapiabi Gap, Alberta, which is located in the Big Horn Mountain Range, 14 miles west of Nordegg, the margin of the Southesk-Cairn carbonate complex is transitional to basinal facies sediments (Figure 2). The sediments of this facies comprise the lower portion of the Mount Hawk Formation and consist of interbedded calcareous shales and argillaceous lime mudstones.

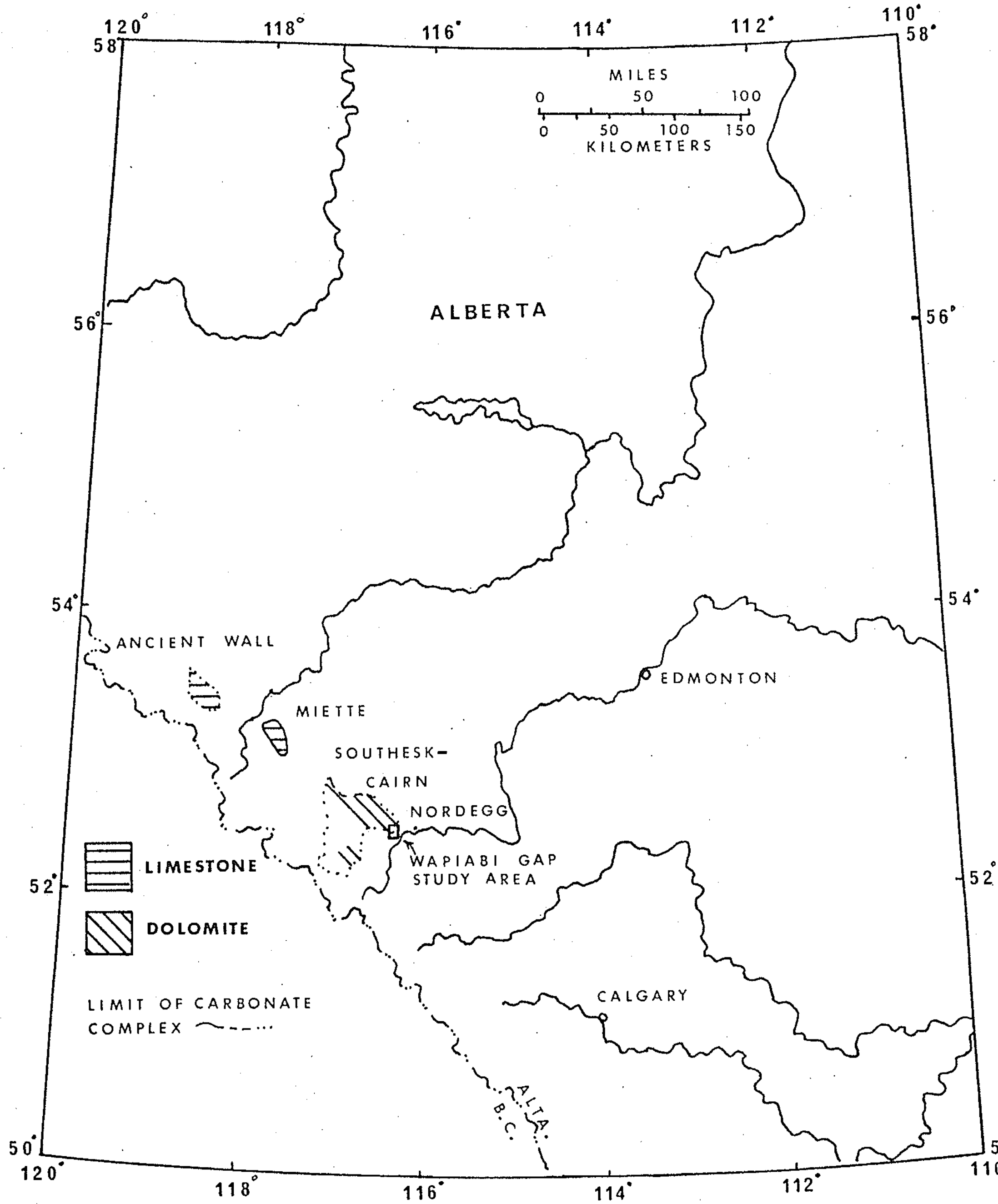
Within the lower portion of the Mount Hawk Formation at Wapiabi Gap are a number of allochthonous carbonate debris beds, consisting of carbonate buildup-derived material which has subsequently been transported to the basin and deposited in a deeper water environment.

The purpose of this study was to examine the allochthonous debris adjacent to the carbonate complex and to:

1. Document the petrography of the debris deposits.
2. Study the diagenesis.
3. Determine the origin of the debris with respect to position within the adjacent carbonate complex.

Figure 1

Distribution of Upper Devonian carbonate complexes in Alberta. (Modified after Toomey et al., 1970)



120°
118°
116°
114°
112°
110°
58°
56°
54°
52°
50°
MILES
0 50 100
0 50 100 150
KILOMETERS
ALBERTA
ANCIENT WALL
MIETTE
SOUTHESK-
CAIRN
NORDEGG
WAPIABI GAP
STUDY AREA
EDMONTON
CALGARY
LIMESTONE
DOLOMITE
LIMIT OF CARBONATE
COMPLEX
ALTA.
B.C.

4. Establish the mode of transport of the allochthonous carbonate debris material to the basin.

Regional stratigraphy

The detailed stratigraphy of the Upper Devonian Fairholme Group of the Southesk-Cairn carbonate complex has been summarized by MacKenzie (1969). The following brief outline of the stratigraphy and inferred depositional histories of the formations is taken from MacKenzie's report.

Paleozoic strata of the Front Ranges are broken by a series of subparallel thrust faults having moderate dip angles and slippage planes which are confined mainly to Upper Cambrian stratigraphy. Comparatively thick Devonian and Mississippian sequences acted as competent units during deformation and these outcrop along segments of undeformed thrust sheets. The Southesk-Cairn carbonate complex in the mountains, in contrast to the undeformed equivalent strata of the Plains has been compressed by crustal shortening and its original areal distribution modified by thrust faulting.

The Upper Devonian Fairholme Group can be divided into two macrofacies: the basinal facies of dominantly argillaceous clastic sediments; and the carbonate facies which comprises essentially autochthonous carbonate deposition (Figure 3).

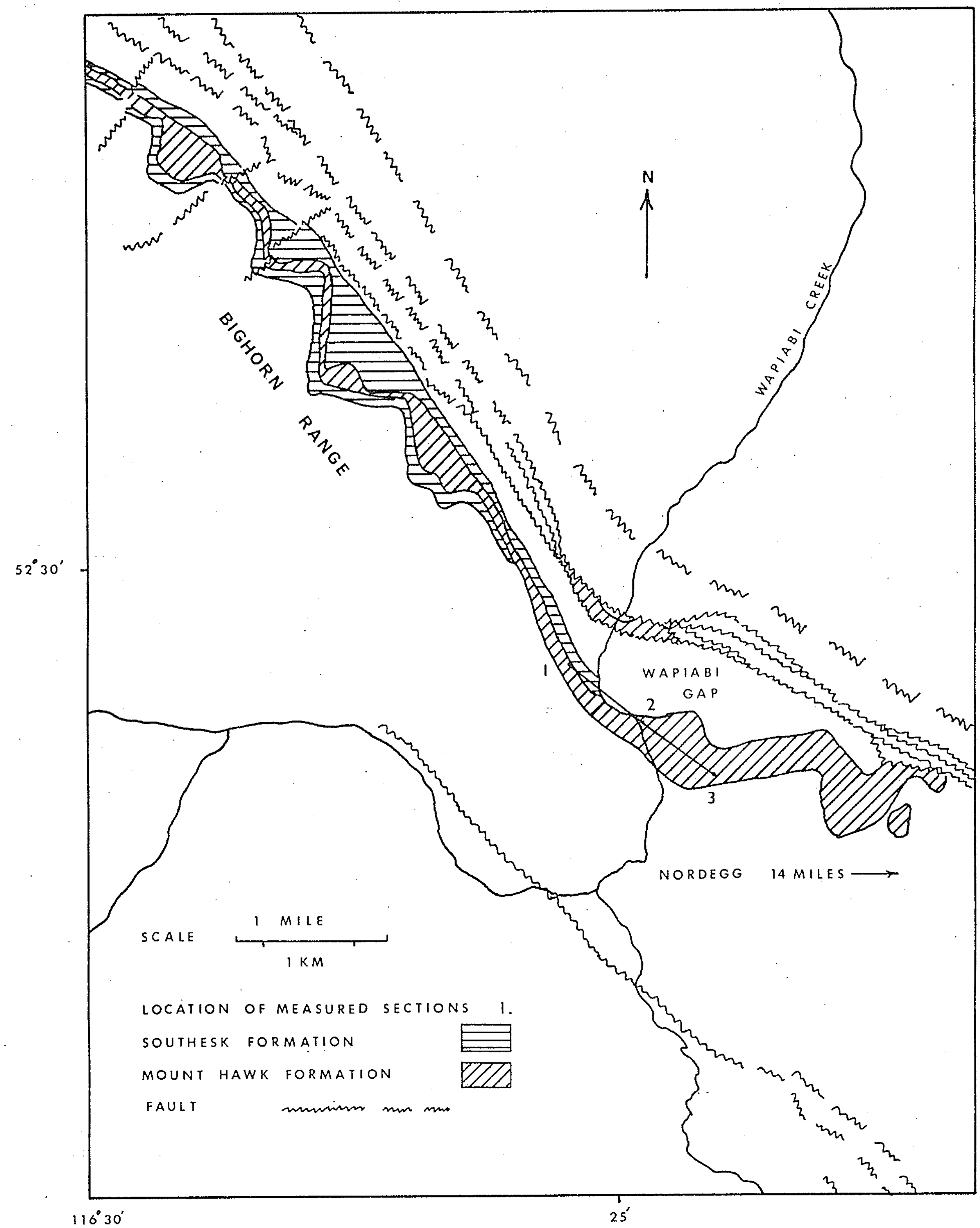
The Southesk-Cairn carbonate complex

The earliest sediments of the Fairholme Group have been termed the Flume Formation and Flume Member of the Cairn Formation in areas where the Flume is overlain by carbonate sediments. The Flume Formation is divided into a lower chert-free carbonate which forms a

Figure 2

Location map of Wapiabi Gap

(Modified after Douglas, 1956a and 1958)


N
WAPIABI CREEK
BIGHORN RANGE
52°30′
1
2
3
WAPIABI GAP
NORDEGG 14 MILES
SCALE
1 MILE
1 KM
LOCATION OF MEASURED SECTIONS 1.
SOUTHESK FORMATION
MOUNT HAWK FORMATION
FAULT
116°30′
25′

widespread platform deposit throughout the carbonate complex region. It was deposited in Upper Devonian seas which transgressed over eroded silty carbonates of Upper Cambrian age. The Flume Member is an upper cherty carbonate unit and in accordance with established nomenclature the combined lower and cherty carbonates are called the Flume Formation where no 'upper Cairn member' occurs above them, and called the Flume Member of the Cairn Formation in areas of carbonate buildup (MacKenzie, 1969). (The writer suggests that the terms Flume Formation and Flume Member of the Cairn Formation is improper usage of stratigraphic nomenclature.)

In topographically higher areas favourable for organic growth carbonate sediments continued to accumulate while argillaceous sedimentation occurred in other parts of the basin. These fossil rich carbonate sediments constitute the 'upper member' of the Cairn Formation.

The Cairn ranges in thickness considerably throughout the carbonate complex but it is much thicker at the margins of the buildups. Beds higher in the sequence of carbonate deposits, constituting the 'upper Cairn member', occupy progressively smaller areas. The Cairn Formation consists predominantly of brown medium crystalline dolomite while spherical stromatoporoids and branching *Amphipora* are the most conspicuous faunal elements.

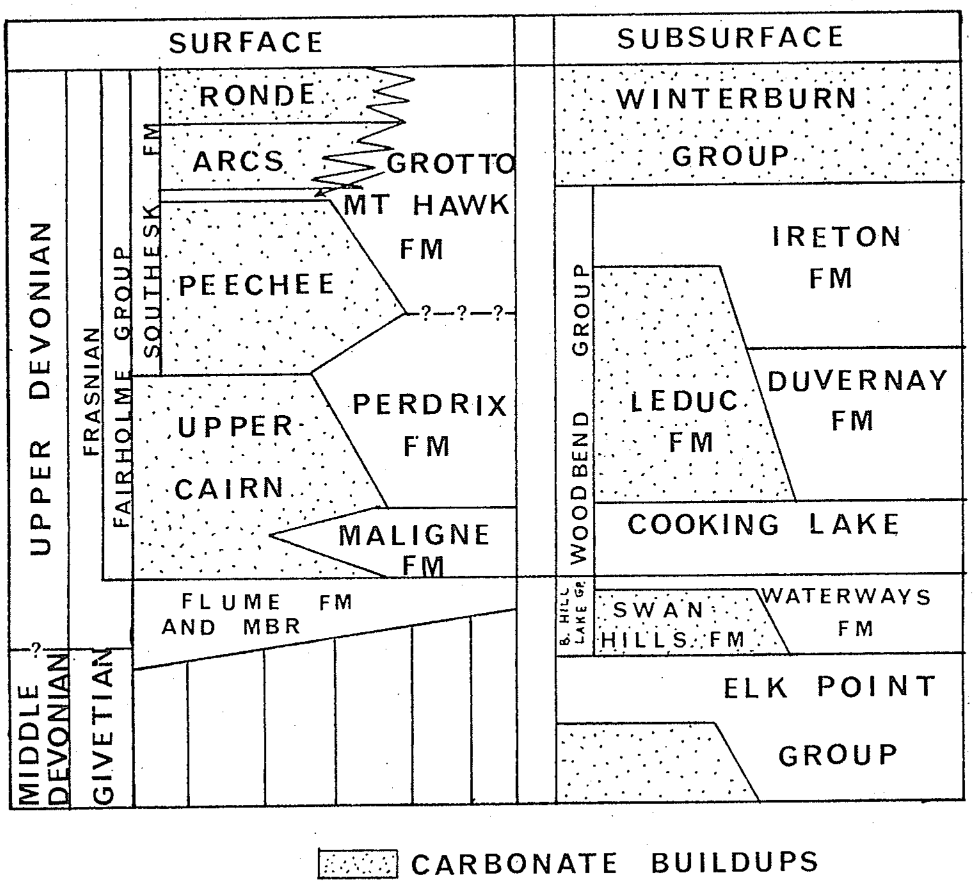
Overlying the Cairn is the Southesk Formation which represents continued carbonate deposition. It differs from the underlying Cairn Formation in that it is more widespread higher in the sequence and extends progressively farther into the basin. The Southesk has been interpreted to have formed during relative crustal stability which resulted in a large accumulation of carbonate sediments that were

Figure 3

Stratigraphic column of Upper

Devonian Fairholme sediments

(Modified after Cook et al., 1972)


SURFACE
SUBSURFACE
UPPER DEVONIAN
FRASNIAN
FAIRHOLME GROUP
SOUTHESK FM
RONDE
ARCS
GROTTO
MT HAWK FM
PEECHEE
UPPER CAIRN
PERDRIX FM
MALIGNE FM
FLUME FM AND MBR
MIDDLE DEVONIAN
GIVETIAN
WINTERBURN GROUP
WOODBEND GROUP
IRETON FM
LEDUC FM
DUVERNAY FM
COOKING LAKE
B. HILL LAKE GP.
SWAN HILLS FM
WATERWAYS FM
ELK POINT GROUP
CARBONATE BUILDUPS

eventually washed out beyond the carbonate complex.

The Southesk Formation has been divided into four members, from the base upwards: The Peechee, Grotto, Arcs and Ronde Members. The Peechee consists of light grey, coarsely crystalline dolomite and for the most part represents a shallow water carbonate bank accumulation. The Grotto Member consists typically of dark brown, finely crystalline dolomite containing abundant coral and stromatoporoid remains. The Arcs Member has its maximum thickness in the central portion of the complex and is absent at and near the periphery (MacKenzie, 1969). The Arcs Member is a light brown microcrystalline limestone containing few fossils. It is inferred to have accumulated in a relatively quiet water environment. Overlying the Arcs Member is the Ronde Member which consists of a lower silty limestone and an upper, bedded, fine-grained limestone. Corals and stromatoporoids are most abundant in the uppermost beds of the Ronde and near the margins of the carbonate complex.

Argillaceous facies

The argillaceous facies of the Fairholme Group is laterally equivalent to the carbonate complex and is for the most part argillaceous limestone and shales. This facies is divided into the Flume, Maligne, Perdrix and Mount Hawk Formations (Figure 3) in ascending order (MacKenzie, 1969).

The Flume Formation is stratigraphically equivalent to the Flume Member of the carbonate complex. The dominant rock type is dark brown, medium crystalline dolomite with some argillaceous limestone. Large globular stromatoporoids and branching *Amphipora* are the main organic constituents of this platform deposit. The Flume has been divided into a lower chert-free unit and an upper cherty carbonate unit.

The Maligne Formation overlies the Flume and can be distinguished from the latter by the absence of black chert lenses. The Maligne consists of dark grey to black, argillaceous, thin bedded, and rubbly limestone. It becomes progressively more calcareous towards the carbonate complex and eventually cannot be distinguished within the adjacent complex.

Overlying the Maligne is the Perdrix Formation which is a recessive series of black to brown weathering shales that are calcareous in the upper part of the sequence. There is generally a relatively abrupt transition between Perdrix shales and the stratigraphically equivalent dolomites of the Cairn Formation.

The Perdrix is overlain by calcareous shales of the lower part of the Mount Hawk Formation. These shales were deposited during the growth of the upper part of the 'upper Cairn member' and the Peechee and Grotto Members of the Southesk Formation (MacKenzie, 1969). Near the carbonate complex the lower zone of argillaceous mudstones and shales become increasingly calcareous and interbedded calcareous shales and limestones become the dominant lithologies. Near the carbonate buildup margins the Mount Hawk frequently contains isolated limestone mounds and lenses in the upper part of the formation (MacKenzie, 1969). The upper part of the Mount Hawk Formation is a grey limestone unit that is stratigraphically equivalent to the Grotto and Arcs Members.

Local stratigraphy

A portion of the Upper Devonian Fairholme succession is exposed at Wapiabi Gap. The present study, however, is restricted to sediments of the lower portion of the Southesk Formation and the stratigraphically equivalent argillaceous sediments of the lower portion of the Mount Hawk Formation. On the northwest side of Wapiabi Creek the carbonate sediments of the lower Southesk, presumably the Peechee Member, are overlain by an accumulation of basinal Mount Hawk sediments (Plate 1a, b). In contrast, on the opposite southeast side of the creek, the succession is entirely Mount Hawk (Plate 1c, d). This carbonate to shale transition occurs within a distance of approximately 1 kilometer (Figure 4). Unfortunately the most critical portion of the facies change has been eroded away.

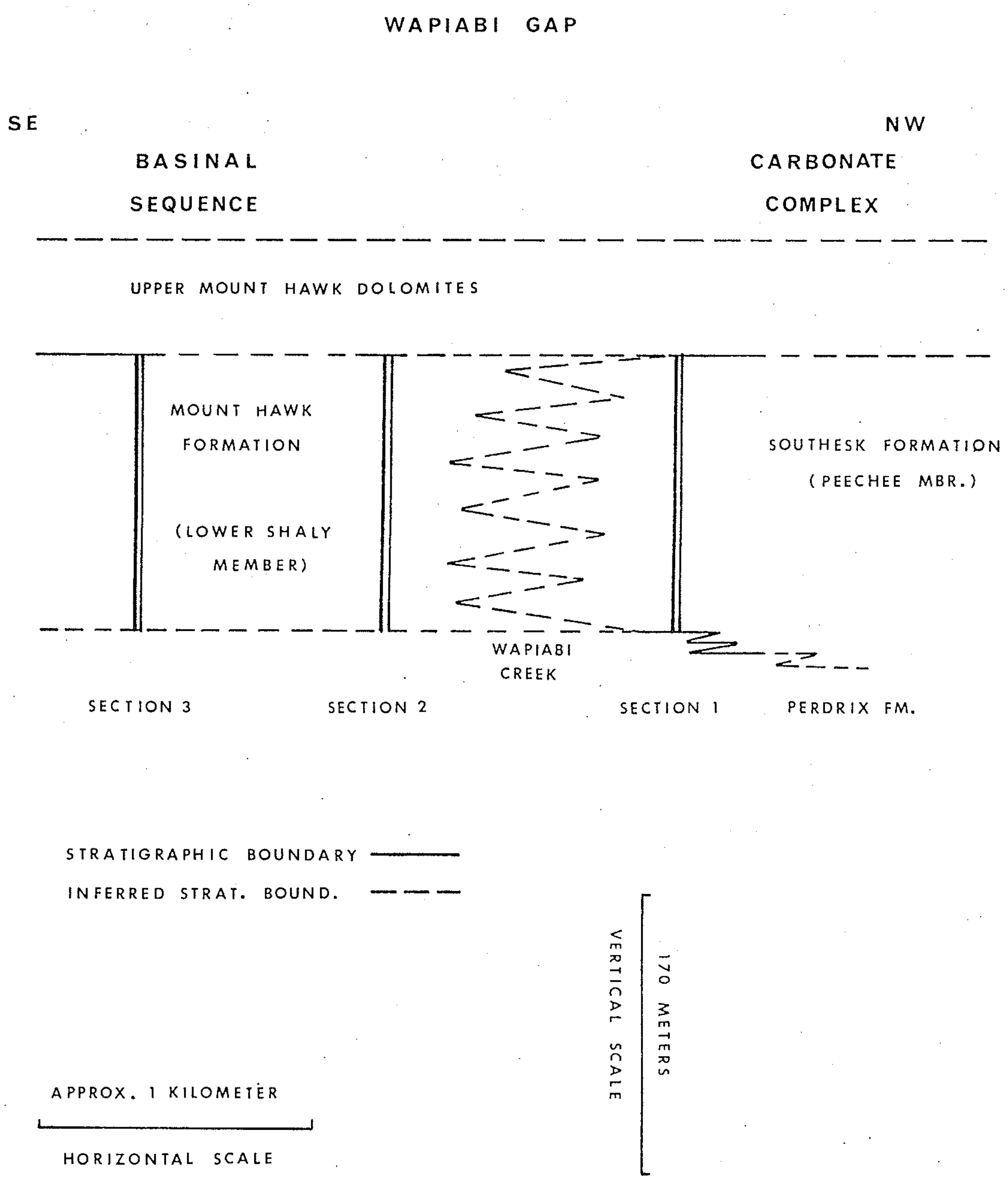
The allochthonous debris beds which are the subject of this report occur within the Mount Hawk interbedded shales and limestones on the southeast side of Wapiabi Creek.

Previous work

Significant studies of Devonian carbonate reef to stratigraphically equivalent basinal sequences in the mountain and plains areas have been undertaken by Belyea and McLaren (1957), Taylor (1957), Hargreaves (1959), and Dooge (1966). McLaren and Mountjoy (1962) and Mountjoy (1965) helped to resolve the problem of stratigraphic equivalence in Upper Devonian carbonate reef to basin transitions in the Jasper region, Alberta. MacKenzie (1965, 1967, 1969) has presented a comprehensive picture of the stratigraphy of the Southesk-Cairn carbonate complex in the eastern Jasper National Park region.

Figure 4

Schematic cross section of formations at Wapiabi Gap showing measured stratigraphic sections


WAPIABI GAP
SE
NW
BASINAL SEQUENCE
CARBONATE COMPLEX
UPPER MOUNT HAWK DOLOMITES
MOUNT HAWK FORMATION
(LOWER SHALY MEMBER)
SOUTHESK FORMATION
(PEECHEE MBR.)
WAPIABI CREEK
SECTION 3
SECTION 2
SECTION 1
PERDRIX FM.
STRATIGRAPHIC BOUNDARY
INFERRED STRAT. BOUND.
170 METERS
VERTICAL SCALE
APPROX. 1 KILOMETER
HORIZONTAL SCALE

Allochthonous carbonate debris occurs near the base of the Mount Hawk Formation in two other Upper Devonian carbonate complexes of the Rocky Mountains, the Ancient Wall and Miette complexes (Figure 1). The debris beds at these localities have been extensively studied by Mountjoy (1967), Stearn (1967), Cook et al. (1972), Hopkins (1972), Strivastava et al. (1972), and Mountjoy et al. (1972). Allochthonous carbonate debris deposits have also been identified in Upper Devonian basinal sediments of the Alberta subsurface at the Windfall pinnacle reef complex by Boyce (1974).

The present study area at Wapiabi Gap was mapped by Mackay (1940). DeWit and McLaren (1950),and Belyea (1954) were the first to describe the reef-shale relationships that occur in the Upper Devonian sediments in this area. McLaren (1955) noted several fossil debris beds 0.5 to 8 feet (0.15 to 2.4 meters) in thickness within the Mount Hawk shales. These are the allochthonous carbonate debris deposits which are the subject of this report. Wapiabi Gap and the adjacent area was later mapped by Douglas (1956a, 1958).

Method of study

A total of 12 days field work was accomplished during August of 1974. During that time three sections were measured and representative samples taken of the various lithologies. Sections were measured using a five foot Jacob's staff. The Peechee Member and a lower portion of the Mount Hawk Formation were measured on the northwest side of the creek. On the southeast side, within the basinal sediments, two sections were measured approximately one and two kilometers beyond the carbonate complex respectively (Figure 2).

Detailed sampling of the lithologies involved a sample spacing of 5 to 10 centimeters in some portions of the sections, and in other portions, for example the shaly intervals, the sample spacing was as much as 10 to 20 meters. The allochthonous carbonate debris was sampled in great detail. Forty (40) samples were collected from the two debris beds near the base of the Mount Hawk and an average of 3 samples were taken from each of the five debris deposits which occur higher in the Mount Hawk sequence. One hundred seventy (170) samples were collected from a total of 1700 feet (510 meters) of measured section.

From the total number of samples collected 100 samples were later cut and polished. A total of 90 thin sections were cut from these slabbed samples.

Thin sections were later stained with Alizarin Red S and potassium ferricyanide solutions following the procedure recommended by Dickson (1965, 1966). In addition 10 shale samples were analysed for mineral identification by x-ray diffractometry.

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CHAPTER 2

ALLOCHTHONOUS CARBONATE DEBRIS

Introduction

Allochthonous carbonate debris deposits occur in basinal sequences adjacent to carbonate complex margins. The terms refer to carbonate material which has been shed from the buildup and subsequently transported to the adjacent basin (Mountjoy, 1972).

Other occurrences

Allochthonous carbonate debris is not unique to the Upper Devonian of the Canadian Rocky Mountains. Mountjoy et al. (1972) state that carbonate debris flows have a world wide occurrence and span the entire time range of the Paleozoic. Talus and reef-derived debris have also been reported from the Recent coral reefs off North Jamaica (Land, 1973; Moore, 1973).

Massive inclined beds of reef talus form up to two-thirds of the Capitan Formation in the Permian Reef complex of the Delaware Basin in Texas and New Mexico (Newell et al. 1953). Newell (1955) also described limestone breccia interbedded with the Cherry Canyon and Bell Canyon Formations of Permian age in west Texas. The breccia beds are composed of unstratified, subangular fragments of limestone in a fine grained matrix and extend several miles into the basin sediments. Pray and Stehli (1962) interpreted outcrops previously referred to as the Bone Springs "patch reefs" (Newell 1953) at the margin of the Delaware Basin, as submarine-channel deposits of allochthonous carbonate megabreccias which were transported by submarine slides. These deposits have subsequently been described by McDaniel and Pray (1967). Rigby (1958) reported slump, debris avalanche, and turbidity current deposits in the basinal sequence of the Permian rocks of west Texas.

Cook et al. (1972) has divided the allochthonous debris material adjacent to the margins of the Miette and Ancient Wall carbonate complexes of Alberta into 4 separate facies; megabreccias, finer rudite sheets, allodapic carbonate sands, and channel deposits. The megabreccias are about 5 meters thick and contain unsorted pebble to boulder-sized clasts of buildup-derived material, (up to 25 x 50 meters in cross section) which are embedded in a dark carbonate mud or wackestone matrix. The size of the clasts becomes somewhat larger towards the bank margin. Clasts of both basinal muds and carbonate bank material are mixed resulting in an unsorted, heterogenous fabric. According to Cook et al. (1972) masses of limestone of uncertain origin occur near Cardinal Mountain at the northwest margin of the Southesk-Cairn carbonate complex. These may be similar megabreccia deposits although MacKenzie (1965, 1967, and 1969) has interpreted most of them as <u>in situ</u> grainstone mounds, and small foreslope bioherms. Playford (1967, 1969) has documented reef-derived carbonate material in the Devonian of the Canning Basin in Western Australia which is similar to the megabreccia deposits at the Ancient Wall and Miette complexes in Alberta.

The finer rudite sheets are the most abundant allochthonous rock type at the margins of the Ancient Wall and Miette carbonate complexes according to Cook et al. (1972). The rudite sheets consist of allodapic carbonate sand containing small fragments ranging from boulder to silt size, and form thin beds 0.3 to 3 meters thick interbedded with basin strata. Hopkins (1972) has inferred that most of the allochthonous clasts were derived from differentially submarine cemented foreslope carbonate sands.

Allodapic carbonate sands are the third allochthonous facies described by Cook et al. (1972). They occur in sheets a few centimeters to 0.5 meters thick and consist of sand-sized grains of shoal-water microfossils and pellets or peloids. The term allodapic refers to shoal-water derived sands which have been transported to a deeper water environment and was proposed by Meischner (1964). Allodapic carbonate sheets volumetrically comprise at least 50% of the allochthonous deposits at the margins of the Ancient Wall and Miette carbonate complexes. Similar allodapic carbonate sands have been studied by MacKenzie (1971, 1973). Sand-sized fragments of echinoderms make up the allochthonous material and it has been inferred that it was originally derived from carbonate banks and deposited on the underlying limestone formation.

Channel deposits constitute a relatively minor allochthonous facies described by Cook et al. (1972). The channels are small-scale features, commonly less than 1 meter deep and approximately 15 meters wide. Sediments in the channels are similar to those of the allodapic carbonate sheets and the finer rudite deposits. The sediment consists of poorly sorted shoal-water and basin-derived sands, pebbles and cobbles. The basal contact forms a U-shaped profile and is clearly erosional in nature which contrasts with the planar bases of the other allochthonous deposits.

In some of the Devonian reef complexes of the Alberta subsurface allochthonous carbonate debris deposits may constitute an important reef marginal facies. Conglomerates and breccias composed of calcarenites and fossil fragments occur in the Redwater Reef complex (Klovan, 1964), the Carson Creek Reef complex (Leavitt, 1968), and some of the Swan Hills reefs (Fischbuch, 1968).

Allochthonous carbonate debris at Wapiabi Gap

The debris beds found within the basinal calcareous shales and argillaceous limestones at Wapiabi Gap (Figure 4) appear to be quite similar to the finer rudite sheets and allodapic carbonate sands described by Cook et al. (1972) as well as the allochthonous echinoderm debris beds studied by MacKenzie (1971, 1973).

There are seven allochthonous debris beds which outcrop in the basinal Mount Hawk shales on the southeast side of Wapiabi Creek. The two lowermost debris deposits are petrographically distinct from the other five which occur higher in the sequence.

Allochthonous debris near the base of the Mount Hawk Formation

The two lowermost debris beds occur near the base of the Mount Hawk Formation. The debris flows adjacent to the Miette and Ancient Wall carbonate complexes occur at the same stratigraphic position. The debris deposits at Wapiabi Gap are also stratigraphically equivalent to the lowermost debris interval described by Boyce (1974).

Using Embry and Klovan's (1971) modification of Dunham's (1962) classification of carbonate rocks by depositional texture, these two lowermost allochthonous deposits can be classified as rudstones. These in turn are petrographically distinct from one another and will be discussed separately.

Lowermost allochthonous debris bed

This debris deposit appears to be conformable with the shales in which it occurs. The thickness of the lowermost debris bed is not known because the lower portion of the deposit does not outcrop. However the part that is exposed is 1.5 meters thick and appears to be the upper portion of the deposit. The rudstone debris bed weathers reddish brown to dark brown in colour and can be traced laterally over a distance of approximately 100 meters. Debris fragments increase in size towards the complex and a few reach boulder dimensions. The uppermost 0.5 meters of the debris bed is composed of finer grained allochthonous debris (fine sand) and a greater amount of tiny (2-6mm in diameter) inarticulate brachiopods than in the lower portion of the deposit. The upper portion is somewhat similar to the "calcarenite cap" facies described by Cook et al. (1972). Orientation of the allochthonous debris is essentially parallel with the bedding throughout the debris deposit, but this feature is most conspicuous in this upper cap portion.

Second debris bed

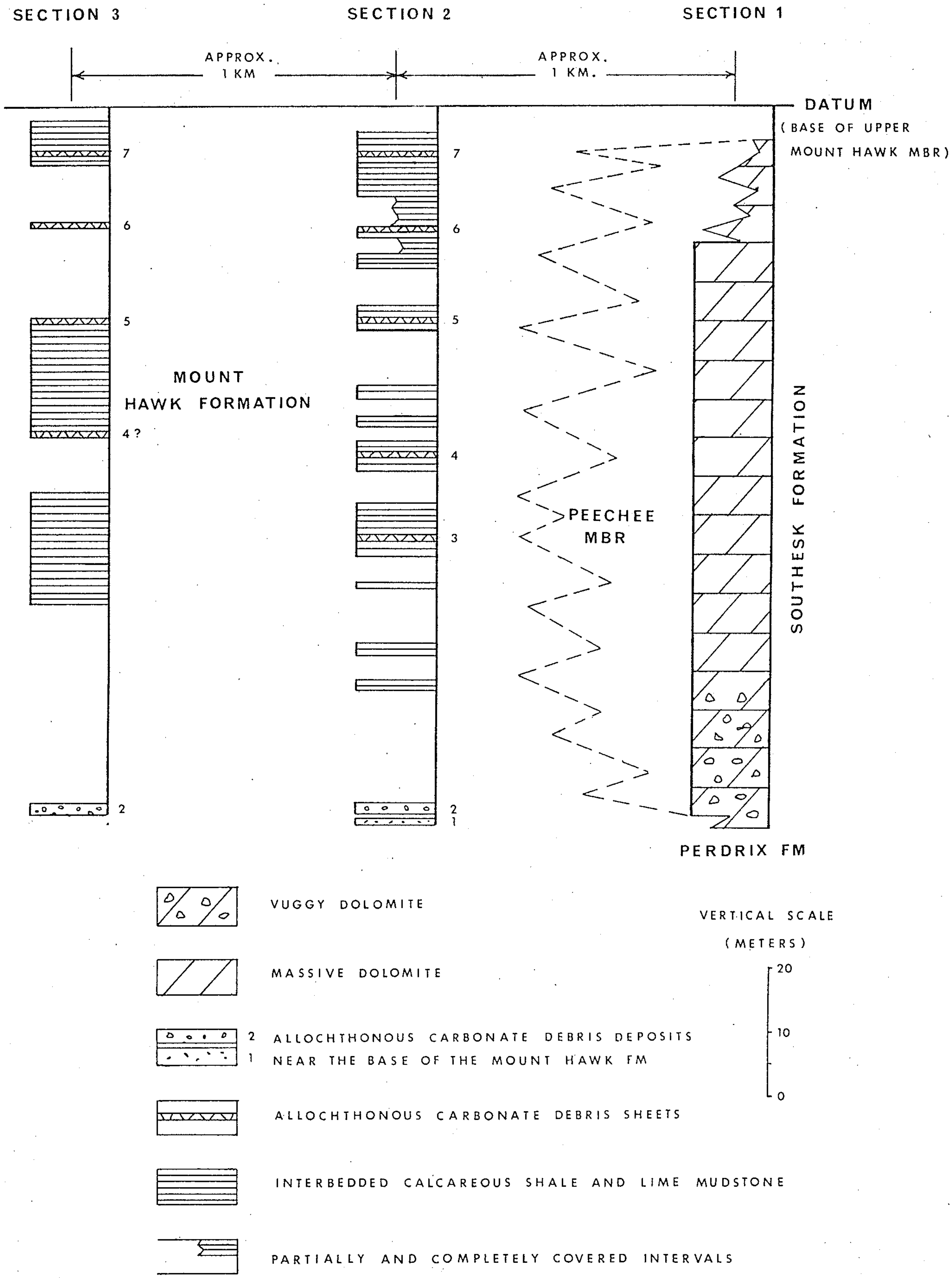
The lower contact of the second debris deposit is covered by shaly talus. This covered interval is approximately 0.3 meters in thickness. Similarly the upper contact of the lowermost debris bed is covered. Hence, it is not known whether or not the two debris deposits are separate from one another, or if indeed they are separate, it is not known what type of lithology separates them (Figure 5). However, the two debris deposits have been separated in this thesis because of their distinctly different petrographic characteristics.

The second allochthonous debris bed is approximately 0.5 meters thick and weathers reddish brown to almost black in colour. Although both upper and lower contacts are obscured by shale talus this debris interval also appears to be conformable with the shales in which it occurs. At the base of section 3 (Figure 5) another debris deposit occurs. This bed has essentially identical petrographic characteristics as the second debris bed that was measured in section 2 and is at the same stratigraphic level in the succession. Therefore it is concluded that both outcrops represent one and the same allochthonous deposit and that the second debris interval extends a distance of at least 2 kilometers beyond the carbonate complex margin (Figure 5).

This debris deposit is a rudstone containing numerous well-rounded lenticular-shaped allochthonous clasts of buildup-derived material, within a fine sand matrix. The clasts have their long dimension oriented parallel to the bedding. The orientation direction of the clasts is roughly normal to the margin of the carbonate complex exposed on the opposite side of Wapiabi Creek. Clasts range from pebble to boulder sizes but the majority have cobble to small boulder dimensions. The uppermost 0.1 meters of this deposit is composed of fine sand-sized allochthonous debris and is similar to the "calcarenite cap" of the lowermost debris bed. There is an abrupt

Figure 5

Stratigraphic sections, lower Mount Hawk and lower Southesk strata, southeast and northwest of Wapiabi Creek, Big Horn Mountain Range


SECTION 3
SECTION 2
SECTION 1
APPROX. 1 KM
APPROX. 1 KM.
DATUM
(BASE OF UPPER MOUNT HAWK MBR)
7
6
5
4?
2
7
6
5
4
3
2
1
MOUNT HAWK FORMATION
PEECHEE MBR
SOUTHESK FORMATION
PERDRIX FM
VUGGY DOLOMITE
MASSIVE DOLOMITE
2 ALLOCHTHONOUS CARBONATE DEBRIS DEPOSITS
1 NEAR THE BASE OF THE MOUNT HAWK FM
ALLOCHTHONOUS CARBONATE DEBRIS SHEETS
INTERBEDDED CALCAREOUS SHALE AND LIME MUDSTONE
PARTIALLY AND COMPLETELY COVERED INTERVALS
VERTICAL SCALE (METERS)
20
10
0

contact between the lower portion of the deposit and this upper calcarenite cap.

Upper allochthonous debris sheets

There are five other debris deposits within the lower part of the Mount Hawk Formation at Wapiabi Gap that occur higher in the sequence and at nearly equally spaced intervals (Figure 5, sections 2 and 3). The thickness of each debris bed is approximately 15 centimeters and all except bed number 3 maintain a constant thickness laterally over a distance of 1 kilometer. For this reason the upper debris beds can be better defined as allochthonous carbonate debris sheets. The bed thicknesses as well as petrographic characteristics are for the most part identical in all five beds and therefore these have been classified as similar type deposits.

The debris sheets were measured in both sections in the basinal succession and no changes in composition were observed laterally. The deposits extend for a distance of at least two kilometers beyond the carbonate complex margin (Figure5).

A typical debris sheet can be divided into two parts: a basal portion and an upper portion. The basal portion constitutes up to 50% of the rock volume visually and is primarily composed of carbonate mud. The upper portion of a debris sheet has essentially a floatstone texture and consists of lenticular and irregular-shaped lutite clasts embedded within a matrix of carbonate sand and mud. The texture of the matrix in this upper portion ranges from a wackestone to a grainstone. The carbonate sand primarily consists of echinoderm fragments.

The contact between the lower and upper portions of a debris sheet is sharp but very irregular and exhibits what appears to be numerous load and cast structures.

CHAPTER 3

PETROGRAPHY AND DIAGENESIS

The carbonate complex

The margin of the carbonate complex at Wapiabi Gap is for the most part composed of massive dolomite. However, the lower portion of the sequence (lower Peechee) contains large (10 - 20 centimeters in diameter) irregular and hemispherical shaped vugs (Figure 5: also Plate 2a). Lining the walls of some of these vugs are faint calcite laminations. The vugs appear to have had an organic origin and may be a result of selective leaching of carbonate reef building stromatoporoids. The upper portion of the section exhibits indistinct bedding. This feature is hardly noticeable at the actual outcrop itself, but becomes apparent at a distant visual examination of the complex margin (Plate 1a, b). The upper 80 meters of section that was measured is essentially massive dolomite (Figure 5) containing small (2 - 3 centimeters in diameter) irregular-shaped vugs (Plate 2b).

Mount Hawk shaly sediments overlie the dolomites of the carbonate complex margin and appear to be conformable with the carbonate sediments. The lower part of the Mount Hawk is evident as a thin (6 meters in thickness) covered interval of shaly talus. The upper portion of the Mount Hawk which consists of finely laminated dolomites appears to conformably overlie the shales of the lower part of the Mount Hawk Formation. The resistant, cliff forming, upper sequence of the Mount Hawk Formation which outcrops on the southeast side of Wapiabi Creek as well, was used as a datum line in the field (Figure 5).

Thin sections of the dolomites of the buildup margins stained with potassium ferricyanide solution revealed that the dolomites are chemically non-ferroan.

The Mount Hawk shales

The lower Mount Hawk succession in which the debris deposits occur at Wapiabi Gap consists of grey to pale green slightly calcareous shales and interbedded lime mudstones. Actual rock outcrop is sparse as the sequence weathers poorly. Most of the sequence is in fact covered by shaly talus.

The interbedded lime mudstones are volumetrically as important as the shale and occur at approximate intervals of 5 to 20 centimeters throughout the succession (Plate 2c). These beds generally exhibit constant thicknesses (5 to 10 centimeters) laterally over a distance of 1 kilometer. However, some beds, particularly in the uppermost 10 meters of the lower Mount Hawk sequence, are nodular.

X-ray diffraction analyses were done on 10 shale samples to determine the mineralogy. The minerals identified are: calcite, quartz, dolomite, illite, kaolinite, chlorite, feldspar, and pyrite.

Lowermost allochthonous debris bed

Components

Framework

The rudstone debris bed primarily consists of unsorted fossil fragments of mostly cobble size material (Plates 2d, e, f). However debris ranges in size from pebble to boulder dimensions. The skeletal fragments form a grain supported rudstone in which fine grained sand and a minor amount of carbonate mud (micrite) occupy the interstitial spaces. The allochthonous debris is essentially a mixture of Thamnopora, echinoderms, inarticulate and articulate brachiopods and bryozoan fragments (Plate 3). Thamnopora and echinoderm debris constitute over 45% of the rock volume (visual estimate).

The margins of the majority of fossil fragments show some degree of alteration to microcrystalline calcite. (In this thesis "microcrystalline" is restricted to carbonate fabrics in which the modal crystal size is between 4 and 60 microns (McKee and Gutschick, 1969).)

Matrix

The matrix of this debris deposit consists of essentially the same carbonate material that comprises the framework. However, the material in this case consists of much finer grained components (fine sand-sized). The major constituent of the matrix is echinoderm debris (80% by volume). Most of the echinoderm fragments show some degree of alteration to microcrystalline calcite around their peripheral margins.

The other important constituent of the matrix is fine sand-sized peloids of microcrystalline calcite. These make up approximately 10 - 15% (visual estimate) of the matrix components. Carbonate mud, calcite pseudospar and skeletal fragments of Thamnopora, brachiopods, and bryozoans, constitute the remainder.

Up to 5% of the constituent components of the matrix have been either partially or completely altered to pyrite.

Cements

The carbonate cement of the Devonian debris deposits is low magnesium calcite and comprises approximately 20 to 40% (visual estimate) of the rock volume in the lowermost debris interval. Chemically, there are two types of carbonate cement: non-ferroan and ferroan calcite which can be distinguished in thin section by Alizarin Red S and potassium ferricyanide stains. There are three different generations of cement in the lowermost debris bed. The first two are invariably non-ferroan, whereas the third generation is ferroan and occludes all interallochem spaces not completely filled by the first and second generation cements.

1. First generation

There are two kinds of cement of distinctly different morphological habits that comprise the earliest cements. These are bladed fringing cement and echinoderm rim cement (Plate 5d, e).

a. Bladed fringing calcite cement

This cement develops on skeletal fragments of all sizes but it is especially well developed on microcrystalline peloids or skeletal grains which have a microcrystalline alteration envelope (Plate 6b). The bladed calcite cement crystals have length-breadth ratios of 3 - 5:1. The long axes of the crystals are oriented normal to the surfaces of the allochems. Bladed calcite cement forms as fairly closely packed fringes completely around allochems or as incomplete fringes.

On any given allochem the fringing cement is better developed on the side of the allochem furthest away from nearby echinoderm grains that have echinoderm rim cement surrounding them (Plate 6d). In contrast bladed fringing cement is poorly developed or absent entirely on the side of the particular allochem closest to the echinoderm grain from which the rim cement grows. Furthermore, echinoderm grains on which a partial or incomplete microcrystalline alteration envelope has developed have bladed fringing cement which has nucleated only on the microcrystalline alteration envelope (Plate 6e, f). Echinoderm rim cement has developed on the unaltered portion of the skeletal grain. This petrographic evidence suggests that the bladed fringing cement and the echinoderm rim cement developed at the same time and in fact competed against one another for growth space.

Bladed fringing cement forms well developed crusts on articulate brachiopod fragments with individual cement crystals exhibiting well developed rhombohedral terminations. Later cement fringes around brachiopod fragments have grown in optical continuity with the cement crystals of this first generation. This later cement can be recognized because it is ferroan and stained blue. Cement fringes on brachiopod skeletal grains are thus often much thicker than those around peloids and bryozoan fragments.

b. Echinoderm rim cement

Echinoderm rim cement is volumetrically the most abundant cement in this allochthonous debris deposit. It makes up over 70% (visual estimate) of the total cement volume. It occurs on allochems which lack a microcrystalline envelope but is not present around echinoderm skeletal grains which have a continuous peripheral microcrystalline rim. The earliest cement on these grains is bladed fringing cement. Almost invariably echinoderm rim cement growing from adjacent allochems will partially or completely surround allochems which have bladed fringing cement. In many cases rim cement completely occludes pore spaces and a single cement crystal poikilotopically (Friedman, 1965) surrounds several allochems.

2. Second generation cement

a. Blocky mosaics

Non-ferroan blocky mosaic cement is the only type of second generation cement. It is found in all allochthonous debris deposits in the present study area. In the lowermost debris bed it occurs as a petrographically later interallochem cement over the earliest generation of bladed fringing and echinoderm rim cement. It fills many of the intrabiotic pore spaces and radiates inwards from the pore walls increasing in crystal size towards the centres of the voids (Plate 7c). Blocky mosaics commonly completely fill leached fossil voids in a similar manner.

3. Late ferroan cement

The last generation of cement is readily distinguished as it is ferroan calcite and stains blue upon application of Potassium ferricyanide solution. This cement is morphologically the same as the earlier cements but unique in that it is chemically different.

Ferroan cement fills any remaining interallochem spaces not occluded by the early generations of cement (Plate 7d). It also forms large single crystals and invariably overlies the earlier cements. This cement commonly exhibits calcite twinning on large void filling crystals.

An intersting characteristic of the ferroan cement is that it will develop on the earlier cements and be optically continuous with them. The result is that the various carbonate cements will be zoned: (i.e. an early non-ferroan zone and a later optically continuous ferroan zone). Zoning has been observed in bladed fringing cement crusts on brachiopod fragments, in echinoderm rim cement and in the blocky mosaics. As many as twelve alternating non-ferroan - ferroan zones have been noted in the blocky mosaic cements, indicating the complex chemical history of this third generation of cement (Plate 7f).

Zoning in cements has been noted in ancient carbonates by several workers (eg. Evamy and Shearman, 1965; Evamy, 1969). Evamy and Shearman (1965) discuss late ferroan zoning in echinoderm rim cement and note that ferroan carbonate cements generally post-date formation of early cements.

Minor components

Other components of minor imporatnce are grapestone-like mud aggregates and pebble to cobble-sized lenticular and irregular-shaped lutite clasts.

Second debris bed

Components

Clasts

The presence of lenticular-shaped allochthonous clasts in the second debris deposit is a characteristic petrographic feature which distinguishes it from the lowermost debris bed.

Roughly 60% (visual estimate) of the total number of clasts are well rounded lenticular lutite clasts having diameters 10 - 20 centimeters. The lutite clasts are generally dark brown to almost black in colour. The composition of these clasts is microcrystalline and cryptocrystalline calcite. The homogeneous carbonate mud texture is characteristic, and in some clasts is interrupted by faint laminations of detrital as well as authigenic quartz.

Ten to fifteen percent of the allochthonous clasts in the second debris bed consist of broken coral debris. These clasts are up to 15 centimeters in diameter. An unidentified Upper Devonian colonial coral and Thamnopora can be recognized. Cryptocrystalline calcite (micrite) fills many of the intrabiotic pores. Broken skeletal fragments of echinoderms, brachiopods and bryozoans are embedded in the intrabiotic mud. Pores that are not completely filled by micritic calcite are occluded with second generation blocky mosaic cement and in some cases ferroan calcite.

The remaining 25% of the clasts is cemented calcarenite debris. The composition of these clasts is essentially identical to the matrix of the lowermost debris bed. The allochemical components are fine sand-sized grains of echinoderms, with alteration envelopes, brachiopods, bryozoans, Thamnopora, peloids, and minor mud aggregates. The relative proportions of each component is also very similar to the matrix in the lowermost debris bed.

The cements which occupy the interallochem spaces within a cemented calcarenite clast are petrographically identical to those in the underlying debris deposit (Plate 7a, d). All three generations are present but the first generation of bladed fringing cement and echinoderm rim cement are volumetrically the most important. This is due to the large amount (over 70% by volume) of echinoderm rim cement.

A few of the cemented calcarenite clasts exhibit what appears to be continuous microcrystalline alteration envelopes around their peripheral margins (Plate 8a).

Matrix

The matrix comprises by a visual estimate approximately 20% of the rock volume. It consists of well sorted and well rounded fine sand-sized skeletal fragments of primarily echinoderms. Skeletal fragments of brachiopods and fine sand-sized peloids are also present but are relatively minor in amount.

Carbonate mud consitutes less than 2% by volume of the matrix. Well sorted, equant calcite crystals resembling Folk's (1965) microspar and pseudospar occur in minor amounts in the matrix. As suggested by Folk (1965) this may well be neomorphic alteration of the original micrite.

Cements

All three generations of cement are found in the interallochem voids in this debris deposit (as well as in the cemented calcarenite clasts). The early generation of bladed fringing cement is, however, less abundant. It occurs as thin fringes around the large clasts. Where several allochems are closely packed together it forms a thin bladed crust over each allochem and drapes between adjacent allochems.

Echinoderm rim cement is again by far the most abundant cement. In most cases one cement crystal poikilotopically encloses several allochems of various types. Rim cement also shows ferroan zoning in the outer portions of many cement crystals.

Overlying the early echinoderm rim and bladed fringing cements are the non-ferroan blocky mosaics of an obviously later generation of cementation (Plate 7d). The cement is analagous to the blocky mosaics of the lower debris interval which the author has termed second generation cement. Blocky mosaic cement is minor in amount but occludes most of the remaining pore space. It has a number of ferroan zones in the peripheral regions of some crystals similar to the zonation in echinoderm rim cement.

As mentioned above,the zonation is attributed to a later period of ferroan calcite cementation. Ferroan cement is identical to the petrographically late cement in the lower debris bed. It occludes the few remaining voids completely and often has the shape of the particular void space it occupies. It also exhibits well developed calcite twinning and rhombohedral calcite cleavage. Ferroan calcite cement fills all of the later fractures which have developed in the rock.

Allochthonous carbonate debris sheets

Lower portion

The allochthonous debris sheets at Wapiabi Gap have been divided by the author into two petrographically distinct portions (Plate 4). The lower portion of a typical debris sheet is a mudstone and consists entirely of microcrystalline calcite. Small unidentifiable fossil fragments are embedded within the basal portion of a debris sheet but are very minor in amount. A few articulate brachiopod and echinoderm fragments are recognizable. The microcrystalline texture of the carbonate mud is homogeneous throughout all of the basal portions of the debris sheets.

Upper portion

The upper portion of the debris sheets are floatstones in texture. Lenticular and irregularly-shaped lutite clasts which weather reddish brown in outcrop are supported in a sand and mud matrix (Plate 4e, f). They are composed of microcrystalline calcite and contain a minor amount of brachiopod and echinoderm fragments as well as some unidentifiable fossil debris. The clasts are petrographically identical to the basal carbonate mud portion of the debris sheets.

Components

Matrix

Supporting the lutite clasts is a matrix that varies in composition from predominantly carbonate mud to predominantly medium and coarse grained carbonate sand. This variation appears to be characteristic of the particular debris interval in question. The 5th and 6th debris sheets have upper portions which are composed of lutite clasts in a predominantly calcarenite matrix. The upper portions of the 3rd and 7th debris sheets on the other hand are composed of lutite clasts supported in essentially a mud matrix containing approximately 5 percent grains. The 4th debris sheet appears to be intermediate between these two extremes and has a top portion consisting of a grain-supported fabric with a relatively abundant amount of interstitial mud. Lutite clasts are randomly oriented within the upper portion as is the case for all of the debris sheets.

The medium to coarse grained sand of the matrix is primarily composed of echinoderm fragments. Brachiopod and gastropod skeletal remains constitute the remaining 5 percent of the sand-sized component. The grains are moderately sorted and show little evidence of extensive abrasion. The carbonate mud is essentially composed of cryptocrystalline and microcrystalline calcite. Microcrystalline calcite is by far more abundant.

Cements

The cementation history of the debris sheets is less complex than that of the debris deposits near the base of the Mount Hawk succession. Non-ferroan blocky mosaic cement fills some of the leached fossil voids. The cement has nucleated on the pore walls and in most cases increases in crystal size towards the cavity centre. This cement is petrographically identical to the second generation blocky mosaics in the lower debris intervals. In many voids the cement is observed to have ferroan zoning, upon application of potassium ferricyanide stain, and is overlain by ferroan calcite cement which commonly entirely occludes the void space. The ferroan calcite cement often appears as one large crystal that exhibits calcite twinning. Ferroan blocky mosaics are also very common.

Echinoderm rim cement is well developed in the predominantly sand matrices of the upper portion of some debris sheets. Unlike the rim cement in the lower debris intervals this cement is entirely ferroan calcite (Plate 7c). Interstitial void space is occluded in most instances by echinoderm rim cement. Void space not filled with echinoderm rim cement is occupied by micrite. Ferroan blocky mosaic cement also occupies interstitial voids but it was not observed to overlie echinoderm rim cement.

Microcrystalline envelopes and grains

The alteration of the margins of skeletal particles is best exemplified in the fine sand-sized echinoderm fragments of the matrix in the lowermost debris deposit. The echinoderm sand grains in the matrix are single calcite crystals. The microcrystalline calcite is evident as either complete or incomplete uneven envelopes around each echinoderm allochem. Small tubes of microcrystalline calcite penetrate into the interior of some allochems and these resemble modern algal borings observed in carbonate sand grains. Indeed, the microcrystalline envelopes (Plate 8b, c) observed on many of the skeletal grains in the present study resemble the micrite envelopes outlined by Bathurst (1966). The only difference is that in the Devonian samples of this study as well as in those of Hopkins (1972) the marginal alteration is microcrystalline calcite, whereas in modern day marginally altered skeletal grains, the alteration rims are generally composed of finer grained micritic calcite. Hopkins (1972) suggests two possible reasons for this difference: (a) a difference in the size of the algae (or other organism) which bored modern and ancient grains, and (b) coarsening of the fine carbonate fabrics by neomorphism.

The other major constituent of the matrix is fine sand-sized peloids of microcrystalline calcite which range in size from silt to coarse sand. The term peloid is a non-genetic one and refers to subspherical to irregularly-shaped microcrystalline and cryptocrystalline carbonate grains grading in size from 0.04 mm to 1 mm (McGee and Gutschick, 1969). Cryptocrystalline is restricted to modal crystal sizes of less than 4 microns by McGee and Gutschick (1969, p. 103). The peloids in the matrix of this debris bed are the same size and shape as the echinoderm skeletal sand. Indeed many of the skeletal allochems have undergone almost complete alteration to microcrystalline calcite except for a small portion of original unaltered skeletal material in the interior of each grain. The close resemblance of the peloids with skeletal grains that are almost completely altered to microcrystalline calcite suggests that many of the peloids are in fact completely altered skeletal grains. Hopkins (1972) makes a similar conclusion with respect to some of the peloids of the foreslope sediments at the Miette and Ancient Wall carbonate complexes.

Products of late subsurface diagenesis

Pyrite

Pyrite is a common material in the debris beds at Wapiabi Gap. In the second debris deposit it has replaced 90% (visual estimate) of the sand-sized skeletal fragments of the matrix. It also forms a peripheral replacement rim around the majority of allochthonous clasts and subsequently has destroyed any microcrystalline calcite envelopes or bladed fringing calcite cement that may have developed around the clast margins. Not all texture, however, is obliterated by pyritization of these rocks. In one clast which is almost entirely pyrite, primary structure is preserved. Upon closer examination using reflected light, fine laminations (stromatolite?) were observed. Pyrite also appears as fine veinlets in the micrite portions of the matrix.

In the lowermost debris interval pyrite is much less abundant but has identical petrographic relationships as those in the overlying bed. It replaces approximately 5 - 10% of the sand-sized skeletal grains. Intrabiotic pores such as those in Thamnopora contain pyrite which has replaced some of the geopetal pelleted mud.

Pyrite in the upper allochthonous debris sheets is again much less abundant than in the second debris deposit. It replaces 10 - 15%

of the echinoderm sand allochems. Many of the skeletal fragments are only partially replaced by pyrite (Plate 9a, b). It preferentially has replaced the peripheral margins of many echinoderm fragments and forms a pyrite rim around the grain boundaries. It also occupies the central civity of some crinoid stem columnals and has replaced what was probably intrabiotic carbonate mud. Euhedral cubic crystals of pyrite have replaced a minor amount of microcrystalline calcite in the more micritic basal portions of the debris sheets.

No cements or dolomite appear to be replaced by pyrite and because of this it is impossible to infer a relative time of emplacement. However, pyrite is formed under reducing conditions and it seems reasonable to suggest that it may have replaced the sand-sized allochems and other microfabrics in the late mesogenetic environment (Choquette and Pray, 1970).

Hallam (1969) studied a pyritized limestone hardground in the Lower Jurassic of Dorset (England) and suggested that the limestones were subjected to submarine diagenesis early in their history, and at a later date in the mesogenetic environment were partially replaced by pyrite. The writer concurs with the concept of partial pyritization of the allochems during the mesogenetic stage of diagenesis.

Silica

Detrital quartz, euhedral authigenic quartz crystals and amorphous silica are the three forms of silica which occur in the debris deposits. Detrital quartz is very minor in amount and occurs as faint laminations in some of the allochthonous lutite clasts in all of the debris deposits. Grains are subangular to rounded and are very fine grained. Detrital quartz grains are also apparent in the microcrystalline calcite of the lower portions of the debris sheet deposits. In these beds it is minor in amount and appears to be randomly scattered throughout the basal portions.

Authigenic quartz crystals and amorphous silica are similar in that they form replacement products. Authigenic quartz forms very minute euhedral prismatic crystals. These are most noticeable in the microcrystalline calcite fabric of the debris sheets and in the peloids of the lower debris intervals. Prismatic quartz crystals are concentrated around the peripheral margins of some peloids but also extend into the interstitial spaces where they appear to have replaced some of the cement. Authigenic quartz crystals also replace ferroan calcite cement in the debris sheets (Plate 9c).

Approximately 5% of the skeletetal grains in all of the debris beds have been partially replaced by amorphous silica. Complete replacement by silica is rare. Echinoderm and Thamnopora fragments appear to be the only fossil type affected by amorphous silica replacement. The replacement product has higher relief in etched thin sections than the surrounding calcite and appears as irregular blotches on the various altered grains (Plate 9b). However, in some cases, the authigenic silica that has partially replaced Thamnopora fragments has a more euhedral habit.

Amorphous silica is also present as very minute veinlets in the second generation blocky mosaic cements. An intricate network of amorphous silica veinlets occurs between individual cement crystals. The silica has either replaced the margins of cement crystals to form what appear to be veinlets or has precipitated from solution along very minute pore spaces between calcite cement crystals.

The replacement of grains and cements by authigenic silica is assumed by the author to be a late mesogenetic process. The presence of large chert nodules and irregular beds of chert in the upper part of the Mount Hawk Formation suggests that the silica has a secondary diagenetic origin.

Dolomite

The next most abundant mineral besides calcite is ferroan dolomite. This mineral constitutes approximately 30% (visual estimate from stained slabs) of the rock volume in the lower two debris intervals. Dolomite preferentially has replaced much of the matrix in these two debris beds. In the lowermost debris deposit the second and third generation cements are generally dolomitized leaving an unaltered skeletal framework. Usually the bladed fringing cement on the skeletal grains and echinoderm rim cement are unaltered (Plate 9d). In some cases stringers of dolomite also cut across otherwise unaltered fossil fragments. These stringers are narrow and straight and suggest that the dolomitization progressed from the cements into small fractures in the grains. Ferroan dolomite fills some of the intrabiotic pore spaces in Thamnopora.

From the petrographic evidence it appears that the cements were most easily dolomitized and grains of the matrix were replaced upon more extensive dolomitization.

In the upper debris sheets dolomite has replaced the ferroan calcite cement to some degree (Plate 9f). Some interstices not filled with ferroan cement are occluded by ferroan dolomite. The dolomite probably has replaced the original interstitial material (carbonate mud or calcite cement). Small dolomite rhombs are evident in some of the interstitial micrite (Plate 9c). In other cases the micrite has been more extensively dolomitized. The individual scattered dolomite rhombs probably represent the initial stages of replacement. Folk (1965) illustrates similar textures. Dolomitization of the debris sheets is much less extensive than in the lowermost debris beds.

Grains which have been partially to almost completely replaced by authigenic silica appear to be replaced in turn by ferroan dolomite. In this way dolomite seems to have preferentially replaced grains rather than cements. However, the writer infers that from the petrographic evidence, the amorphous silica which has replaced grains, has itself been subsequently replaced by dolomite (Plate 10a, b). What appears to be almost complete dolomite replacement of the silica has taken place in the second debris deposit. The very minute euhedral authigenic quartz crystals also show what appears to be partial alteration to dolomite. Dolomitization of the amorphous silica which has replaced portions of echinoderm skeletal grains in the upper debris sheets is apparent as well.

The petrographic evidence given above suggests that ferroan dolomitization is the last diagenetic event besides neomorphism which has affected the debris deposits at Wapiabi Gap. The writer concludes that this process took place in a late mesogenetic environment.

Late neomorphic fabrics

A relatively small percentage of the matrix (about 5%) in the lowermost debris bed, consists of regularly-shaped, equant calcite crystals with smooth planar boundaries which resemble Folk's (1965) pseudospar. The crystal size ranges from 30 to 60 microns in diameter. Crystals are either uniform in size within a certain area or increase in size gradationally over small areas. Micrite is also apparent in minor amounts particularly in intrabiotic pore spaces where it has a pelleted form and acts as a geopetal mud, or completely fills the pores. The presence of micrite in this debris bed suggests that the pseudospar may be a neomorphic product of what was originally carbonate mud.

An interesting feature which was revealed by potassium ferricyanide stain, are "ghosts" of organic structures in the neomorphic pseudospar. These structures, which are blue in colour, are generally round or oval-shaped and exhibit organic-like textures (Plate 10c, d). The "ghosts" appear to cut across crystal boundaries of the pseudospar. The writer suggests that these may be recrystallized skeletal fragments that were originally embedded in carbonate mud that subsequently underwent neomorphism.

CHAPTER 4

CEMENTATION HISTORY

Early lithification

In the debris deposits at Wapiabi Gap there is reasonably strong evidence to suggest that some process of early cementation was taking place shortly after deposition of the allochthonous material. This early carbonate cementation is manifest in the cemented calcarenite clasts within the second debris interval previously described.

The earliest cements in the calcarenite clasts are echinoderm rim and bladed fringing cement. As already noted the petrographic relationships strongly suggest that these two cements formed simultaneously. The earliest cements in the lowermost debris bed are identical and have the same petrographic characteristics. Furthermore, the constituent components of the allochthonous clasts are essentially the same as those which comprise the lowermost debris bed. The relative abundance of each component is the same for both clasts and the lower debris deposit as well. It seems reasonable to conclude that the allochthonous calcarenite clasts of the second debris bed were derived from the already lithified underlying debris deposit. Due to the very nature of a calcarenite clast itself, the writer infers that it must have been a lithified entity. The lithification in this case may be the result of early carbonate cementation (early bladed fringing and echinoderm rim cements). Lithification as a result of compaction of interstitial carbonate mud is unlikely, because of the small percentage of this component (less than 5 percent) in the lowermost debris bed.

Thus it appears clear that the lowermost debris intervals underwent cementation in an eogenetic environment (Choquette and Pray, 1970). It remains to be determined whether or not cementation occurred in an early subaerial or early submarine diagenetic environment.

Previous work on submarine cementation

Early submarine cementation is a process that is known to take place in some modern day carbonate environments (Shinn 1969). It is a phenomenon that is increasingly being recognized in the Recent carbonate environments of the tropical latitudes. Shinn (1969), and Taylor and Illing (1969) have documented submarine cemented hard layers of sand in the subtidal and intertidal regions of the Qatar Penninsula in the Persian Gulf. Partial to complete void-filling submarine cements have been observed in Jamaican reefs by Land (1971) and in the boiler reefs off Bermuda by Ginsburg et al. (1971).

These are only a few cases that have been reported concerning early submarine cementation that is presently taking place. All the known occurrences have similar cements. Submarine cements are high Mg-calcite or aragonite and form fibrous or acicular fringes around grains or in voids. Micritic cements composed of high Mg-calcite or aragonite have also been documented in submarine environments. The bladed fringing cement that is present around grains in the debris deposits of the present study area are some what similar to the modern day examples of submarine cements except that the ancient examples have a slightly coarser grained texture (bladed and not fibrous), and are composed of low Mg-calcite. It is probable that if submarine cementation is going on today it may have been a diagenetic process taking place in the past. Two examples of inferred submarine cementation of ancient limestones are the studies by Purser (1969) and Hopkins (1972). The Middle Jurassic subtidal sediments of the Paris Basin documented by Purser (1969) contain "hard grounds" similar to those of the Persian Gulf region. The cements and the grains they bind were cut by Jurassic boring organisms and are clearly synsedimentary in origin. The sediments overlying each bored surface are open marine types and not transgressive ones. These features strongly suggest early submarine cementation has occurred. The cements described in this case resemble the cements which bind the lowermost debris deposits and the clasts in the second debris deposit at Wapiabi Gap. The short, closely packed calcite druse described by Purser (1969) is similar to the bladed fringing cement of this study.

Hopkins (1972) implies that the foreslope sediments at Ancient Wall and Miette were cemented into discontinuous and nodular layers in the marine environment by processes that are similar to those operating today in the subtidal sands of the Qatar Penninsula described by Taylor and Illing (1969). The bladed and echinoderm rim cements described by Hopkins (1972) are identical to the early cements lithifying the debris beds of the present study area.

Evidence for early submarine diagenesis

General statement

Caution must be used in relating various microfabrics resulting from Recent submarine diagenetic processes with those in limestones having unknown diagenetic histories. It is clear, despite the growing knowledge on submarine cementation that has developed in recent years, that it is still not possible on the basis of morphology alone to differentiate between fresh water cements and those originating in the submarine environment. It is even more difficult to recognize submarine cemented limestones in the geologic column, as the original mineralogy of the cements has changed to low Mg-calcite, and cement morphologies have probably, in many cases, been altered as well.

The author infers that during early Mount Hawk time, at the margin of the Southesk-Cairn carbonate complex in the present study area, some type of sediment gravity flow moved down the foreslope region of the complex and was subsequently lithified in the subtidal environment beyond the carbonate buildup. The lowermost debris bed is the result of this type of flow. The cements which formed at this time and are still present today are bladed fringing and echinoderm rim cement. A second mass flow (i.e. the second debris bed) followed at some later date and in moving down the foreslope of the carbonate complex eroded and subsequently incorporated material from the first sediment mass flow (i.e. the cemented calcarenite clasts). The process of submarine cementation is inferred to have continued after the material of the second gravity flow was deposited, as bladed fringing cement and echinoderm rim cement have nucleated on the various allochthonous clasts of the second debris interval. At some later date second generation blocky mosaic and third generation ferroan calcite cements were precipitated respectively in void spaces of both debris intervals not already occupied by the early submarine cements.

Early submarine diagenesis

As mentioned above the first generation cement morphologies are similar to modern day submarine cements as well as some ancient examples of probable submarine origin. Hopkins (1972) concludes that submarine eogenetic diagenesis took place in his study area during the early Mount Hawk time of the Upper Devonian. At Wapiabi Gap early submarine cementation is believed to have formed the first generation of cements and it is important to note that diagenesis occurred during the same time interval (i.e. early Mount Hawk time) as that proposed by Hopkins (1972).

The cemented calcarenite clasts of the second debris deposit exhibit what appear to be microcrystalline alteration envelopes around their peripheral margins. By analogy with the micrite envelopes found on recent carbonate sand grains (Bathurst, 1966), it is assumed that the microcrystalline calcite envelopes around the ancient examples were produced by endolithic algae or some unknown boring organism in the marine environment. If one were to suppose that the early cements in the debris deposits were formed subaerially this would then mean a lowering of the relative sea level to produce the subaerial exposure necessary to account for the cements in the lowermost debris bed. Subsequently, the second debris deposit was initiated and moved downslope. To account for the microcrystalline envelopes surrounding the peripheral margins of the cemented calcarenite clasts in this debris deposit a relative rise in sea level must take place to submerge the deposit in the marine environment once again. This change in relative sea level would in turn be followed by another lowering of the sea level in order to account for the first generation subaerial cements which have nucleated on and around the allochthonous clasts of the second debris bed.

It is the writer's opinion that the microcrystalline calcite envelopes around grains and clasts resembling modern micritic alteration envelopes, followed by the first generation of cements, can be explained much more easily by invoking early submarine diagenesis for both with a static sea level, instead of suggesting four sea level fluctuations. Furthermore, a stable Devonian sea in the Alberta basin has previously been inferred by Mountjoy (1965) during early Peechee time.

The two lowermost debris intervals are overlain by deeper water sediments. Caution must be used here, as the debris deposits are immediately overlain by a covered interval of shaly talus and the actual rock outcrop is obscured. However, the talus cover is composed of shale and lime mudstone rock fragments only, and it appears that no other type of rock lithology immediately overlies the debris deposits, except these deeper water sediments. If the cements in these deposits were formed during emergence from the sea, it is reasonable to expect that some sort of transgressive sequence of carbonates would have developed over the debris intervals as the sea level began to rise once again. This is not the case at Wapiabi Gap as the debris deposits appear to be immediately overlain by deeper water calcareous shales and interbedded lime mudstones. It is more reasonable to suggest that the allochthonous material was transported into a deeper water environment initially and subsequently deeper water sediments began to accumulate on top of them. Submarine diagenetic processes were acting upon the deposits during this time.

The author concludes that although no single line of evidence which has been discussed above, is in itself positive criteria for establishing a submarine cementation model, taken together a reasonably strong argument can be presented in its favour.

Late mesogenetic cementation

Second generation cement

Blocky mosaic cement fills most of the remaining pore space and overlies the first generation submarine cements in the lowermost debris deposits. Its morphology is distinctly different than that of the early cements and coupled with its overlying relationship with those cements it can be inferred that it is a result of a later period of cementation. It is found in all of the debris deposits including the debris sheets further up in the lower Mount Hawk succession. Its later petrographic relationships as well as its occurrence in all debris deposits throughout the sequence suggest that the cement formed in the mesogenetic environment.

Third generation cement

Ferroan calcite cement occludes any remaining pore space not already filled with the earlier cements. It overlies first and second generation cements and is distinctly different from these in chemistry. It is clearly the result of a final period of cementation that had a very complex chemical history. The ferroan and non-ferroan zoning in some calcite cement crystals show this growth history quite well.

The ferrous iron content of the calcite indicate that during growth of the cement it was periodically subjected to reducing conditions. The mesogenetic environment in which solutions containing

Fe^{2+} and saturated with respect to $CaCO_3$ could provide the reducing conditions necessary and would account for the petrographic features already mentioned. Ferroan calcite cement in ancient rocks is invariably a late cement, post dating formation of early cements. To the writer's knowledge Colley and Davies' (1969) study on Recent-Pleistocene carbonates of the New Hebrides is the only example of early ferroan cements reported in the literature, and in this case the carbonates are associated with volcanic ash rich in ferromagnesium minerals, a rather unique situation. It is therefore concluded that the ferroan calcite cement in the debris deposits at Wapiabi Gap are a late mesogenetic phenomenon.

The iron in the calcite may have originated from two sources. Pyrite and chlorite are iron bearing minerals that are both found in the shales of the basinal sediments in the present study area. Chlorite is present as determined by x-ray diffraction analyses. However pyrite is abundant, especially in the debris deposits themselves. The time of emplacement of the pyrite is not known as it replaces essentially only the allochems, and no relative time emplacement relationships can be observed. It may have indeed been earlier than the ferroan calcite cement and therefore provided a derivation source for the iron.

Comparisons to other studies can be made. Oldershaw and Scoffin (1967) concluded that late ferroan calcite cements were found only in those limestones which are closely associated with clayey sediments. They suggested that the iron was derived from the clay minerals during later diagenesis. Similarly, Hopkins (1972) found that ferroan calcite cements occur in limestones associated with chlorite bearing shales of the Mount Hawk and are absent in limestones associated with chlorite free shales of the Perdrix Formation.

The association of iron-bearing carbonate with argillaceous sediments can also be seen in the dolomites at Wapiabi Gap. The dolomites of the debris deposits which are closely associated with the Mount Hawk shales are an iron-bearing variety. However, the dolomites of the carbonate complex are iron-free. This suggests that the iron is in some way related to and perhaps derived from the Mount Hawk argillaceous sediments.

CHAPTER 5

ORIGIN OF DEBRIS

Introduction

A large body of knowledge concerning the paleoecology of Devonian carbonate complexes of Alberta has been accumulated in the past 15 years through studies done on the three Rocky Mountain outcrops of Upper Devonian age, (eg. Mountjoy, 1965; MacKenzie, 1969) as well as subsurface Leduc complexes of equivalent age, (eg. Klovan, 1964) and the somewhat older Middle and Upper Devonian Swan Hills complexes (eg. Fischbuch, 1968). It has been firmly established that these ancient carbonate buildups are similar to modern day reef complexes in that the various organisms which contribute to their formation are numerous and variable, and that certain species occupy specific ecological positions or niches within the reef structure. Some of the work done on paleoecology is summarized in Figures 6 and 7.

Stratigraphic relationships between buildup and basin

In the present study area the debris beds near the base of the Mount Hawk Formation cannot be directly correlated with the carbonate buildup strata as the critical portion of the carbonate-shale transition is entirely missing. Similar correlation problems exist in the other carbonate complexes of the Front Ranges. However, by visual extrapolation of the lower portion of the Mount Hawk sequence at Wapiabi Gap it is apparent that the lower portion of the Peechee Member of the Southesk Formation comprising the carbonate complex is the equivalent stratigraphic succession. Whether or not the basinal sequence of the lower part of the Mount Hawk, which contains the debris beds, was deposited at the same time as or shortly after Peechee carbonate buildup deposition is not known.

One of the few localities where direct relationships between buildup and basinal sediments can be observed occurs at the Ancient Wall carbonate complex (Mountjoy, 1967). The foreslope sequence at the base of the Mount Hawk Formation at this locality can be traced beneath marginal upper Peechee bioherms. Hopkins (1972) suggests that accumulation and lateral spreading of buildup sediments may have caused instability of these marginal bioherms and portions of the buildup margin were subsequently displaced to produce the megabreccias near the base of the Mount Hawk Formation. These have been described by Cook et al. (1972). Similarly, Hopkins (1972) suggests that the base of the lower Mount Hawk is stratigraphically equivalent to buildup sediments immediately above the lower Peechee marginal bioherms of the Miette carbonate complex.

The writer suggests that similar stratigraphic relationships exist in this study area and that the debris material near the base of the Mount Hawk Formation at Wapiabi Gap was derived from the Peechee Member of the Southesk Formation.

Origin of debris

In discussing the origin of debris from the Peechee Member of the lower Southesk Formation one assumption is made: the marginal carbonate buildup at Wapiabi Gap consisted of a stromatoporoid biohermal or biostromal growth during early Peechee time. This assumption is considered for two reasons.

1) Marginal bioherms are evident in the lower portion of the Peechee at the Miette carbonate complex (Hopkins, 1972). Marginal bioherms also exist throughout a considerable protion of the Peechee Member at the Ancient Wall complex (Mountjoy, 1967).

2) Large hemispherical vugs, some of which contain calcite laminations on the void walls, are abundant in the dolomitized sequence of the carbonate complex at Wapiabi Gap (Plate 2a, b, c) (Figure 5). The vugs strongly suggest that stromatoporoids did exist in a relatively abundant quantity and did contribute to "reef" growth, but subsequently have been leached away.

It is quite possible that in the present study area the debris material was derived from the lower portion of the Peechee Member in the present study area. If this is the case it becomes advantageous to refer to a typical late Middle, or early Upper Devonian reef model with its various biofacies to enable a more precise interpretation to be made concerning the place of origin.

On the other hand, it is just as feasible to suggest that the allochthonous material was derived from the sediments above the lower Peechee bioherms at Wapiabi Gap. These sediments, although completely altered to dolomite at present were possibly carbonate sands which formed a shallow water bank deposit. According to MacKenzie (1969) the Peechee Member of the Southesk-Cairn complex is a carbonate bank deposit consisting of essentially sand-sized material that formed during a stable phase of the Devonian sea. Similarly, the upper portion of the Peechee at the Miette carbonate complex lacks the marginal bioherms of the lower Peechee and instead consists of laminated, sand-sized carbonate sediments containing fenestral porosity (Hopkins, 1972).

Both models for the derivation source of the debris may have been possible, as the true stratigraphic relationships are missing, and consequently both cases will be discussed.

Reef model

Studies on Devonian reefs, especially those in the Alberta subsurface, have resulted in the establishment of certain paleoecological zonations which are typical of the various regimes that constitute a generalized reef model. The reef model is shown at the top of Figures 6 and 7 with the various organisms that occupy certain ecological niches within the reef at the side of the page. Work done by some of the authors which have contributed to Devonian reef knowledge in Alberta and elsewhere is summarized.

It can be clearly seen from Figures 6 and 7 that the organisms of the debris beds in the present study area could have originated in the forereef and basinal regimes of the reef model. To reiterate, these organisms are Thamnopora (a tabulate coral), echinoderms, inarticulate and articulate brachiopods, and bryozoans.

It is important to note the absence of any stromatoporoids in the allochthonous debris material. Figure 7 illustrates the organic reef position that these organisms occupied during reef development. This observation strengthens the argument for a forereef derivation rather than an organic reef source. Likewise, the absence of Amphipora

Figure 6

Summary of paleoecological positions

of reef organisms in a

Devonian reef model

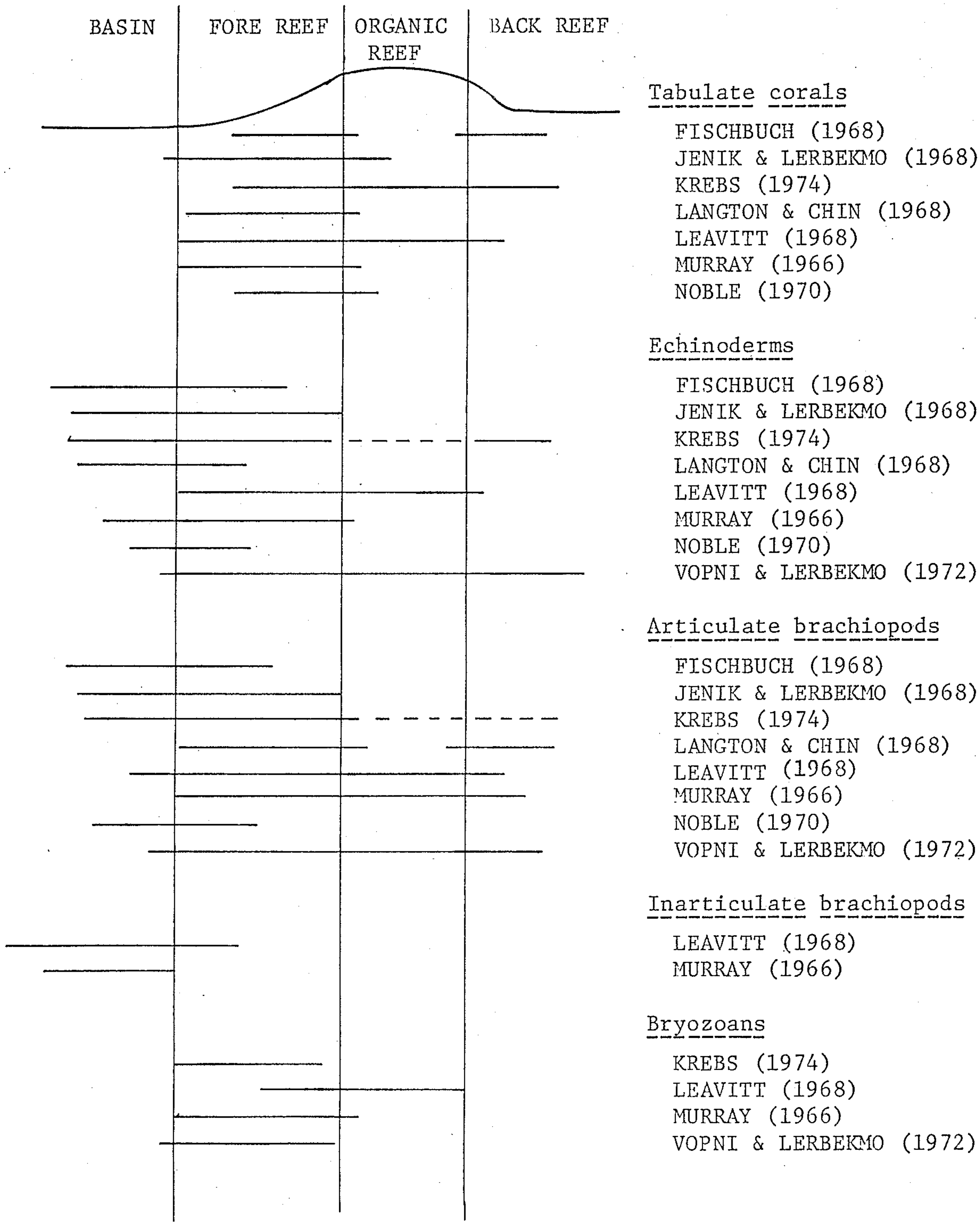
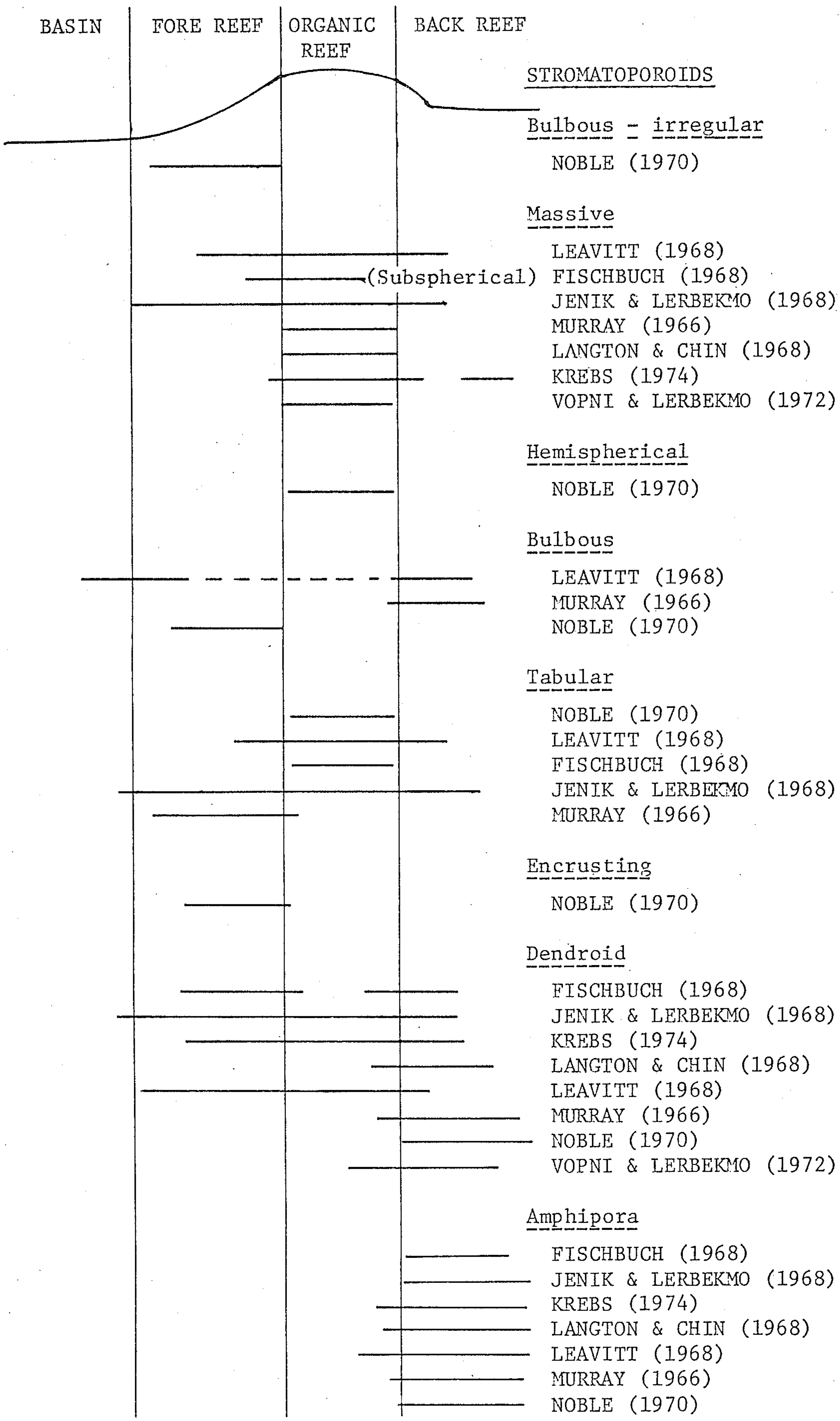

BASIN
FORE REEF
ORGANIC REEF
BACK REEF
Tabulate corals
FISCHBUCH (1968)
JENIK & LERBEKMO (1968)
KREBS (1974)
LANGTON & CHIN (1968)
LEAVITT (1968)
MURRAY (1966)
NOBLE (1970)
Echinoderms
FISCHBUCH (1968)
JENIK & LERBEKMO (1968)
KREBS (1974)
LANGTON & CHIN (1968)
LEAVITT (1968)
MURRAY (1966)
NOBLE (1970)
VOPNI & LERBEKMO (1972)
Articulate brachiopods
FISCHBUCH (1968)
JENIK & LERBEKMO (1968)
KREBS (1974)
LANGTON & CHIN (1968)
LEAVITT (1968)
MURRAY (1966)
NOBLE (1970)
VOPNI & LERBEKMO (1972)
Inarticulate brachiopods
LEAVITT (1968)
MURRAY (1966)
Bryozoans
KREBS (1974)
LEAVITT (1968)
MURRAY (1966)
VOPNI & LERBEKMO (1972)

Figure 7

Summary of paleoecological positions

of stromatoporoids in a

Devonian reef model


BASIN
FORE REEF
ORGANIC REEF
BACK REEF
STROMATOPOROIDS
Bulbous - irregular
NOBLE (1970)
Massive
LEAVITT (1968)
(Subspherical) FISCHBUCH (1968)
JENIK & LERBEKMO (1968)
MURRAY (1966)
LANGTON & CHIN (1968)
KREBS (1974)
VOPNI & LERBEKMO (1972)
Hemispherical
NOBLE (1970)
Bulbous
LEAVITT (1968)
MURRAY (1966)
NOBLE (1970)
Tabular
NOBLE (1970)
LEAVITT (1968)
FISCHBUCH (1968)
JENIK & LERBEKMO (1968)
MURRAY (1966)
Encrusting
NOBLE (1970)
Dendroid
FISCHBUCH (1968)
JENIK & LERBEKMO (1968)
KREBS (1974)
LANGTON & CHIN (1968)
LEAVITT (1968)
MURRAY (1966)
NOBLE (1970)
VOPNI & LERBEKMO (1972)
Amphipora
FISCHBUCH (1968)
JENIK & LERBEKMO (1968)
KREBS (1974)
LANGTON & CHIN (1968)
LEAVITT (1968)
MURRAY (1966)
NOBLE (1970)

negates the back reef environment as a possible source of debris material.

Furthermore, as mentioned previously, about 60% of the allochthonous clasts in the second debris deposit are composed of carbonate mud. The writer suggests that these were derived from thin limestone units interbedded in deeper water shales similar to that which can be observed in the basinal or nearslope sequences at the present time. One can make the assumption that similar lithologies existed in the foreslope regime during early Mount Hawk time, but today this portion of the reef model is entirely missing. Argillaceous sediments with interbedded thin carbonate mud units do, however, occur in the foreslope sequences at the Miette and Ancient Wall carbonate complexes (Hopkins, 1972).

The writer infers that as the sediment mass flow moved down the forereef slope under the action of gravity, carbonate mud material from deeper positions on the forereef slope or foreslope were incorporated into the moving flow.

Carbonate bank model

Another possible origin for the allochthonous debris is the finer grained carbonate sediments from the middle Peechee Member of the Southesk Formation. Hopkins (1972) infers that the carbonate sediments above the lower Peechee bioherms at the Miette complex represent deposits in a lagoonal environment. Similarly, according to Mackenzie (1969), shallow water conditions prevailed in his study area during this period of the Devonian, resulting in a thick carbonate sand bank being deposited which constitutes the Peechee Member of the Southesk-Cairn carbonate complex.

In light of the above discussion the writer suggests that the massive dolomites that constitute most of the stratigraphic section of the buildup margin at Wapiabi Gap represent a carbonate sand bank deposit. The writer also suggests that sand-sized sediments from the bank margins adjacent to the basin were probably more readily shed into the deeper water environment than carbonate sediments from the interior of the bank deposit.

Extensive dolomitization has destroyed all primary depositional textures in the buildup margin. If it is actually the case that the lowermost debris beds are composed of material shed from a carbonate bank, then insights into the types of organisms that contributed to bank development can be made as the debris deposits still retain much of their primary textures and components. The organisms which comprise the lowermost debris beds are Thamnopora, and other colonial corals, echinoderms, brachiopods and bryozoans. These organisms were probably instrumental in bank development.

The carbonate mud clasts may have been derived from deeper water sediments similar to those described in the Devonian reef model.

Origin of upper debris sheets

The allochthonous debris sheets that are found higher in the Mount Hawk sequence may have been derived from a skeletal sand biofacies on the flanks of a typical Devonian reef. Most reefs in the Alberta subsurface contain a partially to well developed skeletal margin facies (eg. Klovan, 1964; Leavitt, 1968). Similarly, coral reefs of today (eg. Jamaica) have skeletal sand deposits which have developed on their foreslope regimes (Land and Goreau, 1974).

However, it is more likely that the debris sheets in the Mount Hawk sequence at Wapiabi Gap were derived from a carbonate bank. Two lines of evidence suggest that this is the case.

1) As mentioned previously the finer grained dolomites above what appear to be the lower Peechee bioherms in the present study area, in light of MacKenzie (1969), were possibly carbonate sands which formed a bank deposit.

2) Although the stratigraphic relationships are missing between basin and buildup in the study area, the inferred relationship is that the middle of the lower part of the Mount Hawk which contains the debris sheets is stratigraphically equivalent to the bank and shelf margin sands of the upper Peechee. This inference is justified because it is apparent upon visual extrapolation of this portion of the Mount Hawk sequence, that the stratigraphically equivalent buildup strata is the upper Peechee Member. Furthermore, according to Hopkins (1972), the inferred stratigraphic relationships between basin and buildup at Miette are exactly the same as suggested here.

The origin of the irregular and lenticular-shaped carbonate mud clasts in the debris sheets is similar to the origin of the mud clasts in the lower debris intervals. However, depositional textures which are particularly well developed in the third, fifth and sixth debris sheets enable a more elaborate interpretation to be made concerning the origin of the mud clasts. In these debris sheets the basal and upper portions are easily identifiable because of their differences in composition. Along the contact between the basal and upper portions are irregularly-shaped load and cast structures. Portions of the basal carbonate mud extend upwards in an irregular fashion, and into the upper part of the debris sheet. Other mud structures show complete separation from the basal portion and are actually discrete irregularly-shaped lutite clasts. Still other clasts are lenticular in shape with smooth surfaces suggesting that they have undergone some abrasion during transport.

In a similar fashion the upper portion of the debris sheets extends downwards in the form of small irregular lobes of packestone and grainstone composition into the basal carbonate mud portion. These textural features suggest that both the upper and lower parts of the debris sheets although different in composition had similar viscosities, probably low. The textures certainly suggest that the lower carbonate mud portion was not lithified before the upper portion of essentially echinoderm fragments was deposited. However, the lenticular-shaped mud clasts which the writer suggests have been eroded from the bottom portion of the debris sheets must have had a certain amount of consistency to them as they were being transported.

The writer suggests that shortly after carbonate mud was deposited in the foreslope or deeper portions of the forereef regime, a sediment gravity flow consisting of echinoderm skeletal debris was initiated, perhaps higher on the forereef slope, and subsequently moved downslope. Portions of the already deposited but unlithified foreslope carbonate mud were eroded and incorporated into the flow as irregular and lenticular mud clasts. This phenomenon took place five times during the deposition of the lower portion of the Mount Hawk Formation which resulted in the production of the five upper allochthonous carbonate debris sheets. Due to the frequency at which this process has been inferred to have taken place, the writer suggests that this phenomenon is a natural process in normal Devonian carbonate buildup evolution and consequently does not need to be explained by imposing unusual catastrophic events such as earthquakes or subaerial exposure to account for them. Cook et al. (1972) suggests that these initiating mechanisms may have been involved in the genesis of the allochthonous debris in the foreslope sequences at Miette and Ancient Wall.

CHAPTER 6

INITIATION AND MODE OF TRANSPORT

Detachment and initiation of mass movement

One question that is immediate in discussing allochthonous carbonate debris is: how was this material brought from its original depositional site to the basin. The processes which caused carbonate buildup material to become detached and move downslope under the action of gravity are only speculative. In this study area the critical portion of the carbonate to shale transition is missing and direct relationships between buildup margin and basin cannot be made. Furthermore, studies on foreslope talus of modern carbonate environments are few, (Land, 1973; Moore, 1973) and the processes which give rise to forereef debris are poorly understood. However, Cook et al. (1972) and Mountjoy et al. (1972) have suggested a number of causal mechanisms for carbonate material detachment and initiation of downslope movement in certain ancient deposits.

Although the causal mechanisms of detachment and initiation are not known, it is obvious that gravity played an important role in debris initiation, transport, and deposition. The original slope angle of the buildup margin upon which this force acted cannot be determined because the original buildup margin slope and foreslope sequence has been eroded away. However, slope angles have been inferred at other localities that have better rock exposure and that have retained more of their foreslope sediments than at Wapiabi Gap. Mountjoy et al. (1972) determined the maximum slope of the buildup margin at the most proximal part of the upper megabreccia debris sheet at southeast Mount Haultain of the Ancient Wall complex to be about 10 degrees for its upper surface over a slope distance of 100 meters. Cook et al. (1972) notes that basinward much gentler slopes occur and most bank-margin and adjacent basin strata probably accumulated on much lower slopes.

The writer can only suggest that debris movement may have occurred over similar slope angles of the buildup margin in the present study area.

Several mechanisms suggested by Cook et al. (1972) which would probably initiate detachment and mass movement are: 1) faulting of the carbonate buildup and adjacent strata, 2) storm and/or wave erosion, 3) catastrophic events such as earthquakes and tsunamis, 4) gravitational instability caused by depositional or diagenetic factors, and 5) subaerial exposure and subsequent erosion of the buildup.

Faulting cannot be ruled out as a causal mechanism for debris detachment and initiation although there is no evidence of any faults present at the buildup margin in the present study area. Again the critical portion of the transition is needed to accommodate a more precise interpretation. However, according to Cook et al. (1972) faulting was not observed in the Miette and Ancient Wall carbonate complexes except in the younger Devonian sequences.

Storm and/or wave erosion may have been responsible for the initiation of mass movement. In modern day carbonate reefs both of these result in reef debris being broken from the reef tract and transported landward. Unfortunately little is known about the action of waves and storm activities in the modern carbonate environments in providing forereef talus and debris.

Earthquakes, which possibly may have been accompanied by tsunamis, would provide tremendous amounts of kinetic energy to a carbonate complex and provide a triggering mechanism for mass movement. It is conceivable that these catastrophic events could have occurred a number of times in the past to account for the seven debris intervals in the present study area. This initiating mechanism for detachment and movement of material from the buildup is favoured by Cook et al. (1972) and Mountjoy et al. (1972). According to Cook et al. (1972) page 473, "Sudden shocks or vibrations caused by earthquakes could have momentarily increased pore-fluid pressure to produce a buoying effect that would have fractured rigid material above an unstable substrate, and provided requisite initial dilation for mass movement."

Subaerial exposure of the upper portion of the buildup margin could conceivably make it gravitationally unstable. Transport of debris material downslope and into the lowered sea would be consistent with the inferred submarine diagenetic history. Furthermore, subaerial exposure as an initiating mechanism would explain the regional distribution of the debris deposits which occur near the boundary of the Mount Hawk and upper Perdrix strata in all three Mountain carbonate complexes as well as in the stratigraphically equivalent subsurface strata at the Windfall pinnacle reef complex. This was first suggested by Boyce (1974). On the other hand however, in the present study area, the allochthonous debris clasts lack vadose features (Dunham, 1969) such as dissolution channels and vugs, and diagenetic silt which might be expected in subaerially exposed carbonate material. Cook et al. (1972) and Mountjoy et al. (1972) (Miette and Ancient Wall) discount subaerial exposure on the basis of the same reasoning and the "lack of an unconformable surface at the base of the debris sheets . . . and the lack of the debris beds interfingering and/or being continuous with debris of an obvious subaerial erosional origin" (Cook et al. 1972, page 471).

Lastly, gravitational instability caused by depositional factors is the simplest geological explanation which may account for the observable features of these debris intervals. Accumulation of carbonate sediment in a relatively static sea with respect to the top of the buildup margin might eventually cause over-steepening of the margin and gravitational instability. Mass movement of material would be initiated at a point when a component of the gravitational stress exceeded the inclined shear resistance of the accumulated mass of carbonate sediment.

It is the writer's opinion that gravitational instability of a large accumulation of carbonate sediment, triggered by tremendous shocks produced by earthquakes, could have initiated mass movement and produced the allochthonous debris deposits near the base of the Mount Hawk Formation at Wapiabi Gap, as well as at the other mountain carbonate complexes, and the debris interval at Windfall.

Mode of transport

Submarine gravity movements have been divided into four gradational types (Dott, 1963): 1) submarine rock falls, 2) slides and slumps, 3) sediment mass flows, and 4) turbidity currents. The basis of the divisions are dependant upon the inferred movement behavior of the mass (elastic, plastic, or viscous fluid flow), the degree of sliding versus flowage, and the physical interaction between solids and fluids.

1) Submarine rock fall deposits are characteristically situated only a short distance from their original derivation source and have been transported over steep slope angles. The term simply implies rolling or freefall of individual clasts. Arguments against this type of deposit as a possibility with respect to the debris deposits of the present study area are: a) the debris deposits at Wapiabi Gap are relatively thin and sheet-like in nature and b) are laterally quite extensive, occurring at a distance of 1 kilometer from the carbonate complex margin and extend for a distance greater than 2 kilometers from the buildup.

2) The initial mass movement of debris may have begun as submarine slides and/or slumps. Mass flows do indeed originate as slides and slumps and convert to some type of sediment mass flow when break up of the initial fabric of the sediment occurs. Unfortunately the carbonate to shale transition immediately adjacent to the buildup has been eroded away and any evidence of fault planes or slumping has been erased. The portions of the lowermost debris deposits that are visible in outcrop show no evidence of such features such as faults, flow rolls, folded and twisted strata or disruption of underlying strata. However, this type

of sediment transport cannot be overruled.

3) Sediment mass flows or sediment gravity flows consist of sediment moving downslope under the action of gravity (Middleton and Hampton, 1973). Such flows are distinguished from fluid gravity flows by the relative importance of sediment and fluid in driving the flow. In a fluid gravity flow such as a stream or ocean current, the fluid is moved by gravity and drives the sediment along, but on the other hand, in a sediment gravity flow it is the sediment that is moved by gravity, and the sediment motion moves the interstitial fluid. Middleton and Hampton (1973) have classified mass flows into four categories according to the nature of the dominant sediment support mechanism. Turbidity flow, one of the divisions of Dott's (1963) classification, is included as one of the four types of sediment gravity flows in this more recent proposal.

The four main categories are: a) turbidity currents, in which the sediment is supported mainly by the upward component of fluid turbulence, b) fluidized sediment flow, in which the sediment is supported by the upward flow of fluid escaping from between the grains as the grains are settled out by gravity, c) grain flows, in which the sediment is supported by direct grain-to-grain interactions (collisions or close approaches), and d) debris flows, in which the larger grains are supported by a "matrix" of a mixture of interstitial fluid and fine sediment, which has a finite yield strength. The nature of the sediment support mechanisms which characterize each type of mass flow is summarized in Figure 8.

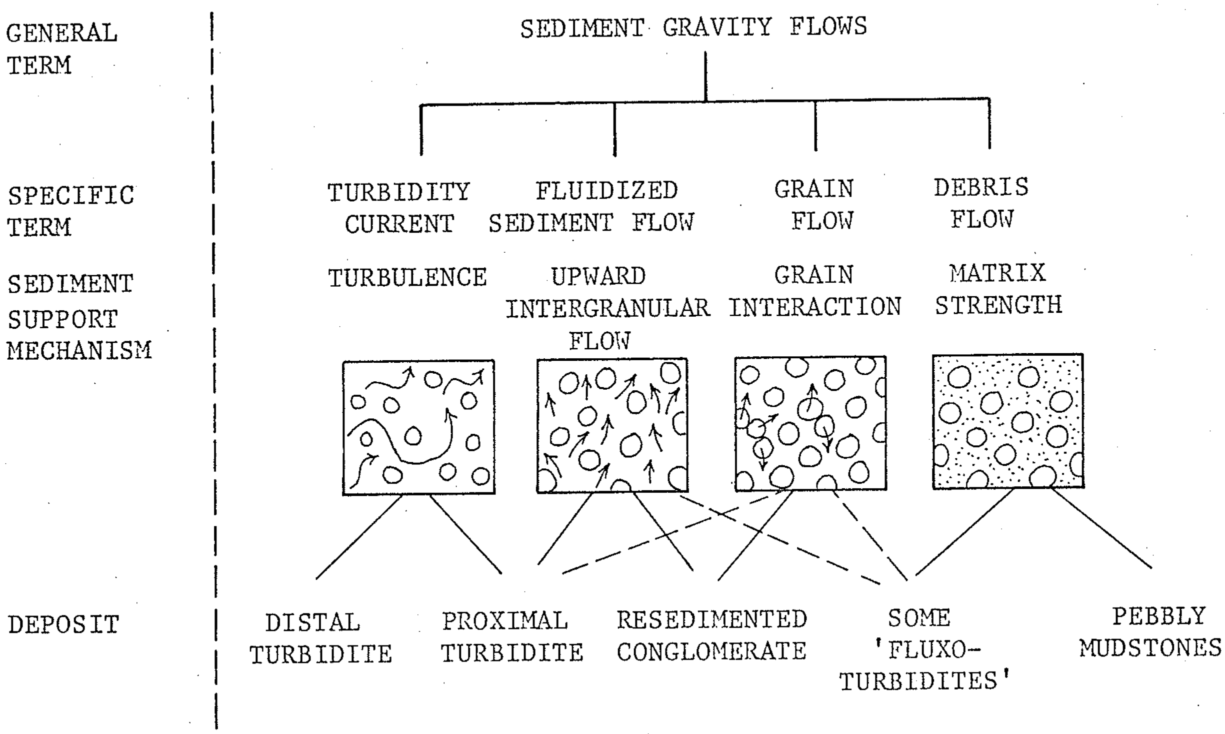
Middleton and Hampton (1973) note that this classification is a genetic one and that some of the mechanisms proposed are hypothetical.

Figure 8

Classification of sediment gravity flows

(after Middleton and Hampton, 1973)

CLASSIFICATION OF SUBAQUEOUS FLOW MECHANISMS



after Middleton and Hampton (1973)

Furthermore, they caution that in real sediment gravity flows more than one mechanism will be operating during the course of transportation and deposition. Other mechanisms such as traction may operate during the last stages of deposition and produce or modify some of the textures and structures in the sediment bed that is finally deposited from the flow. In the field it would be very difficult then to distinguish between deposits formed from the different types of flows.

Figure 9, taken from Middleton and Hampton (1973), illustrates what would be the characteristics of each of the hypothetical sediment gravity flows, in the unlikely case that only one sediment-support mechanism was to operate during deposition. The primary depositional structures and textures observable in the two lowermost debris deposits in the present study area are not well exposed on account of poor outcrop availability. However, several textures are apparent: a) although the contacts are covered, both deposits appear to be conformable with the sediments in which they occur, b) grain orientation parallel to flow, c) lateral grading of large sized debris clasts, d) a finer clacarenite top or "calcarenite cap" (Cook et al., 1972).

An interpretation as to the type of transport mechanism or flow is difficult when based on only a few depositional textures. Furthermore it is necessary to bear in mind the variable number of processes that may operate during transport and final deposition (eg. traction, saltation, support by turbulence, dispersive pressure). However, as can be seen in Figure 9, grain flow and turbidity flow have some of the features found in the two lowermost debris deposits at Wapiabi Gap. The parallel orientation of clasts to the flow direction and the flat upper contact are suggestive of a grain flow type of sediment gravity flow. The lateral

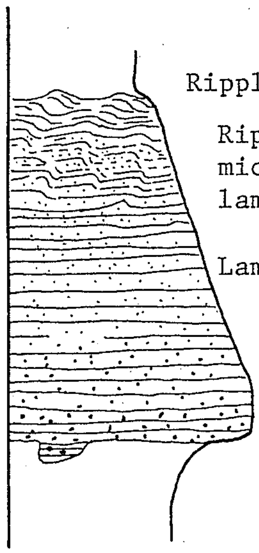
Figure 9

Sequence of structures in hypothetical

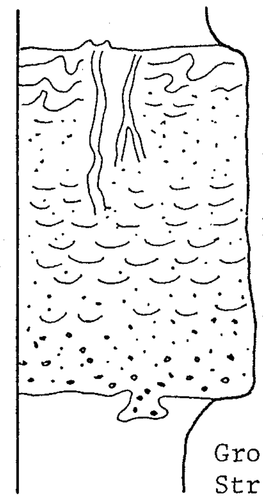
single - mechanism deposits

(after Middleton and Hampton, 1973)

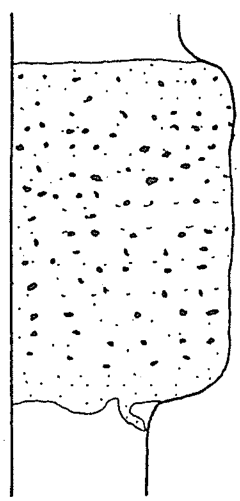
TURBIDITY CURRENT



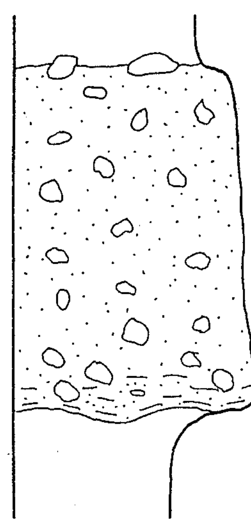
FLUIDIZED FLOW



GRAIN FLOW



DEBRIS FLOW



grading on the other hand is characteristic of turbidity currents. Sanders (1965) proposed that grain flows may be a companion to some turbidity currents. He suggested that mass flows consist of two parts: an upper turbidity current with grains supported by the upward component of turbulence, and a lower faster moving grain flow with grains supported by dispersive pressure. Middleton and Hampton (1973) note that at high energy conditions grain flows may become turbulent and that the turbulence would help support the grains, in addition to the support provided by dispersive pressure. Furthermore, they suggest that a continum may exist between grain flows and turbidity currents and some flows may be combinations of the two types.

Deposition from grain flows, according to Middleton and Hampton (1973, page 18) is by mass emplacement: "In contrast to traction current deposition, typical of rivers and ocean currents, in which grains are laid down particle by particle upon the non-moving bed, mass emplacement involves a sudden 'freezing' of the flow resulting in simultaneous deposition of a layer several grains thick". Similarly, turbidity currents may undergo rapid deposition for example in proximal regions due to decay of intense turbulence. Rapid deposition may also result from rapid flattening of the slope.

The calcarenite cap of finer carbonate sediment immediately above the two debris deposits of the present study area may be features resulting from a turbulent flow mechanism. Cook et al. (1972) proposes that the graded allodapic cap facies that occurs at the upper few centimeters of the two megabreccia debris sheets in the Mount Haultain area of the Ancient Wall carbonate complex were deposited gradually from turbulent suspensions. The calcarenite caps of the debris deposits at Wapiabi Gap are similar to the graded calcarenite facies described by Cook et al. (1972) in that they occur at the tops of the debris deposits and consist of finer grained material. However, the ones at Wapiabi Gap lack a graded texture.

Hopkins (1972) describes calcarenite caps on some breccia beds in the foreslope sediments at the Ancient Wall and Miette carbonate complexes. He suggests that the caps may represent deposition from turbulent or tractive (may vary from bed to bed), sediment-laden currents, which were initiated high on the foreslope or on the margin of the buildup. These currents over-rode the differentially cemented foreslope sediments, increased the shear pressure on the layers below, and resulted in grain flow of the mass. Alternatively, Hopkins (1972) suggests that bottom currents set in motion by the displacement of sediment by liquefaction or slumping, distributed the finer sediments as a thin and sometimes discontinous blanket over the breccia beds.

Genesis of upper allochthonous debris sheets

The five allochthonous carbonate debris sheets which occur higher in the lower portion of the Mount Hawk sequence at Wapiabi Gap have several primary depositional features. These are: a) irregular and lenticular-shaped lutite clasts, b) a carbonate sand upper portion which lacks a laminated fabric and a graded texture, and appears massive except for the contained lutite clasts, c) a basal portion of carbonate mud, and d) irregularly-shaped load and cast structures at the contact between the lower and upper portions of a debris sheet.

These deposits may be a result of phenomena similar to those described by Shepard and Dill (1966). These workers reported numerous occurrences of small-scale grain flows in the upper reaches of submarine canyons. They observed "rivers of sand" cascading down floors of canyons and remarked on the ability of these flows to erode bedrock of the canyons. In the modern carbonate environments such as Jamaica (Goreau and Land, 1974) sumbarine flows consisting of sand and cobble-sized reef detritus are transported down the forereef tract and foreslope regimes. The phenomena is proposed by the writer to have taken place periodically during the Upper Devonian in the present study area.

MacKenzie (1973) suggests grain flow and/or turbidity flow mechanisms of sediment transport were responsible for producing the Upper Devonian allochthonous echinoderm debris beds associated with the Ramparts Formation. Echinoderm sediment flows (grain flows or turbidity currents) similar to those suggested by MacKenzie (1973), initiated high on the foreslope or forereef tract of the carbonate buildup in the present study area, could conceivably have moved downslope under the action of gravity, and could have eroded foreslope muds and incorporated the mud material as large irregular to lenticular-shaped lutite clasts. The load and cast structures observed would probably indicate that the muddy sediment was not lithified but had a comparitively soft consistency to it. Indeed they do indicate that the viscosity and strength of the sand and mud was low enough to permit deformation of the interface between them.

CHAPTER 7

SUMMARY AND CONCLUSIONS

Summary

Sediments of the lower portion of the Mount Hawk Formation adjacent to the Upper Devonian Southesk-Cairn carbonate complex outcrop at Wapiabi Gap, Alberta, in The Big Horn Mountain Range of the Canadian Rocky Mountains. These sediments were found to consist of interbedded slightly calcareous shales and lime mudstones. Within this sequence are seven allochthonous carbonate debris deposits. The two lowermost debris deposits that occur near the base of the Mount Hawk Formation are distinctly different in morphology and petrography from the five allochthonous debris sheets which occur higher in the Mount Hawk sequence. These lowermost debris deposits are morphologically and petrographically different from one another as well.

The lowermost debris interval, which outcrops approximately one kilometer beyond the carbonate buildup margin, is a rudstone of unknown thickness consisting of fragmented skeletal debris. Debris fragments increase in size laterally towards the carbonate complex over a distance of approximately 100 meters. They range in size from silt to small boulder dimensions. The allochthonous debris consists of skeletal remains of Thamnopora, echinoderms, inarticulate and articulate brachiopods, bryozoans, and peloids of microcrystalline calcite. This deposit has a "calcarenite cap" of finer grained sand-sized material composed of inarticulate brachiopods and echinoderm skeletal debris.

A covered interval (0.3 meters in thickness) occurs between the lowermost debris deposit and the second debris bed. Hence, it is not known whether or not these two allochthonous debris deposits are indeed separate from one another. However they have been, separated in this thesis because of their distinctly different petrographic characteristics. The second debris bed is about 0.5 meters thick and is a rudstone consisting of well-rounded lenticular-shaped clasts of buildup-derived material, within a fine sand-sized matrix. Clasts range from pebble to boulder size and are oriented approximately normal to the margin of the carbonate complex. The top portion (0.1 meters) of this deposit is composed of fine sand-sized allochthonous debris and is similar to the "calcarenite cap" of the lowermost debris deposit. Most of the allochthonous debris consists of clasts of carbonate mud, but approximately 25% are cemented calcarenite. Microcrystalline calcite envelopes surround the peripheral margins of some of the cemented calcarenite clasts and these resemble micritic alteration envelopes found on skeletal grains in many modern carbonate environments.

The earliest carbonate cements which are found in both debris deposits, as well as in the cemented calcarenite clasts of the second debris deposit, are bladed fringing and echinoderm rim cement. These are overlain by a second generation of blocky mosaic cement. The last cement, which is morphologically the same as the earlier generations, but also occludes any remaining void space, is chemically very different in that it is ferroan calcite. Zoning is evident in this last generation of cement.

The five allochthonous carbonate debris sheets that occur higher in the Mount Hawk sequence are much thinner (about 15 centimeters thick) than the lower debris intervals and maintain a constant thickness laterally over a distance of 1 kilometer. They are conformable with the shales in which they occur and have sharp and relatively flat upper and lower boundaries. Each debris sheet consists of two portions: a basal portion of carbonate mud, and an upper portion which has a floatstone texture and consists of irregular and lenticular-shaped lutite clasts embedded in a matrix of echinoderm sand and carbonate mud. The contact between the basal and upper portions is sharp and highly irregular and exhibits what appear to be load and cast structures. The petrography is similar to that in the two lowermost debris deposits except that the earliest generation of carbonate cement is not evident.

Late diagenesis has affected the allochthonous carbonate debris deposits at Wapiabi Gap. Pyrite has partially and completely replaced many of the sand-sized skeletal allochems in all deposits. In particular, approximately 90% (visual estimate) of the fine sand-sized skeletal grains of the matrix in the second debris bed have been pyritized. Authigenic silica, in the form of amorphous silica and euhedral quartz crystals, has partially replaced all three generations of carbonate cement and has preferentially replaced some grains of skeletal debris. Ferroan dolomite has preferentially replaced some of the carbonate cement in all debris deposits (all three generations have been partially altered) and has replaced portions of the authigenic silica.

Conclusions

1. The source of the carbonate debris material in the lowermost debris deposits is thought to be the lower part of the Peechee Member of the Southesk Formation.
2. This portion of the carbonate complex may have been: a) a stromatoporoid rich bioherm or biostrome and the allochthonous debris probably originated on its forereef and foreslope positions or b) a carbonate bank and in this case the debris material may have originated on the bank margins.
3. The second allochthonous debris deposit is inferred to have originated high on the foreslope or forereef regimes and was transported downslope under the action of gravity. As it moved downslope it eroded already lithified material from the lowermost debris deposit and incorporated this debris as calcarenite clasts into the flow. The carbonate mud clasts of this second debris bed are inferred to have been eroded from pre-existing foreslope sediments.
4. The echinoderm sand material in the upper allochthonous debris sheets probably originated from the middle part of the Peechee Member. This portion of the buildup is inferred to have been a carbonate sand bank deposit. The echinoderm sand debris is thought to have been derived from the margins of the bank deposit, and as it was transported into the deeper water environment, it incorporated carbonate mud from the underlying foreslope sediments as irregular and lenticular-shaped clasts. The load and cast structures that are apparent at the contact between the basal and upper portions of the debris sheets indicate that carbonate mud

sediment of the foreslope were not lithified at the time that mass movement was initiated.

5. The initial cause of movement is not known but the writer feels that simple gravitational instability of the bank margins could account for the production of the five upper allochthonous debris sheets.

6. The two lowermost debris deposits may have originated by gravitational instability of the buildup margin, triggered by sudden earthquake shocks.

7. The mode of transport of the buildup-derived material is thought to have been grain flow and/or turbidity flow types of sediment gravity flows.

8. The earliest generation of carbonate cement (bladed fringing and echinoderm rim cement) is believed to have been the result of early submarine cementation.

9. The second generation (blocky mosaics) and the zoned, pore - occluding ferroan calcite cements are inferred to have formed later in a mesogenetic environment. Similarly, the replacement of materials by pyrite, authigenic silica and ferroan dolomite are likely the result of diagenesis in a mesogenetic environment.

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PLATE 1

THE CARBONATE BUILDUP AND

STRATIGRAPHICALLY EQUIVALENT BASINAL SEDIMENTS

Pe - Peechee, Mh - Mount Hawk, P - Palliser

a View of the carbonate buildup margin looking northwest. Photograph was taken from the top of the shale slope shown in Plate 1c. The measured stratigraphic section A is shown on the photograph.

b Ground level view of the buildup margin.

c Photograph taken from the buildup margin looking southeast across Wapiabi Creek. View of the lower Mount Hawk sequence which contains the allochthonous carbonate debris deposits. Measured stratigraphic section B is shown.

d A closer look at the shale slope seen in Plate 1c. Most of the slope is covered with talus consisting of broken rock fragments of shale and lime mudstone. In the extreme upper portion of the photograph, thin unit in outcrop (arrow) is one of the allochthonous carbonate debris sheets.

PLATE 1

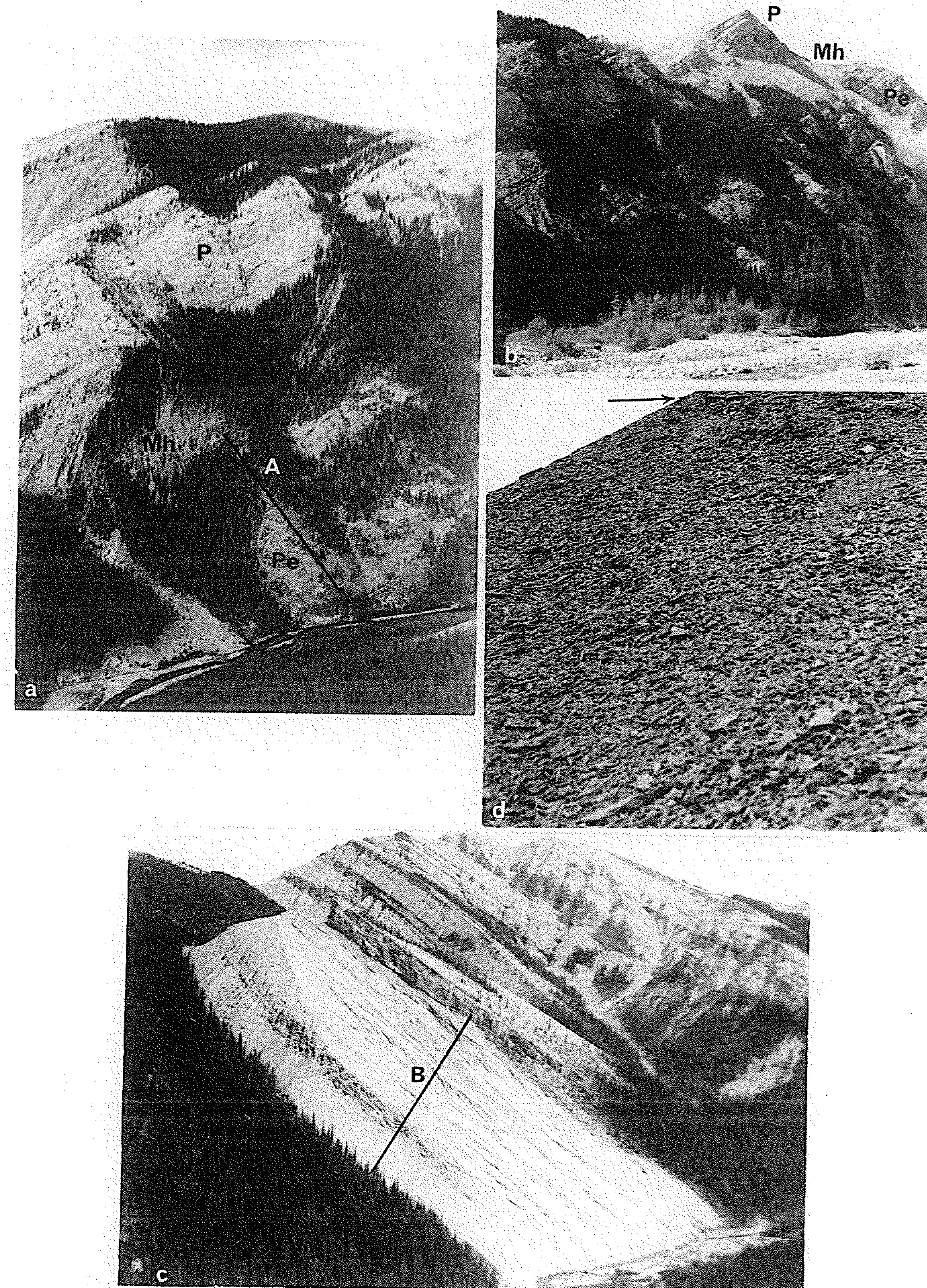

PLATE 2

SEDIMENTS OF THE CARBONATE

BUILDUP MARGIN AND THE LOWER MOUNT HAWK FORMATION

a — This photograph illustrates the vuggy nature of the buildup margin dolomites in the lower part of the Peechee Member. This shot was taken near the base of the Peechee Member at Wapiabi Gap.

b — Massive dolomite containing small irregular-shaped vugs characteristic of the upper part of the Peechee.

c — This photograph shows the well bedded nature of the shales and lime mudstones which characterize the lower Mount Hawk sequence. The more weather resistant units which stand out are the thin lime mudstone beds.

d — Bedding plane view of the lowermost allochthonous debris deposit.

e — A closer view of the lowermost debris bed showing the broken skeletal debris which is characteristic of this deposit.

f — Skeletal remains of Thamnopora, echinoderms, and brachiopods are visible in this bedding plane view of the lowermost debris deposit.

PLATE 2

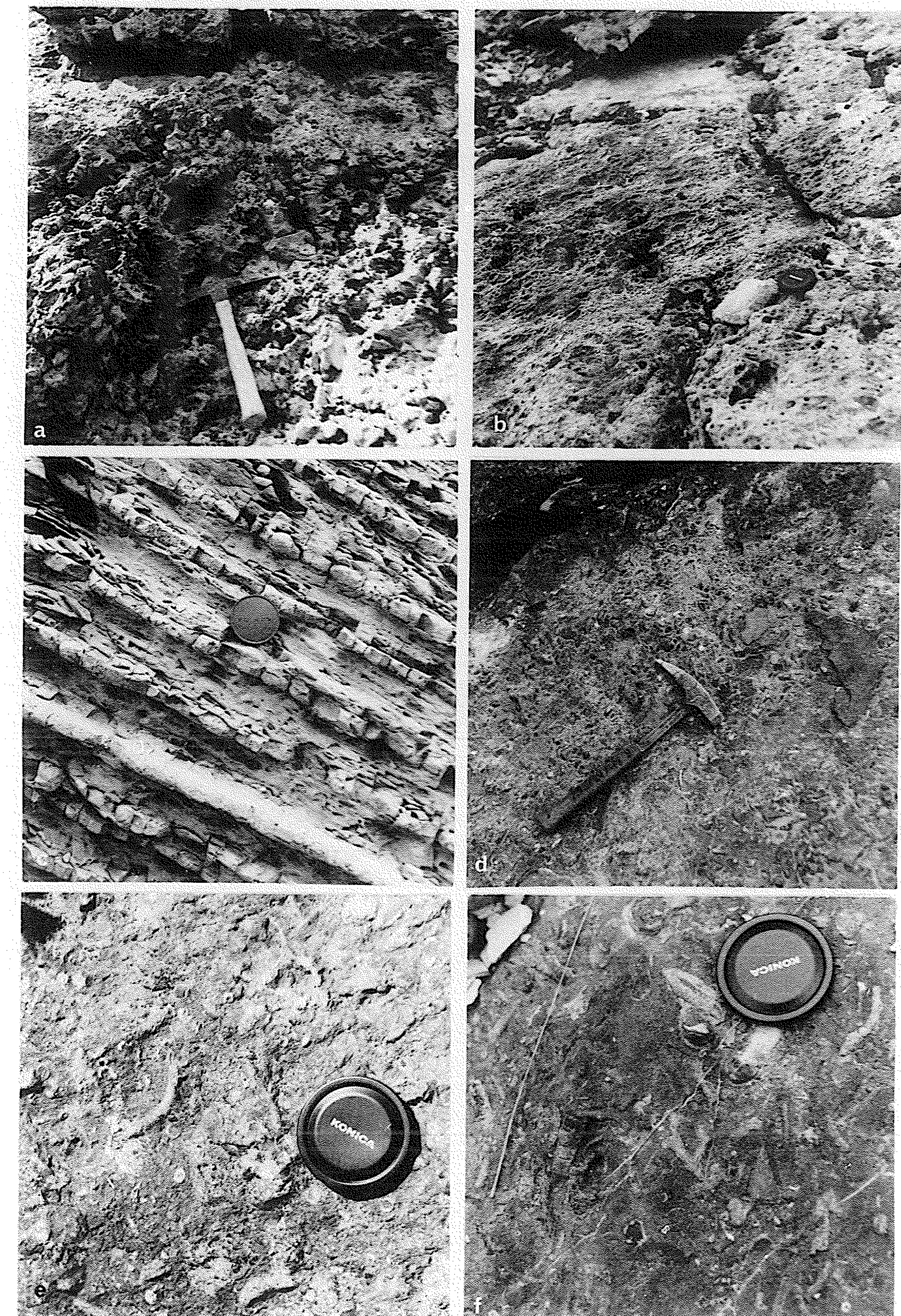

PLATE 3

LOWERMOST ALLOCHTHONOUS DEBRIS BED

Poor exposure of this deposit made possible bedding plane view photographs only.

a Bedding plane view of lowermost allochthonous debris deposit. Broken skeletal debris consisting of echinoderms and brachiopods can be seen in this photograph.

b Close-up view of this deposit, showing large Thamnopora fragment embedded in a fine sand-sized matrix of skeletal remains.

c This photograph illustrates the components of framework and matrix that comprise this deposit.

d Large fragments of broken echinoderms are the most abundant allochthonous component of this debris bed.

PLATE 3

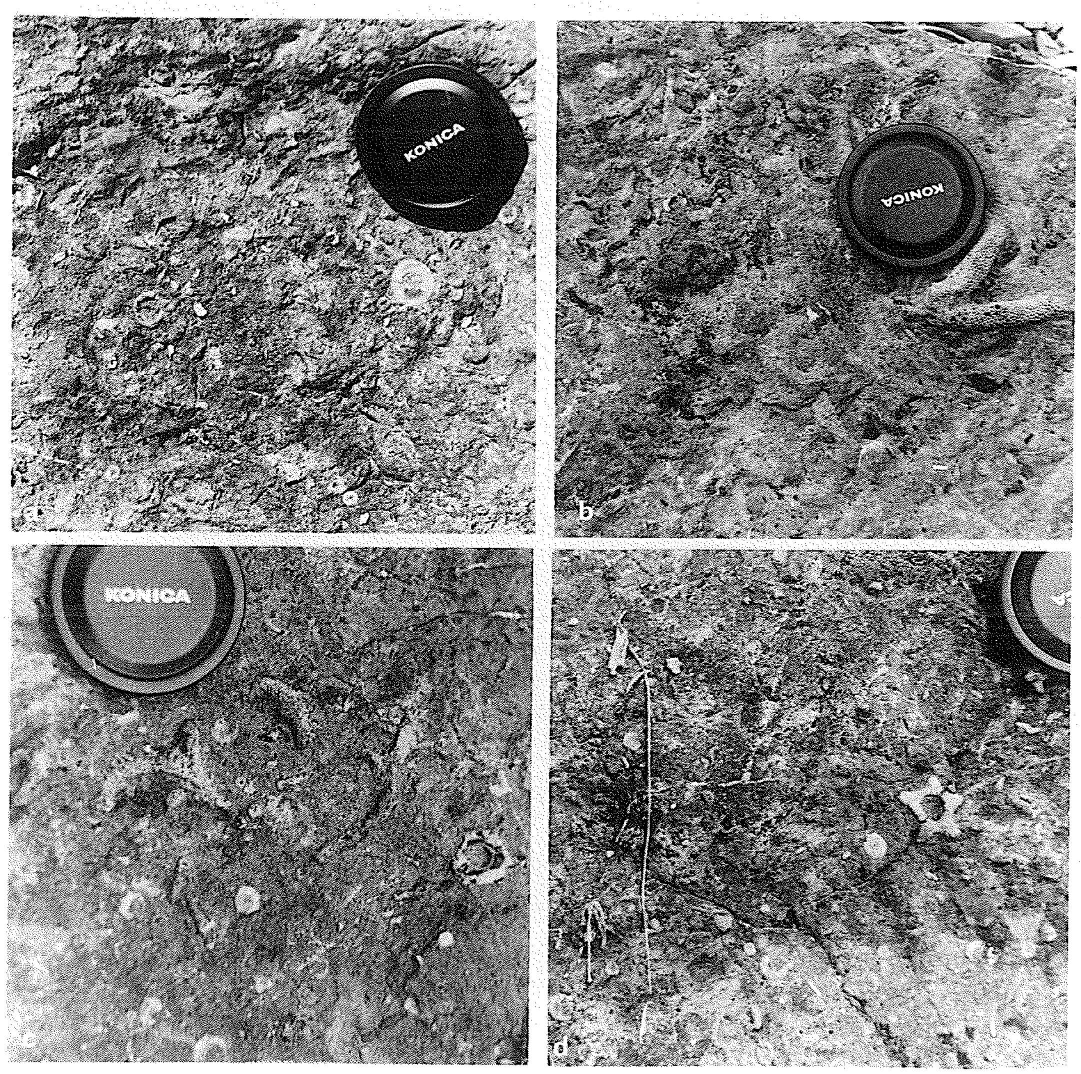

PLATE 4

ALLOCHTHONOUS CARBONATE DEBRIS SHEETS

a — Outcrop (arrows) of the fourth allochthonous carbonate debris sheet. (Head of hammer is resting on the top of this bed). This view illustrates the planar upper and lower contacts of the debris sheet and its conformable relationship with the lower Mount Hawk shales. Basal portion of this bed is a light shade of grey. The upper portion of echinoderm sand and lutite clasts is slightly darker in colour.

b — Closer view of the same debris sheet (arrows) illustrating the irregular nature of the contact between basal and upper portions. Contact is emphasized by dashed line.

c — This photograph shows the 6th allochthonous debris sheet. The lighter grey portion is the basal part of this debris sheet.

d — Photograph of the same debris sheet in c, showing the irregular nature of the contact between lower and upper portions.

e — Bedding plane view of the third allochthonous debris sheet clearly illustrating the carbonate mud clasts embedded in a matrix of sand in the upper portion of this deposit.

f — Photograph of the same deposit shown in e, showing lenticular-shaped mud clast (upper right of photograph) within a fine sand matrix. Clast in the centre of the photograph may be a fragment of a fish bone.

PLATE 4

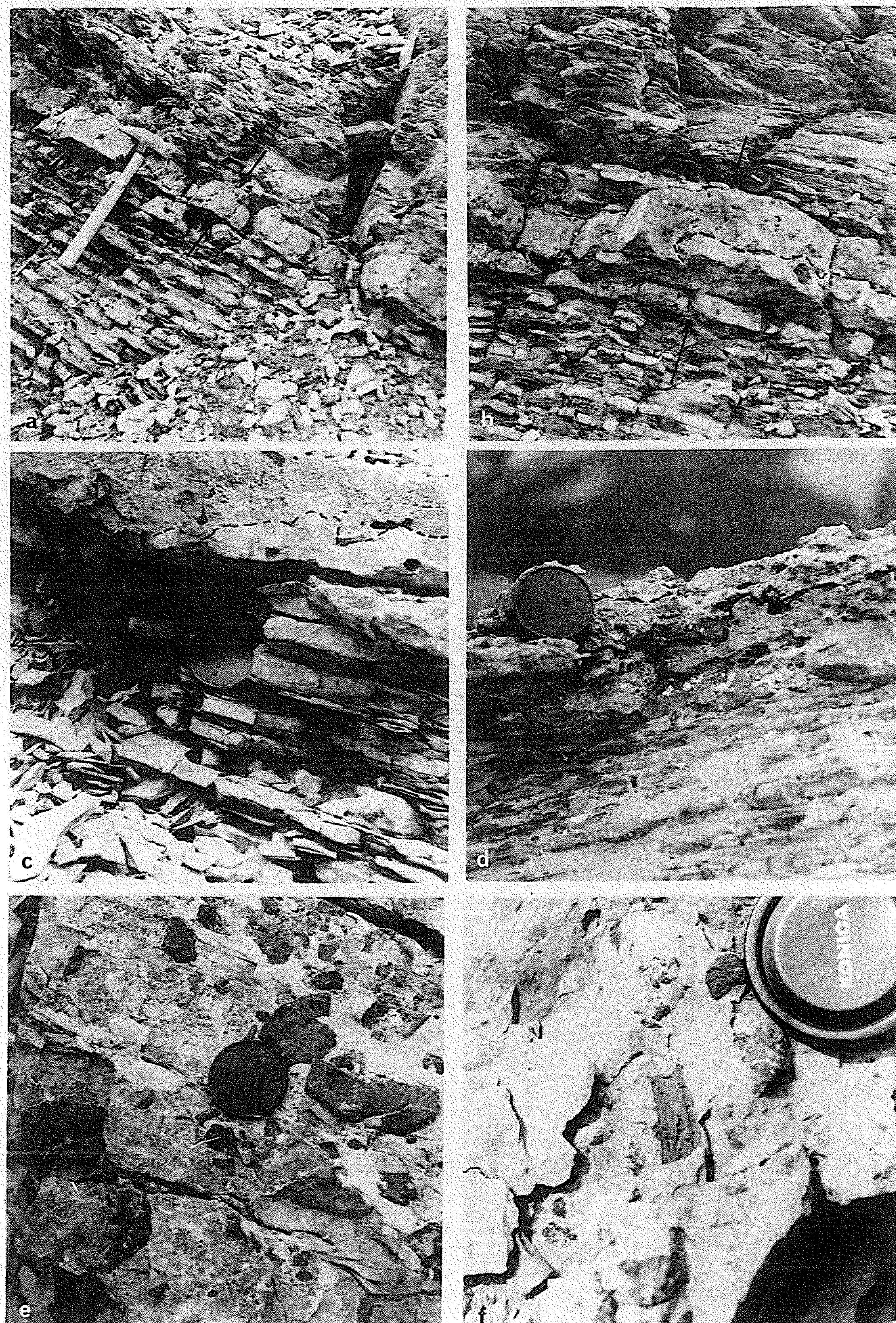

PLATE 5

PHOTOMICROGRAPHS OF THE LOWERMOST ALLOCHTHONOUS DEBRIS DEPOSITS

F - bladed fringing cement, R - echinoderm rim cement

B - blocky mosaic cement

a This photograph illustrates a cemented calcarenite clast within the second debris deposit. The lower half of the photograph shows a cemented calcarenite clast within a fine sand matrix (upper half of photograph). The margin of this clast has been pyritized which is evident as a thick, uneven, dark line running through the middle of the photo. Sand-sized fragments that are black have been pyritized. The matrix contains an abundance of pyritized skeletal fragments.

b Pyritized sand-sized skeletal debris of the second debris deposit appear black. Bladed fringing cement F, surrounds mud aggregates of the matrix.

c Bladed fringing cement is evident on a skeletal fragment (upper right hand portion of photo) in the matrix of the second debris bed. Blocky mosaic cement B, overlies the earlier bladed fringing cement.

d Early echinoderm rim cement R, has nucleated on most of the echinoderm fragments within the lowermost allochthonous debris deposit. Later, blocky mosaic cement B, overlies this earlier generation.

e Echinoderm rim R, and bladed fringing cement F, are the two earliest cements within the lowermost debris deposit. The bladed fringing cement is better developed on the side of the allochem that is furthest away from the grain on which echinoderm rim cement has nucleated.

PLATE 5

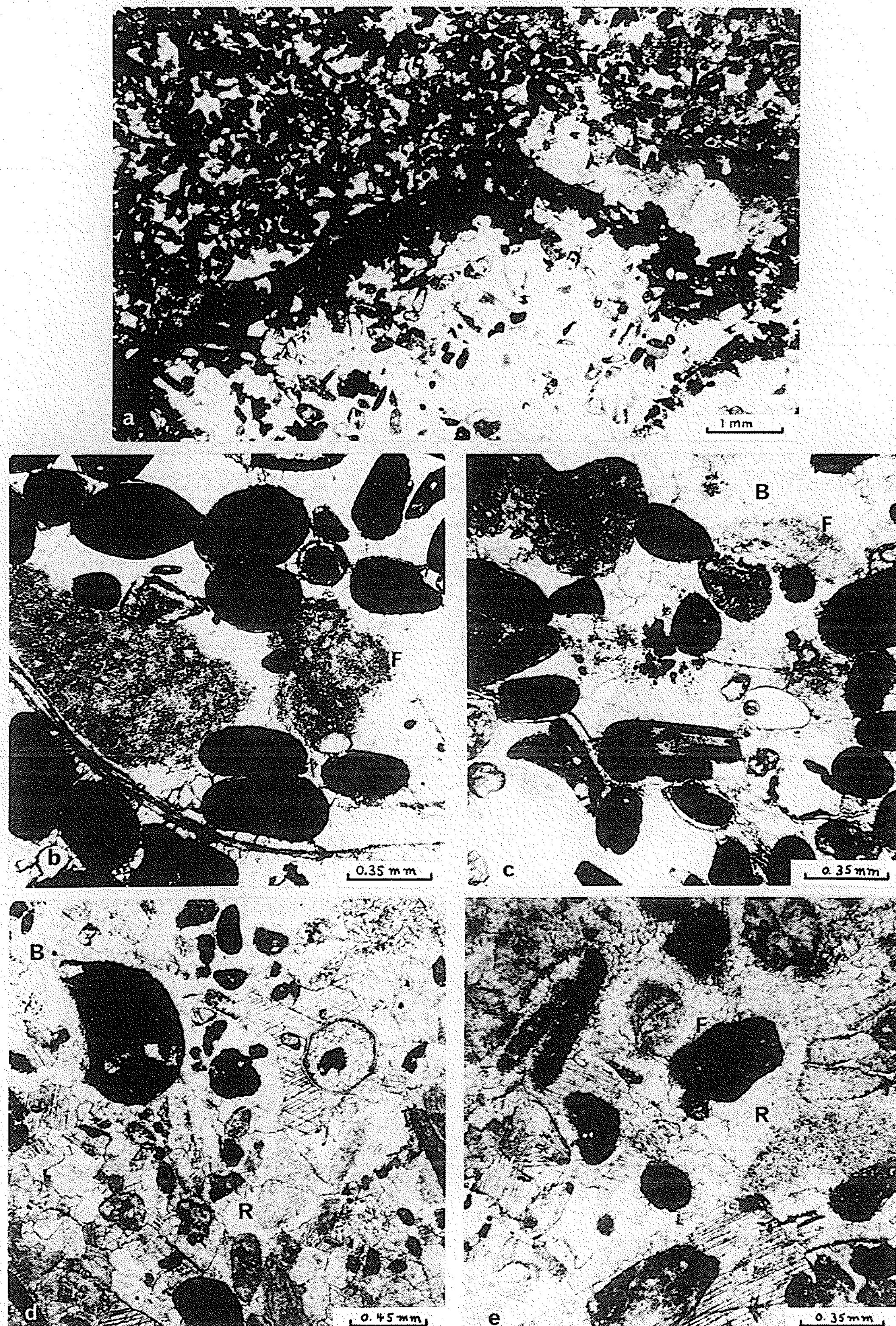

PLATE 6

PHOTOMICROGRAPHS OF THE EARLIEST

GENERATION OF CARBONATE CEMENTS

C - ferroan calcite, M - Microcrystalline alteration envelope

a Bladed fringing cement F, is well developed on allochems within the cemented calcarenite clasts of the second allochthonous debris deposit. Microcrystalline alteration envelopes M, have developed on many grains.

b Bladed fringing cement surrounds a skeletal grain that has been partially altered to microcrystalline calcite M, in a cemented calcarenite clast of the second debris deposit.

c Three generations of cement are visible in this photomicrograph of a cemented calcarenite clast. Bladed fring cement surrounds all the allochems. Blocky mosaic cement B, overlies this first generation cement. Ferroan calcite C, which appears dark grey because it has been stained, overlies the earlier cements and occludes the remaining void space.

d Bladed fringing cement F, is better developed on the side of the allochem furthest from the echinoderm rim cement R in the lowermost debris bed. This petrographic characteristic suggests that these two cements developed at the same time and competed for growth space. The allochem has almost completely been altered to microcrystalline calcite, M.

e This photomicrograph of a cemented calcarenite clast in the second debris bed illustrates an echinoderm grain with a partially developed microcrystalline alteration envelope M. Bladed fringing cement F, has developed on the part of this grain that has been altered. Echinoderm rim cement R, has developed on the unaltered portion of the allochem and completely envelopes the grain on which it has nucleated. This evidence suggests that the bladed fringing cement and the echinoderm rim cement developed at the same time, and the morphology of the carbonate cement is dependant upon the kind of substrate on which it mucleates.

f Same view as in e, but under crossed micols.

PLATE 6

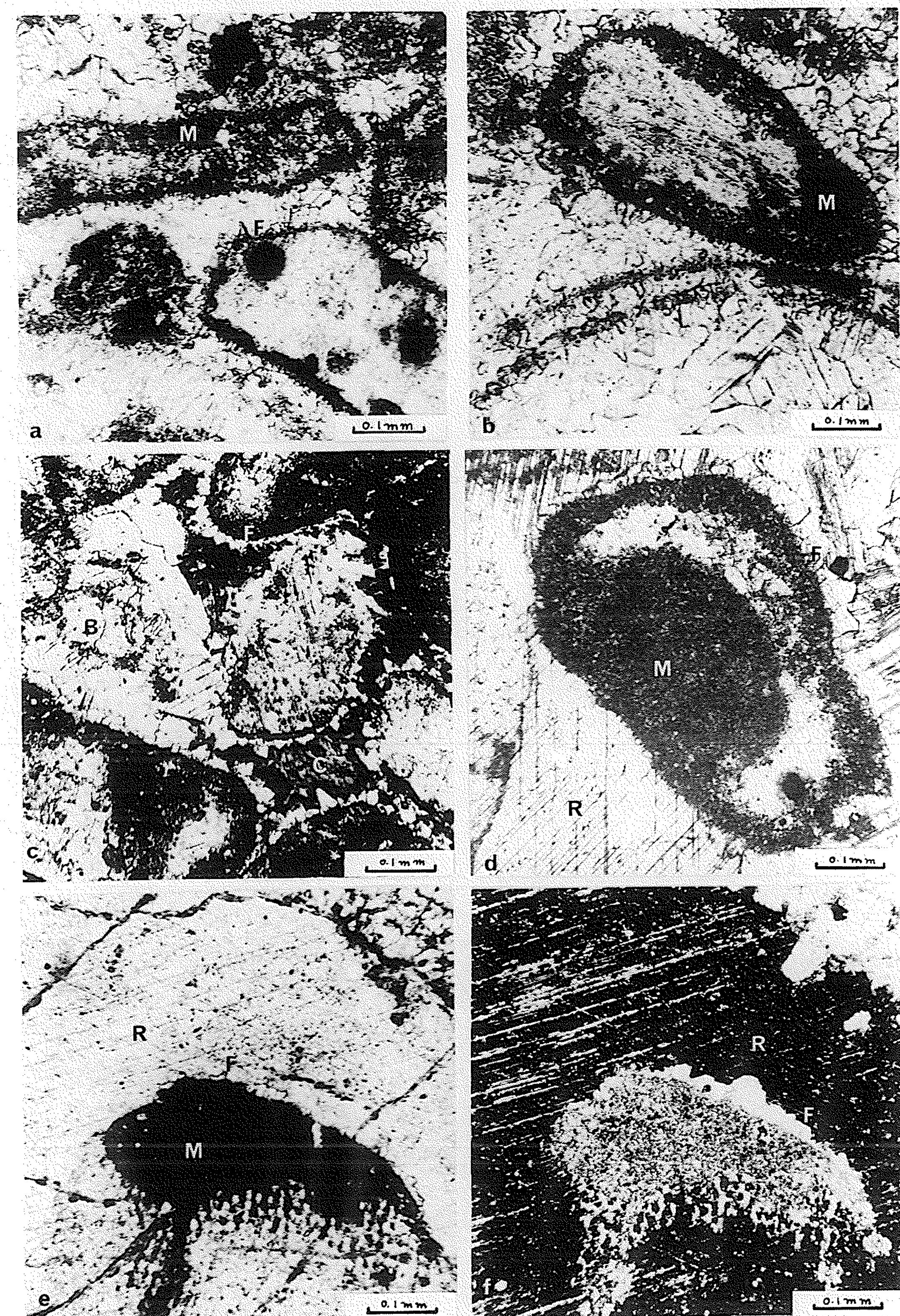

PLATE 7

PETROGRAPHIC DETAILS OF LATER CEMENTS

a Blocky mosaic cement B, (second generation) clearly overlies the earlier blading fringing cement F, and the echinoderm rim cement R, in the sediments that comprise the matrix of the second allochthonous debris deposit.

b The earliest generation of cement surrounding the allochem (bladed fringing, F) is overlain by second generation blocky mosaics B, within the sediments of the matrix of the second allochthonous debris deposit.

c Second generation blocky mosaic cement B, fills the intrabiotic pores of a Thamnopora fragment in the lowermost debris interval. Peloids of carbonate mud also occupy some of the intrabiotic pores.

d Ferroan calcite C, occludes the remaining void space in a cemented calcarenite clast. It overlies the early generations of blocky mosaic B, echinoderm rim R, and bladed fringing cement F. Ferroan calcite cement often exhibits calcite twinning.

e Ferroan echinoderm rim cement R, has developed on many of the allochems in the upper portions of the allochthonous debris sheets.

f Ferroan - non ferroan zoning is evident in the blocky mosaics B, and echinoderm rim cements of the third generation in a cemented calcarenite clast.

PLATE 7

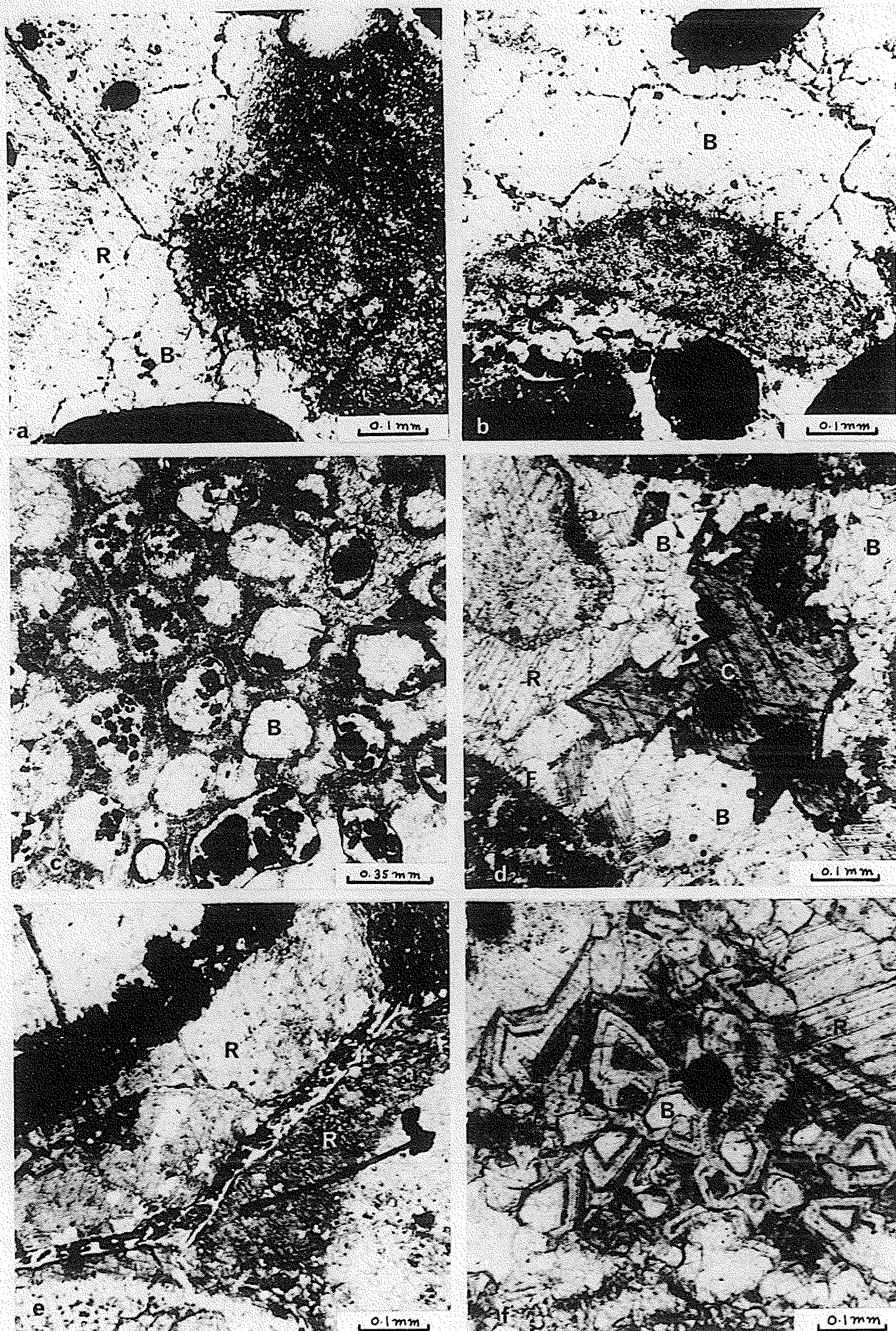

PLATE 8

PHOTOMICROGRAPHS OF MICROCRYSTALLINE

ALTERATION ENVELOPES

a A cemented calcarenite clast of the second allochthonous debris deposits exhibits what appears to be an alteration envelope of microcrystalline calcite M. The clast in this photomicrograph occupies the lower half of the picture.

b Complete alteration envelopes of microcrystalline calcite M, surround many allochems in the lowermost debris deposit.

c A closer view of the microcrystalline alteration envelope M, that has developed on allochems within a cemented calcarenite clast.

PLATE 8

PLATE 9

PETROGRAPHIC DETAILS OF

LATER DIAGENETIC PRODUCTS

Authigenic silica S, ferroan dolomite, D

a This photomicrograph shows an echinoderm grain in the upper portion of a debris sheet that has partially been replaced by pyrite along its peripheral margins. The pyrite appears black in this photomicrograph.

b Amorphous silica S, has partially replaced this echinoderm grain within an allochthonous debris sheet. A black pyrite rim is also evident around the margins of this grain.

c Euhedral authigenic quartz crystals S, have partially replaced the blocky mosaic cements B that occupy some interstices in the upper allochthonous debris sheets. The blocky mosaic cement is composed of ferroan calcite.

d Ferroan dolomite D, has replaced some of the cement in the lowermost debris deposit. Echinoderm grains, surrounded by echinoderm rim cement R, have remained unaltered.

e This photomicrograph illustrates partially dolomitized carbonate mud that fills some of the interstices in the upper portion of an allochthonous debris sheet. Rhombs of ferroan dolomite have replaced the carbonate mud. This may represent the initial stages of alteration to dolomite.

f In the upper portion of an allochthonous debris sheet, ferroan dolomite D, has partially replaced the echinoderm rim cement composed of ferroan calcite that fills the interstice.

PLATE 9

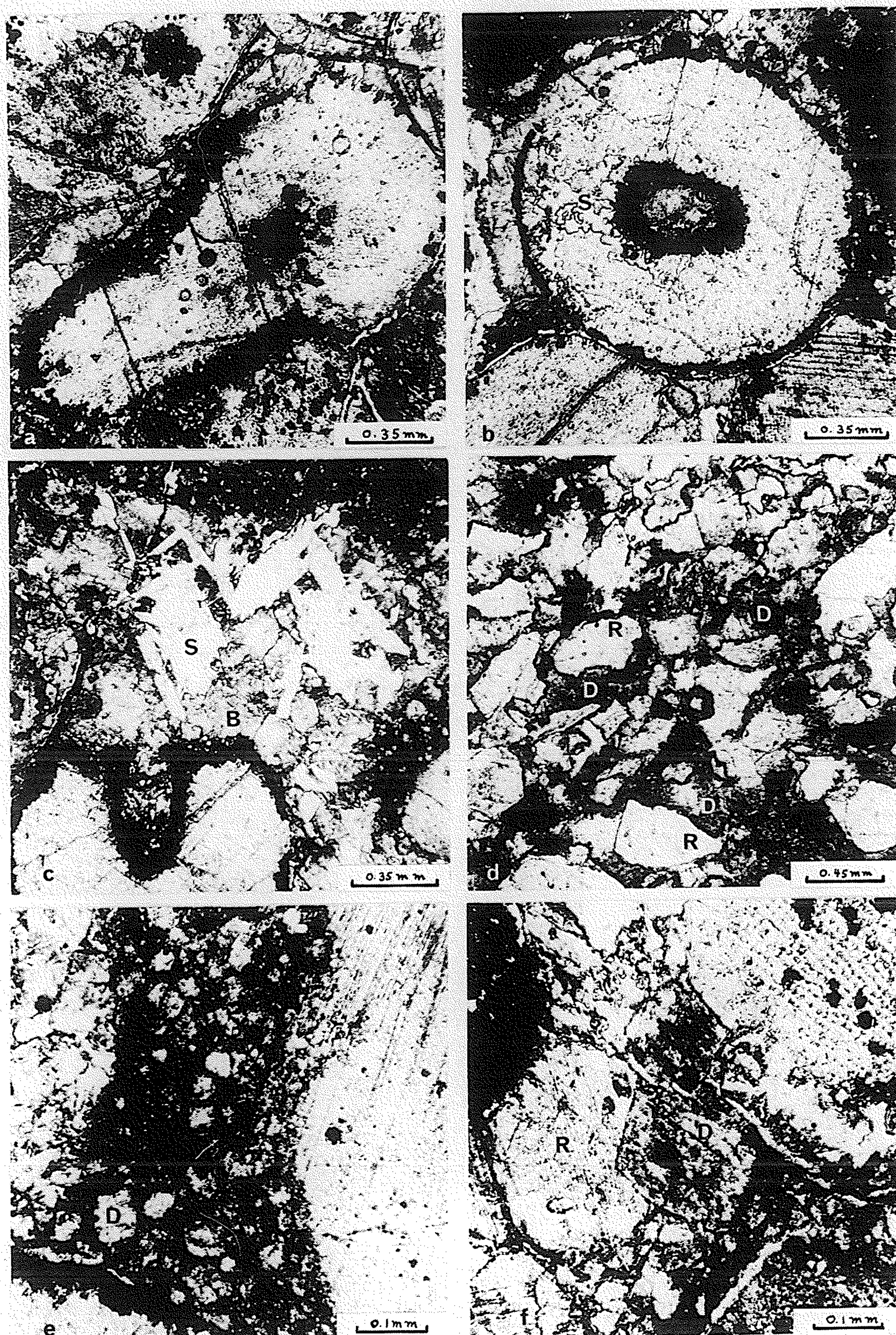

PLATE 10

PETROGRAPHIC DETAILS OF

LATER DIAGENETIC PRODUCTS

a Ferroan dolomite D has partially replaced amorphous silica S in the sediment of the upper portion of a debris sheet. Amorphous silica has partially replaced the peripheral regions of the echinoderm fragment.

b This photomicrograph is a close up view which illustrates the ferroan dolomite D, replacement of amorphous silica S, in the sediments of the upper allochthonous debris sheets. Amorphous silica has partially replaced the echinoderm fragment.

c Ghosts of organic textures were made apparent by staining blue, upon application of Potassium ferricyanide solution to the thin sections. These textures would otherwise not be apparent. The boundaries of the calcite crystals pass through these textures. The writer suggests that these textures may represent recrystallized skeletal fragments that were embedded in what was originally carbonate mud.

PLATE 10