PETROGRAPHIC EXAMINATION OF DOLOMITIZATION,

MIETTE CARBONATE COMPLEX,

JASPER PARK, ALBERTA.

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By

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ABSTRACT

Upper Devonian carbonate complexes show varying degrees of dolomitization throughout Alberta. The Miette complex of Jasper Park contains penecontemporaneous dolomite in several forms within platform and biostromal formations. Isolated dolomite euhedra selectively replace more permeable cement fabrics; less permeable micrite muds, intraclasts and globular stromatoporoids are not extensively dolomitized. *Amphipora*-rich beds and brecciated reef margin biostromes are almost totally replaced by dolomite, presumably because of their initial high porosity. Small-scale dolomite fronts have not selectively replaced host rocks; they occur in micrite, calcite spar and chert. Repeated penecontemporaneous mixing of fresh and salt water in the phreatic zone is the suggested mechanism for dolomitization. Fluctuations in sea level are inferred from cement fabrics, erosion surfaces and intertidal facies, detrital dolomite beds, and a general stratigraphic sequence of growth and extinction of organic banks and biostromes. Later diagenetic dolomite is present in veins and vug fillings.

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1. INTRODUCTION

The Devonian of Western Canada

The Middle and Upper Devonian of Western Canada were periods of extensive carbonate development. Transgression and regression of shallow seas resulted in construction of biostromes separated from each other by marine shales. The porosity of these biostromes relative to the surrounding shales and overlying less permeable carbonates created excellent hydrocarbon traps. Devonian limestone and dolomite reefs comprise over one-half of the oil producing stratigraphic zones in Alberta, accounting for almost 30 billion barrels estimated original recoverable reserves (Haun, 1974). The Swan Hill, Redwater, Bonnie Glenn and Leduc Woodbend fields have produced nearly 2 billion barrels of oil from the Winterburn and Woodbend Groups and the Beaverhill Lake Formation, since their discovery about 25 years ago.

This economic impetus has stimulated numerous subsurface and outcrop studies of Devonian Reefs. The Miette Complex in Jasper Park, Alberta, offers exposure from back-reef lagoon through reef front into basinal shales. The stratigraphy at Miette was outlined by Mountjoy (1965), and its development was linked to that of the Ancient Wall Complex to the northwest (Mountjoy, 1967). Petrography of the basal Flume Member of the Cairn Formation was undertaken by MacQueen (1960), and the relationship of carbonate buildups to the basinal Mount Hawk and Perdrix Formation shales was studied by Hopkins (1972).

Noble (1970) analysed biofacies zonation within the Miette complex, and Kobluk (1972) gives a detailed account of stromatoporoid paleoecology at the reef's southeast margin. The present study is an investigation of the pattern and processes of dolomitization in the Miette Complex.

Regional Setting

The Miette Complex is one of a group of similar structures which developed in Alberta during the Middle and Upper Devonian. Exposed on two thrust sheets in the Front Ranges approximately 30 km northeast of Jasper, the Miette Complex is flanked by the Ancient Wall Complex 60 km to the northwest, and by the Southesk Complex 40 km to the southeast. These developments can be correlated through the subsurface to the Redwater, Leduc, and Swan Hills reefs in central Alberta (Fig. 1). Composed of bioherms, biostromes, calcareous sands and associated sediments, the Miette 'Reef' comprises the Fairholme Group of southern Alberta, correlating with the Woodbend and Winterburn Groups of the subsurface (Fig. 2).

Mountjoy (1965) divided the Fairholme Group at Miette into two dominant facies: a carbonate facies represented by the Cairn and Southesk Formations, and an argillaceous carbonate facies, divisible into the carbonate Flume and Maligne Formations and the argillaceous Perdrix and Mount Hawk. The Cairn Formation is the approximate lateral equivalent of the Perdrix, Maligne and Flume Formations, and the Southesk intertongues laterally with the argillaceous Mount Hawk (Fig. 3).

The Sassenatch Formation overlies both the carbonate and the surrounding Mount Hawk Formation, and is in turn overlain by Fammenian

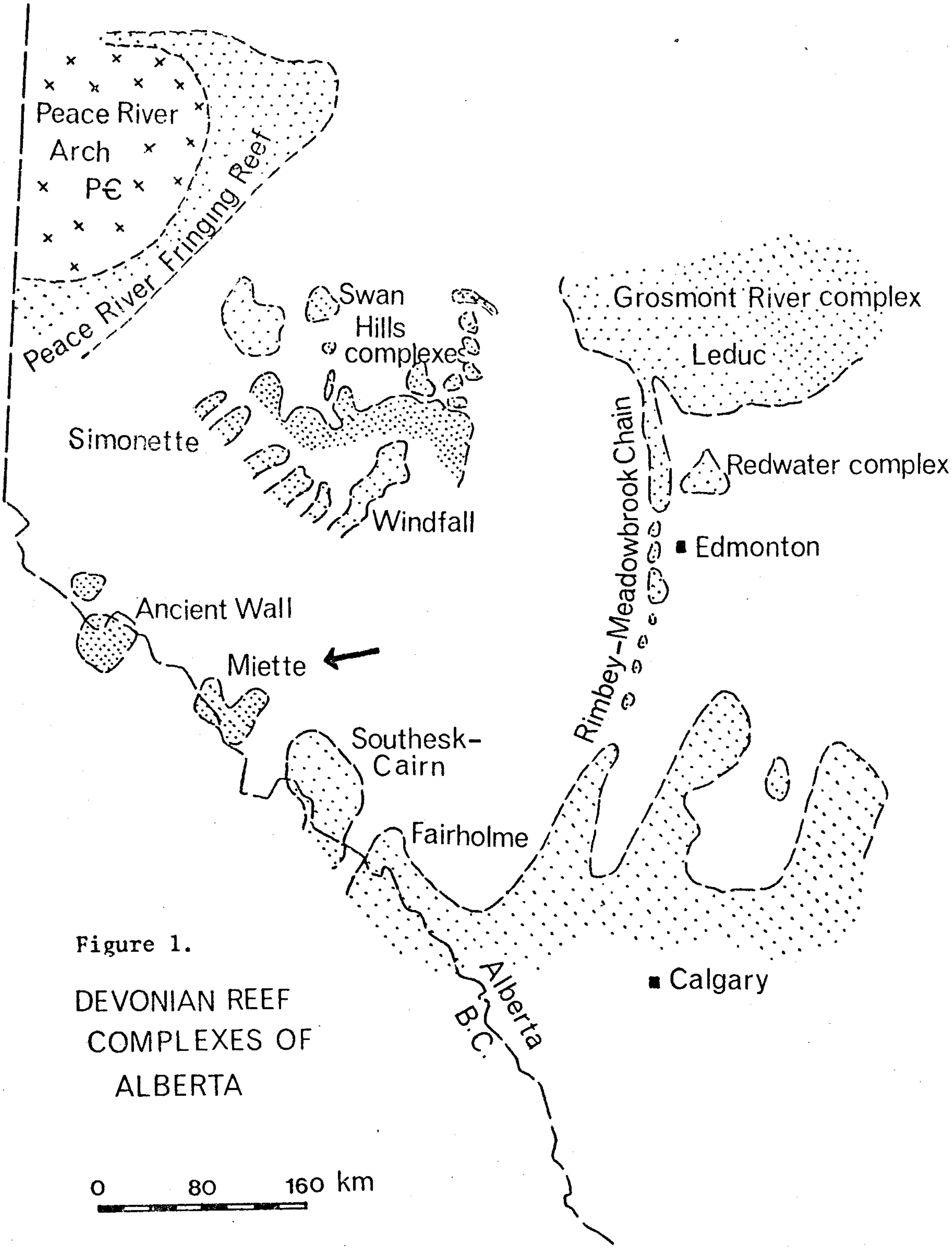


Figure 1.

DEVONIAN REEF
COMPLEXES OF
ALBERTA

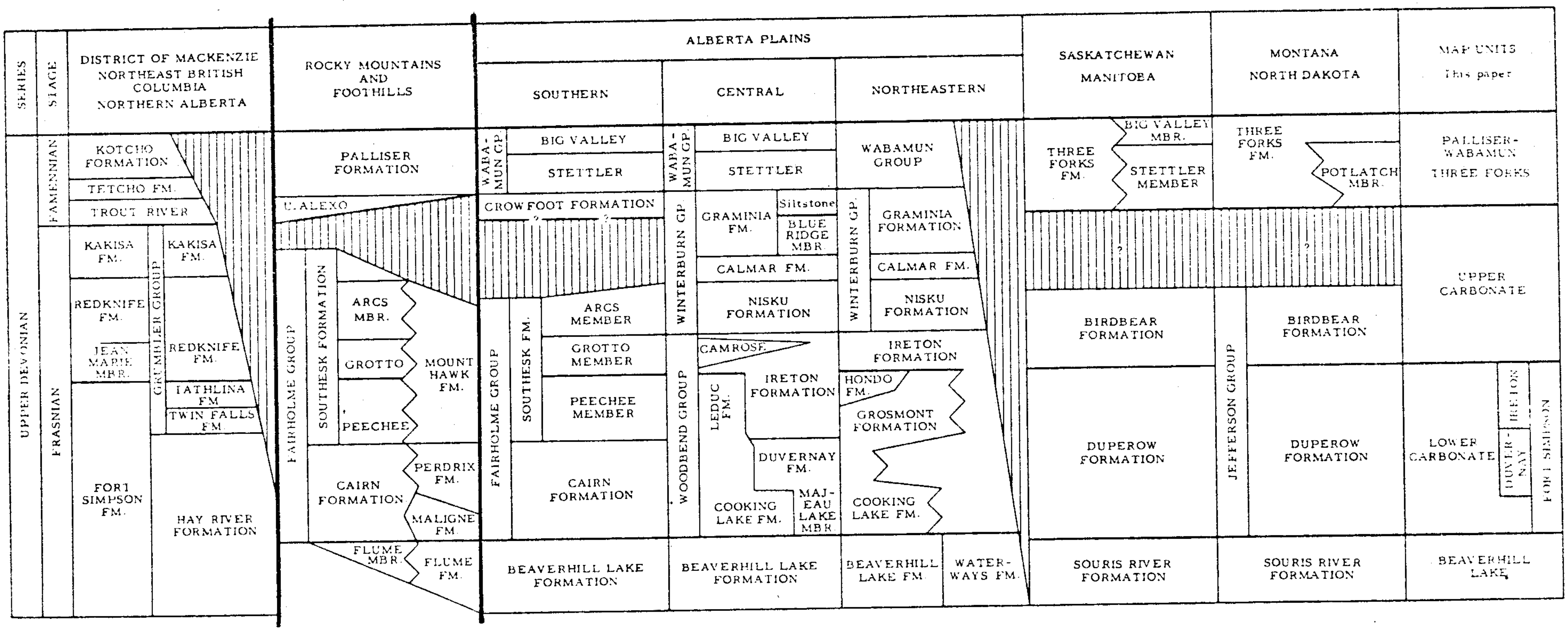


Figure 2. Upper Devonian stratigraphy of Western Canada. From Belyea, 1964.

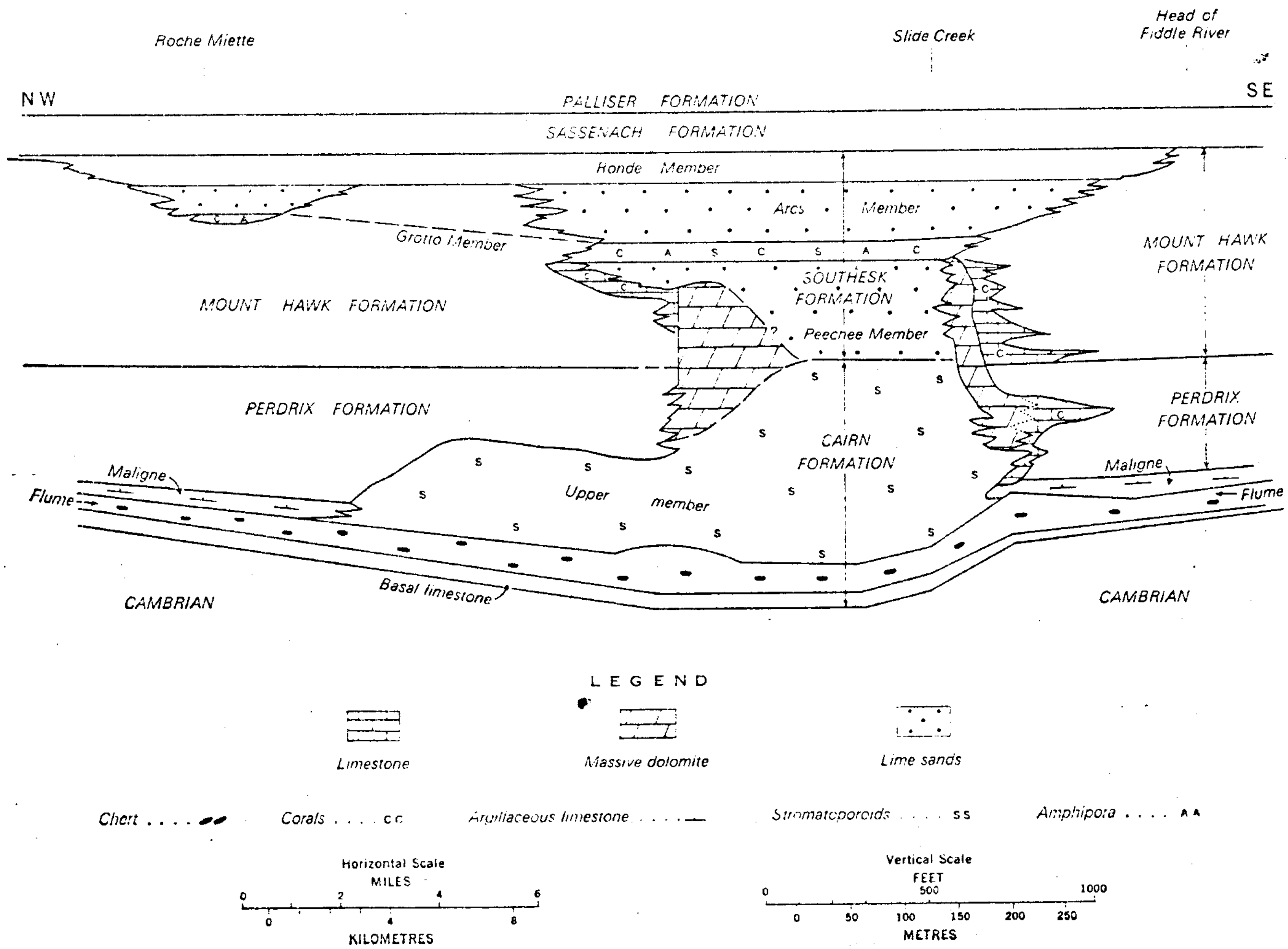


Figure 3. Schematic diagram of Miette complex. From Mountjoy (1965) fig. 4.

Stage limestones and dolomites of the Palliser Formation.

Purpose of Study

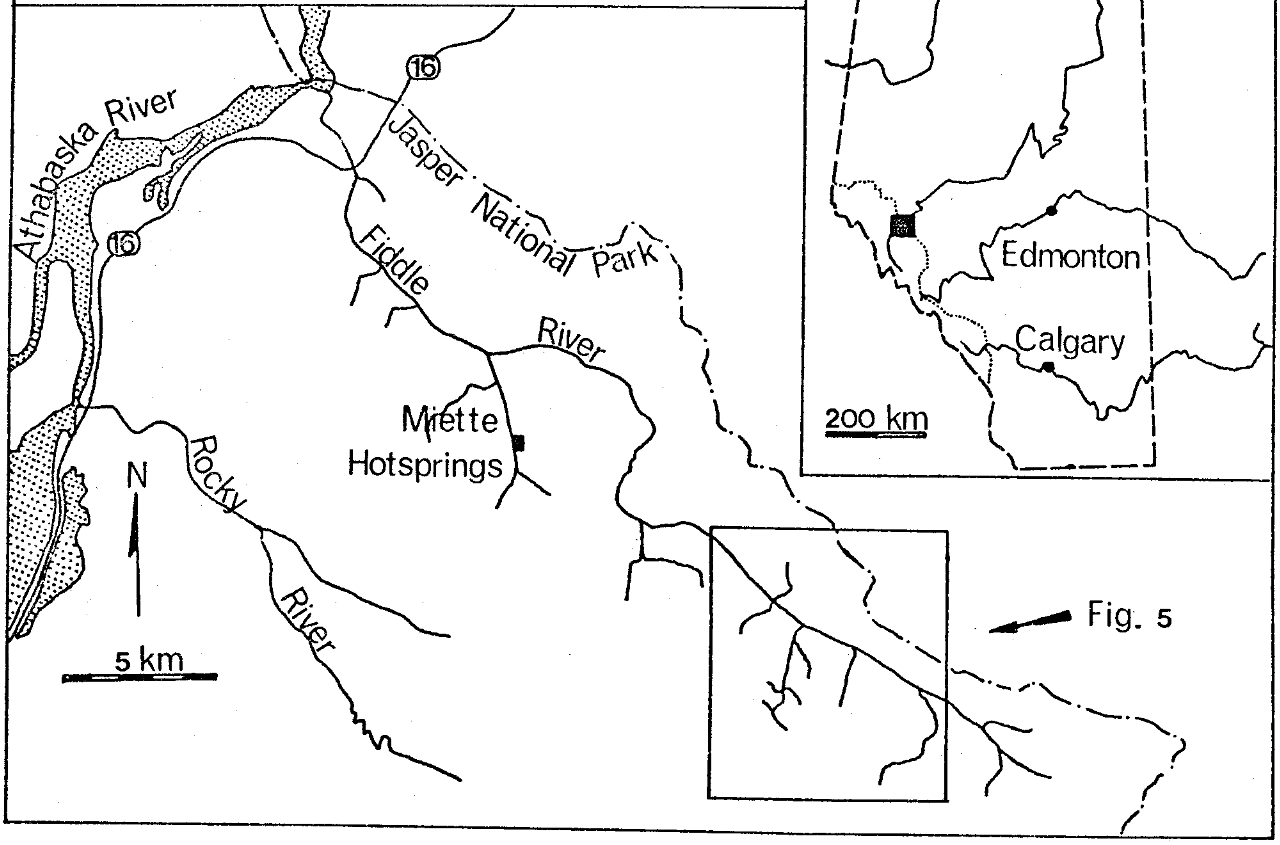
The presence of dolomite in carbonate reservoir rocks is usually condusive to extraction of hydrocarbons. Dolomites are generally more permeable than limestones and often contain more vuggy porosity. In the Leduc Formation at Redwater, dolomite-limestone contacts form some permeability traps (Levorsen, 1954). Where oil and gas occur in reservoirs consisting of both limestone and dolomite, the dolomite and dolomitic rocks are generally more prolific producers of petroleum.

This study is an examination of the nature of dolomite occurrence at the southeast margin of the Miette Complex, with emphasis on: a) the morphological variations of dolomite, b) preferred areas of dolomite crystallization and selective dolomitization, c) dolomite's relationship to diagenesis.

Methods of Study

Field study at the Miette Complex was undertaken at Slide Creek (Tp41, R25W5) in late August, 1974. The reef area is accessible by foot or horseback from Miette Hotsprings by following the Fiddle River approximately 9 km upstream (southeast) to its junction with Slide Creek (Figs. 4, 5). Outcrop areas lie in the Miette Range where it is incised by Slide Creek, exposing interdigitating reef margin dolomites and basinal shales on the southeast, and more lagoonward sediments to the northwest.

Fig. 4 Location of study area



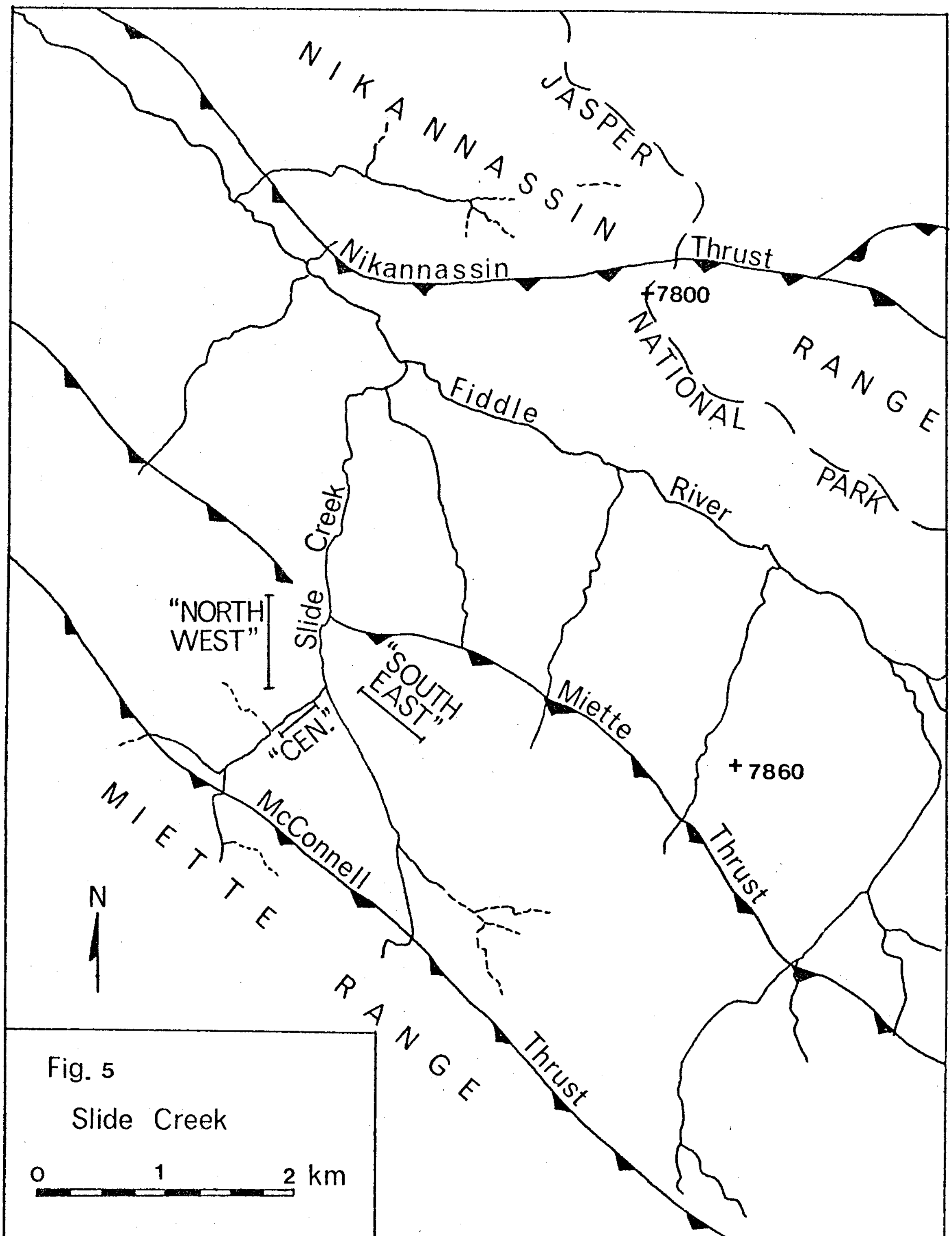


Fig. 5

Slide Creek

A total of 55 hand samples were collected from sections measured by Kobluk (1972). Samples were randomly located at intervals of approximately 30 m of stratigraphic thickness, with additional specimens being taken in areas of visible limestone-dolomite contacts.

Section "Southeast One" (Kobluk, 1972), on the southeast side of Slide Creek spans about 250 m beginning above the top of the Cambrian unconformity (Fig. 6). Samples were collected from the Flume and Upper Cairn Member of the Cairn Formation, and include specimens of reef margin dolomite.

Limestones of the "Slide Creek Centre" section (Kobluk, 1972) are for the most part undolomitized and comprise the Southest Formation from the lowermost Peechee Member to the terrigenous Ronde Member (Fig. 7). Centre Section parallels a northeast-flowing fork of Slide Creek which exposes grey, fine-grained, fenestral limestones thought to represent a lagoonal facies (Mountjoy, 1965).

The "Northwest Section" (Kobluk, 1972) covers 424 m from the top of Cambrian strata on the northwest side of Slide Creek to the Palliser Formation (Fig. 8). At this section, samples were recovered of the dolomitic limestones and dolostones which form the Cairn and Southest Formations.

Forty-nine thin sections were cut from representative lithologies and stained for calcite and ferrous iron content using Alizarin Red S and Potassium Ferricyanide (Dickson, 1965; 1966). In addition, each hand specimen was cut, polished and etched in 5% HCL for further examination. Component mineralogies were estimated by point-counting

Figure 6. Southeast section. Mississippian (M), Cambrian (Є), Flume (F), Cairn (C), Southesk (S), Perdrix (Px), Mount Hawk (MH), Palliser (P). Reef margin dolomite facies (Dm). North is to the left.

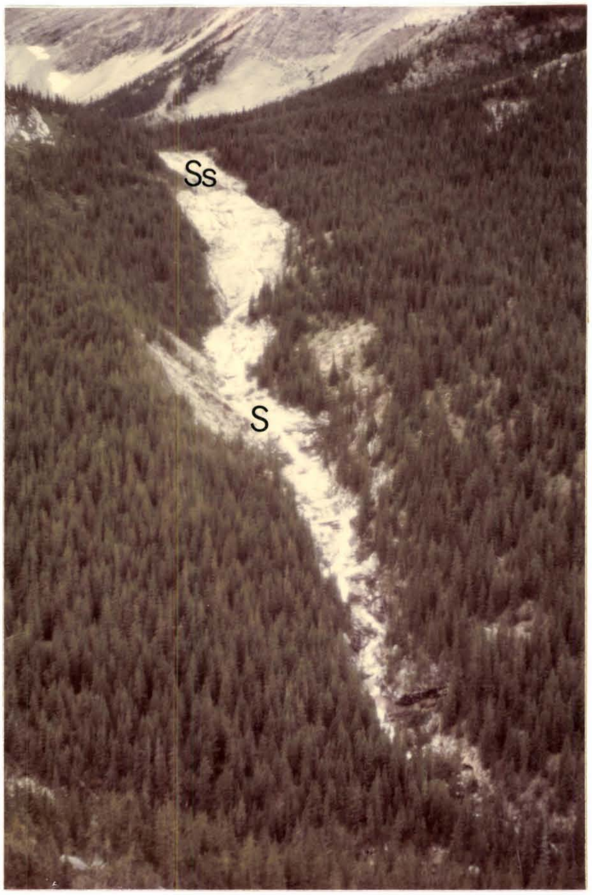


Figure 7 (left), Centre section. Figure 8,(below) Northwest section. Flume (F), Cairn (Cn), Southesk (S), Sassenatch (Ss), Palliser (P). Note light-coloured Utopia Member in Flume Formation.

a minimum 150 points on each stained section. Non-carbonate material was separated from each specimen by dissolution in 20% HCL, and the insolubles examined under binocular microscope. Detailed petrographic reports are presented in Appendix 1; traverse locations are shown on Figure 9.

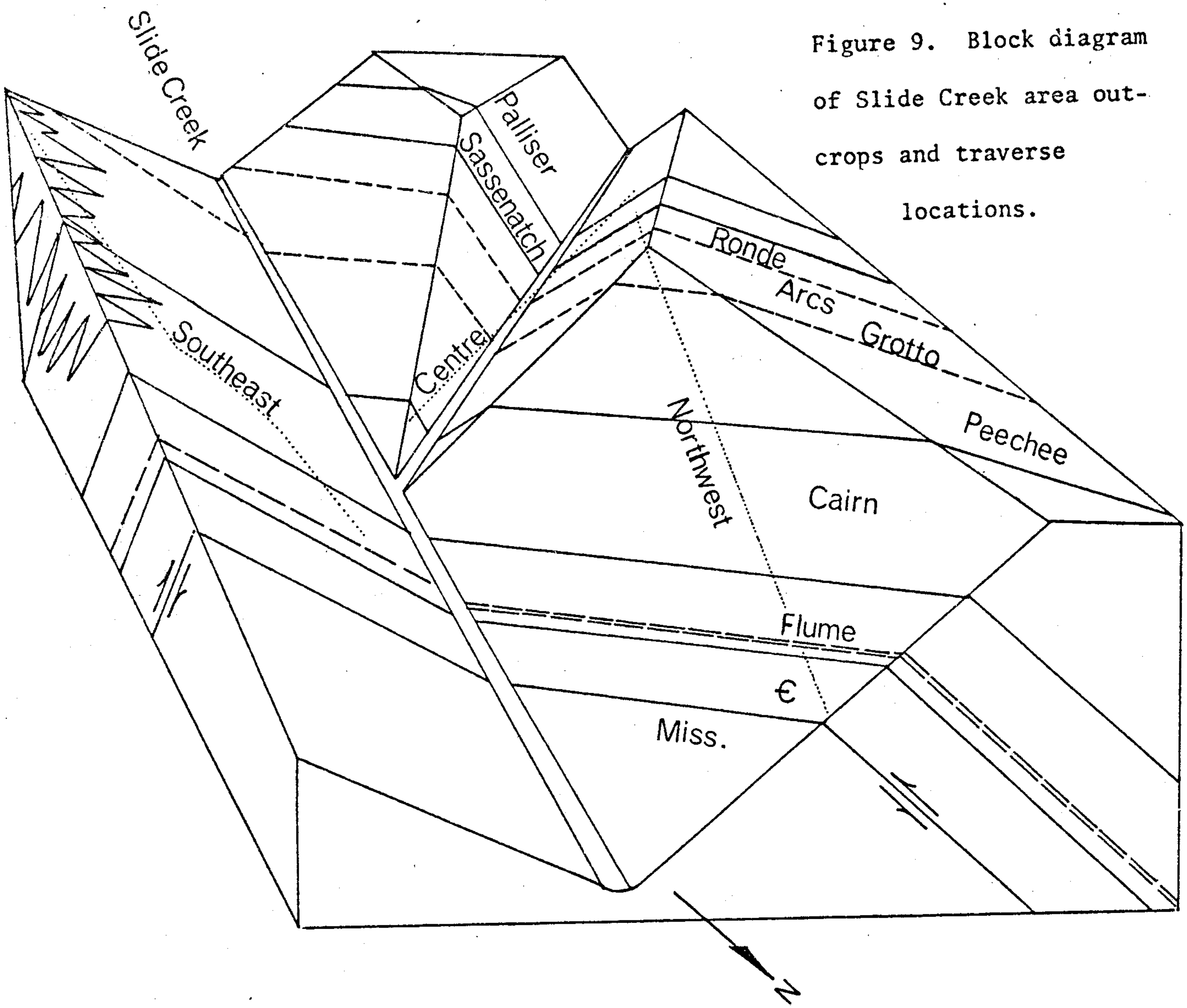


Figure 9. Block diagram of Slide Creek area outcrops and traverse locations.

2. STRATIGRAPHY OF THE MIETTE COMPLEX

Introduction

The stratigraphic sequence at Miette -- platform carbonates, overlain by basal stromatoporoid reef development, followed by an upper lime sand or dolomite phase -- coincides with lithologic changes in the Ancient Wall, Southesk, Redwater and Leduc reefs of Alberta (Mountjoy, 1965; Belyea, 1964; Andrichuk, 1958a; Klovan, 1964). The parallel development of these structures is explained in terms of sea level fluctuations resulting from interaction between epeirogenic movements of a complexly faulted craton, eustatic sea level changes and differential subsidence. Mountjoy (1965) derived a seven-stage model for development of the Miette Complex, including three transgressive phases, three stable phases, and a final regression. Further details of Miette Complex development and paleoecology are given in Mountjoy, 1965 and 1967; Kobluk, 1972 and 1975; Noble, 1966; and Cook, 1972.

Subsidence and widespread slow transgression inundated the structurally positive Western Alberta Arch during the early Upper Devonian (Belyea, 1964). Mountjoy (1965) and Cook (1972) believe this paleohigh became a locus for deposition of platform carbonates in the latter half of the Devonian.

Flume Formation or Member

The Flume Formation is the lowest formation of undoubted Devonian age in the central Alberta Rockies (Belyea , 1964). The lower contact is a low-angle unconformity separating the Flume from the Cambrian Waterfowl Formation.

Cook (1972) recognizes two cycles of carbonate deposition in the Flume Formation at Miette and interprets the limestone and dolomite facies as components of a shallow shelf. Initial transgression of a shallow sea over Cambrian strata resulted in deposition of "lower platform" argillaceous limestones, about 3 m thick at Miette. The overlying Utopia Member forms a distinctive light grey marker horizon and extends, in the subsurface, to the Whitecourt area, 130 km to the northeast (Farmer and Pitcher, 1964). Unfossiliferous, thin bedded, fenestral limestones of this unit are believed products of an intertidal or supratidal environment.

Following brief subaerial exposure which locally channelled the top of the Utopia, deepening seas promoted colonization of the area by stromatoporoids. Dark brown to black, stromatoporoidal, dolomitic limestones of the "upper platform" cycle form the remaining 32 m of the Flume, building a total thickness of 38 m for this formation at Miette. Chert beds, nodules and lenses are common in the Upper Flume. MacQueen (1960) suggests a diagenetic origin for the chert, noting the presence of monaxon sponge spicules and partly silicified fossils and sediments. The top of the Flume is indistinct, but has been taken by Mountjoy (1965) as the uppermost cherty horizon in the base of Cairn Formation strata.

Cairn Formation

Widespread subsidence across Alberta during Frasnian time resulted in transgression of deeper waters from the north, overlapping onto the Alberta Arch (Douglas, 1970), and drowning much of the Flume stromatoporoid platform beneath a deepening sea. Mountjoy (1965) has demonstrated that upper Cairn stromatoporoid banks were localized on relatively positive parts of the pre-Devonian high where shoaling occurred on the upper Flume platform. To the east, a broad evaporite basin developed on shallow shelves marginal to a landmass in Montana and North Dakota (Belyea, 1964), but in the Miette area conditions favoured continued growth of stromatoporoid fauna.

The Upper Cairn Formation at Miette is 170 m to 190 m thick. Consisting of grey, micritic peloidal limestones and dolomites similar to the underlying Flume Formation, it is distinguished (Mountjoy, 1965; Kobluk, 1972) by a lack of chert, presence of more massive bedding and larger globular and cylindrical stromatoporoids. Biohermal developments are common, and are separated laterally and vertically by light grey calcarenite. McLaren (1956) divides the Cairn Formation into a lower Flume Member (the Flume Formation of Cook, 1972), and an upper, organic-rich, stromatoporoidal limestone. Above the Flume, the Cairn Formation may be further subdivided into a middle, light-coloured, massive stromatoporoid-rich dolomite, and an upper, thin bedded, Amphipora-rich dolomitic limestone (Kobluk, 1972). The Upper Cairn Member has been extensively dolomitized where it lies in contact with the surrounding basinal Perdrix shales.

Cairn deposition represents local accumulation of reefs and skeletal debris on the wide Flume Platform, and is similar to the Cooking Lake Formation in the lower Woodbend Group of central Alberta

(Belyea, 1964). At Miette, the carbonate mound intertongues laterally and abruptly with black pyritic shales of the Perdrix Formation (Hopkins, 1972). The Perdrix is unfossiliferous except for a few thin beds of black argillaceous limestone in the immediate vicinity of the Cairn. The Duvernay and Ireton Formation shales share a similar relationship with Cairn equivalents to the east.

Southesk Formation

The stromatoporoid-rich "black reefs" of the Cairn Formation grade upwards into light-coloured, less argillaceous limestones altered to massive dolomites at the reef margin. At Miette, the basal Peechee Member of the Southesk Formation consists of about 90 m of light grey, finely-laminated peloidal limestone (Mountjoy, 1965) with massive structureless dolomites at lateral contacts with lower Mount Hawk shales. Characterized by a general absence of the massive stromatoporoids typical of the underlying Cairn, the Peechee Member is equivalent to Leduc formation reefs of the Upper Woodbend Group. The Redwater, Golden Spike and Leduc Reefs show aphanitic limestone grading to massive crystalline dolomites at the margins (Klovan, 1964; Waring and Layer, 1950). Peechee equivalents in eastern Alberta platforms are typified by cyclical repetition of shaley limestone, shale, dolomite and anhydrite (Belyea, 1964).

A sharp division separates the unfossiliferous, fine-grained Peechee Member from the overlying dolomitic, Amphipora-rich Grotto Member. This division is diachronous across the area of reef development in Alberta (Belyea, 1964), and represents a regressive phase interrupted by a succession of carbonate tongues. At Miette, the Grotto and Arcs Members of the Southesk Formation represent two of these cycles of carbonate deposition.

The Grotto Member elsewhere is typically coral-rich, but at Miette Amphipora and globular stromatoporoids dominate. The finely-crystalline dolomites and dolomitic limestones of the Grotto are 9 to 18 m thick, and grade laterally into dark grey, coral-rich argillaceous limestones of the Mount Hawk Formation. An abrupt contact with the overlying Arcs Member marks the top of the Grotto.

The Arcs Member of the Southesk Formation consists of 50 to 60 m of light-brownish grey aphanitic limestone. Of greater areal extent than the underlying Grotto, the Arcs is variously altered to medium-coarse grained dolomite. It is analagous to the lower Winterburn Nisku Formation in central Alberta, which shows increasing dolomitization and anhydrite content towards the east (Belyea, 1964).

The uppermost member of the Southesk at Miette is the Ronde, about 30 m of thin-bedded, fine-grained, silty lime sands. Thickness varies in the Miette area, and the Ronde appears to grade laterally into argillaceous limestones of the upper Mount Hawk Formation. The erratic presence of this unit throughout the region (Mountjoy, 1965) suggests a period of uneven subaerial exposure during Ronde deposition, and marks termination of reef development at Miette. An erosional surface forms the top of the Ronde Member at Ancient Wall (Mountjoy, 1965) and is assumed present at Miette.

Sassenatch Formation

The Sassenatch Formation consists of approximately 40 m of argillaceous limestones, quartz sand and siltstone. Accompanied by pronounced lamination, slumping and cross-bedding, the Sassenatch reflects the beginning of the final transgressive phase of the Devonian.

Palliser Formation

A narrow gradational contact separates the Sassenatch from overlying massive platform carbonates of the Palliser Formation. Almost 230 m thick at Miette, the dark grey, fine-grained Palliser limestones suggest a depositional environment similar to the modern Bahama Banks (Beales, 1956).

3. PETROGRAPHY

Petrographic examination of the Miette Complex reveals several carbonate lithologies and distinctive patterns of dolomitization. Diagenetic features include multiphase calcite cement, replacement by chert, precipitation of ferroan calcite and crystallization of dolomite.

Flume Formation

The Flume Formation, within the Miette Complex, is composed of three members: a thin, basal argillaceous limestone, the middle, light-coloured Utopia Member, and 'upper platform' stromatoporoidal development. The Utopia Member is predominantly intrasparite, while the Upper Flume consists of dark stromatoporoidal limestone interbedded with black and grey chert.

The Utopia Member overlies about 3 m of 'lower platform' Flume limestone on the Northwest Section, and is 3 m thick. Peloids and micritic peloidal composite grains comprise 62% of the Utopia Member, and enclose abundant calcispheres. Generally only mildly compacted, peloidal grains less than 0.5 mm in diameter and larger aggregate intraclasts are cemented by two stages of calcite: an initial finely-bladed to blocky isopachous crust 30 to 50μ thick, followed by coarse and often poikilotopically overgrown spar. There is no gradation between the two sizes present in the cement, only an abrupt change to large sparry crystals which fill remaining intergranular voids. No dolomite is present in the Utopia Member.

Overlying the channelled and often hematite-stained top of the Utopia are about 32 m of cherty bioclastic limestones which form the 'upper platform' member of the Flume. Overturned and broken hemispherical stromatoporoids are characteristic of the Upper Flume, and are replaced by neomorphic sparry calcite in the galleries and micrite in the pillars and laminae. Commonly, stromatoporoids and other faunal debris (Amphipora, shell fragments) have cloudy, patchy, micrite envelopes up to 2 mm thick. Narrow, bifurcating micrite tubules up to 20μ in diameter penetrate less than 1 mm into the stromatoporoids from the inner margin of the micrite envelopes. The patchy nature of the envelopes and presence of micrite-filled tubules suggest centripetal replacement by micrite of the stromatoporoids, resulting from the activity of boring algae (Bathurst, 1971; Kobluk and Risk, 1974).

Silica-filled tube-like structures penetrate deeper into stromatoporoid skeletons. Chert-filled tubes frequently have euhedral calcite centres and cloudy brown chert cores about 500μ in diameter. These tubes aresurrounded by radially crystallized chalcedony to a thickness of about 1 mm, and are enclosed by a mixture of cloudy chert and aphanitic calcite, which often coalesces between tubes and forms stringy networks (Fig. 10). MacQueen (1960) noted the presence of monaxon sponge spicules in the Upper Flume, and dolomite euhedra within chert nodules. No sponge spicules were observed in this study although rare 1 mm long, needle-like, hexagonal prisms are found in matrix material. The presence of chert tubules inside skeletal fragments suggests the presence of boring organisms, perhaps sponges similar to

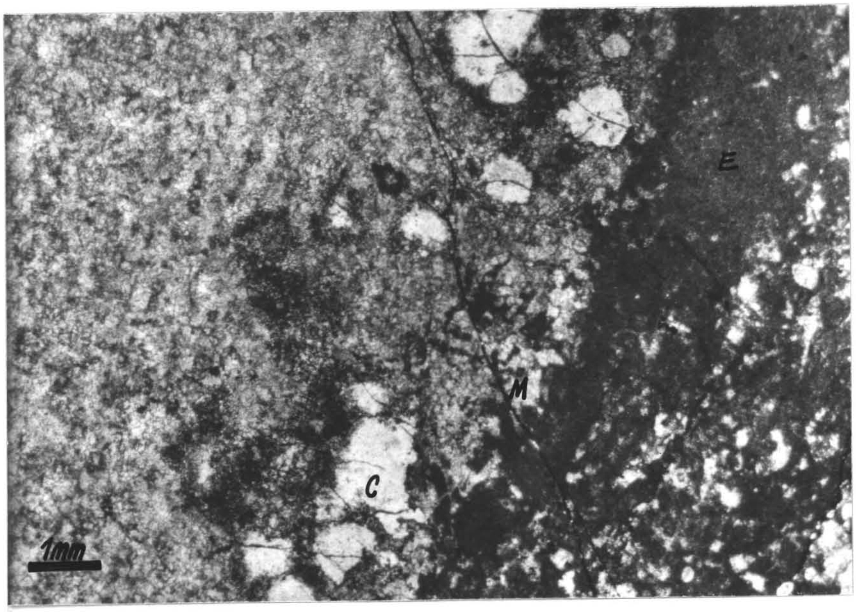


Figure 10 SEFM1. Globular stromatoporoid with chert- and micrite-filled tubules, (C,M); micrite envelope (E).

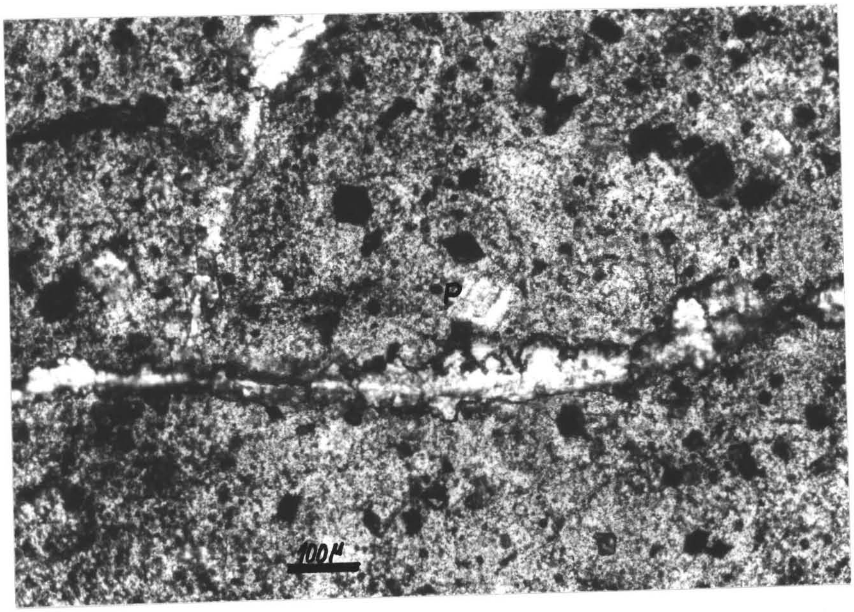


Figure 11. SEFM4. Bedded chert with pseudomorphs of dolomite (P) and later stage dolomite.

modern Cliona. Until spicules are found associated with the tubules, this suggestion remains unsubstantiated. Micrite envelopes and tubules are found on shell fragments and aggregate grains in the matrix, but chert nodules are not found within micritic envelopes or in matrix peloids.

Amphipora is locally abundant but not widespread in the Flume. Brachiopod and pelecypod fragments are common. Calcispheres are contained in some rounded intraclasts. The remainder of the matrix consists of loosely- to tightly-packed micritic peloids and composite grains of uncertain origin. Judging from the abundance of algal borings, peloids could be totally micritized shell fragments. Fecal origin of the peloids cannot be ruled out, considering the uniform size (0.5 mm), the ellipsoidal shape, and the abundance of invertebrates as a source of the pellets. As in the Utopia Member, two distinct phases of calcite spar are evident in the cement: a finely crystalline crust, and coarse, clear overgrowth. Coarse spar fills only small interstices in strongly compressed lime muds, but occupies larger areas and often forms poikilotopic overgrowths in more loosely packed beds. Tight packing produces peloids with polygonal outlines, but fine-grained, isopachous calcite crust coating each grain indicates this first phase of cement formed before compaction.

Microcrystalline, organic-rich, bedded and nodular chert is a replacement feature in the Flume. Silica pseudomorphs after brachiopod and pelecypod shells, calcispheres and intraclasts indicate the secondary nature of the chert. Dolomite euhedra 0.1 to 0.2 mm in diameter are scattered throughout, but the presence of larger rhombohedral pseudomorphs in the chert indicates a multiple replacement sequence (Fig. 11).

Dolomite content varies throughout the "upper platform" Flume. Discrete rhombohedra less than 0.3 mm in diameter and larger aggregates of dolomite have preferentially replaced sparry void-filling calcite before peloidal or fossil material. Dolomite is not found in bulbous stromatoporoids or their micrite rims, but often fine-grained aggregates encrust the outer surfaces of faunal debris. Coarse dolomite coexists with sparry calcite as a void filler in shell cavities, and frequently does not replace the fine-bladed internal calcite crust. Euhedral scattered single crystals of dolomite form about 5% of some bedded cherts.

Well-defined lobes of finely-crystalline dolomite are marked by stylolitic contacts with surrounding material and concentration of clays. In peloidal rocks, micritic peloid ghosts and fragments commonly are retained behind the advancing fronts (Fig. 12). Dolomite content ranges from 0 to 10% ahead of the lobes and from 50 to 100% inside the tongues themselves. These fronts show little preference for replacement, swallowing peloids, cement and chert without discrimination. Hemispherical stromatoporoids, however, are not replaced by dolomite.

Dedolomitization is evident in some samples; calcite spar has replaced dolomite along cleavage planes, centripetally from outer edges, or at intersections of cleavage traces, imparting an overall ragged and poikilotopic appearance to dolomite crystals. Sparry calcite

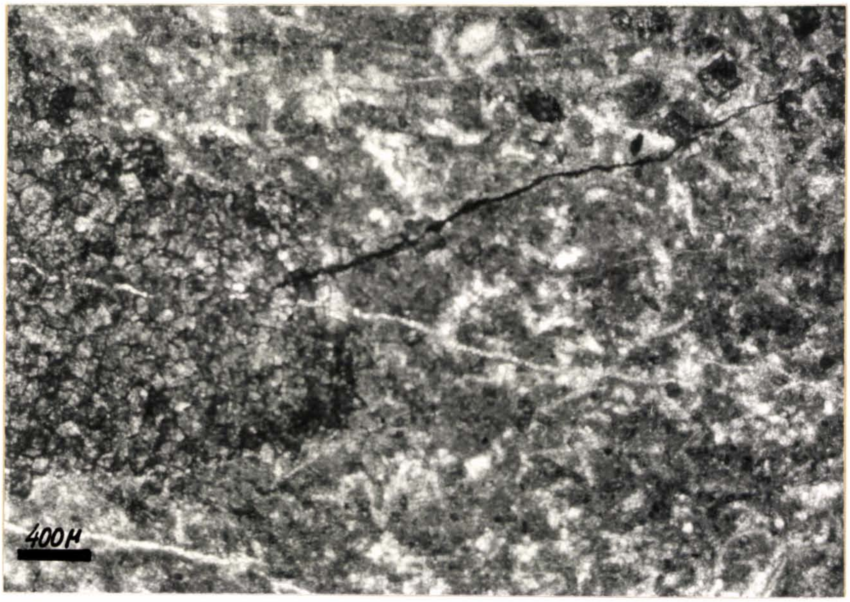


Figure 12. SEFM4. Lobe of sucrosic dolomite in peloidal micrite. Note discrete dolomite crystals in matrix; peloid ghosts in dolomite lobe.

Figure 13. Biostromal unit (dark grey) in calc-arenite.

pseudomorphs are much clearer than original spar cement, and are syntaxial with dolomite optic orientation.

Dolomite shows only occasional strong permeability control through the Flume section. Sparry calcite is replaced preferentially over micritic peloids in some cases, but in others there is no selective dolomitization. Both strongly- and mildly-compacted peloidal muds show dolomitized interstices. Stromatoporoids other than Amphipora are not dolomitized.

Cairn Formation

Stromatoporoid biostrome development typifies the Cairn Formation. In classifying the Flume as the basal member of the Cairn Formation, Mountjoy (1965) also divided the Upper Cairn into two members; a Middle member of biostromal limestone, and an Upper member of darker, Amphipora-rich calcarenites, together totalling 125 m.

The Middle Upper Cairn contains three lithologic facies: a dark, biostromal dolomitic limestone, surrounded by light grey calcarenites interbedded with Amphipora-rich dolomites. The biostromal facies is common near the base of this member and resembles the underlying Flume platform (Fig. 13). Stromatoporoids are replaced by granular, neomorphic calcite and are embedded in a matrix of biosparmicrite consisting of mottled peloidal micrite intraclasts and shell fragments. Matrix componants are cemented by two stages of calcite: an initial finely-bladed crust, and later coarse granular spar (Fig. 14).

Dolomitization in this facies of the Middle Cairn has not

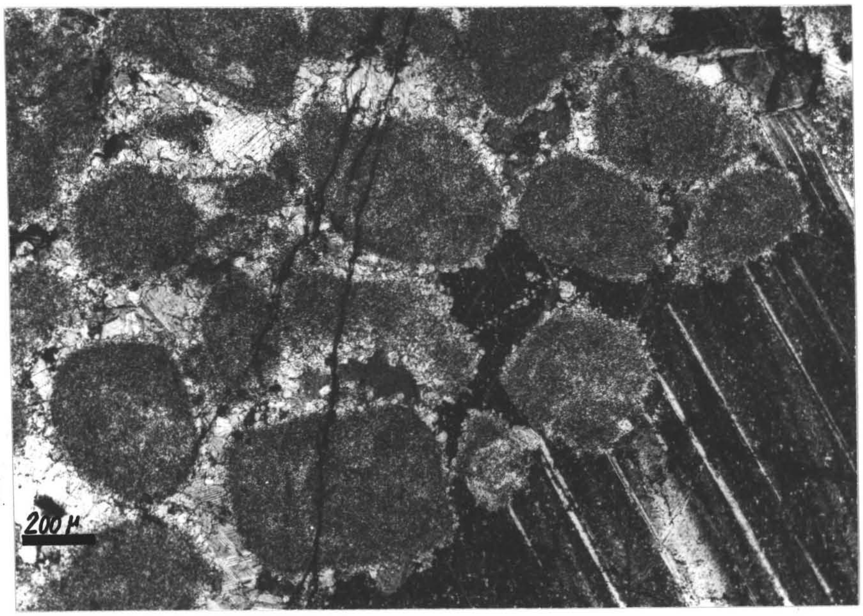


Figure 14. NWUC3. Calcite cement in biosparite. Fine, bladed crust on intraclasts followed by coarse, blocky spar.

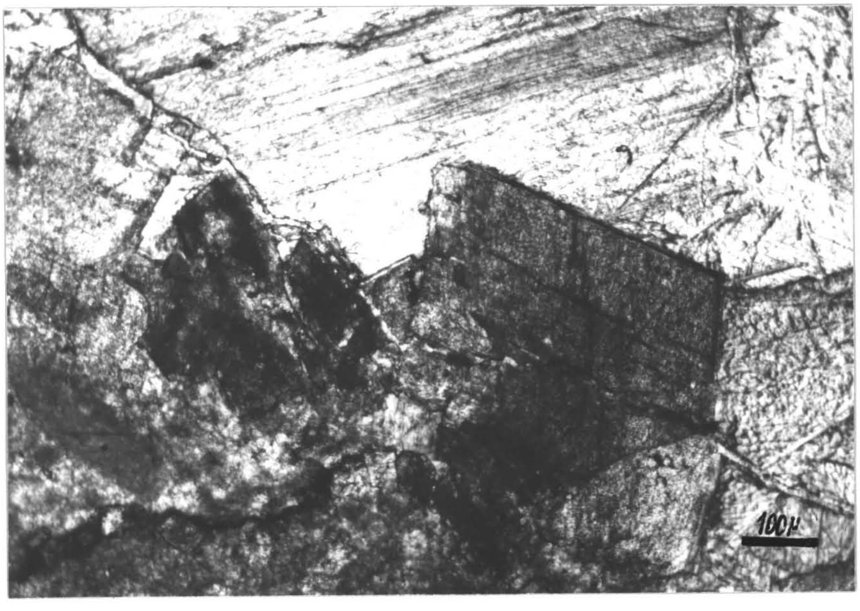


Figure 15. SEUC1B. Dolomite: coarse rhombohedra replace coarse calcite in shell fragment; fine crystals grow in micritic matrix.

proceeded along the distinct fronts common in the Flume. Instead, zoned and ragged-edged euhedra appear to diffuse from concentrations in the matrix. Fine-grained dolomite crystals replace microspar in the matrix and coalesce into local aggregates. Dense microcrystalline calcite intraclasts are not dolomitized, but dolomite is pervasive in the surrounding sparry and micrite-mottled matrix.

Replacement of fine-grained calcite has resulted in irregular growth of dolomite crystals. Micrite intraclasts are not extensively dolomitized, nor are areas of coarse spar. Heterogeneous mixtures of spar and micrite are more often replaced by dolomite. Coarse-grained dolomite inhabits veins. In one specimen, dolomite in a large shell fragment replaces calcite spar along the inner margin of the upper edge, forming crystals equal in size to the replaced calcite (Fig. 15). The replacement has proceeded inward from the shell edge, as well as outward into the matrix. Average total dolomite content of the biostromal facies is 20%.

Bioclastic calcarenites surrounding the biostromes (Fig. 13) contain poorly-sorted micritic intraclasts, calcispheres, shell fragments, Amphipora and other stromatoporoid debris. Large in situ stromatoporoids are absent. Vuggy porosity is well-developed. The disordered nature of many of these rocks, as well as the presence of overturned stromatoporoid fragments and intraclasts of the same matrix, suggests a highly agitated environment.

Dolomite is best developed in areas of medium-grained blocky calcite spar, where the nature of the replacement sequence imparts a ragged-edged appearance to dolomite crystals. Dolomite has replaced fine-grained matrix material but is not pervasive in intraclasts of neomorphic spar which have the dimensions of Amphipora fragments. A sample from calcarenite immediately adjacent to a biostrome on the southeast section is completely undolomitized, and contains no recognizable fossil remains.

Dolomite occurs as a common vein mineral in the calcarenite facies, replacing coarse sparry calcite. These veins also cut through areas of dolomite concentration and appear to be late stage phenomena, yet in some areas, dolomite replaces vein calcite, suggesting yet a second stage of dolomite. Average dolomite content in this facies is about 25%.

One of the most distinctive facies of the Miette complex is the "Amphipora dolomite", which forms laterally extensive beds averaging 1.5 to 2 m thick on the Northwest and Southeast sections. Amphipora fragments about 5 mm in diameter and several centimeters long form up to 75% of this facies, lying parallel to bedding. Both fossils and matrix are replaced by dolomite, which comprises 95 to 100 per cent of these rocks. In thin section, distinction between Amphipora fragments and the dolomite matrix is made on the basis of crystal size and content of brown organic material. Amphipora is replaced by coarser-grained, clear, intergrown dolomite; the surrounding dolomite is finer-grained and quite cloudy (Fig. 16). Fossil fragment boundaries are not clear; some dolomite crystals have grown through them, with the apparent fossil margin in the centre of the crystal.

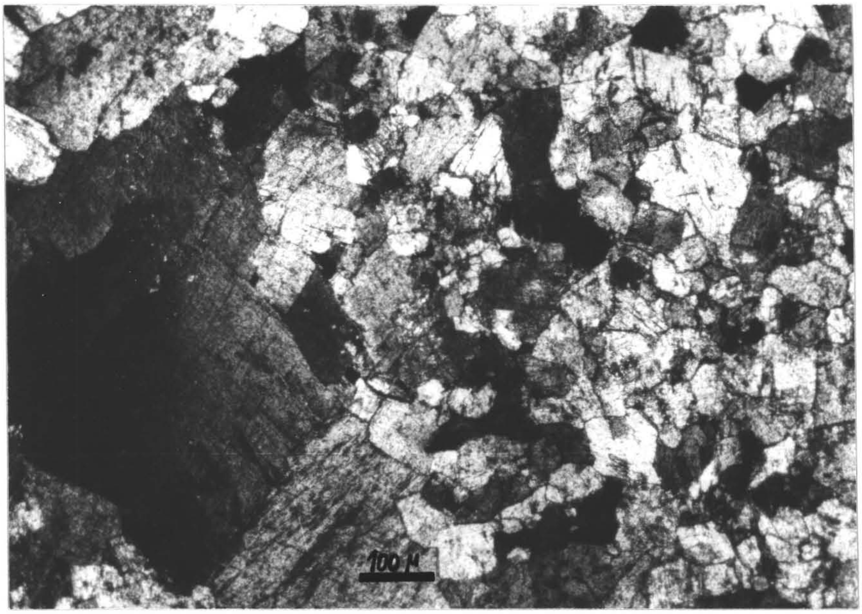


Figure 16. SEUC5. *Amphipora* dolomite. Coarse, clear crystals of dolomite replace *Amphipora*; fine, cloudy crystals replace matrix. Crossed nicols.

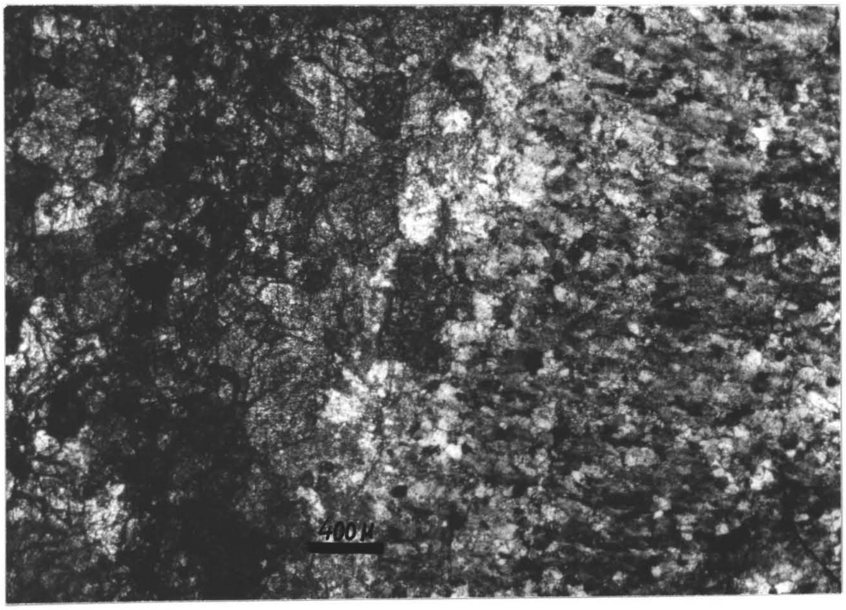


Figure 17. SEUUC7. Undolomitized hemispherical stromatoporoid (right), partially dolomitized robust digitate stromatoporoid (left), and totally dolomitized *Amphipora*-rich matrix.

At this stage in the growth of the complex, increased water depth caused some lateral restriction of the Middle Upper Cairn, but the formation was still widespread(Mountjoy, 1965). Stromatoporoid biostromes were likely patchy developments with lime muds between them in which debris accumulated; Amphipora thickets occurred in sheltered areas.

Organic bank development was restricted to marginal bioherms during late Upper Cairn time as a result of continued rising sea level. The upper Upper Cairn comprises two facies: Amphipora dolomites similar to those of the middle Upper Cairn and massive reef margin dolomite which interdigitates laterally with basin facies of the Perdrix Formation. Some overturned and globular stromatoporoids are present in the upper member, embedded in an Amphipora-rich matrix. The micritic rims common to Flume Formation stromatoporoids appear to have been extensively replaced by medium-grained dolomite encroaching from the outside rim (Fig. 17), but the interior remains elongate neomorphic calcite. In one specimen, a digitate stromatoporoid (Stachyoides sp.?) has been partially replaced by medium-grained dolomite from the outside margins and from internal void spaces (Fig. 17). The matrix is 97% dolomite, identical to the "Amphipora dolomite" of the middle Upper Cairn: coarse, clear dolomite occupies Amphipora fragments; fine, cloudy dolomite fills intermediate spaces. Late stage calcite spar occupies some internal cavities in Amphipora fragments.

Reef margin dolomite on the southeast section forms a massive, irregular unit some 40 m thick. Coarsely crystalline and densely intergrown, the dolomite has well-developed pinpoint and vuggy porosity. Crystals are often distinctly zoned, with cloudy centres. Grain size varies from 30μ to 1mm over the space of a few millimeters. If present, bedding is contorted and indistinct. Fossil fragments are obliterated, but in some areas coarse- and fine-grained dolomite crystals appear similar to the Amphipora-rich facies. There is no evidence of a rigid framework in the samples studied; the margin dolomite seems to be an irregular, porous biostrome of brecciated fragments.

Amphipora dolomites of the topmost Upper Cairn interbed with increasing thicknesses of unfossiliferous lime mud northwest of the margin dolomites.

Southesk Formation

Interbedding of Amphipora dolomite and laminated limestone marks a transition into the Southesk Formation. Reef margin dolomites extend upward laterally equivalent to the Peechee Member of the Southesk. The Peechee Member is generally undolomitized, finely-laminated fenestral limestone, and contains vague micrite peloids, 3 to 5 per cent calcispheres and a few large micrite-coated shell fragments. Fenestrae range from fine, irregular patches of sparry calcite oriented parallel to bedding, to isolated circular vugs almost 2 mm across filled with a fine, bladed calcite crust and coarse central spar. Larger vugs contain a sequence of replacement minerals (Fig. 18). Euhedral pyrite grains are common around the lower edges, followed by a crust of fine-grained, blocky calcite about 50μ thick. Euhedral,

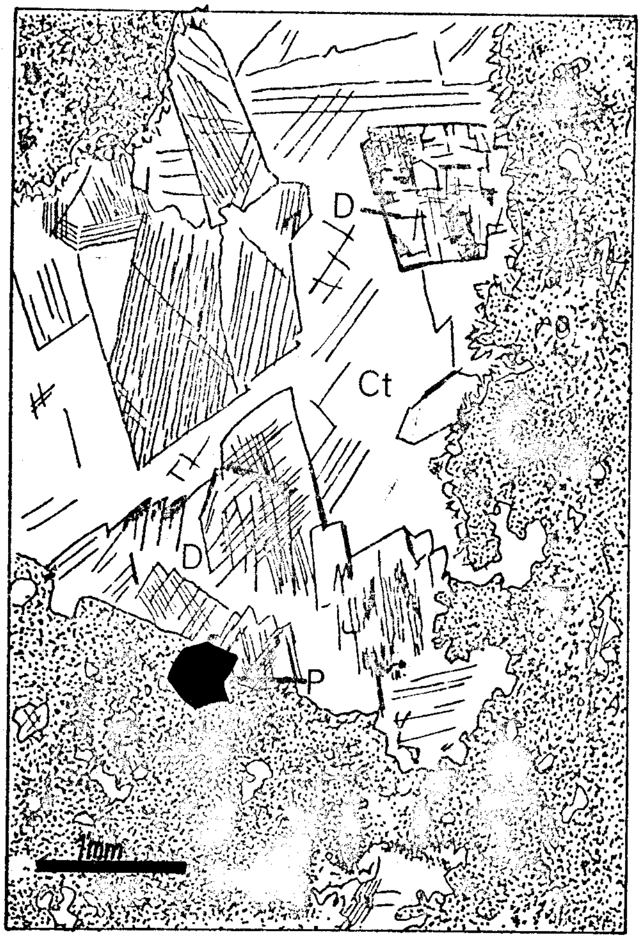
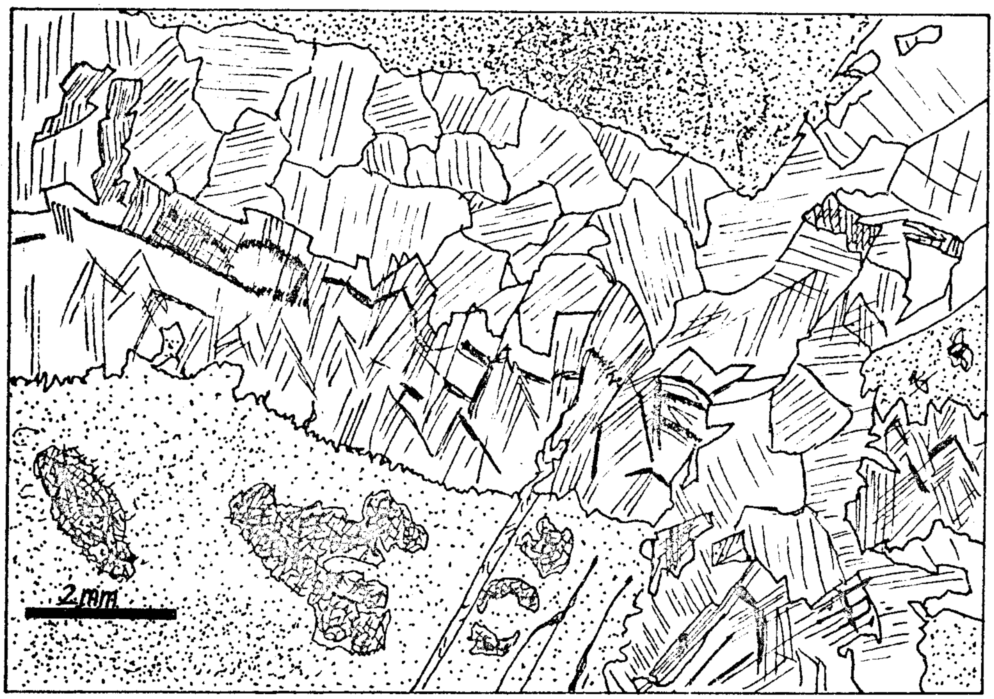


Figure 18 (left). Dolomite-filled fenestra in Arcs Member. Pyrite (P) and dolomite (D) grow at base, dolomite grows over calcite crust on sides. Late stage calcite fills remaining space. NWSK7.

Figure 19 (below). CPC2. Curved crystals of dolomite in vein through Peechee. Late stage calcite fractured and displaced dolomite crystals.



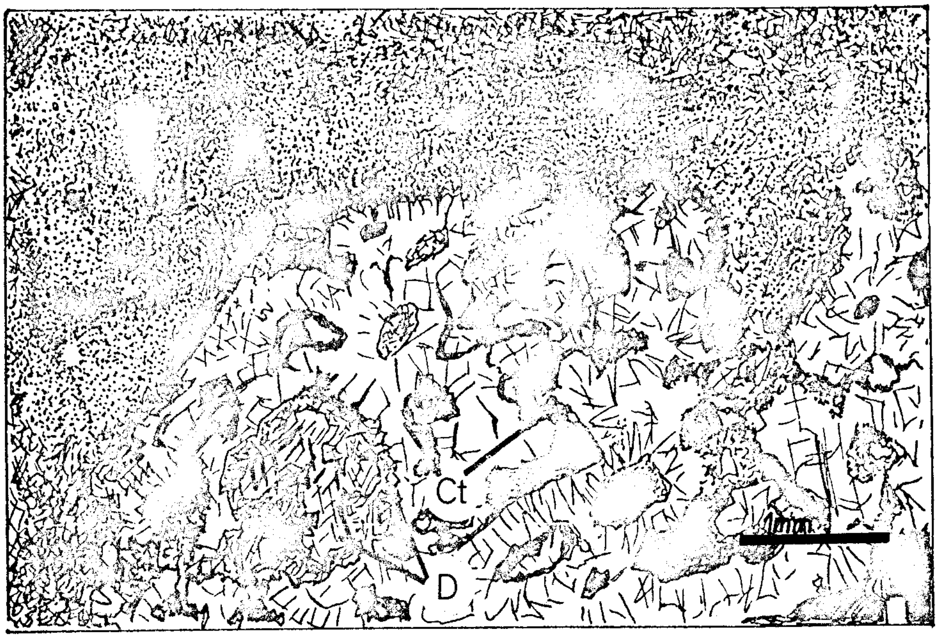
slightly curved dolomite crystals fill part of the vugs and have grown from the base and walls of the fenestrae. The dolomite rhombohedra have grown directly onto the floors of voids, but on the walls are nucleated onto the fine calcite crust. The final stage in fenestral fillings is zonedferroan or pure calcite in large, clear, intergrown crystals. Where dolomite is not present, filling of void space, including interiors of oncolites is completed with coarsely crystalline, zoned, ferroan and non-ferroan calcite. Dolomite veins are common, and dolomite appears to have grown as primary crystals within them, not a secondary replacement (Fig. 19). Long, zoned, blades of ferroan dolomite grow both from the top and bottom margins of veins. Sparry calcite fills remaining spaces and frequently has fractured the dolomite, wedging cleavage planes apart. Occasionally, calcite veins cut through dolomite veins. Hexagonal quartz prisms 0.1 mm in diameter and up to 1 mm long comprise less than 1% of Peechee muds and are probably authigenic.

Grotto Member. Organic bank development ceased at the reef margin late in the period of Peechee deposition. Mountjoy (1965) suspects rise of sea level out-paced the rate of reef buildup, resulting in drowning of most of the Miette complex except for a few coral banks in the Mount Hawk Formation. Slight lowering of sea level allowed recolonization of *Amphipora* thickets, suggested by accumulations of this organism, in the Grotto Member. *Amphipora* with well-preserved internal structures comprises an average of 10% of these rocks, and is partially replaced by dolomite. Dolomite in the matrix clearly replaced micritic mud ahead of shell fragments and sparry patches -- a sequence the reverse of replacement patterns observed in the Flume Formation. In Amphipora fragments, which are normally both micritic and sparry calcite, dolomite has replaced calcite with crystals of grain size equivalent to the original calcite (Fig. 20).

Most of the matrix is micritic mud, with some sparry calcite patches. Calcispheres average 5%; some quartz silt is present in amounts less than 2%. Dolomite averages about 20%, mainly in the form of fine (0.5 mm) euhedral rhombs, rarely as coarse aggregates. The presence of thin units of laminated, very fine-grained silty dolomite suggests some erosion and redeposition of nearby dolomite facies. These units are found in the Grotto Member on the Northwest Section, and are no more than a meter thick. Dolomite grains average 0.1 mm in diameter and are well-sorted; laminae are less than 1 mm thick, and contain 5 to 10 per cent quartz silt. Clay partings separate some laminations and brecciation is obvious in others (Fig. 21). Uniformity of crystal size, preservation of laminae and calcite cement suggest these are thin beds of detrital dolomite.

Arcs Member Overlying the Grotto Member with an abrupt contact are fenestral limestones of the Arcs Member. Petrographically, the Arcs is identical to the Peechee Member, with dolomite and ferroan calcite fenestral fillings.

Ronde Member Silty micritic limestones of the Ronde Member are undolomitized, and represent the final stage of Miette complex deposition. Overlying terrigenous siltstones of the Sassenatch



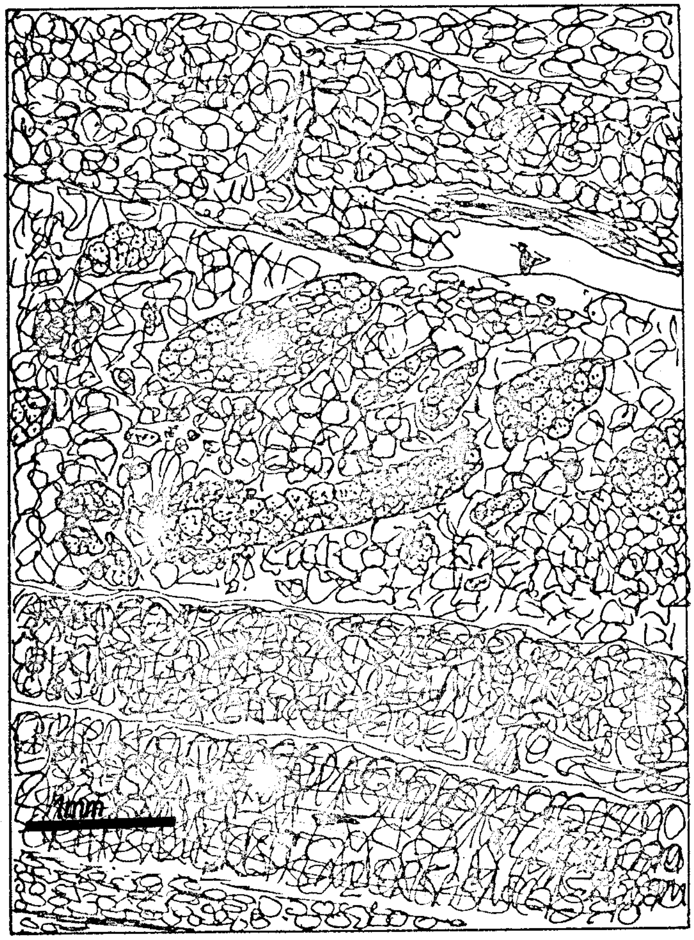


Figure 20 (above) NWUC2. Dolomite replaces calcite in <u>Amphipora</u> with grain size equal to that replaced.

Figure 21 (left) NWSK5 Detrital dolomite. Note intraclasts of the same material embedded in centre lamina. Cement is calcite.

Formation cover reef and basinal facies alike, and form a base for the massive lime mud banks of the Palliser Formation.

4. DISCUSSION

To form dolomite, cations of Magnesium and Calcium must be alternately selected from solution to form a cyclic arrangement of cation and carbonate layers. Although the Mg/Ca ration of seawater is 5.3, which should allow nucleation of dolomite, formation of the crystal is inhibited by crowding of ions in solution and clustering of hydrated Magnesium ions on growing crystal surfaces. Dolomite forms under two natural environments at present: hypersaline lagoons and evaporite basins such as the Persian Sabkhas, the island of Bonaire and Australia's Coorong District, and in locations where fresh and salt water mix in phreatic zones, as in Florida and North Jamaica. A discussion of the major models of Recent dolomitization is found in Bathurst (1971) and list of recent papers is presented in the References.

In the Miette complex, dolomite occurs in several forms. In the upper Flume, dolomite fronts appear to have advanced through peloidal limestone without selection, while dolomite replacement ahead of the fronts is best developed in areas of blocky calcite, between peloids and other intraclasts (Fig. 22). Dolomite crystals occur between peloids and inside shell fragments but do not always replace the fine bladed calcite crust. Land (1970) interpreted calcite cements from the Pleistocene of Bermuda in terms of the hydrologic zone of their formation. A fine, bladed crust up to 45μ thick formed around grains in the marine phreatic zone as calcite precipitated into pore spaces filled

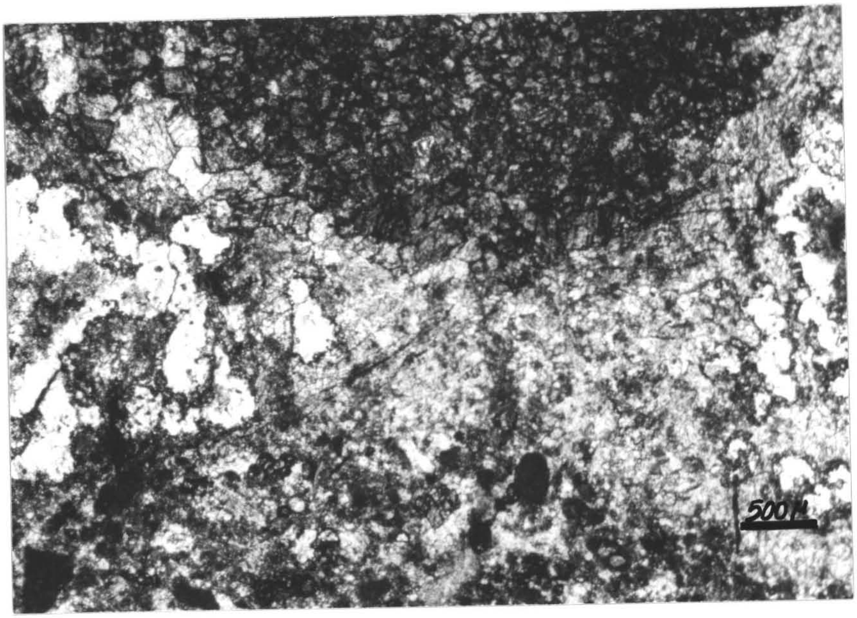


Figure 22. SEFM2A. Lobe of sucrosic dolomite (top) encroaching into biopelsparite. Less dense dolomite concentration at bottom.

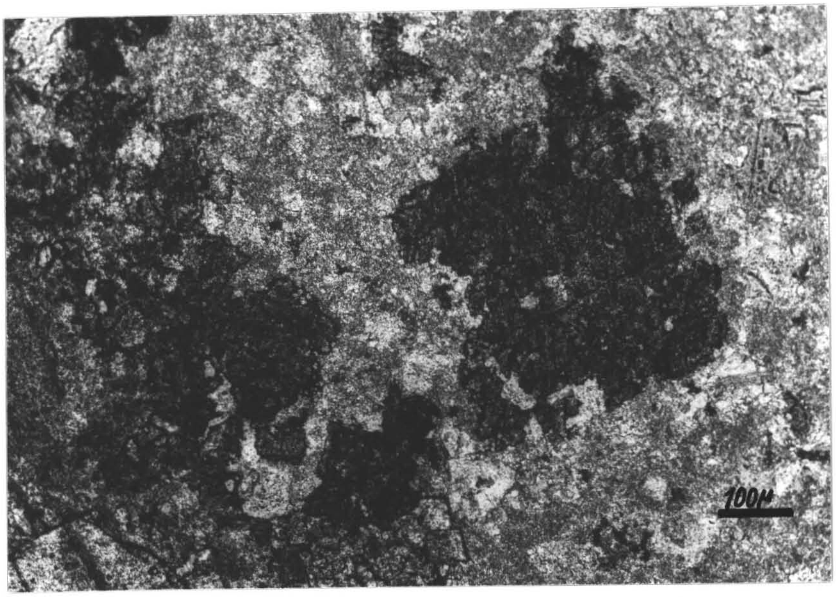


Figure 23. NWSK3B. Dolomite growth in matrix of mixed crystal size is uneven, imparting a ragged appearance to the rhombohedra.

with sea water. In the meteoric phreatic zone, large, blocky calcite crystals fill interstices between grains. Land also notes that in areas where the marine phreatic passed into the meteoric phreatic zone, a thin isopachous crust is followed, without grain size gradation, by a coarse-grained, blocky calcite cement. This sequence of cementation is identical to that found in intraclastic rocks of the Flume and Upper Cairn Formations. In Bermuda, the marine zone passes into the meteoric as beaches accrete seaward; at Miette, two-stage cement may be evidence for sea level fluctuation. An isopachous crust of aragonite or calcite precipitated under original marine conditions. Lowering of sea level extended the meteoric zone and induced precipitation of coarse spar.

Assuming sea level fluctuations created two phases of cementation, a mechanism for dolomitization is proposed. Mixing of salt and fresh water in the meteoric phreatic zone would decrease the concentration of ions in solution, but maintain a Mg/Ca ration close to that of sea water. Folk and Land (1975) give examples of Pleistocene and Recent dolomitization in Florida, Jamaica and Yucatan where freshwater influx into the marine phreatic zone has lowered salinity enough to allow crystallization of dolomite. Dolomite found in association with coarse cements and shell fillings in the Flume Formation may be penecontemporaneous or early diagenetc, formed as magnesium-rich marine interstitial waters came into contact with meteoric waters during of soon after precipitation of calcite cement. This relationship is also found throughout the Upper Cairn Formation, but is not without exception. The Utopia Member of the Flume Formation contains very distinct two-stage calcite cement, but is generally undolomitized. It is possible that the absence of organic matter was a hindrance to dolomite nucleation, or that calcite cementation proceeded to completion without the long term immersion in brackish water necessary for dolomitization.

Permeability control of dolomitization is implied in the foregoing discussion, and is supported by the fact that in the Flume, Cairn and Southesk Formations, only those rocks which are assumed to be initially very permeable show extensive dolomitization. Large, globular stromatoporoids rarely are dolomitized unless the surrounding matrix material approaches 100% dolomite, as in reef margin areas. Percolation of dolomitizing groundwaters may have been inhibited by an impermeable envelope of algae or micrite, also seen on peloids and intraclasts. Dolomitizing fluids appear to have been channelled around impermeable objects in the matrix; dolomite crystals often form fine aggregates along outer margins of stromatoporoids, or replace calcite at the walls of shell fragments.

In the Cairn and Southesk Formations, dolomite preferentially replaces areas of varied crystal size rather than micritic intraclasts or coarse sparry calcite crystals. Micrite has a larger grain surface area but lower permeability, and micritic intraclasts may have been enveloped in algae. Coarse spar has relatively small surface area and is impermeable except by dissolution. Neither of these crystal sizes is extensively replaced if the bed contains dolomite. Replacement of variably sized matrix calcite imparts a ragged appearance to dolomite crystals (Fig. 23).

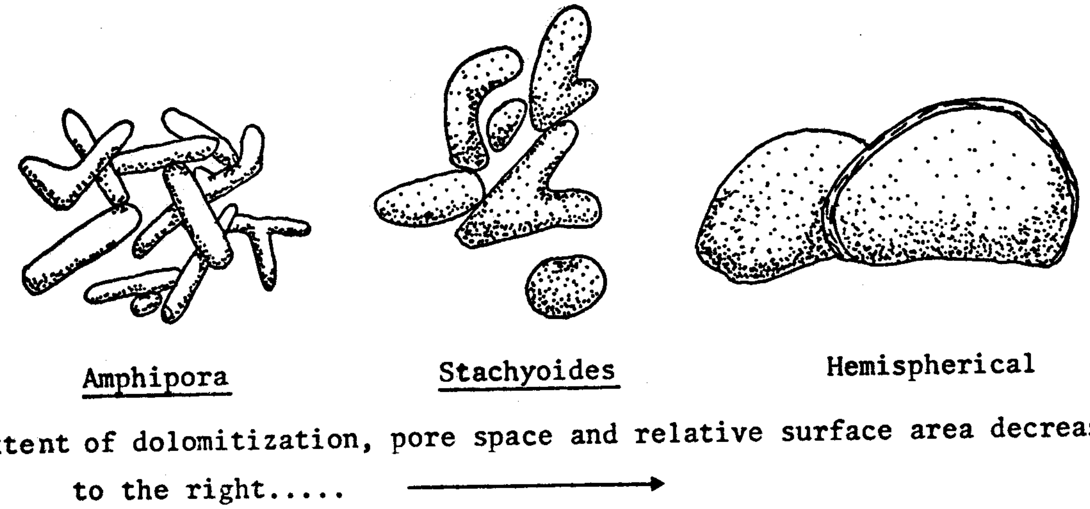


Figure 24. Illustration to show relationship of surface area, size of pore space and extent of dolomitization of stromatoporoid sediments.

The most extensive dolomitization has taken place in Amphipora-rich beds and on the reef margin in the Cairn and Southesk Formations. Amphipora is usually found completely dolomitized or in more advanced s stages of replacement than other stromatoporoids within the same bed. Over the space of several millimeters, Amphipora may be completely replaced by dolomite, more robust Stachyoides partially replaced, and hemispherical stromatoporoids resistant except at outermost margins. This phenomenon is probably a function of surface area to volume ratio. Amphipora is more susceptible to dolomitization due to relatively large surface area and the inherent permeability of a sediment composed largely of skeletal fragments (Fig. 24).

Reef margin dolomites may be penecontemporaneous or later stage diagenetic, but probably are a function of original permeability. The disoriented, brecciated appearance of these dolomites through the Cairn and Southesk Formations suggests they were originally quite porous and open to flushing by potentially dolomitizing fluids. Andrichuk (1958a) describes maximum dolomitization in Cairn equivalents of the Leduc reef at the core of the reef, not at the margin as at Miette. Dolomitization is also greatest at the cores of modern coral atolls in the Pacific (Berner, 1965). Berner proposed a reflux-type model for Pacific atolls, with dense, magnesium-rich brines sinking through the magnesian-calcite sediments of the lagoon floor and dolomitizing them under pressure deep beneath the surface. Andrichuk (1958a) observed that where wave agitation was assumed greatest on the Leduc reef and Redwater reef front, rapid precipitation of $CaCO_3$ probably inhibited dolomite formation. Sediments laterally equivalent to the margin dolomites at Miette range from the partially dolomitized biostromal and calcarenite facies and the Amphipora dolomites of the Cairn to the dolomite-free Peechee Member of the Southesk. Cairn sediments behind the margin often contain brecciated and overturned stromatoporoids and other debris, suggesting wave or current action. The Peechee Member is a fine-grained laminated fenestral limestone probably of tidal origin (Shinn,1968; Mountjoy, in press). If the internal areas of the Miette complex were under the influence of shallow water currents and tides, then the porous marginal biostromes may have been repeatedly flushed with sea water and occasionally with fresh water from subaerial exposures.

Peechee Member equivalents in the Leduc and other central Alberta reefs are typified by varied conditions of deposition, shifting biostromal patch reefs, subaerial exposure and restricted illite soil development (Belyea,1964). No evaporites exist at Miette, so a reflux model will not explain dolomite development at the margin. If the presence of tides or irregular subaerial exposure can be concluded from petrographic evidence, it is possible that flushing of the porous reef margin by fresh and salt water mixtures may have induced dolomitization. Porous, Amphipora-rich beds may also have been affected in this manner, while fine-grained, compacted muds such as the Peechee and Arcs Members would have been much less permeable, hence less susceptible to replacement by dolomite.

Reef margin dolomites may owe their origin in part to later diagenetic processes during compaction and compression of the sediments of the reef and basin. Connate salt water trapped in basinal shales might have been squeezed out during compression and forced into more permeable and porous reef margin rocks. Autobrecciation of the reef margin during compaction might further have developed permeability.

It is conceivable that some organisms of the Miette complex secreted magnesian-calcite skeletons, which would provide an additional source of Mg^{2+}; these organisms themselves would presumably be more readily dolomitized. Amphipora may have been such an organism, but inferences of this sort must remain unsubstantiated, especially because stromatoporoids have not yet been successfully classified.

Replacement of dolomite by chert, and subsequent dolomitization of the chert is a phenomenon observed by Armstrong (1970) in Mississippian dolomites of Alaska, and Walker (1962) in Ordovician limestones of Wisconsin. In the Flume Formation, silica pseudomorphs of dolomite rhombohedra are among the relict textures of limestone in bedded and nodular chert.

Subsequent dolomitization of the chert is evident in small dolomite euhedra "floating" in the chert, and in replacement by aggregate dolomite behind distinct fronts. Amorphous silica is very soluble in solutions of pH greater than 9, while increased pH induces precipitation of a carbonate phase (dolomite if conditions are right). Thus, multiple chert-dolomite replacement may indicate fluctuations of pH in the formation waters, possibly produced by decay of organic matter in a later diagenetic phase.

The phenomenon of lobes of dolomite aggregates replacing matrix constituents along stylolitic fronts is thought to be a later stage process, primarily because of its lack of permeability control. Magnesium-rich fluids may have been squeezed through the Flume and Cairn Formations during compaction of the reef and basin sediments. Dissolution of existing calcite created the stylolitic fronts of insolubles and some peloid or intraclast ghosts remain behind the fronts. Concentrations of sparry calcite found in association with the fronts may have been precipitated when the dolomite replacement process halted.

Dolomite veins and fenestrae fillings in the Peechee and Arcs Members of the Southesk Formation appear to be primary crystals from a post-cementation diagenetic stage. Autobrecciation and compaction possibly opened the small fissures through which magnesium-rich solutions flowed. Some fenestrae in the Peechee and Arcs resemble burrows, and contain granular pyrite, presumably from organic decay. Dolomite rhombohedra in these "burrows" may have been formed simultaneously with dolomite veining, or induced by increased pH within the restricted cavities.

The presence of thin detrital beds in the Grotto Member of the Southesk Formation implies that penecontemporaneous dolomite was being eroded from the Miette vicinity. Regression of sea level beginning at the end of Peechee deposition may have locally exposed portions of the marginal biostromes, or brought them into a surf zone.

A final stage in diagenetic development involved filling of most remaining pore spaces in all facies of the reef with calcite spar. Dedolomitization is evident in some of these late stage calcites, with calcite pseudomorphs in optical continuity with partially replaced dolomite. This may have coincided with late stage compression during lithification or with the development of stylolites which are pervasive throughout the complex. Stylolites were the last major diagenetic process to affect the Miette reef, concentrating dolomite crystals along with other insolubles at the surfaces of solution.

5. CONCLUSIONS

Dolomitization on the Miette complex has proceeded in several stages from penecontemporaneous to diagenetic. Late diagenetic reflux is not suggested for the Miette reef, as there is no evidence for the presence of evaporites or for the lack of permeability control which such a model demands (Hsü, 1966). Interbedding of dolomitic and non-dolomitic rocks precludes late stage regional dolomitization.

1) Penecontemporaneous dolomite occurs as discrete and aggregate rhombohedra in relatively permeable matrix materials. These include a) cement of heterogeneous crystal size, b) *Amphipora*-rich beds, c) reef margin biostromes. Penecontemporaneous dolomite is probably very early replacement of unstable aragonite or magnesian-calcite.

2) The proposed mechanism for early dolomitization is mixing of salt water with meteoric water in the phreatic zone, similar to Pleistocene and Recent sediments of Jamaica, Florida and Yucatan (Folk and Land, 1975).

3) Reef margin dolomites of the Cairn and Southesk Formations may have been formed by flushing of sea water through marginal biostromes during tidal cycles or infrequent subaerial exposures.

4) Connate water squeezed from compacting sediments may have aided dolomitization of the reef margin and caused migration of dolomite fronts through partially lithified sediments of the Flume and Cairn Formations. These lobes are not controlled by permeability; dolomite replaces micrite, spar and chert.

5) A chert-dolomite replacement cycle in the Flume Formation indicates a) initial partial dolomitization of calcite or aragonite sediment, b) replacement by chert, c) partial dissolution of chert and replacement by dolomite, possibly as a result of high pH.

6) The presence of boring and burrowing organisms is implied in the Flume Formation by silica-filled tubules and micrite filaments in stromatoporoids and intraclasts; in the Cairn Formation by centripetal replacement by micrite of shells and intraclasts, and in the Southesk Formation by dolomite-filled burrows in tidal sediments. No spicules, scolecodonts or conodonts were found.

7) Thin units of detrital dolomite in the Grotto Member of the Southesk Formation imply the existance of a penecontemporaneous dolomite in the near vicinity.

8) In general, dolomitization at Miette was controlled by permeability of the host material. Permeable Amphipora-rich beds are dolomitized across the entire southeast margin exposure, while reef margin dolomites end abruptly at fine-grained, impermeable Peechee Member lime muds. The major source of magnesium for dolomitization is assumed to have been sea water, but the mechanism for replacement of calcite required mixing with meteoric waters.

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APPENDIX

THIN SECTION DESCRIPTION

PROCEDURE

Forty-nine thin sections were cut from representative lithologies of the Miette complex. All were etched in HCl and stained following the method outlined by Dickson (1965; 1966), which uses a combination of Alizarin Red S and Potassium Ferricyanide. This procedure stains calcite and dolomite as follows: Dolomite $(Ca,Mg)(CO_3)_2$ remains unstained;

Ferroan Dolomite $(Ca(Fe,Mg)(CO_3)_2$ stains blue;

Calcite $CaCO_3$ stains red;

Ferroan Calcite $(Ca,Fe)CO_3$ stains purple.

Additional petrologic information was obtained from polished and etched slabs of each sample. Qualitative examination of insoluble residue after dissolution in HCl was accomplished with a binocular microscope. Point counts of a minimum 150 points on each slide furnished constituent percentages.

FLUME FOMATION

Samples: SEFM1, SEFM2A, and 2B, SEFM3, SEFM4, SEFM5A and 5B, NWU1, NWFM1, NWFM2.

<u>SEFM1</u> Dolomitic limestone. Globular stromatoporoid replaced with micrite and calcite spar. Chert-filled borings less than 1mm diameter penetrate to 4mm. Micrite-filled tubules 0.05 to 0.2mm diameter penetrate to 1mm. Laminated micritic external envelope 2mm thick. No dolomite within stromatoporoid or micrite envelope. Matrix surrounding stromatoporoid is biomicrite: 10% peloids less than 0.8mm diam., 40% intraclasts:

micrite and peloid aggregates up to 1.5mm diam, compacted, showing flattened outlines but separated by calcite spar cement. 5% calcispheres within intraclasts, 0.5mm diam. 4% shell fragments -- small brachiopods, ostracodes; disarticulated, replaced by sparry calcite, up to 2mm long. 30% sparry calcite cement: fine, bladed crystals form crust of edges of peloids and intraclasts; probably a replacement of penecontemporary cement which precipitated before compression flattened some intraclasts. Secondary, large calcite crystals fill the remaining space. 11% dolomite: discrete and aggregate rhombs up to 1mm diam. in matrix only. Replaces coarse spar between peloids. Calcite spar-filled fractures are early diagenetic in some cases, crossing intraclasts without penetrating the surrounding matrix.

<u>SEFM2A</u> Chert occurs as nodules and stringers. Borings in stromatoporoid fragments coalesce to form irregular cherty masses. A poorly-sorted, disordered matrix of <u>Amphipora</u>, disarticulated and articulated brachiopods, ostracodes, intraclasts, peloids. Common intraclasts of similar matrix material, micrite chips, broken sparry shell fragments. 20% dolomite: euhedra less than 0.4mm diam. and aggregates within interstitial calcite. Aggregates are confined within lobes, composed of dolomite euhedra and coarse calcite spar. Dolomite lobes appear to have advanced through matrix material unselectively.

<u>SEFM2B</u> Similar to SEFM2A. Brachiopod shells are more often articulated and commonly [illegible]lled with calcite spar and coarse-grained dolomite. 17% dolomite: [illegible] to 0.9mm euhedra, preferentially replacing areas of heterogeneous [illegible] size. Coarse (1.5mm) crystals in shell interiors.

Dolomite often fills internal areas of shells but does not replace the fine calcite crust. Chert-filled tubules common in stromatoporoids and Amphipora, very commonly centered by a singleeuhedral calcite crystal 0.25mm diam. Chert tubules often show a central core of aphanitic brown chert under 0.5mm diam, surrounded by radial chalcedony to a diameter of about 1mm, all enclosed by a cloudy chert and micrite envelope about 0.5mm thick.

SEFM3 Well-sorted and densely-packed micritic peloids 0.5mm diam., near polygonal. Intraclasts with calcisphere centres. Cement is fine-grained calcite crust deposited before compaction. Dolomite in tongues of equant euhedra in peloidal matrix. Dolomite content of matrix ranges from 0 to 15% and is selective of interstices between peloids but grows across their boundaries. Behind fronts, dolomite comprises 50 to 100% containing some ghosts of peloids. Fronts are stylolitic and marked by concentrations of insolubles -- clays, hematite, bitumin.

SEFM4 Organic-rich brown chert replaces original limestone matrix; contains pseudomorphs of calcispheres, shell fragments, intraclasts and dolomite euhedra. Matrix is micrite with sparry mottlings; 5% shell fragments, 2% calcispheres. 5% dolomite in the chert, 0.1 to 0.2mm rhombohedra. 12% dolomite in matrix: dense aggregates in lobes replacing both chert and micrite. Quartz-filled veins and microfaults in chert. Calcite-filled veins in micrite extend through dolomite lobes and are broken and replaced by dolomite elsewhere.

SEFM5A Matrix material as in SEFM4, containing a large brachiopod with spiralia intact. Micritized shell fragments contain chert-filled tubules as in SEFM1, with calcite centres. Veins through micrite intraclasts contain matrix material as well as calcite spar and coarse dolomite, suggesting penecontemporary brecciation. 17% dolomite: scattered and aggregate rhombohedra prefer fine sparry interstices. No dolomite in stromatoporoid fragments or micrite intraclasts; not in shell rims but in internal spaces. Dolomite rarely is found in areas of coarse calcite, then is coarse-grained itself (1 to 2 mm). Fine, discontinuous calcite-filled veins are cut by dolomite rhombohedra. Stylolites are common.

SEFM5B Matrix similar to SEFM5A but contains fewer shell fragments (5%), more large broken stromatoporoids. Chert in calcite-centred tubules in stromatoporoid fragments and micritized shells. Hexagonal authigenic quartz needles (2%). Outside of stromatoporoid fragments, the matrix is 80% dolomite.

NWU1 Utopia Member. 62% loosely-packed peloids and intraclasts of micrite, containing 11% calcispheres. Peloids 0.5mm in diam, intraclasts less than 1.5mm diam. Cement is sparry calcite in two stages: a fine bladed crust less than 50u thick, followed by coarse, occasionally poikilotopically overgrown crystals. Common small stylolites filled with reddish hematite and clays. No dolomite.

NWFM1 Fenestral biomicrite. Micrite intraclasts containing chert tubules comprise about 10%. Intraclasts broken, filled with matrix material and coarse calcite spar. 7% dolomite: small (0.2 to 0.3mm) rhombohedra and aggregates; common at stromatoporoid fragment edges and as replacement of matrix calcite crystals. Shell fragments comprise 6%, calcispheres 1%. Fine calcite veins normal to bedding predate dolomite crystallization and growth of stylolites.

NWFM2 Well-preserved stromatoporoid with chert-filled, calcite-centred tubules at its edge. Dolomite comprises less than 1% of matrix; euhedra 0.3 to 0.4 mm diam.

UPPER CAIRN FORMATION -- MIDDLE MEMBER

Samples: SEUC1A, and 1B, SEUC2, SEUC3, SEUC4A and 4B, SEUC5, SEUC6, NWUC1, NWUC2.

SEUC1A Biopelsparite matrix: 10% intraclasts, 5% calcispheres, 15% elliptical micrite peloids less than 0.5mm diam, 10% shell fragments, 20% calcite cement. 40% dolomite: zoned discrete or aggregate rhombohedra preferentially replaving cement of varied crystal size. Poikilotopic appearance of dolomite formed as crystals grew and surrounded calcite. Late stage dolomite Veins. "Biostromal facies".

SEUC1B Matrix similar to SEUC1A bu contains 15% dolomite. Biopelsparite with micrite peloids, large shell fragment, sparry cement. Dolomite: scattered euhedra and dense lobate aggregates in matrix , coarse (1.5mm) euhedral crystals growing inside and outside of shell rim. Dolomite appears to assume the crystal size of the calcite being replaced.

SEUC2 Calcarenite from beside a biostrome. UNdolomitized bioclastic lime mud: 10% irregular micrite intraclasts less than 1mm diam. 5% calcispheres, [illegible] brachiopods and ostracodes, 25% sparry calcite cement, 50% irregular, patchy micrite, less than 1% iron oxide grains.

SEUC3 Biopelsparite. Indistinct, mottled micrite peloids, 10% brachiopod and ostracode shell fragments, 7% calcispheres in sparry matrix. 50% dolomite: discrete rhombohedra and coalescing aggregates. Concentrations of 60 to 100% dolomite in lobes replacing peloids and spar in matrix. Coarse dolomite and sparry calcite coexist in veins which cut through all constituents.

SEUC4A *Amphipora* dolomite. 30% *Amphipora* fragments,completely replaced, along with matrix, by dolomite. Dolomite in *Amphipora* is coarse-grained (1mm) and clear, dolomite in matrix is finer-grained (0.5mm) and cloudy, containing vague peloidal outlines. Rere intergranular late stage calcite.

SEUC4B Biopelmicrite. Intraclasts of micrite, 30% peloids, 5% calcispheres, 1% quartz needles. Microspar matrix with irregular patches of red-brown amorphous material which is insoluble in HCl and separates as fibres. 35% dolomite: Discrete rhombohedra 0.5mm in diam., some with poikilotopic calcite inclusions. Dolomite preferentially replaces micritic matrix; peloid ghosts are found within dolomite crystals. Stylolites are common, concentrating clays, quartz and dolomite along solution surfaces.

SEUC5 Similar to SEUC4A. *Amphipora* dolomite. 75% *Amphipora* parallel to bedding.

SEUC6 Similar to SEUC5. *Amphipora* dolomite. 20% *Amphipora*, 70% dolomite matrix, 2% late stage calcite in interstitial spaces between dolomite crystals in Amphipora.

NWUC1 Crystalline dolomite from 4-foot bed. 99% dolomite, no recognisable fossils, pinpoint and vuggy porosity. Late stage calcite pore filling.

NWUC2 Bioclastic dolomite. 60% Amphipora with minor dolomitization of internal spaces. Brecciated Amphipora and micrite intraclasts in a matrix of dolomite. 30% dolomite: r gged-edged, poikilotopic, occasionally rounded crystals comprise most of the matrix. Crystal size varies from 0.1 to 1.0mm.

UPPER CAIRN FORMATION UPPER MEMBER

Samples: SEUUC7, SEUUC8, SEUUC9, SEUUC10, SEUUC11, NWUUC3, NWUUC4.

SEUUC7 Amphipora dolomite. 65% Amphipora in matrix beween hemispherical stromatoporoid and Stachyoides fragments. Dolomite does not occur within the large stromatoporoid, partially replaces the robust digitate Stachyoides and totally replaces Amphipora and its surrounding matrix. This appears to be a pile of biostromal debris in an Amphipora-rich matrix.

SEUUC8 Crystalline "reef margin" dolomite. Unbedded, medium to coarse-grained, intergrown dolomite comprises 98%. 2% calcite spar in veins and small vugs. Cloudy patches of amorphous brown material are structureless.

SEUUC9 Similar to SEUUC8. 98% dolomite; average diam. 1.0mm, zoned. Grain size varies from 0.5 to 1.5mm over several millimeters. Late st stage calcite spar fills intergranular spaces.

SEUUCN10 Massive crystalline dolomite. UNdulating bedding. Dolomite comprises 90%, large calcite spar crystals in vug or vein contain smaller dolomite crystals and have forced dolomite cleavage planes apart.

SEUUC11 Crystalline dolomite, similar to SEUUC10. Contains brown, amorphous, vaguely peloidal mottling and late stage calcite.

NWUUC3 UNdolomitized pelsparite. Looseley-packed, parallel-laminated peloidal matrix. 15% micrite intraclasts up to 9mm long, 5% calcispheres, 1% ostracodes, 60% peloids 0.1 to 1.0mm diam. Some peloids are encruste with calcite and hematite (?). Cement is two-stage calcite spar: fine crust followed by coarse overgrowth. This bed is in the transition zone from Upper Cairn to the Peechee Member of the Southesk Formation.

NWUUC4 *Amphipora* dolomite, interbedded with units similar to NWUUC3. 50% *Amphipora*; 99% dolomite, 1% late stage calcite.

SOUTHESK FORMATION PEECHEE MEMBER

Samples: CPC2, CPC3, CPC4, CPC5, CPC6A, CPC7, NWSK2, NWSK4.

CPC2 Dismicrite. Fine-grained fenestral limestone. 4% calcispheres in matrix of fine-grained calcite with irregular patches of coarse spar. 1% hexagonal quartz needles. Initial fenestrae fill is calcite, followed by zoned ferroan calcite. Zoned ferroan dolomite occurs only in late stage veins, following precipitation of a fine calcite crust in places and succeeded by coarse calcite.

CPC3 Dismicrite. Cloudy brown micrite with calcite spar-filled fenestrae arranged in subparallel manner to bedding. Undolomitized.

CPC4 Dismicrite containing micrite-rimmed pelecypod shells. No dolomite.

CPC5Pelsparite. Peloidal micrite in calcite spar cement. Laminated, with common stylolites. Dark laminae are more tightly compressed. 4% quartz silt, 2% iron oxide grains.

CPC6 Undolomitized microsparite. Micrite-coated oncolites. Micrite outer rim, fine-grained calcite spar interior ring (grain size 0.08 to 0.1mm) 1.5mm thick becoming coarser towards centre. Internal space filled with bladed spar up to 0.7mm long growing inward, followed by coarse ferroan calcite. Surrounding matrix similar to CPC5 but slightly coarser-grained.

CPC7 Stylolite marks a division between ferroan microspar and non-ferroan micrite. Undolomitized.

NWSK2 Dismicrite. Calcite and ferroan calcite fill fenestrae. Ferroan dolomite and later calcite occupy veins. Fenestrae show initial bladed internal calcite crust, indicating they were open soon after deposition.

NWSK4 Biodismicrite. 5% calcispheres, 5% shell debris in fine-grained calcite and micrite matrix with spar-filled fenestrae. Undolomitized.

SOUTHESK FORMATION GROTTO MEMBER

Samples: NWSK1B,1M and 1T, NWSK3A and 3B, NWSK5A and 5B,
NWSK6L and 6U.

NWSK1B Disordered intraclasts of relatively clear microspar and rare brachiopods and ostracodes (2%) in a matrix of brown, cloudy dolomite, microspar, and 1% euhedral hematite (0.15mm diam). 45% dolomite.

NWSK1M Stromatoporoid breccia in biopelmicrite matrix. Calcispheres 1%, shell fragments 2%, vague micritic peloids; stromatoporoid fragments replaced by neomorphic elongate calcite crystals. 24% dolomite: cloudy brown aggregates in stromatoporoid fragments; pitted aggregates associated with stylolites; vein filling in late stage.

NWSK1T Biopelsparite. Disordered, mottled mass of brachiopod fragments (2%), Amphipora (9%), calcispheres (1%), micrite peloids 0.25mm diam. 10%, in a heterogeneous matrix of fine-grained calcite, micrite, coarse sparry patches and dolomite. 36% dolomite: crust of fine-grained crystals in matrix on micrite intraclasts; clear, pitted aggregates of coarse crystals (2mm diam.); fine-grained (0.5mm) cloudy,brown, pitted rhombohedra.

NWSK3A and 3B Microsparite. 10% Amphipora fragments in matrix of faintly-laminated microspar. 20% dolomite: irregular patches of intergrown, sucrosic crystals and scattered floating euhedra.

NWSK5A and 5B Laminated detrital dolomite. Finely-laminated granular dolomite and 10% quartz silt, both less than 0.3mm diam. Some brecciation, clay partings, ferroan calcite cement. 3% euhedral pyrite 0.25mm diam; calcite veins parallel and perpendicular to bedding.

NWSK6L Finely crystalline (0.08 to 0.2mm) dolomite with fenestrae of coarse, clear dolomite, and some small patches of interstial calcite.

Pyrite euhedra less than 0.7mm diam. comprise 2%. Accessory amounts of euhedral quartz. Dolomite occurs as fine matrix crystals 0.08 to 0.2mm diam; fenestrae fillings 0.5mm diam, and vein rhombohedra 1.2mm diam. coexisting with coarse calcite.

NWSK6U Biomicrite immediately overlying NWSK6L. Poorly sorted, unoriented shell debris -- brachiopods, ostracodes, pelecypods (20%), 5% calcispheres, 1% quartz silt, 40% micrite matrix and intraclasts, 10% sparry calcite, 20% dolomite. Dolomite occurs as fine-grained, cloudy euhedra, preferentially replacing micrite matrix areas before intraclasts or shells. Two-stage calcite cement is evident in shell fragments; dolomite rarely replaces the fine initial crust but does replace coarser spar.

SOUTHESK FORMATION ARCS AND RONDE MEMBERS

NWSK7 ARCS MEMBER Biomicrite with fenestral calcite. 70% micrite matrix containing 5% calcispheres, 12% brachiopods and ostracodes, 1% quartz silt, 14% calcite spar and late stage ferroan dolomite in veins and fenestrae.

NWSK8 RONDE MEMBER Pelsparite. Less than 2% shell fragments and calcispheres in a faintly-laminated matrix (40%) of micrite peloids 0.2mm in diameter. Pockets of calcite spar in sub-parallel fenestrae; medium-grained spar cement. Some undulating clay partings and accessory iron oxide grains. No dolomite.

SASSENATCH FORMATION

NWSS1 Undolomitized, quartz-rich pelsparite. Parallel-laminated micrite (30%), with 20% peloids and intraclasts 0.2mm diam., 15% quartz silt, 33% sparry calcite cement.

CSS1 Undolomitized quartz siltstone. Subround to subangular quartz silt (0.25mm) cemented by calcite.