SEDIMENTOLOGY AND DIAGENESIS
OF MIDDLE DEVONIAN WINNIPEGOSIS REEF COMPLEXES
DAWSON BAY, MANITOBA

by

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ABSTRACT

Winnipegosis reef complexes probably consist of coalesced buildups, 75 to 100 m thick. They occur on a platform, 10 to 15 m thick. Basin sediments, 10 m thick, surround the complexes.

Six facies are identified: 1) platform (lower and upper platform subfacies); 2) buildup interior; 3) buildup flank (laminated, bioturbated, cemented subfacies); 4) organic rim; 5) stromatolite cap; 6) basin (Brightholme, Ratner Members).

Diagenesis occurred in four diagenetic environments: 1) open marine; 2) subaerial/meteoric; 3) restricted marine/shallow subsurface; 4) deeper subsurface. Fibrous cements occur in the cemented subfacies. Calcrete horizons with pendant cements formed in the stromatolite cap facies. All sediments are dolomitized.

Isotopic data suggest that dolomitization occurred in the restricted marine and shallow burial environments in fluids derived from normal to slightly hypersaline Middle Devonian marine waters. Dolomitizing fluids derived from either the mechanical compaction of encasing evaporites or deeper formation waters were probably funnelled into the buildups.

Minor fracturing and calcite cementation occurred in the deeper subsurface. Dedolomitization and calcitization of evaporites probably occurred at greater depths.

RESUME

Le complex de recifs du Winnipegosis consiste probablement en une agglomération verticale de 75 à 100 m d'epaisseur. Ces agglomérations de recifs se retrouvent sur une plateforme de 10 à 15 m d'épaisseur. Le complex est entoure de sediments basinaux de 10 m d'épaisseur.

Six faciès sont identifiés: 1) plateforme (sous-facies a la base et au sommet de la plateforme), 2) l'interieur de l'agglomération de récifs, 3) les flancs de l'agglomeration de récifs (sous-facies laminés, bioturbes et cimentes), 4) pourtour organique, 5) chapeau superieur stromatolique, 6) basin (Membres de Brightholme et Ratner).

La diagénèse est présent dans quatre environments diagénètiques: 1) mer ouverte, 2)subaérier/meteoritique, 3) sous surface profond. Les ciments fibreux (columnaires) sont presents dans le sous-faciés cimenté. Les horizons de caliche présentants des ciments pendulaires se forment dans le chapeau supérieur stromatolique. Tous les sédiments sont dolomitises.

Les données isotopiques suggèrents que la dolomitisation se produisit dans des environments marins et d'enfouissement peu profond à même des fluides puisés des eaux Devoniennes de salinité normale a quelque peu hypersaline. La compaction mécanique des sequences évaporitiques superieurs a probablement servi a acheminer les fluides a l'agglomeration de récifs.

Une fracturation mineure ainsi qu'une cimentation de calcite sont présentes dans des environments d'enfouissement plus profond. La dédolomitisation ainsi que la calcitisation des séquences évaporitiques sont presentes beaucoup plus profondément.

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CHAPTER 1. INTRODUCTION AND GEOLOGICAL FRAMEWORK

This research project investigates the sedimentology and diagenesis of the Winnipegosis Formation in Dawson Bay, Manitoba.

1.1 OBJECTIVES

1. Identify and describe the major lithofacies.
2. Interpret the depositional history of the carbonate buildups and related basin facies.
3. Investigate sedimentological evidence for sea level fluctuations during Winnipegosis time.
4. Describe and interpret the diagenetic textures.
5. Determine the potential sources of dolomitizing fluids, and suggest possible mechanisms of dolomitization.

1.2 LOCATION OF THE STUDY AREA

The Dawson Bay area occurs at the north end of Lake Winnipegosis in central Manitoba (Fig. 1). Specifically, the study area is situated between latitudes 52°45'N and 53°15'N, and longitudes 100°30'W and 101°15'W on NTS map sheets 63C and 63F (scale 1:250 000); between townships 43 and 28, and ranges 21 and 25 west of the Prime Meridian.

1.3 PREVIOUS STUDIES

The first detailed investigation of the Winnipegosis outcrop belt was undertaken by J.B.Tyrrell in 1888 and 1889. He described the dolostone exposures in Dawson Bay, and assigned them to the Winnipegosan Formation (Tyrrell, 1892). While working with Tyrrell, Whiteaves (1892) collected and identified many fossils including the pentamerid, <u>Stringocephalus</u> <u>burtini</u> - an index fossil that confirmed the

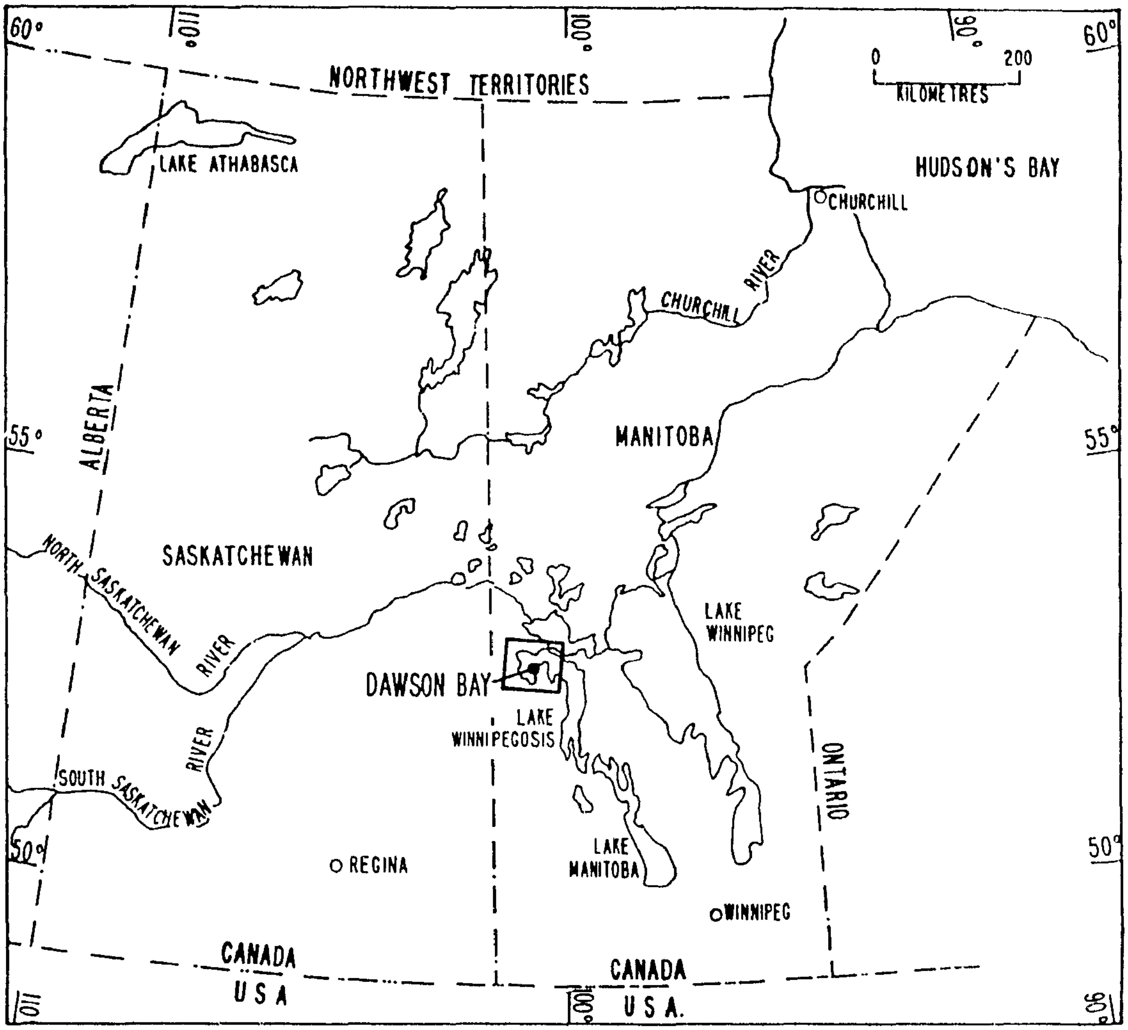


Fig. 1 Index map of Prairie Prcvinces showing location of Dawson Bay, Lake Winnipegosis, Manitoba

Middle Devonian age of these rocks.

Baillie (1951) provided a detailed account of the sedimentology and paleontology of the Winnipegosan bioherm (klintar) facies in Dawson Bay. In addition, he proposed a revised classification of Devonian rocks in the Elk Point Group, and changed the name of the Winnipegosan Formation to the Winnipegosis Formation (Baillie, 1953, 1955).

Jones (1964, 1965) subdivided the Winnipegosis Formation into lower and upper members corresponding to the platform and reefal sediments. Carbonate laminites, named the Ratner Member, were restricted to interreef areas, and were interpreted to be facies equivalent to the carbonate buildups (Wardlaw and Reinson, 1971).

Kendall (1975) recognized the interbedded nature of the 'off-reef' bituminous laminites and 'reef' derived detritus on the foreslope facies of carbonate banks in Saskatchewan. He suggested that the evaporitic Ratner beds represented the basal sediments of the Prairie Evaporite Formation. Furthermore, he proposed that these sediments were not facies equivalent to the buildups but, in fact, postdated them.

In a useful regional study, Norris et al. (1982) incorporated considerable drill hole and outcrop data, and provided a general overview of the stratigraphic and sedimentological history of the Devonian outcrop belt. In addition, a systematic report on the conodont paleontology was included.

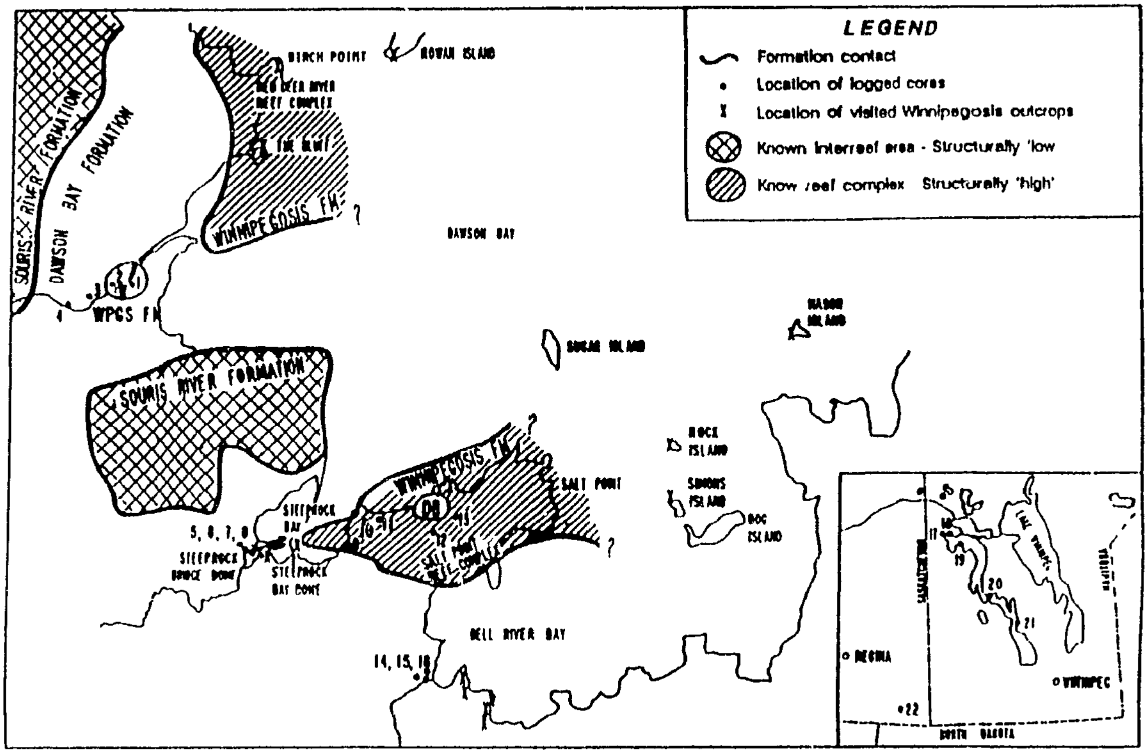
McCabe (1986) assembled the latest of a series of field trip guidebooks to the outcrop belt, in which recent core data has helped clarify stratigraphic relationships between 'reef' and 'off-reef' sediments. Also, the guidebooks provide: 1) a useful overview of the stratigraphic relationships between the

Winnipegosis Formation and younger Devonian beds; and 2) a general description of buildup and basin sedimentology.

Since the recent oil discoveries in Saskatchewan, the Winnipegosis buildups in Saskatchewan, Manitoba and North Dakota have received considerable attention from geologists. Sedimentological models outlining buildup development in the different regions have been published: for example, Saskatchewan (Martindale and Orr, 1987; Martindale and MacDonald, 1989), Manitoba (Teare, 1987; Rosenthal, 1988) and North Dakota (Perrin, 1982; Ehrets and Kissling, 1987; Precht, 1987).

1.4 METHODS AND PROCEDURES

During the summers of 1986 and 1987, seven weeks were spent logging, photographing and sampling 1700 metres of diamond-drill core from 21 wells of Winnipegosis buildup, platform and basin sediments at the Manitoba Department of Mines core facility, University of Manitoba, Winnipeg (Fig. 2). Six drill cores of Winnipegosis sediments were studied from outside the study area: the Cameron Bay basin well, (M-3-73), situated 20 km to the northeast; the Overflow Bay wells, M-6-78, M-7-73, situated 20 km to the north; the Gunnlaugson limestone buildup, (M-5-87), and the Meadow Portage basin well, (M-5-76), are respectively located 250 km and 150 km southeast of Dawson Bay; and the Home Oil Macoun well, 14-35-04-10W2, located in the southeast corner of Saskatchewan. Core was provided courtesy of the Manitoba Department of Mines and Inco Ltd. The Home Oil Macoun well core was sampled for carbon, oxygen, and strontium isotope analysis. In August 1987, three weeks were spent undertaking detailed sedimentological mapping of the Winnipegosis exposures in Dawson Bay.



1. M-18-77
2. M-10-72
3. 47-76-14
4. 47-76-2
5. M-17-81
6. M-8-86
7. M-7-86
8. S-5-75
9. M-5-87
10. 635-48
11. M-4-87
12. 635-47
13. 635-46
14. M-2-84
15. M-3-84
16. M-3-85
17. M-6-76
18. M-12-71
19. M-3-73
20. M-2-87
21. M-5-76
22. 14-35-04-10W2M

For well locations and core logs, refer to Appendix 4.

Fig 2 Geology of the Dawson Bay area and location of logged cores in Manitoba and Saskatchewan

Two hundred and fifty petrographic thin sections were made to study sedimentary and diagenetic textures. All thin sections were stained with Alizarin Red S and potassium ferricyanide using the technique outlined by Dickson (1965). Selected thin sections were studied under cathodoluminescence at McGill University. Six specimens were analyzed for strontium isotope composition at McMaster University by Professor R.McNutt. Forty three specimens were analyzed for carbon and oxygen isotope composition at the University of Michigan by Professor K.C.Lohmann.

1.5 REGIONAL GEOLOGIC FRAMEWORK

Winnipegosis buildups are scattered throughout the southern half of the Middle Devonian Elk Point Basin. The basin extends from the Northwest Territories, across the prairie provinces, and into North Dakota (Grayston et al., 1964). It is bounded by the Presqu'ile Barrier to the northwest, the Peace River Arch and West Alberta Ridge to the west, the Black Hills Uplift to the south, and the craton to the east (Fig. 3). The exact distance to the eastern limit of the basin is uncertain as all stratigraphic evidence has been eroded away. However, McCabe (1967) demonstrated that the depositional strike of the Winnipegosis fringing shelf was abruptly truncated at right angles by the northwesterly trending erosional edge indicating that the basin margin must have occurred a considerable distance to the east (Fig. 4)

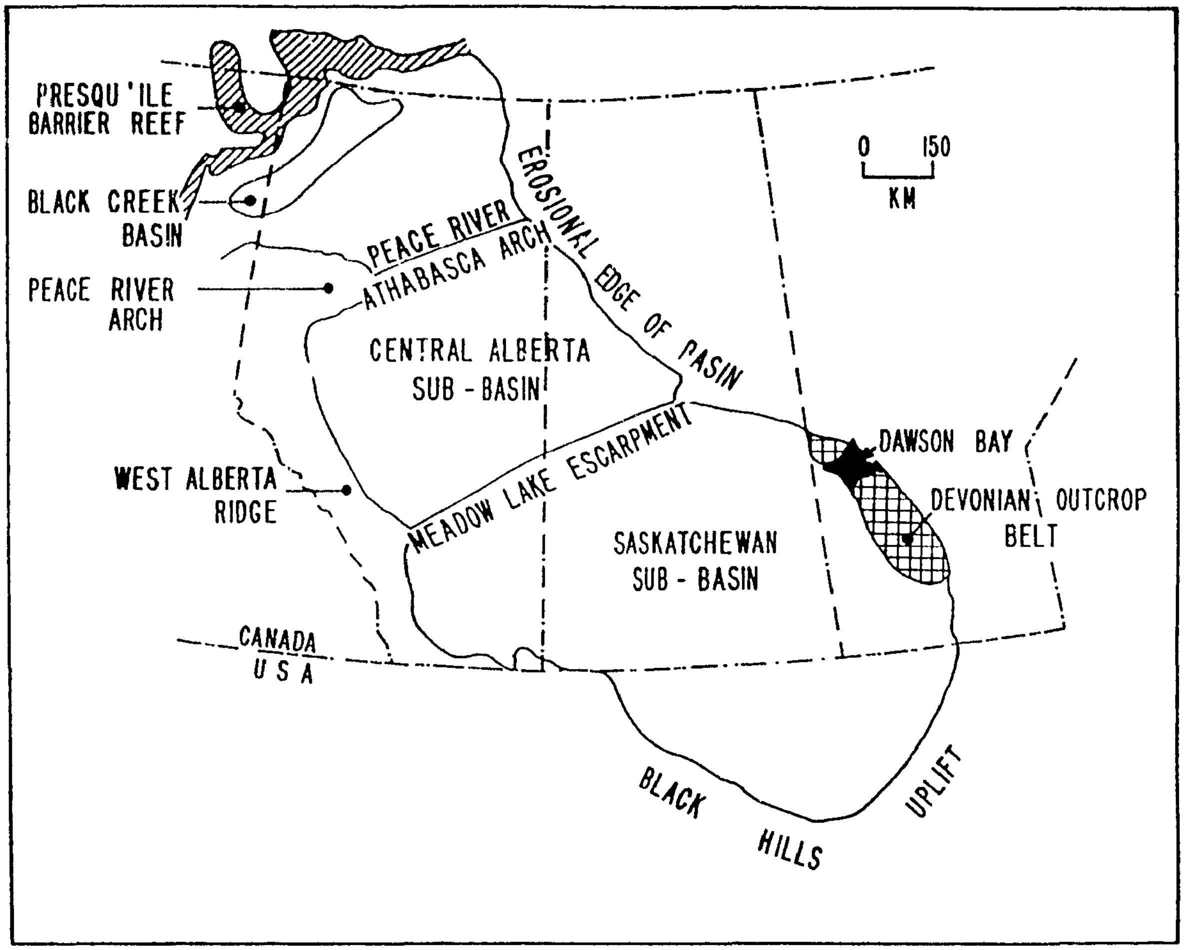


Fig. 3 The Middle Devonian Elk Point Basin

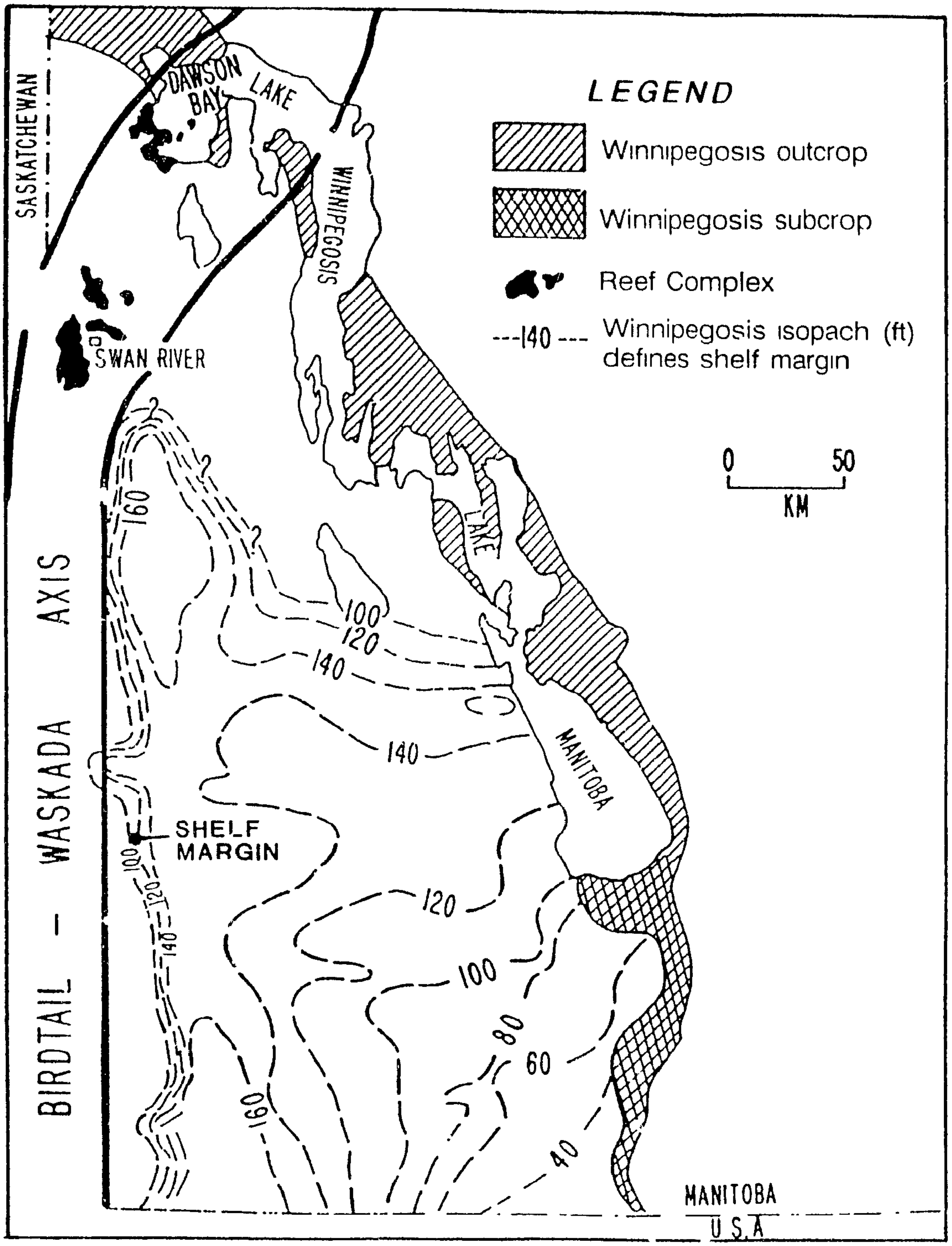


Fig 4 Isopach map of the Winnipegosis Formation in southern Manitoba

NOTE 1) the Birdtail–Waskada Axis represents the boundary zone between the Superior and Churchill crustal plates

2) the truncation of the Winnipegosis isopach by the erosional edge (modified after Norris et al, 1982) indicates that the basin may have extended some distance eastward prior to erosion

The basin is divided into several subbasins in which carbonate shelf and buildup sediments were deposited contemporaneously. To the northwest, the Black Creek basin contains the hydrocarbon producing Keg River and Zama carbonate buildups (e.g., Schmidt et al., 1985). In general, Winnipegosis buildups are located in the Saskatchewan subbasin limited by the Meadow Lake Escarpment to the north and the Transcontinental Arch (Black Hills Uplift) to the south. The Dawson Bay exposures of the Winnipegosis buildups occur on the northern flank of the preserved portion of the subbasin (Fig. 3).

1.6 REGIONAL TECTONICS

The well defined western edge of the Winnipegosis fringing bank falls on the projected boundary of the Birdtail-Waskada Axis, between the Churchill and Superior crustal plates (Fig. 4) (McCabe 1986). Furthermore, the Dawson Bay and Swan River 'reefal' complexes occur along this zone. Structural flexure across the zone may have controlled the inception and orientation of the Dawson Bay buildups (Norris et al., 1982).

1.7 REGIONAL STRATIGRAPHY

The general stratigraphy of the Elk Point Group is outlined in Figure 5. The red dolomitic shales of the Ashern Formation represent the basal deposits of a transgressive event which flooded the Elk Point Basin in the Eifelian. These deposits are conformably overlain by the Winnipegosis Formation which is divisible into four members: the platform sediments of the Lower Winnipegosis Member, the buildups of the Upper Winnipegosis Member, the basinal bituminous mudstones of the Brightholme Member and the basinal bituminous laminites, dolomitic mudstones and calcitized evaporites of the Ratner Member. The term 'Brightholme Member' was informally applied

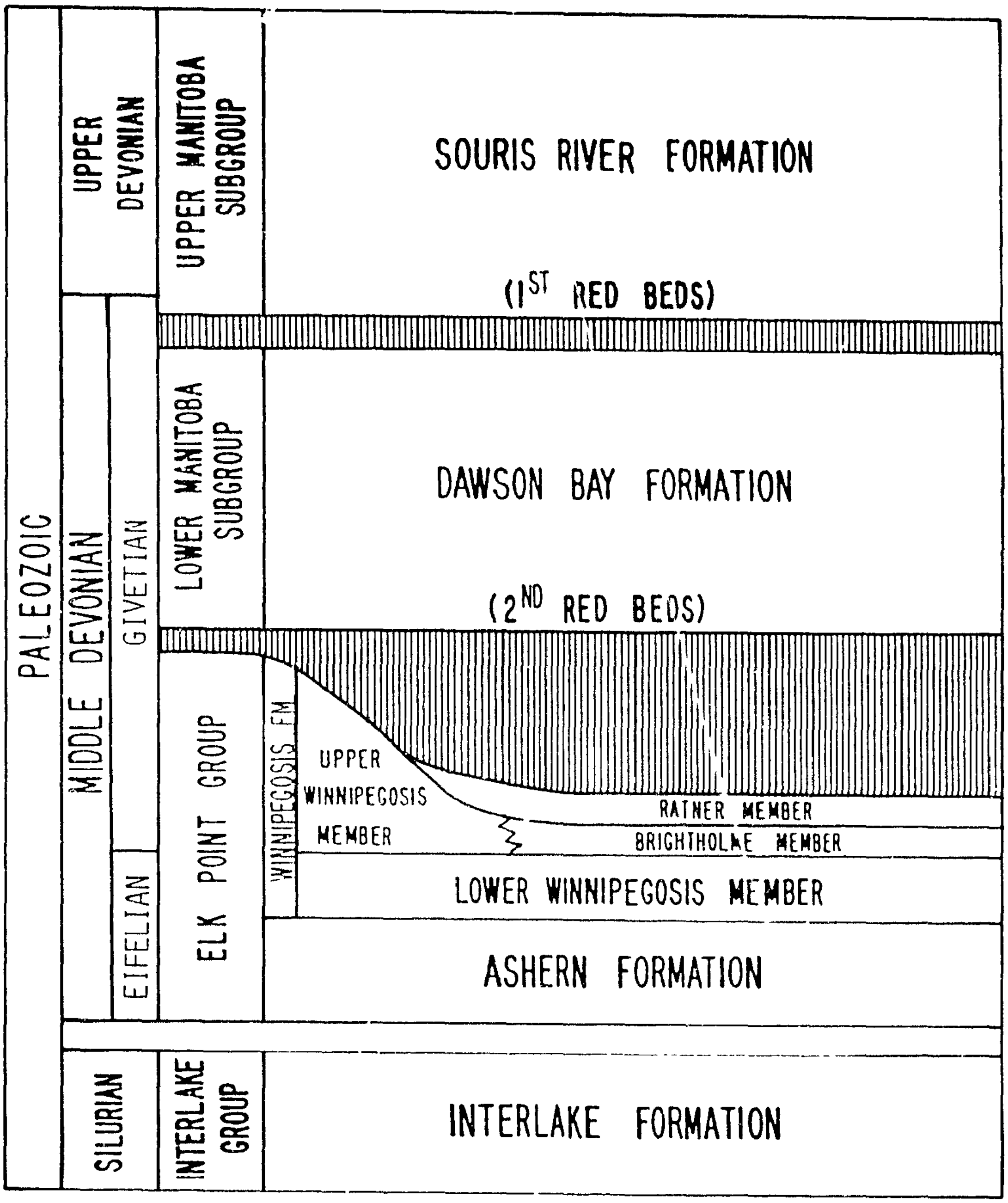


Fig. 5 Table of Devonian formations in the outcrop belt

to the bituminous mudstones in Saskatchewan (Kendall, pers. comm., 1988). In the study area, the evaporites of the Prairie Evaporite Formation have been dissolved causing the structural collapse of younger Devonian formations on top of the underlying Winnipegosis. The Frasnian Souris River Formation outcrops in structurally low areas that correspond to the Winnipegosis 'interreef' or basin environments. The Dawson Bay Formation is preserved draping over the underlying Winnipegosis Formation. The gently rolling topography in the field area is attributed to this doming of the Dawson Bay limestones by the Winnipegosis buildups.

1.8 DEPOSITIONAL FRAMEWORK OF THE DAWSON BAY BUILDUPS

The buildups in the Dawson Bay area are 75 to 100 m thick, and are situated 250 km north of the fringing shelf (Fig. 4) (McCabe, 1986). Because of the uniformity of buildup thicknesses and a regional dip of only 1.8 m/km, 'reef-supported' structural highs and 'interreef' structural lows are readily defined in outcrop and from core (McCabe pers.comm., 1986; Norris et al., 1982). Subsequently, at least two 'reef' complexes, the Red Deer River Complex and the Salt Point Complex, may be mapped in the outcrop area (Fig. 2).

A second important inference can be made if the Dawson Bay buildups are of uniform height (McCabe, 1986). As Winnipegosis exposures on the islands of Dawson Bay are traced up regional dip to the northeast, each outcrop corresponds to sections that become stratigraphically lower within the buildup succession. To the southwest, the Steeprock Bay Dome is the stratigraphically highest buildup exposure, whereas Mason Island represents the most up-dip, and stratigraphically lowest buildup exposure to the northeast (Fig. 2). Extrapolation of the regional dip would place the base of the Mason Island section about 25 m above the platform (McCabe, 1986).

From the data available, it is not possible to determine the original size, shape or extent of the 'reef' complexes with certairty. Horizoncal beds of the Dawson Bay Formation on the Salt Point Complex suggest that the underlying Winnipegosis buildups are flat topped (McCabe 1986). Other outcrop exposures, such as the Bluff, appear to be separated from the main complexes and may represent more simple buildups. Possibly, the 'reef' complexes began as groups of individual accumulations of shoaling sediments. During buildup development, the lateral accretion of flank sediments caused individual buildups to merge to form larger single complexes on the order of a few kilometres across.

CHAPTER 2. SEDIMENTOLOGY

2.1 INTRODUCTION

The petrologic and petrographic characteristics of Winnipegosis depositional units are outlined under six environmental facies: platform, interior, flank, organic rim, stromatolite cap, and basin. The platform facies is subdivided into the lower and upper platform subfacies. The flank facies is subdivided into three subfacies: laminated, bioturbated, and cemented. The basin facies is subdivided into two subfacies that correspond to the Brightholme and Ratner Members (Fig. 6).

This chapter includes a summary of the sedimentological data, an outline of platform, buildup and basin sedimentation, and a discussion of sea level fluctuations during Winnipegosis time. The sedimentology plates appear at the end of the chapter.

The term 'buildup' refers to the thick accumulations of carbonate sediments above an underlying platform (Plate 1A). The terms 'reef' or 'pinnacle-reef' were considered inappropriate because of the relative paucity of organic framework in individual buildups. Nevertheless, the term 'reef complex' is used to describe the larger agglomerations of buildups. All figures outlining buildup development are schematic, and do not represent the cross sectional profile of any one buildup or complex. Diagrams outlining the stratigraphy and sedimentology of all logged cores and outcrop sections occur in Appendices 3 and 4.

Winnipegosis rocks were classified following Dunham (1962) and Embry and Klovan (1971). Microfacies analysis was carried out following schemes by Wilson (1975) and Flugel (1982). Fossils

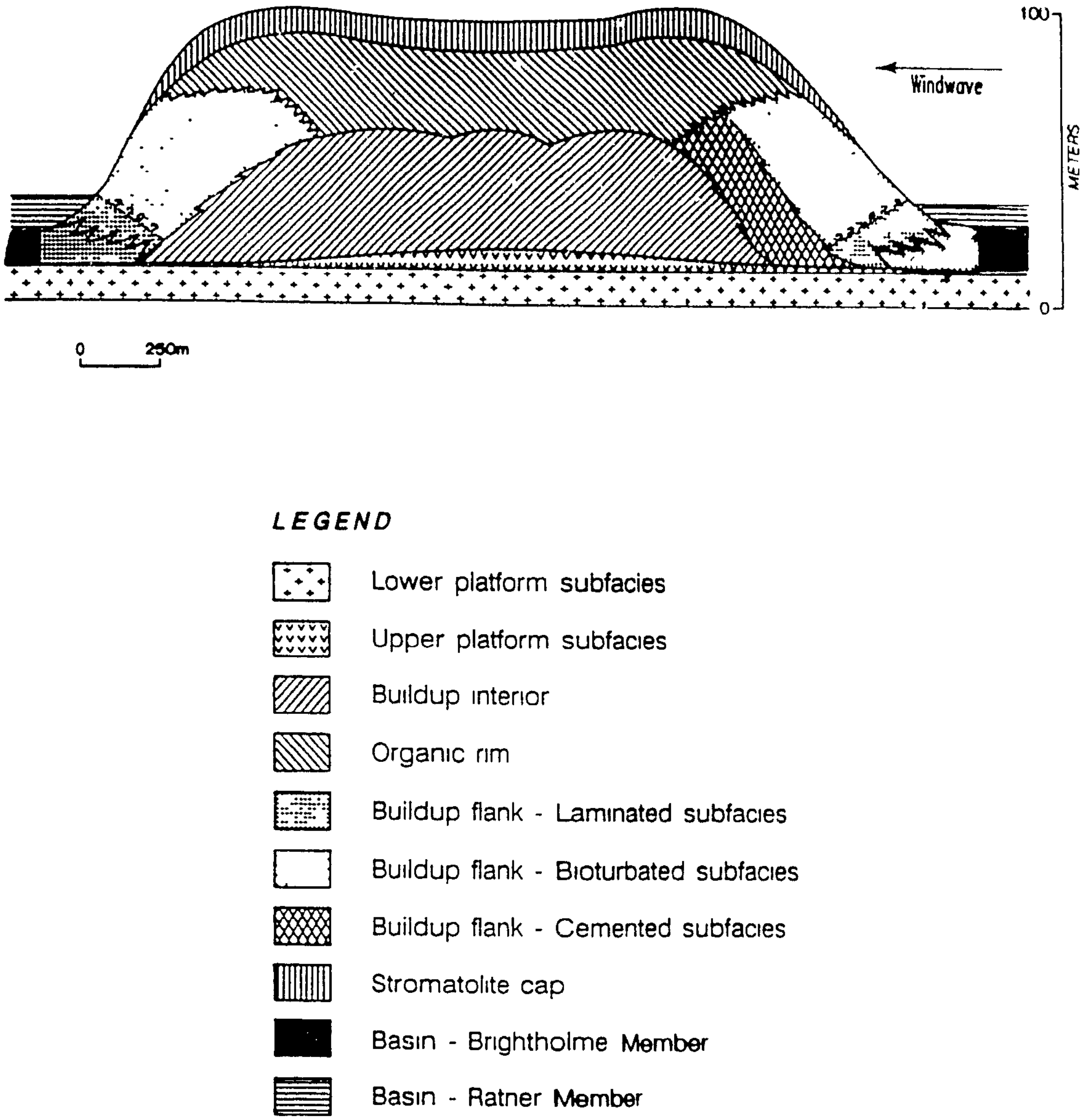


Fig. 6 Schematic diagram of the Winnipegosis facies and subfacies

were identified from compendiums of photomicrographs and their descriptions by Horowitz and Potter (1971) and Scholle (1979).

2.2 CARBONATE PLATFORM

The regionally extensive platform facies of the Lower Winnipegosis Member is observed in all drill cores which penetrate the entire Winnipegosis Formation; it is not exposed in outcrop. In the study area, these sediments are completely dolomitized, and are differentiated into lower and upper platform subfacies.

2.2.1 Lower Platform Subfacies

The lower platform subfacies underlies both buildup and basin sediments (Fig. 7). It is relatively uniform in thickness, ranging from 10 m to 12 m. Predominantly, the sediments are comprised of mottled crinoid wackestones and packstones. Brachiopods are common, and ostracods and bryozoans occur in minor amounts. The light coloured mottles are surrounded by a darker brown, finely crystalline mud.

2.2.2 Upper Platform Subfacies

The upper platform subfacies overlies the lower platform subfacies, and varies in thickness from 3 to 5 m beneath buildups and 0.5 to 1.0 m beneath basin sediments (Fig. 7). Beneath the buildups, these sediments are comprised of brown crinoid packstones (Plate 1B). Beneath the buildup flank sediments, stromatoporoid floatstones and wackestones contain abundant black bituminous wisps of preserved organic matter incorporated into the rock matrix by bioturbation (Plate 1C and D).

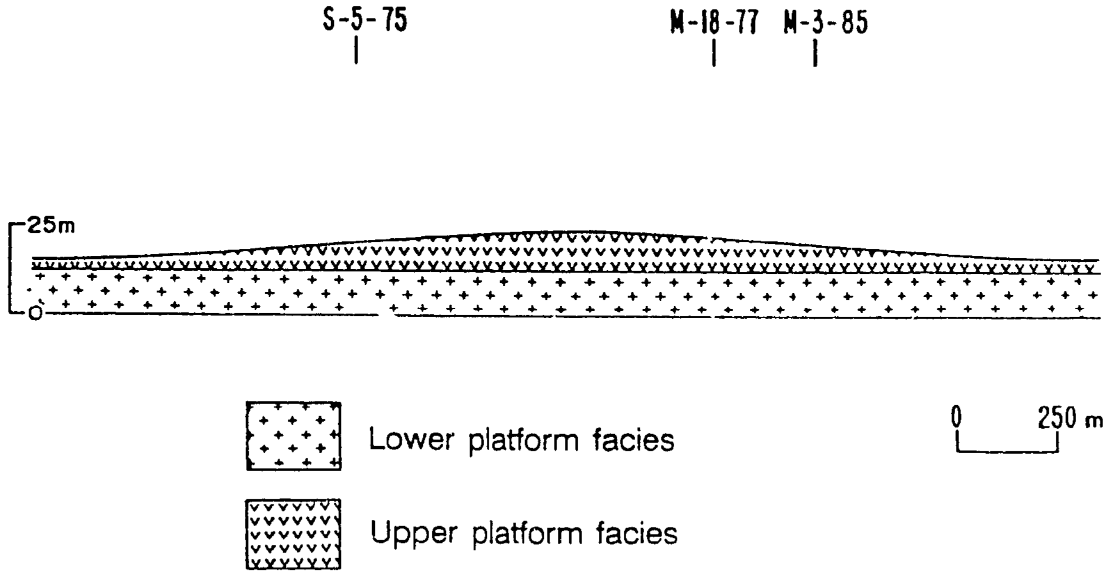


Fig. 7 Lower and upper platform facies

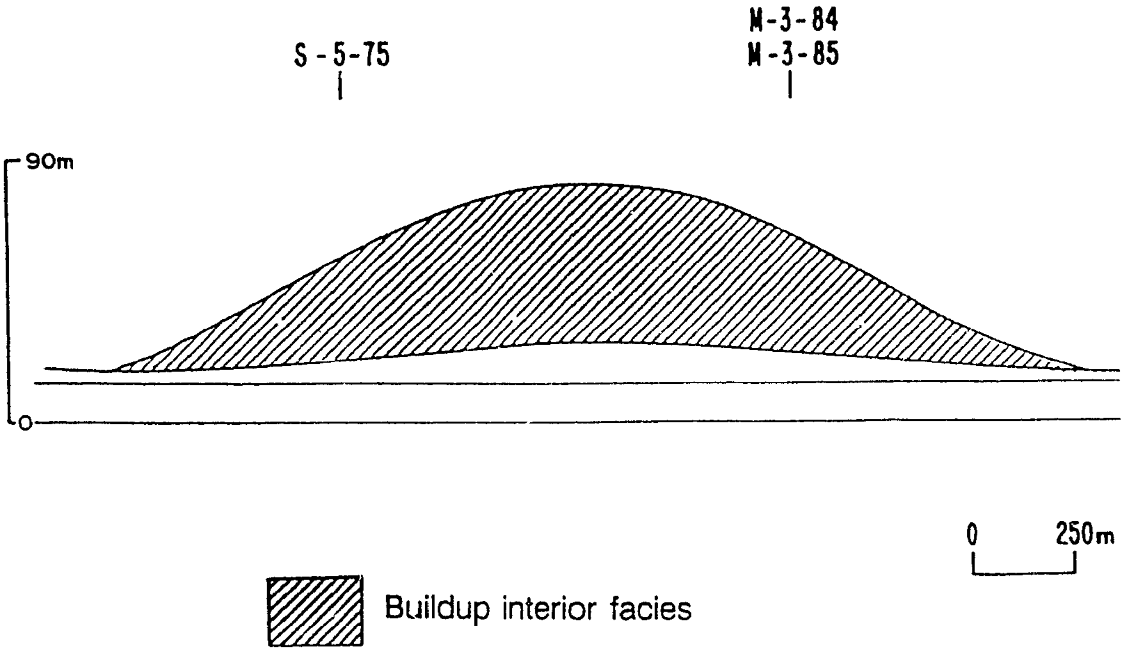


Fig. 8 Buildup interior facies

2.3 CARBONATE BUILDUP

Carbonate buildups, 75 to 100 m thick, are comprised of four facies: Interior, Organic Rim, Flank, and Stromatolite Cap.

2.3.1 Interior Facies

The interior facies represents the first 35 to 45 m of buildup development, and are best observed in outcrop on Mason and Rock islands (Figs. 2, 8). In outcrop, this facies is well bedded with individual beds varying in thickness from a few centimetres to 1.5 m (Plate 2A). The beds are comprised of fossiliferous and pelleted wackestones and floatstones. The dominant fossil types are whole (non-fragmented) bryozoans, crinoids and calcareous algae with lesser amounts of branching corals (Thamnopora), sponges, brachiopods and ostracods (Plate 2B). Scattered fragments of massive corals and stromatoporoids represent less than 5% by volume of the total bulk of the interior facies.

From the study of outcrop exposures, the significant role of bryozoans as sediment stabilizers was recognized for the first time. Extensive meadows of densely concentrated bryozoans cover exposed bedding surfaces (Plate 2C). The delicate fenestellids, several centimetres in length, are preserved lying flat. In cross section, the fine texture of the fenestellid zooecial apertures are impossible to identify especially when dolomitized. In core, the visible fossil fragments are easily mistaken for the debris of thin shelled brachiopods or tabular and dendritic stromatoporoids.

In addition to bryozoans, crinoids and branching corals are common sediment stabilizers in the interior facies. The concentration, degree of articulation and diameter of crinoid stems increase toward the buildup cores. On the interior facies margins, the stems are completely disarticulated, and individual columnals (2 to 5 mm diam.) are randomly scattered throughout the crinoid wackestones. In the central interior facies, the stems are more intact (up to 10 to 15 cm long), and vary from 0.5 cm to 1.5 cm in diameter (Plate 2D).

Calcareous algae are also significant fossil components, but dolomitization can obscure their fine textural detail. Furthermore, algal remains are often observed as a hash of filamentous debris. The dominant algae are the large and robust members of the Udoteacean Family; e.g., Paralitanaia (Plate 3A). Observed in lesser amounts are: the encruster, Wetheredella (Plate 3B); the binder, Sphaerocodium (Plate 3C); and the floater, Tentaculites (Plate 3D).

The identification of sponges is made difficult by poor preservation. However, the reticulate pattern of the internal structure of sponges is often associated with a black micritic and clotted fabric in the fossiliferous floatstones (Plate 4A). In addition, the molds of sponge spicules are sometimes preserved (Plate 4B).

In addition to the sediment stabilizing roles of bryozoans, crinoids and calcareous algae outlined above, early submarine cements may feature importantly in the construction of the buildups (see Chapter 3).

2.3.2 Organic Rim Facies

In the ecological succession of Winnipegosis faunal communities, the large framebuilding organisms only appear in abundance toward the top of the buildups (Fig. 9). Massive, tabular and encrusting stromatoporoid and massive coral framestones are readily recognized in situ throughout the upper ten to fifteeen metres of the buildup outcrop exposures,

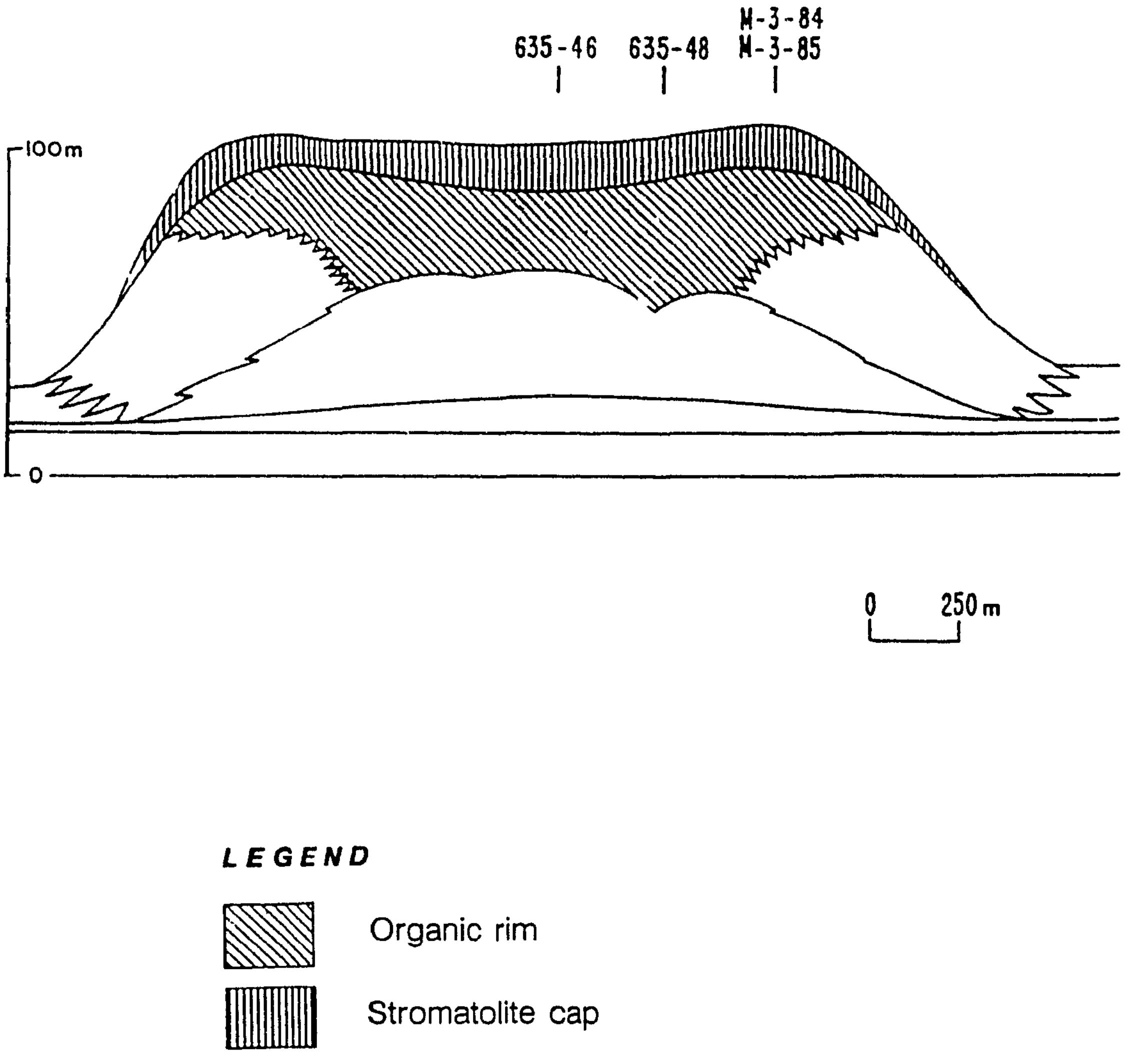


Fig. 9 Organic rim and stromatolite cap facies

(Rock Island, Simons Island and the Bluff, Fig. 2). In core, the overall abundance of framebuiding organisms appears less than in outcrop. In small core specimens, it is difficult to determine whether the framebuilders are in situ or disturbed.

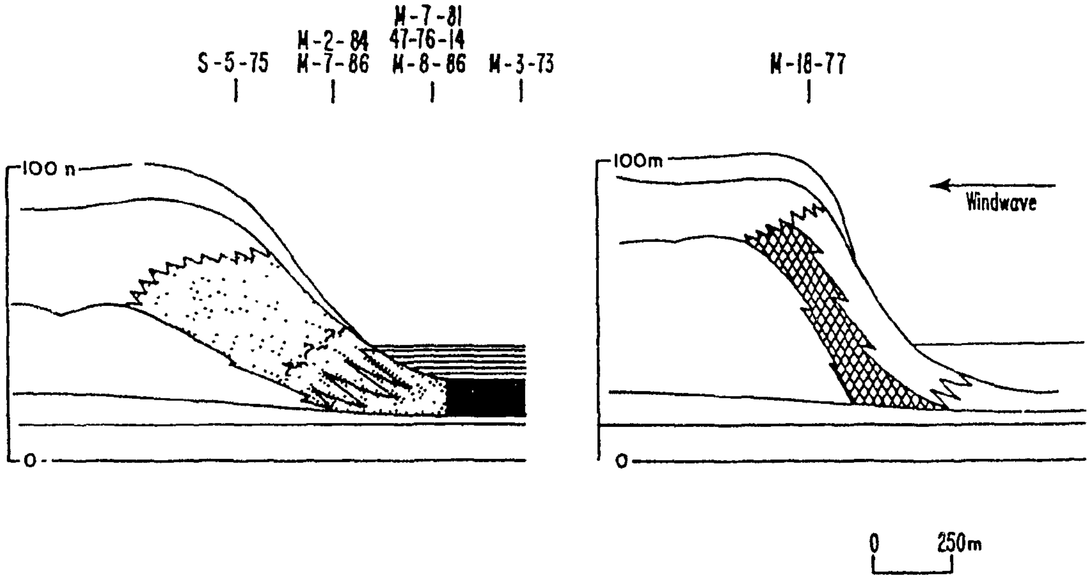
The principal massive coral species are Favosites (Plate 4C), Dendrostella (Plate 4D), Alveolites (Plate 5A), and Syringopora (Plate 5B). In addition, the enigmatic tabulate coral/sponge species, Chaetetes, is particularly common (Plate 5C). Stromatoporoids are common throughout (Plate 5D). Crinoid floatstones and rudstones are present in considerable quantities. A large variety of other organisms are also observed such as branching and encrusting corals (Plate 6A), brachiopods, nautiloids (Plate 6E), orthocones, gastropods, trilobites and solitary corals. Udoteacean algae and bryozoans are absent.

2.3.3 Flank Facies

The flank facies is divided into three subfacies: 1. Laminated subfacies; 2. Bioturbated subfacies; 3. Cemented subfacies (Fig. 10). The Steeprock Bridge Dome well profile demonstrates the stratigraphic relationship between the laminated and bioturbated subfacies (Fig. 11). In addition, these subfacies occur together in cores 47-76-2 and 47-76-14.

2.3.3.1. Laminated Subfacies

The laminated subfacies varies from 1 to 35 m in thickness, and thins toward the interior facies (Fig. 11). It contains dolomitized bituminous laminated mudstones (0.1 to 1.0 m thick) interbedded with crudely graded beds of dolomitized, light brown mudstones, and fossiliferous wackestones and floatstones (0.25 to 1.0 m thick) (Plate 6C). The internal stratification of these facies increases in dip from 2 to 5



LEGEND

BUILDUP FLANK FACIES

⁘ Bioturbated subfacies

▒ Laminated subfacies

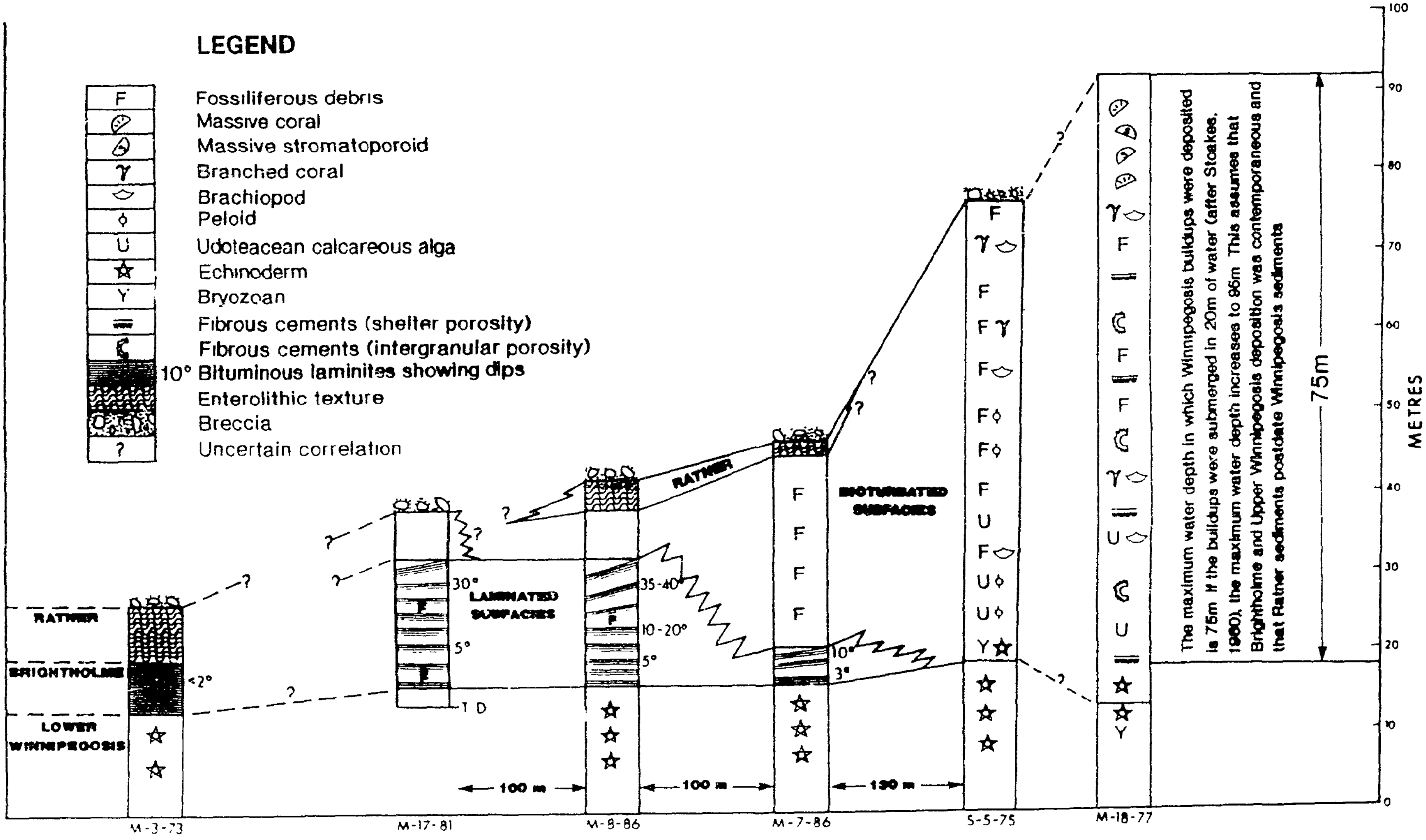
▩ Cemented subfacies

BASIN FACIES

■ Brightholme Member

▤ Ratner Member

Fig. 10 Buildup flank and basin facies with constituent subfacies



The maximum water depth in which Winnipegosis buildups were deposited is 75m If the buildups were submerged in 20m of water (after Stoakes, 1980), the maximum water depth increases to 95m This assumes that Brightholme and Upper Winnipegosis deposition was contemporaneous and that Ratner sediments postdate Winnipegosis sediments

Fig 11 Steeprock Bridge Dome Core Profile A stratigraphic cross-section showing the interfingering relationship between the laminated and bioturbated subfacies The section includes four cores, M-17-81, M-7-86 M-8-86 and S-5-75 that were drilled across the flank of the Steeprock Bridge Dome buildup Although cores M-18-77 and M-3-73 were not drilled at this location they represent typical buildup (cemented subfacies) and basin sedimentology and are included in this section to show the assumed buildup to basin transition A maximum water depth of 75 metres in which the buildups were deposited was also determined from this section degrees at the base to 30 to 35 degrees at the top (Fig. 11).

The wackestones and floatstones contain variable amounts of finely comminuted and unidentifiable fossiliferous debris and larger clasts of massive stromatoporoids, branching corals, calcareous algae, brachiopods, bryozoans and crinoids. The long axes of elongate clasts are frequently orientated down-slope.

The bituminous mudstones are black and very finely laminated. The individual laminations are rarely interlaminated with stringers of light brown mudstones. Rare burrows are present.

2.3.3.2 Bioturbated Subfacies

The bioturbated subfacies varies in thickness from 8 m to 40 m, and thickens toward the interior facies (Fig. 11). They consist of light brown mudstones and fossiliferous floatstones. The fossil content includes fragments of the branching and colonial corals, <u>Thamnopora</u>, <u>Favosites</u>, and <u>Dendrostella</u>, and tabular and bulbous stromatoporoids, calcareous algae, crinoids and abundant brachiopods (Plate 7A).

In outcrop (e.g., the Bluff), these weather-resistant sediments form massively bedded cliffs. Dips of the external stratification of the buildup flanks range from 5 to 20 degrees (e.g. McCabe, 1986).

2.3.3.3 Cemented Subfacies

Information concerning the cemented subfacies is based on a single core, M-18-77, that penetrates 80 m of Upper Winnipegosis buildup facies and 10 m of Lower Winnipegosis platform facies (Fig. 11). The lower 50 m of the Upper

Winnipegosis section is comprised of 3 to 5 m intervals of dolomitized fossiliferous grainstones interbedded with thinner units of floatstones and mudstones. This interval is overlain by a 30 m interval of bioturbated subfacies sediments. In the grainstones, the principal fossil type is the Udoteacean calcareous alga, Paralitanaia. Coral and stromatoporoid debris, brachiopods, ostracods and various genera of calcareous algae also occur.

Significantly, dolomitized submarine fibrous cements fill the intergranular porosity in the grainstones (Plate 7B). Although scattered occurrences of similar cements are observed filling shelter porosity in the interior facies, this relatively thick interval of cemented grainstones appears to be local in extent. The M-18-77 drill hole is from an isolated buildup close to the western margin of the Red Deer River reef complex (Fig. 2, Drillhole #1). However, the exact location of the hole with respect to the different buildup facies is uncertain.

2.3.4 Stromatolite Cap Facies

The stromatolite cap facies is well exposed in outcrop at the Steeprock Bay Dome cliffs and in core (e.g., Inco 635-46, Inco 635-48, M-2-84, M-3-84) (Fig. 9). It represents a 5 to 10 m thick interval of strata that overlies the organic rim facies at the top of the buildups; it thins rapidly down the buildup flanks, and is rarely observed low on the flank facies. The strata are laminated, and contain a distinct fenestral texture (Plate 7C and D). The rocks consist of dolomitized, white to light brown, peloid oncolite grapestone packstones and grainstones (Plate 8A). Laterally linked 'cabbage head' stromatolites are common (Plate 8B). The calcareous algae Uslonia, Calcispheras, Biospheras, and Parathurammina, are present in abundance (Plate 8C and D). Gastropods, brachiopods (the pentamerid index fossil, Stringocephalus burtini is particulalry common) and sponges are scattered throughout the sediments. Lenses of chaotically arranged bioclastic debris (e.g. brachiopod, coral, gastropod) are interlayered with the fenestral beds.

Laterally extensive horizontal truncation surfaces (can be traced for at least 10 m) are periodically interlayered with the fenestral strata. They are covered by thin beds (0.05 to 0.10 m thick) of grey, very finely cross laminated mudstones that pinch and swell around lenses of bioclastic debris (Plate 8B). In core, these surfaces are associated with thin intervals of peloids, composite and coated grains, and oncolite breccias interbedded with stringers of dolomitic green shale (Plate 9A and B).

The bulk of the stromatolite cap facies consists of thick beds (0.5 to 1.5 m) of fenestral grainstones. Horizontal elongate lobes (upto 2 m long, 0.1 to 0.15 m wide) of grey mudstone, and boulder-sized, angular, rip-up clasts of fenestral grainstones (teepee structures) occur throughout the fenestral strata (Plate 9C).

Pisolites (1.0 to 1.5 cm diam.) occur rarely throughout the fenestral grainstones. They are often connected 'in series' by common laminations (Plate 9D). Horizontal intervals of cream and brown coloured calcrete, 0.10 to 0.50 m thick, are distributed intermittently throughout the upper 4 m of the fenestral strata in the Steeprock Bay Dome outcrop. Calcrete consists of thin plates, crusts and glaebules (Plate 10A) (Chapter 3).

2.4 BASIN

The basin environment refers to all deeper water environments that occur between the reef complexes. Basin sediments are divided into two distinct members of the Winnipegosis Formation, the Brightholme Member and the overlying Ratner Member. The total thickness of these deposits is approximately 10 m (Fig. 11). Basin sediments do not outcrop, and can only be studied in core (M-3-73, M-5-76).

2.4.1 The Brightholme Member

The Brightholme Member is 5.0 m thick, and lies directly above the upper carbonate platform subfacies (Figs. 10, 11). It consists of horizontal, finely laminated bituminous mudstones identical to those that occur interbedded in buildup-derived carbonate debris flows in the flank facies (Plate 10B). These sediments contain up to 6% TOC, and are thermally immature (Osadetz, pers.comm., 1988).

2.4.2 The Ratner Member

The Ratner Member is 5.0 m thick, and lies directly above the Brightholme Member (Fig. 10, 11). The lower Ratner sediments are comprised of varved bituminous laminites intercalated with thin intervals (1.0 to 3.0 mm thick) of brown dolomitic mudstones (Plate 10C). Sediments in the upper part of the Ratner contain calcitized enterolithic horizons (1.0 to 2.5 mm thick) interbedded with dedolomitzed mudstones and laminites (Plate 10D)

Ratner sediments are overlain by at least two genetically unrelated solution breccias and the shales of the Second Red Beds (Figs. 5, 11). The evaporites of the Prairie Evaporite Formation have been completely removed by solution.

2.5 SUMMARY

1. The carbonate platform of the Lower Winnipegosis consists of the lower and upper platform subfacies. The lower platform subfacies is relatively uniform in thickness (10 to 12 m), and contains mottled crinoid wackestones and packstones. The upper platform subfacies expresses subtle relief due to accumulations of crinoid packstones (3 to 5 m thick) that lie adjacent to depressions filled by fossiliferous debris and convoluted wisps of bituminous mudstones (0.5 to 1.0 m thick).

2. The carbonate buildup, 75 to 100 m thick, is divided into four facies: interior, organic rim, flank, and stromatolite cap. The interior facies, 35 to 45 m thick, is well bedded and contains bryozoan crinoid calcareous algae wackestones and floatstones. Various forms of corals, stromatoporoids and other organisms occur in minor amounts. The organic rim facies occurs toward the upper 20 m of the buildups, and contains massive coral and stromatoporoid framestones. The flank facies is divided into three subfacies: laminated, bioturbated, and cemented. The laminated subfacies, 1 to 35 m thick, contains bituminous laminated mudstones interbedded with units of crudely graded fossiliferous wackestones and floatstones. The dip of these beds increases upward through the subfacies. The bioturbated subfacies, 8 to 40 m thick, is structureless, and contains mudstones and fossiliferous floatstones. The cemented subfacies is very local in extent, and contains fossilferous grainstones cemented by marine fibrous cements. The stromatolite cap facies, 5 to 10 m thick, overlies the organic rim facies at the top of the buildups. These rocks contain fenestral peloid oncolite grapestone grainstones with varying amounts of calcareous algae, gastropods and sponges scattered throughout. In addition, brecciated oncolites, large rip-up clasts (teepee structures), green shale stringers, erosional truncation surfaces, elongate mud lobes and pisolites are

commonly distributed in these facies.

3. Basin sediments, 10 m thick, are divided into the Brightholme and Ratner Members. The Brightholme, 5 m thick, contains finely laminated bituminous mudstones. The lower Ratner, 4 m thick, overlies the Brightholme, and contains varved bituminous laminites intercalated with thin intervals of mudstone. The upper Ratner, 1 to 2 m thick, contains calcitized evaporites and dedolomites. A thin horizon of brecciated carbonate overlies the Ratner beds.

2.6 DISCUSSION

2.6.1 CARBONATE PLATFORM

The fossil content and relatively uniform thickness of the lower platform sediments suggest that normal marine conditions prevailed throughout the Elk Point Basin during the Eifelian. Although these mottled sediments are dolomitized, this texture is also observed in the stratigraphically equivalent non-dolomitized Elk Point limestones situated 200 km to the south of the Dawson Bay area. Norris et al. (1982) attributed these textures to bioturbation rather than to diagenesis. The mottled texture in the Lower Winnipegosis is similarly interpreted to be due to bioturbation.

The thickness variation of the upper platform corresponds to the differentiation of the platform into topographic highs and lows. Whether the distribution of these highs was structurally controlled is not clear. Norris et al. (1982) suggested that flexure along the junction between the Churchill and Superior crustal provinces, the Birdtail-Waskada Axis, may have exerted some influence on the inception and orientation of the buildup complexes in the Dawson Bay area. Regionally however, Winnipegosis buildups are randomly scattered throughout the southern half of the Elk Point Basin, and show little preferred orientation with respect to structural lineaments in the basement (Perrin, 1982; Wilson, 1984; Ehrets and Kissling, 1987). It is clear therefore that the influence of tectonic activity on Winnipegosis buildups is perhaps not as well defined as for the Upper Devonian reef trends in the Alberta Basin (e.g., Mountjoy, 1980).

The faunal variety and density on the highs represent the pioneering stage of buildup development, possibly signifying the onset of shoal sedimentation. Similar platform thickenings have not only been identified and interpreted as shoals in other Lower Winnipegosis platform sediments (Wilson, 1984; Ehrets and Kissling, 1987; Martindale and Orr, 1987) but also in the Middle Devonian Lower Keg River Member (Langton and Chin, 1968; Rhodes et al., 1984; Qing, 1986), and in the Upper Devonian Flume and Cooking Lake Members (Andrichuk, 1956; Mountjoy, 1980).

Preservation of bituminous wisps in topographic lows marks a change in local marine conditions from well aerated to restricted and anaerobic bottom waters. However, evidence for bioturbation in these sediments indicate that although conditions were becoming anaerobic facilitating the preservation of the organic matter, a more hardy infauna still existed under these conditions.

The upper platform represents deeper water sedimentation which correlates with a proposed global eustatic rise in sea level that occurred in late Eifelian time (Johnson et al., 1985). Although carbonate systems can maintain growth in optimum conditions under any increase in the rate of sea level rise (e.g. Schlager, 1981; Neumann and Macintyre, 1985), this rise of sea level probably restricted carbonate sedimentation to the highs developed on the upper platform.

2.6.2 CARBONATE BUILDUP

2.6.2.1 Interior Facies

The well bedded interior facies is interpreted to represent a vertical succession of shoals. Although classic framebuilders such as massive corals and stromatoporoids are rare, organisms such as bryozoans, crinoids and robust calcareous algae more suited to sediment stabilization prevailed during the deposition of this facies.

The role of the bryozoan as a sediment stabilizer and framebuilder has been largely unrecognized by previous workers in the Middle Devonian buildups in western Canada. However, Cuffey (1977) has discussed their ability to stabilize sediment in many Paleozoic reefs and bioherms. The bulk of biohermal cores of Silurian pinnacle reefs in the Michigan Basin consists of up to 40% bryozoans (Gill, 1985). Similarly, the dense concentrations of bryozoans in the Winnipegosis sediments probably played a significant framebuilding role during the deposition of the interior facies.

A recent reappraisal of calcareous algal taxonomy has resulted in the reclassification of the genus, Litanaia, to the Family Udoteacea (Mamet pers.comm., 1988). Although previous workers on the Winnipegosis have described Litanaia as a codiacean alga (e.g., Perrin, 1982; Ehrets and Kissling, 1987; Martindale and Orr, 1987), it is referred to as an udoteacean henceforth. The distribution of living calcareous codiaceans provide a good basis for interpreting environmental regimes of similar fossil forms such as Litanaia (Wray, 1977). Most forms colonize sand and muddy substrates where the rhizoids of the plants penetrate the soft sediments to develop holdfasts. They tend to live below intense wave agitation under strongly illuminated conditions. In the Winnipegosis buildups, the udoteaceans probably contributed to the stabilization of the interior facies below wave base.

2.6.2.2 Organic Rim Facies

Whether the organic framework forms a continuous rim around the buildup is uncertain. Careful documentation of the distribution of buildup organisms on Knob Two, the Bluff, indicates that framebuilders form a narrow rim along the northeastern-eastern margin of the buildup (Fig. 12). However, the relatively low abundance of framework encountered in core from other buildups indicates that organic rims are discontinuous. The distribution of framework in the Winnipegosis is likely determined by local environmental factors such as proximity to nutrient sources, exposure to well oxygenated waters, and accessibility to sunlight. The distribution of framebuilders on the northeast margin of Knob Two might indicate that this particular margin was preferentially exposed to nutrient-rich, well oxygenated waters. The relationship between the windward margins of the buildups and the distribution of framebuilders is supported by the southwesterly direction of prevailing winds in the Elk Point Basin proposed by Heckel and Witzke (1979).

In drill core, the organic rim varies from zero to four metres in thickness and pinches out across the underlying buildup flanks. This stratigraphic relationship indicates that the organic rim facies overstepped the underlying flank sediments during the late stages of organic rim construction. A similar development of organic framework occurs in the Winnipegosis buildups of Saskatchewan and North Dakota (Wilson, 1984; Ehrets and Kissling, 1987; Martindale and Orr, 1987).

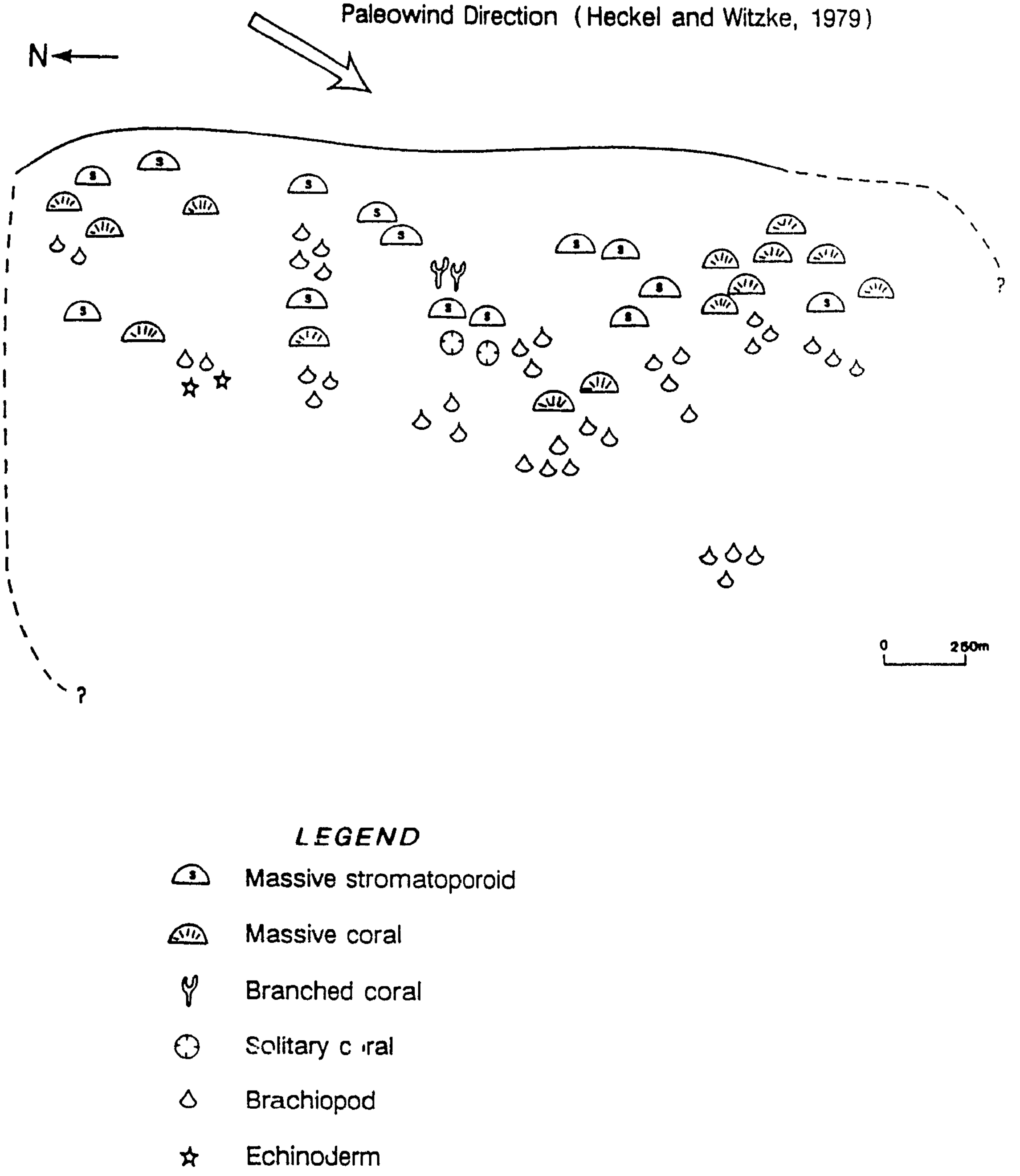


Fig. 12 Knob Two, The Bluff. A plan view showing the distribution of frame builders and other organisms along the northeastern-eastern margin of the buildups

2.6.2.3 Flank Facies

2.6.2.3.1 Laminated Subfacies

The graded bedding and preferential orientation of fossiliferous clasts in the carbonate beds of the laminated subfacies reflect hydraulic transportation and sorting of the constituent allochems. The carbonate beds represent fossiliferous debris flows derived from the interior facies that were shed down the buildup flanks. These relatively catastrophic episodes of sedimentation (possibly storm-induced) periodically interrupted the deposition of pelagically derived organic matter preserved as the bituminous laminated mudstones. Similar graded debris flows, or calciturbidutes, interbedded with bituminous laminites occur on the flanks of Keg River and Winnipegosis buildups in Alberta and Saskatchewan (Davies and Ludlam, 1973). The preservation of these sedimentary structures and the organic-rich mudstones indicate that bottom waters were predominantly anoxic. Furthermore, the increase in the dips of the internal stratification of these flank sediments reflect the vertical accretion of successive shoals in the interior facies.

2.6.2.3.2 Bioturbated Subfacies

The massive cliff forming beds observed on the Bluff represent the accumulation of carbonate mud and skeletal debris on the buildup flanks. The increase in the abundance of organic framework debris situated in the upper third of the bioturbated subfacies indicates that the organic rim eventually became a principal source of material for flank sedimentation. The randomly scattered distribution of skeletal allochems, and the conspicuous absence of laminated bituminous mudstones strongly suggest that these sediments were intensively bioturbated under oxic conditions.

2.6.2.3.3 Cemented Subfacies

Although the submarine cements in drill core M-18-77 are diagenetic phenomena, and are discussed in detail in Chapter 3, their distribution in the flank facies may be of sedimentolgical significance. The windward or paleowindward margins of many modern and ancient carbonate buildups are cemented by texturally similar submarine cements (e.g., James et al., 1976; Marshall and Davies, 1981; Marshall, 1983; Walls and Burrowes, 1985; Aissaoui et al., 1986; Kerans et al., 1986) The M-18-77 Winnipegosis buildup was exposed to relatively open marine waters from the north and northwest. The cemented grainstones possibly represent the buildup margin which was subjected to strong agitation by prevailing winds and waters. However, fibrous cement distribution in the flank facies requires further investigation before a clear relationship between this subfacies and paleowind direction can be established.

2.6.2.4 Stromatolite Cap Facies

Although stromatolites grow in relatively quiet supratidal to subtidal waters (Kinsman, 1966; Kinsman, 1969; Playford and Cockbain, 1976; James, 1983), the grainstone texture of the fenestral strata suggests that these sediments were deposited in agitated waters. Furthermore, the elongate mud lobes, the large rip-up clasts (teepees) of fenestral strata, and the oncolitic breccias represent erosion, brecciation and deposition by intense hydraulic activity such as storms. This evidence for peritidal sedimentation is similar to the teepee structure and related breccia deposits of the Triassic Calcare Rosso of Val Brembana, Italy (Assereto and Kendall, 1977)

The laterally extensive truncation surfaces also represent submarine erosion. They are often associated with green shale stringers, brecciated oncolites and stromatolitic debris of possible storm origin. This interpretation of the origin of the green shale is consistent with that of Wendte and Stoakes (1982) and Machel (1985) who consider green shales interbedded with the carbonates of the Upper Devonian Swan Hills and Nisku buildups to be marine muds stirred up and deposited during storms. The few occurrences of dissolved oncolites indicate that some of the surfaces may have been exposed to a freshwater influence before being buried by more submarine deposits (Chapter 3). Furthermore, the recementation of brecciated oncolites by radiaxial fibrous cements reflect a marine influence during the deposition of these sediments (Chapter 3).

The laminations that connect individual pisolites indicate that these structures formed in situ, and are therefore quite distinct from other coated grains in the Winnipegosis sediments. Similarly, pisolites are quite distinct from other coated grains in the Pisolite Cap facies, Winnipegosis Formation, south-central Saskatchewan (Wardlaw and Reinson, 1971) . Whether Dawson Bay pisolites formed in marine phreatic or vadose diagenetic environments is not certain. However, they do meet certain criteria that would favour a submarine origin (after Esteban (1974) and Esteban and Klappa (1983): 1. they are associated with fenestral grain-supported carbonate rocks; 2. they are not directly associated with caliche; 3. they are well laminated, whereas calcrete glaebules are poorly laminated (Chapter 3).

Although the plates and crusts in Winnipegosis calcrete may resemble similar textures in travertine (e.g., Esteban and Klappa, 1983; Folk et al., 1985), the occurrence of glaebules (e.g, Esteban and Klappa, 1983) strongly suggests that these cream and brown coloured bands are calcrete that modified, and therefore post-dated, the stromatolite cap facies.

Furthermore, the considerable amount of sedimentary evidence for erosion, brecciation and deposition of the cap sediments by intense hydraulic activity is not typical of the relatively quiet depositional environments of hot spring travertines.

The restriction of calcrete to the upper 4m of the Steeprock Bay dome and the very rare occurrences of calcrete at the same stratigraphic levels in core suggest that only the highest portions of the buildups were ever periodically exposed to vadose diagenetic processes. This contrasts with the evidence for karst throughout North Dakota Winnipegosis buildups that is interpreted to represent sustained exposure of the buildups in this area at the end of Winnipegosis time (Perrin, 1982).

2.6.3 BASIN

The Brightholme mudstones represent the accumulation and preservation of pelagically derived organic matter. The lack of evidence for bioturbation indicates that bottom waters were completely anaerobic and unsuitable for infaunal organisms.

These deposits are probably contiguous with the bituminous laminites interbedded with the buildup flanks. Hence, they are facies equivalent to the carbonate buildups. Further careful drilling of the buildup-basin transition would confirm this important stratigraphic relationship. Although Dawson Bay Brightholme mudstones are immature with regard to hydrocarbon generation, the geochemistry of recently discovered oils from the Winnipegosis Formation in southern Saskatchewan indicate that the oils may have been derived from local petroleum sources such as the Brightholme Member in the Upper Elk Point Group (Brooks et al., 1988).

The original mineralogy of the Ratner Member calcitized horizons was probably gypsum or anhydrite. In Saskatchewan, very similar textural evidence for the calcitization of anhydrite occurs in the Ratner sediments (Shearman and Fuller, 1969). Noncalcitized varved and laminated evaporites occur at the base of the Muskeg-Prairie Evaporite formations in Alberta and Saskatchewan that are texturally similar to the Dawson Bay basin deposits (Fuller and Porter, 1969; Wardlaw and Reinson, 1971; Davies and Ludlam, 1973; Kendall, 1984).

The varves of bituminous mudstones may correspond to the seasonal life cycles of plankton. In modern evaporitic environments, salinity-tolerant species of plankton tend to bloom in enormous concentrations usually after an influx of nutrient-rich, open marine waters (Kirkland and Evans, 1981). After death, these organisms settle out of the water column, and are preserved in anoxic waters on the basin floor.

In the Saskatchewan outcrop belt, the Ratner sediments onlap the flanks of the Keg River-Winnipegosis buildups to heights of at least 20 m, and thus postdate buildup development (Kendall, 1984). Despite close well control in the study area, the stratigraphic relationships between the Ratner Member and the buildups cannot be established with certainty. However, the textural similarity between the sediments in the study area, Saskatchewan and Alberta strongly supports the proposal that all Ratner sediments throughout the Elk Point Basin postdate buildup development.

The brecciated deposits are interpreted to represent the remnants of carbonate horizons within the evaporite succession which collapsed on top of the basin sediments during evaporite solution; for example, the Quill Lake beds (after Wardlaw and Reinson, 1971).

2.6.4 WINNIPEGOSIS WATER DEPTHS

The principal controls on cratonic basin sedimentation are global eustatic changes in sea level and basin subsidence. It has become clear from work by Sloss (1963) and Vail et al., (1977) that eustatic sea level changes are perhaps the most important of the two controls. Other workers have reported on the sedimentological, stratigraphic and paleontological implications of worldwide sea level fluctuations (e.g., Mesolella et al., 1974; McKerrow, 1979; Lenz, 1982). In particular, Johnson et al. (1985) used conodont biostratigraphy to demonstrate that Devonian transgressive-regressive events may have been synchronous around the globe.

Various mechanisms have been proposed to explain subsidence patterns based on the stratigraphic evidence of basin fill and the rheological properties of the earth's lithosphere and asthenosphere (e.g., Sleep and Snell, 1976; Burke, 1976; McKenzie, 1978; Quinlan and Beaumont, 1984). Fowler and Nisbet (1985) suggested that the gabbro/eclogite phase transformation model, first proposed by Haxby et al. (1976), provided a possible mechanism for the subsidence history of the Williston Basin which is inextricably linked to that of the Elk Point Basin.

The Elk Point Basin was a shallow basin in which wide, gently sloping shelves restricted marine circulation. In the northwest of the basin, the Presqu'ile Barrier probably restricted circulation further by limiting the exchange of waters between the basin and the open sea (Maiklem, 1971). However, the eastern margin of the basin is poorly defined, and relationships between basin and open marine waters are uncertain (Williams, 1984). Basin sedimentation was characterized by nearshore carbonates, deeper water evaporite fill, and minimal clastic invasion.

Transgressing Eifelian seas covered much of the Mackenzie platform, and advanced southeastward depositing the Lower Keg River and Upper Chinchaga Formations in northwestern Alberta (Grayston et al., 1964; Johnson et al., 1985). In the southern portion of the Elk Point Basin, argillaceous dolostones of the Ashern Formation were deposited unconformably over the Lower Silurian Interlake Group (Johnson and Lescinsky, 1986) (Fig. 5). These dolostones may represent the reworking of a residual soil formed during the Late Silurian to Early Devonian erosional period (Norris et al., 1982). As sea level rose, the Lower Winnipegosis platform carbonates were deposited under relatively open marine conditions.

Although knowledge of variations of water depth is critical to the understanding of carbonate platform and buildup development, few attempts have been made to quantify this parameter due to: 1) a lack of core control across subsurface buildup to basin profiles; and 2) the logistical difficulties of tracing beds laterally in mountain outcrops.

Certain assumptions were made to determine an estimate for maximum water depth at the end of Winnipegosis time. First, the water in which the basin sediments were deposited must have been deep enough to accomodate the preserved thickness of buildup and basin sediments. Second, the variety of lithotypes made it impossible to determine a reasonable correction factor for differential compactional effects; subsequently, the calculated value for water depth is a maximum value. Third, a subjective estimate of the depth of water which covered the buildups was included to determine a total water depth. In the Upper Devonian Alberta Basin, Stoakes (1980) proposed that carbonates were immersed in at least 20 m of water based on a comparison with modern environments. This value may be too high for an interior basin such as the Elk Point Basin and so should be considered a maximum value.

The faunal assemblage and bioturbated nature of the Dawson Bay Lower Winnipegosis platform sediments represent deposition in relatively deep subtidal waters. However, it is not possible to determine an accurate water depth in which platform sediments were deposited. Rosenthal (1988) proposed that depths did not exceed a few tens of metres during deposition. Wardlaw and Reinson (1971) reported that the presence of algal oncoliths and breccias in the Saskatchewan platform sediments represented deposition in shallow, agitated waters perhaps accompanied by periodic exposure.

An estimate of 95 m (assumes that the buildups were submerged by 20 m of water) for the maximum water depth at the end of buildup development was determined from a composite core profile across an idealized Winnipegosis buildup (Fig. 11). This calculation is based on the assumption that the Ratner sediments are correctly interpreted to postdate buildup development; therefore, the Brightholme laminated mudstones represent the maximum thickness (5 m) of basin sediments deposited during buildup development. Kendall (1975) determined a similar water depth for Winnipegosis deposition from an outcrop occurrence in Saskatchewan "where steeply dipping, fore-bank deposits pass downward into a thinly bedded laminated styliolinid-rich argillaceous unit". From this, he concluded that the basin sediments "must have accumulated under water at least as deep as the thickness of the neighbouring banks, up to 75 m".

During the deposition of the basal interior facies, the increase in flank dip from 3° at the base to 35° at the top indicates that sea level was rising during the early Givetian. At this time, the principal buildup constructors (bryozoans, echinoderms and udoteacean calcareous algae) were well suited to quiet, sub wavebase conditions; furthermore, the classic framebuilding organisms, better suited to higher energy surf zone conditions, were conspicuously absent. Later in the buildup depositional history, the interior fauna were displaced by the framebuilders as the organic rim facies developed vertically and laterally over underlying flank and interior sediments. This ecological succession of deeper water to shallower water faunal communities indicates that the buildups eventually 'caught-up' to sea level facilitating the proliferation of framebuilding organisms in shallower, more agitated waters (after Schlager, 1981; Neumann and Macintyre, 1985). Furthermore, the deposition of the stromatolite facies and the development of calcrete horizons in the upper few metres of the buildup indicate that the depositional environments shifted from subtidal to intertidal waters, and that sea level may have fallen slightly exposing the buildup crests to vadose diagenetic processes.

The extent of sea level fall in the Elk Point Basin has been a contentious issue amongst workers. Fuller and Porter (1969) and Shearman and Fuller (1969) interpreted the Ratner Member sediments in Saskatchewan to be sabkha-type stromatolitic deposits. Similarly, Baillie (pers. comm., 1986) favoured this interpretation for the Ratner sediments in the Manitoba outcrop belt. From this evidence, they inferred that sea level fell and entirely exposed the buildups. More recently, Kendall (1989) favours the proposal that desiccation occurred in the Elk Point Basin after Winnipegosis time. Similarly, Perrin (1982) interpreted North Dakota inter-reef laminites to be stromatolitic, and reported extensive evidence for freshwater karsting in the buildups. However, Wardlaw and Reinson (1971) and Davies and Ludlam (1973) noted that the abundant cellular plant tissue in the Saskatchewan laminites was of planktonic origin representing submarine rather than supratidal sedimentation. Furthermore, Davies and Ludlam (1973) demonstrated that the undisturbed laminites and interlaminated anhydrite could be correlated basin wide and were therefore sub wavebase sediments.

In Dawson Bay Brightholme and Ratner sediments, the laminites cannot be correlated over wide areas due to the lack of core control, and dolomitization has obliterated all faunal evidence from the laminites. However, the absence of sabkha-related sedimentary features such as bioturbated carbonate muds, aeolian and beach sands, mudcracks, storm-related rip-up clasts and evidence for caliche development indicate that these sediments were not deposited in a supratidal environment. However, the preservation of undisturbed bituminous laminites represents deposition below wavebase in anoxic waters. Similarly, Wardlaw and Reinson (1971) and Davies and Ludlam (1973) proposed that the Saskatchewan basin sediments are sub wavebase deposits.

In summary, steep flank dips and a relatively deep water faunal community in the interior facies indicates that the Givetian sea level rose during the formative stages of buildup development. As buildups 'caught-up' to sea level, the deeper water bryozoans, crinoids and calcareous algae were displaced by massive corals and stromatoporoids better suited to the shallower, agitated conditions. The deposition of the stromatolite cap facies represents a shift from subtidal to intertidal depositional environments. The development of calcrete in the cap facies suggests that sea level reached a stillstand or fell slightly during the later stages of buildup development. However, the preservation of the Brightholme and Ratner laminites, mudstones and evaporites in subtidal waters indicate that the adjacent basin waters were up to 95 m deep during the final stages of buildup development.

2.7 SEDIMENTOLOGY PLATES

PLATE 1

A) Rock Island, Dawson Bay. The Rock Island outcrop exposure represents the lower portion (interior facies) of a Winnipegosis buildup. Cliff heights range from five to ten metres.

B) Upper Platform Subfacies. Thick accumulations of dolomitized crinoidal (C) floatstones form topographic highs on the platform upon which further buildup development occurred. Centimetre scale. M-18-77 (3). 315 ft..

C) Upper Platform Subfacies. Black bituminous wisps were incorporated into dolomitized stromatoporoid (S) and coralline (C) floatstones during the earliest stages of buildup development. Centimetre scale. M-3-85 (4). 285 ft..

D) Upper Platform Subfacies. A well defined burrow (B) and mottled texture (M) represents bioturbation of the bituminous and micritic mudstones that accumulated in the topographic lows of the platform. These lows later contained the bituminous mudstones of the basin facies. Centimetre scale. M-7-86 (3). 240 ft..

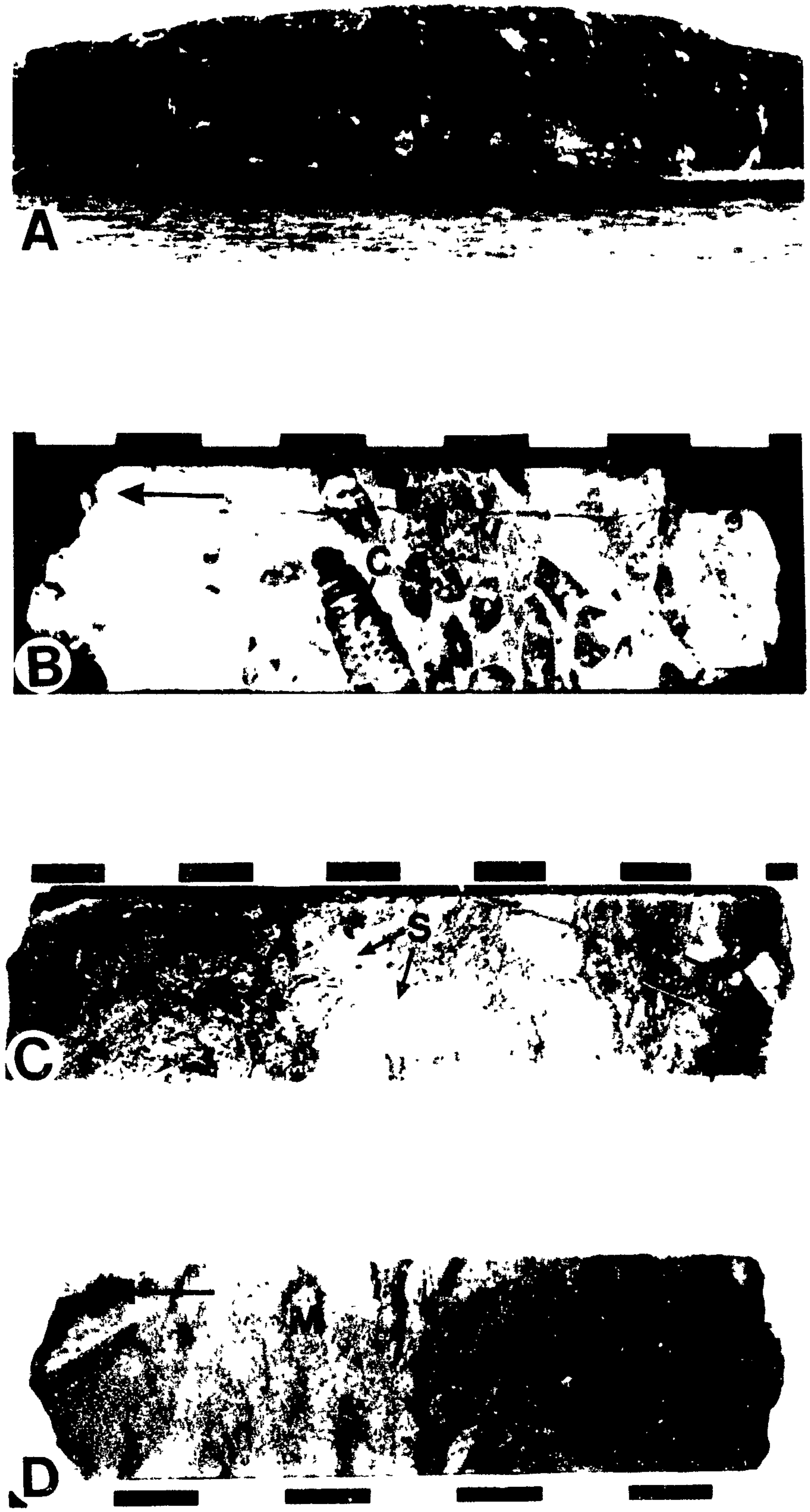

A
B
C
C
S
D
f
M

PLATE 2

A) Interior Facies. A well bedded outcrop exposure illustrates the vertical succession of shoals in the buildup interior facies. Cliff height is approximately ten metres. Mason Island.

B) Interior Facies. A typical fossil assemblage of dolomitized branching corals (Thamnopora (T)) and fenestral bryozoans (B) in early interior facies sediments. Mason Island.

C) Interior Facies. Extensive meadows of dolomitized bryozoans (B) cover the bedding planes of individual shoals in the interior facies. Bryozoans were largely responsible for the stabilization of interior facies sediments. Mason Island, S-Bry..

D) Interior Facies. Intact stems of robust crinoids (C) litter beds throughout the core of the interior facies. These organisms contributed to the stabilization of buildup sediments. Mason Island, S-17.

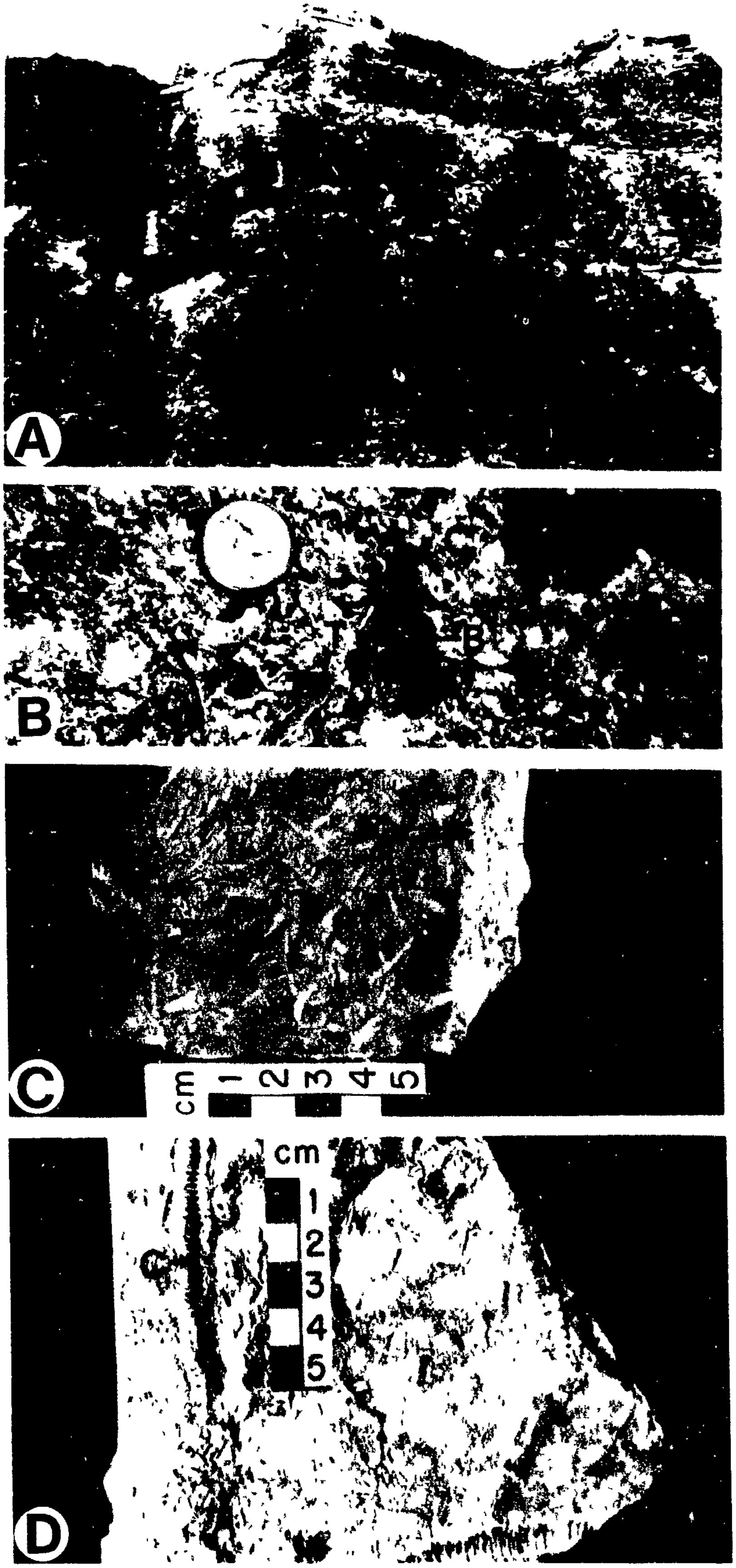

A
B
C
cm 1 2 3 4 5
cm 1 2 3 4 5
D

PLATE 3

A) **Interior Facies.** The large and robust (dolomitized) Udoteacean calcareous alga, Paralitanaia, (P) is similar to modern calcareous algae that stabilize sediments in strongly illuminated, sub-wave base waters. Scale bar, 1.13 mm.. Plane light. S-5-75 (8). 235 ft..

B) **Interior Facies.** The encrusting calcareous alga, Wetheredella (W), is widely scattered throughout the wackestone and floatstone matrices in the interior facies. This specimen provides an excellent example of allochem preservation by fabric retentive microcrystalline replacement dolomite. Scale bar, 0.3 mm.. Plane light. S-5-75 (8). 235 ft..

C) **Interior Facies.** The characteristic chain link texture of the binding calcareous alga, Sphaerocodium (S), is identified throughout the dolomitized carbonates of the interior facies. Scale bar, 0.3 mm.. Plane light. S-5-75 (8). 235 ft..

D) **Interior Facies.** The floating calcareous alga, Tentaculites (T), is rarely observed in the interior facies. This specimen is particularly well preserved by fabric retentive microcrystalline replacement dolomite. Scale bar, 2.69 mm.. Plane light. Mason Island, S-41.


A
B
S
C
D

PLATE 4

A) **Interior Facies.** The black micritic and clotted fabric represents the reticulate pattern of the internal structure of sponges (S). These poorly preserved remnants of sponge debris are encrusted by laminations of possible algal origin and several generations of dolomitized acicular fibrous cement (C). Scale bar, 2.69 mm.. Plane light. M-3-85 (50). 77 ft..

B) **Interior Facies.** Molds of sponge spicules (S) are rarely preserved throughout the interior facies. Scale bar, 0.3 mm.. Plane light. S-5-75 (8). 235 ft..

C) **Organic Rim Facies.** The massive coral, Favosites (F), is intermittently distributed in the relatively narrow organic rim facies. Rock Island.

D) **Organic Rim Facies.** The disphyllid coral, Dendrostella (D), is particularly common throughout the upper organic rim facies. The Bluff, 87S-1.

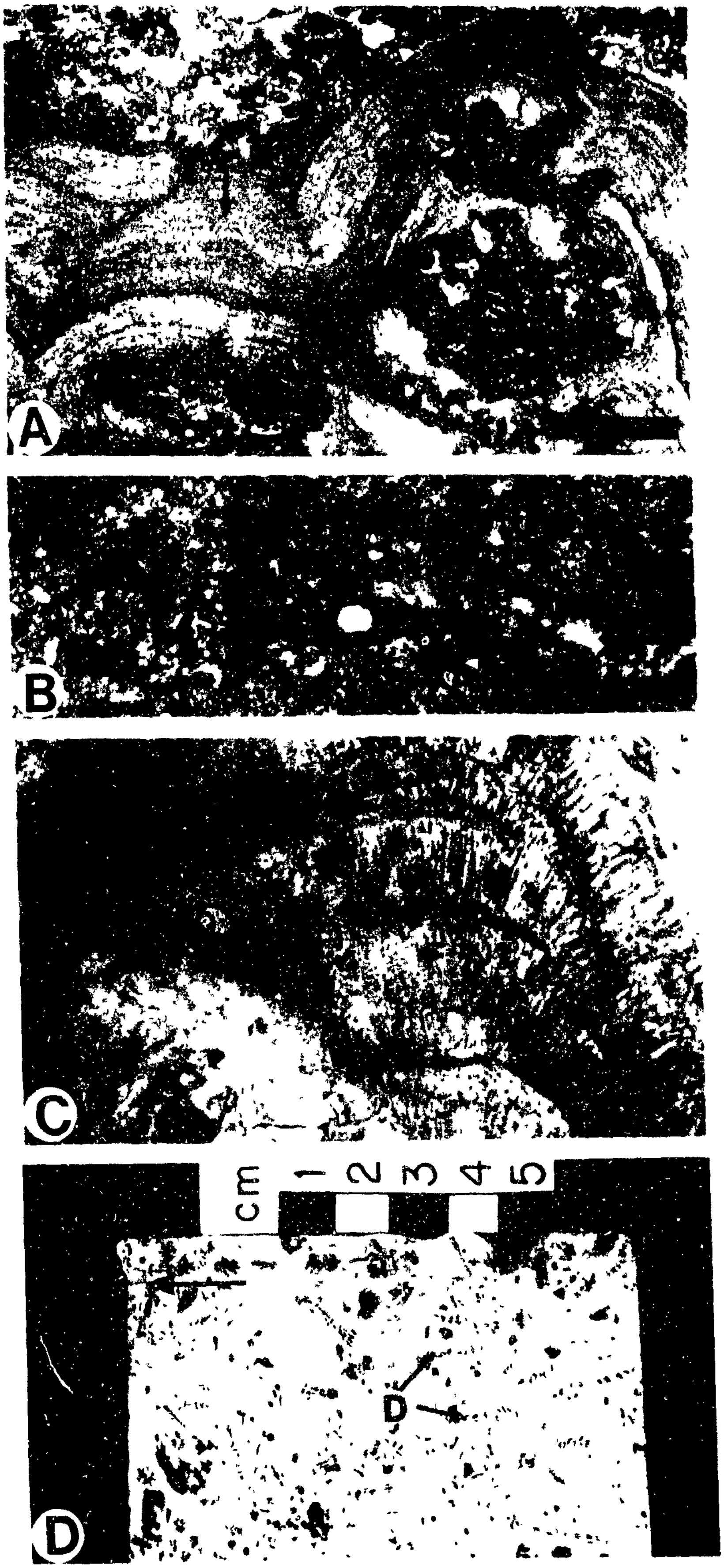

A
B
C
cm
1
2
3
4
5
D
D

PLATE 5

A) Organic Rim Facies. The tabulate coral, Alveolites (A), encrusts bulbous stromatoporoid debris (S). Scale bar, 2.0 mm.. Mason Island. S-63 B/2.

B) Organic Rim Facies. A cross sectional view across the corallites of the dendritic coral, Syringopora (S). Scale bar, 2.69 mm.. Plane light. The Bluff, S-101B.

C) Organic Rim Facies. The enigmatic sponge/coral species, Chaetetes (C), was a principal framework constructor during the later stages of buildup development. Note the distinct growth banding in this specimen (B). The Bluff, S-84.

D) Organic Rim Facies. Bulbous stromatoporoids range in size from a few centimetres to over a metre in diameter and are common throughout the organic rim facies. This particular specimen is approximately the size of a cricket ball. Simons Island.

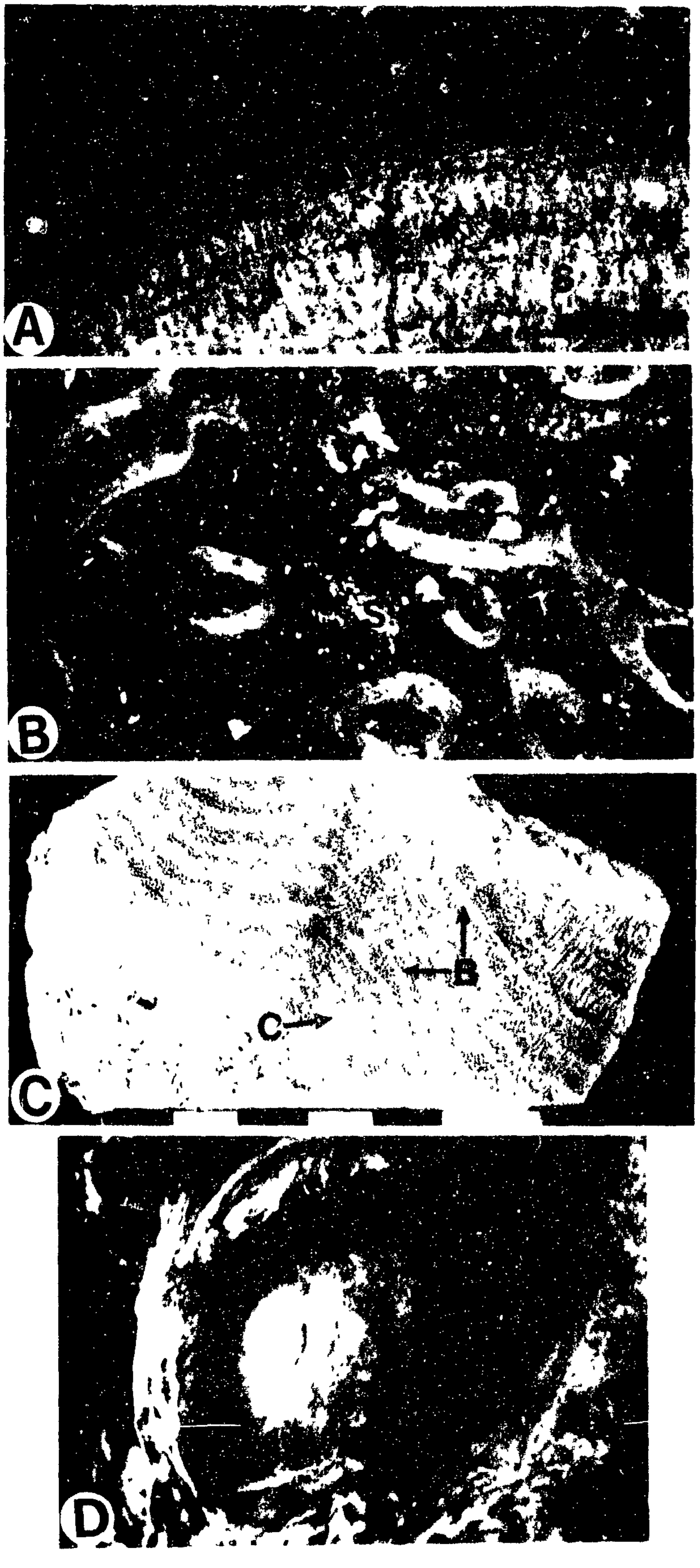

A
B
B
S
C
B
C
D

PLATE 6

A) Organic Rim Facies. A typical faunal assemblage of stromatoporoids (S) and the branching coral, Thamnopora (T), are observed in the outcrop exposures of the organic rim facies. The Bluff.

B) Organic Rim Facies. Coiled nautiloids are amongst a wide variety of non framebuilding organisms preserved in the organic rim facies. The Bluff.

C) Flank Laminated Subfacies. Dolomitized bituminous laminated mudstones (M) are interbedded with light coloured fossiliferous wackestones and floatstones (L). The fossil content and crude graded bedding in the carbonate intervals indicate that they were deposited as episodic, buildup-derived debris flows shed down the buildup flanks. The bituminous mudstones were pelagically derived, and are probably contiguous with the basinal bituminous mudstones. The internal stratification of these facies increases in dip from 2 to 5 degrees at the base (B) to 30 to 35 degrees at the top (T). The dips represent the continual accretion of flank sediments during buildup development. The preservation of the bituminous mudstones suggest that the original sediments were deposited in anoxic bottom waters. M-6-86, core boxes 160-312 ft..

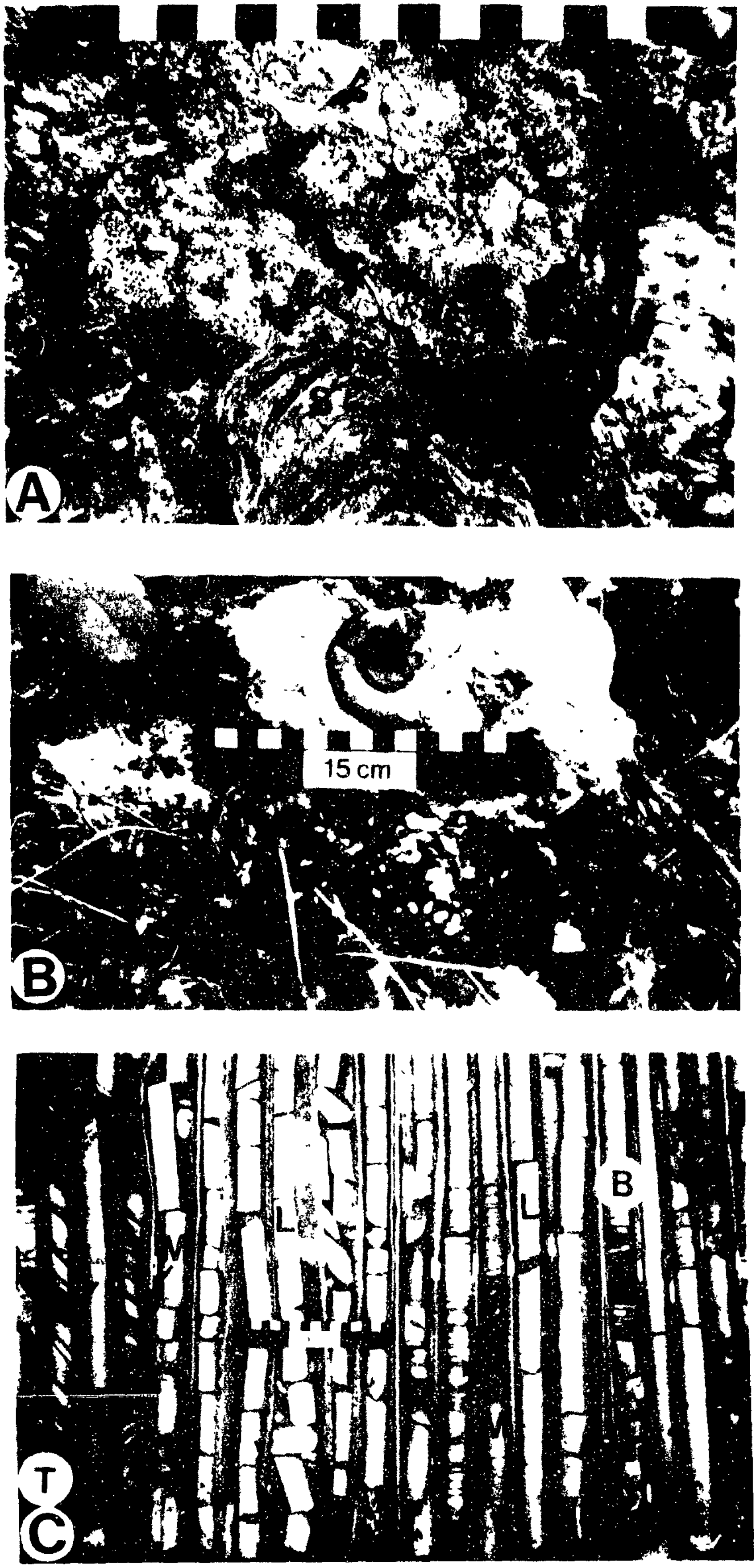

A
B
15 cm
M
L
L
B
T
C

PLATE 7

A) Flank Bioturbated Subfacies. Chaotically arranged skeletal debris (D) derived from organic rim facies was deposited in a pelleted mudstone matrix. Bituminous mudstones are conspicuously absent in this subfacies indicating that the original sediments were bioturbated by infaunal organisms in aerobic waters. M-6-78 (10). 80 ft..

B) Flank Cemented Subfacies. At least two generations of submarine fibrous cements (C) infills intergranular porosity in a dipping interval of calcareous alga grainstones. The grainstones are interbedded with thinner units of wackestones/packstones (W/P) typical of flank sedimentation. Centimetre scale. M-18-77 (20). 22 ft..

C) Stromatolite Cap Facies. Laminated fenestral strata represent the final stage of post-buildup carbonate sedimentation. Birch Point.

D) Stromatolite Cap Facies. Outcrop (O) and core (C) samples of the coated grain grainstones and associated fenestral textures. 635-48 (20). 120 ft.. Canadian quarter for scale. Steeprock Bay Dome Cliffs.

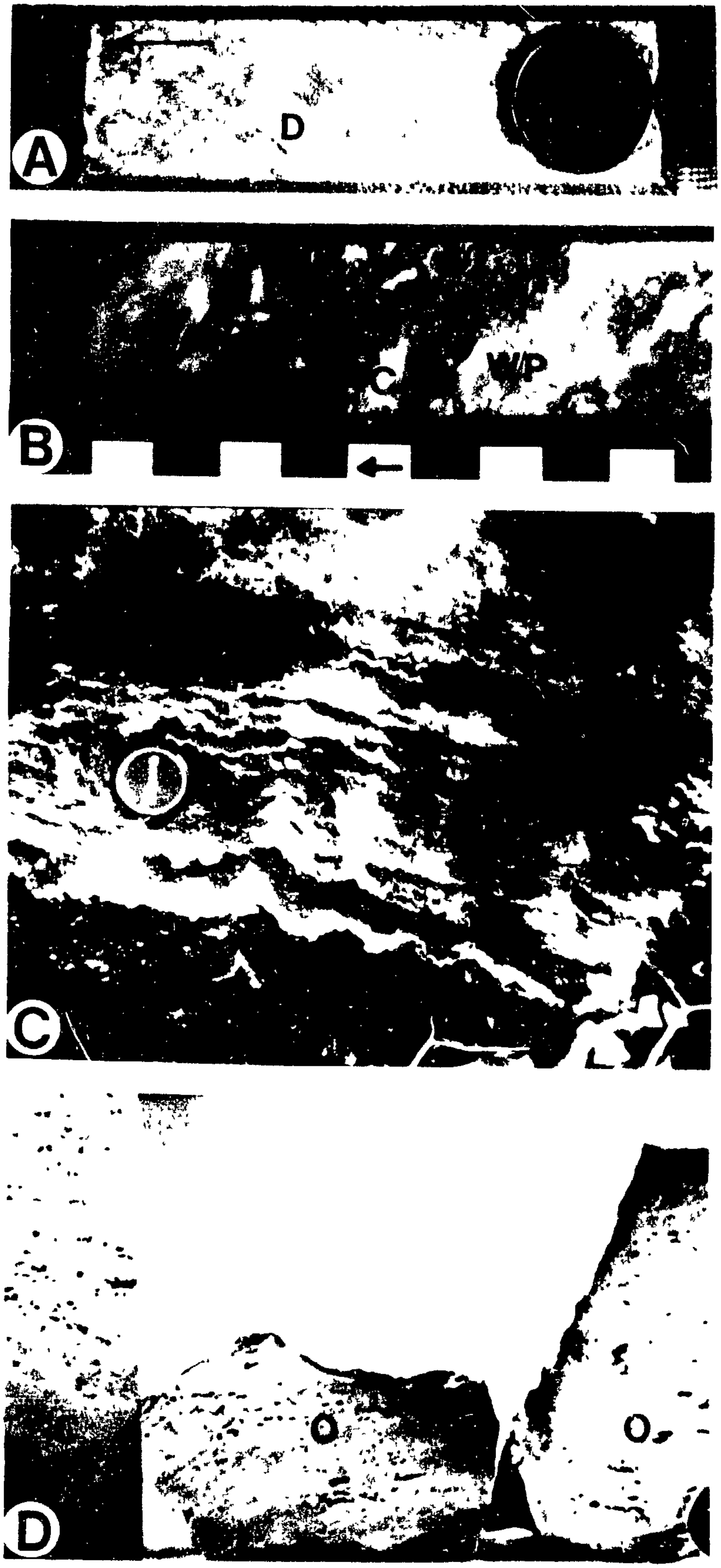

D
A
C
W/P
B
C
O
O
D

PLATE 8

A) **Stromatolite Cap Facies.** Dolomitized grainstones and packstones containing a wide variety of coated grains such as peloids, oncolites (O), and grapestones (G) represent sedimentation in relatively agitated waters during the final stages of buildup development. Centimetre scale. M-3-85 (50). 70 ft..

B) **Stromatolite Cap Facies.** The fenestral texture outlines two laterally linked cabbage-head stromatolites (S1, S2 defined by cut lines). The crests of these structures are capped by a horizontal truncation surface (T) and a unit of very finely laminated mudstones (M). Steeprock Bay Dome Cliffs.

C) **Stromatolite Cap Facies.** The calcareous algal cyst, Uslonia (U). Plane light. Scale bar, 0.3 mm.. M-3-84 (44). 77 ft..

D) **Stromatolite Cap Facies.** The calcareous algal cysts, Parathurammina (P) and Biospheras (B). Scale bar, 0.95 mm.. Plane light. M-3-84 (23). 90 ft..

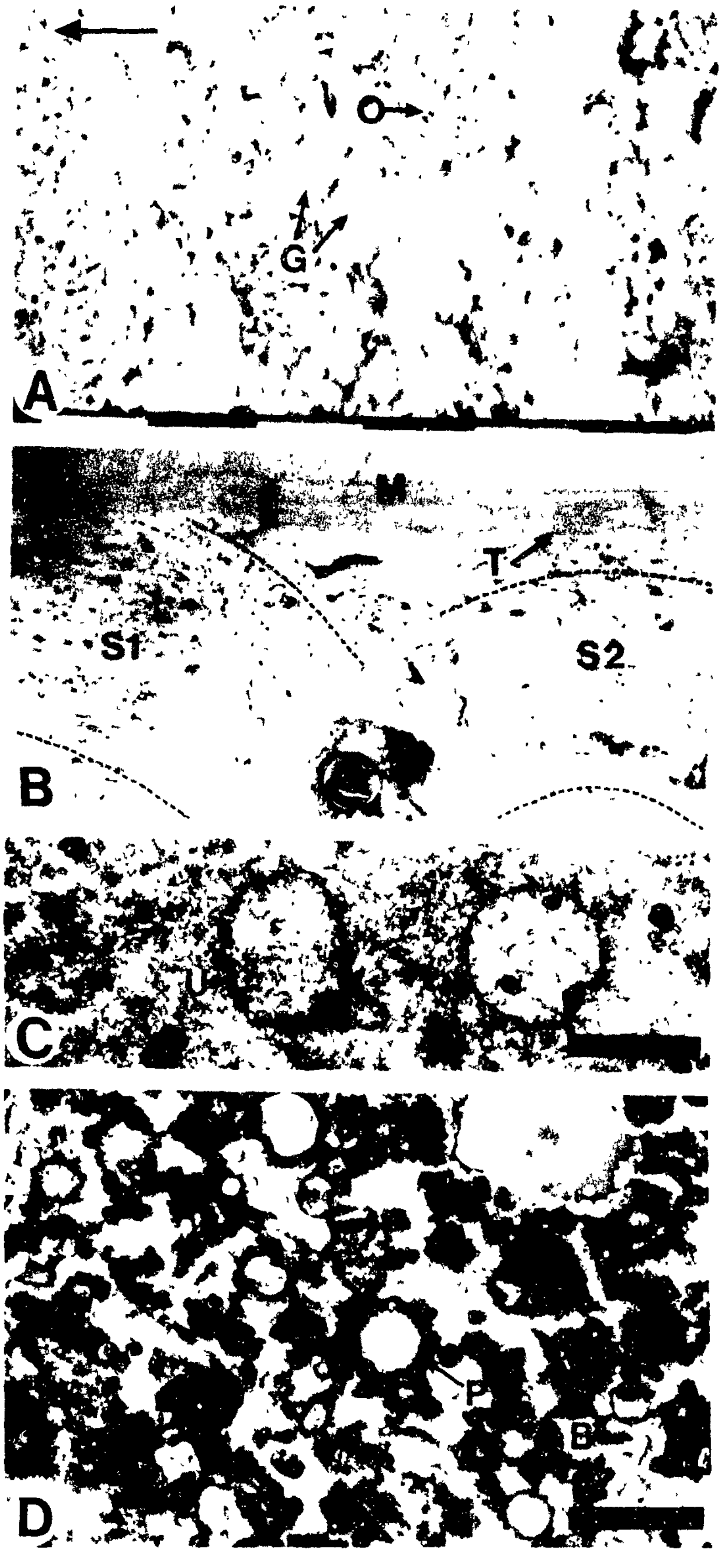

A
O
G
B
M
T
S1
S2
C
D
P
B

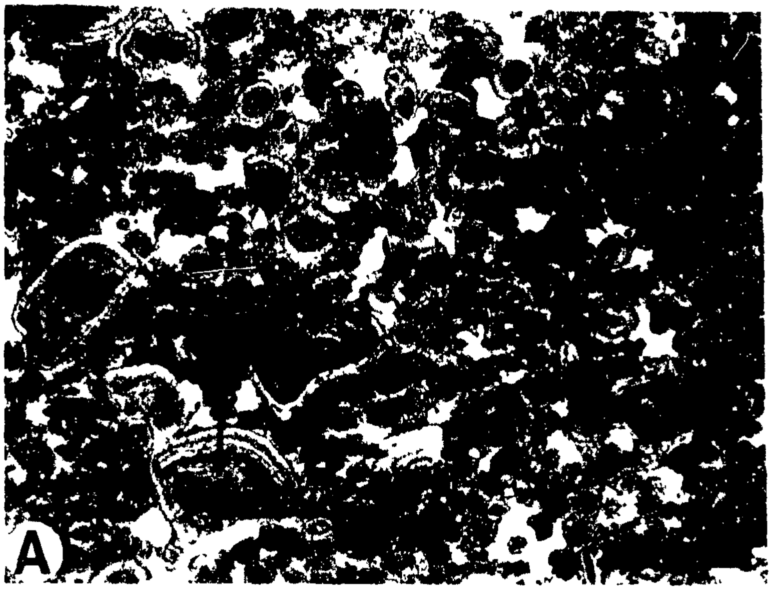
PLATE 9

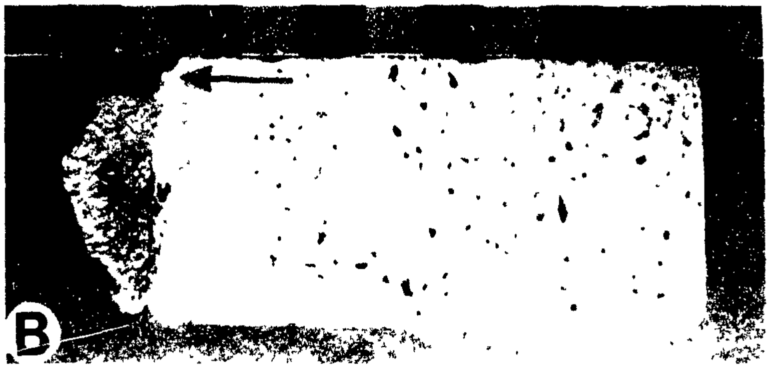
A) Stromatolite Cap Facies. Peloid (P), composite grain (C), and oncolite (O) grainstones. Note generations of submarine acicular fibrous cement (A) that encrust coated grains; note also the brecciated cemented coated grains (B). The brecciated grains suggest that strongly agitated hydraulic conditions prevailed during the latter stages of post-buildup carbonate sedimentation. Scale bar, 2.69 mm.. Plane light. Salt Point Cliffs. SPB 4B.

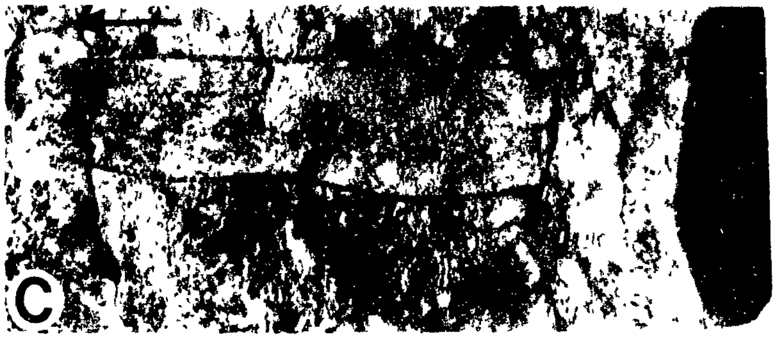
B) Stromatolite Cap Facies. Thin beds of green shale (S) are often interbedded with the coated grain grainstones. The green shales were probably stirred up in deep water environments during periodic storm activity and deposited in the shallow water stromatolite cap facies. Centimetre scale. 635-46 (30). 58 ft..

C) Stromatolite Cap Facies. Large angular rip-up clasts of brecciated fenestral strata (teepee structures) (B) are incorporated into undisturbed fenestral strata. These teepees represent the destructive force of intense storm activity during the deposition of these facies. Hammer head for scale. Steeprock Bay Dome Cliffs.

D) Stromatolite Cap Facies. The common laminations between the pisolites (P) show that these structures formed <u>in situ</u>. The pisolites' association with grain-supported carbonates suggest that they were formed in a submarine environment. Steeprock Bay Dome Cliffs.


A


B


C

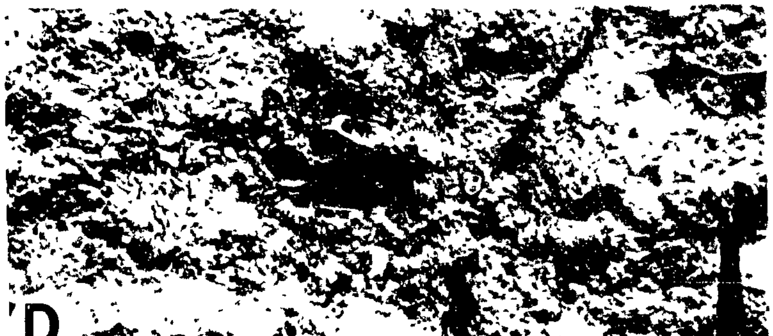

D

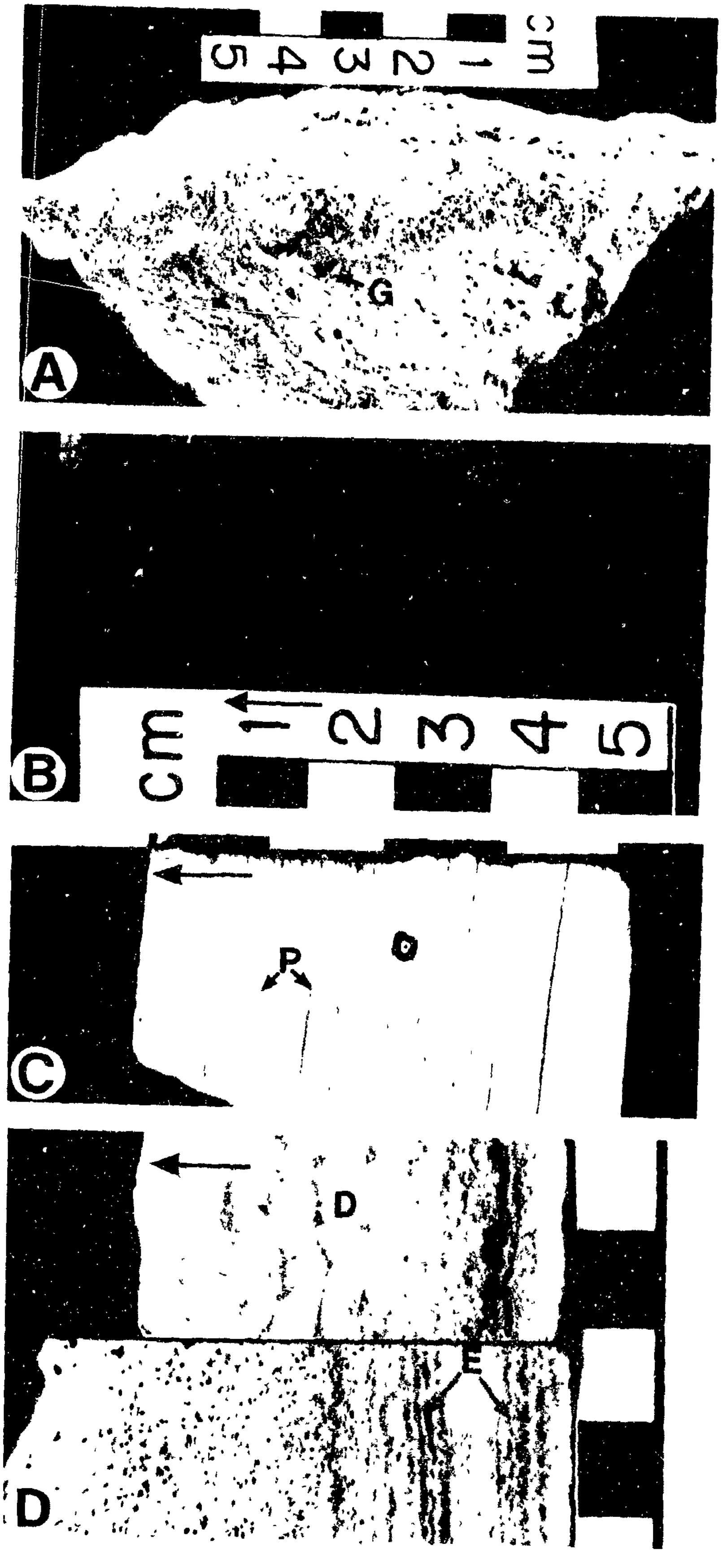
PLATE 10

A) **Stromatolite Cap Facies. Calcrete.** The limited distribution of calcrete to the upper four metres of the buildups indicate that only the uppermost parts of the buildups were exposed to subaerial diagenetic processes. The crenulated and banded texture of calcrete and related calcrete glaebules (G) are observed in this sample. Steeprock Bay Dome Cliffs.

B) **Basin. Brightholme Member.** The black bituminous, laminated mudstones of the Brightholme Member represent basin sedimentation during buildup development. These deposits are most probably contiguous with the bituminous mudstones interbedded with buildup-derived flank sediments in the laminated subfacies. M-3-73 (3), 87 ft.

C) **Basin. Ratner Member.** Varved bituminous partings (P) are interlaminated with thin intervals of dolomitic mudstones in lower Ratner Member sediments. Centimetre scale. M-3-73 (6), 69 ft.

D) **Basin. Ratner Member.** Upper Ratner sediments are interbedded dedolomites (D) and calcitized evaporites (E). Note the relict enterolithic texture of the calcitized evaporites. Centimetre scale. M-6-86 (12), 56 ft.

A
cm
1
2
3
4
5
G
B
cm
1
2
3
4
5
C
P
D
D
E

CHAPTER 3. DIAGENESIS

3.1 INTRODUCTION

The diagenesis of the Winnipegosis carbonates is complex. Many of the early fabrics are modified by later diagenetic processes such as dolomitization and dissolution. Often, they can only be clearly distinguished and photographed under cross nicol prisms. All dolomites and calcites are nonferroan. The limestone buildup calcites are nonluminescent, the dolomites express a dull and uniform luminescence, and the cavity and fracture filling calcites show bright luminescence across crystal terminations and boundaries. A paragenetic sequence of all the diagenetic features is presented in Figure 13. The diagenesis plates appear at the end of the chapter.

The stratigraphic distribution, petrography, and relative timing of precipitation of each of the diagenetic fabrics are presented according to four principal diagenetic environments: 1) open marine; 2) subaerial/meteoric; 3) restricted marine/shallow subsurface; 4) deeper subsurface. The open marine diagenetic environment represents normal sea waters favourable for the early lithification of Winnipegosis sediments by microcrystalline and fibrous cements. Subaerial/ meteoric conditions are associated with the early evaporative draw down of water in the Elk Point Basin, and the subsequent exposure and modification of the upper parts of the buildups. The restricted marine/shallow subsurface diagenetic environments represent conditions in which hypersaline waters were possibly responsible for dolomitization on the seafloor and in the shallow subsurface. The deeper subsurface diagenetic processes include fracturing, dissolution, calcite cementation, dedolomitization and evaporite calcitization.

Under the section, Geochemistry, $\delta^{13}C$, $\delta^{18}O$, and $^{87}Sr/^{86}Sr$

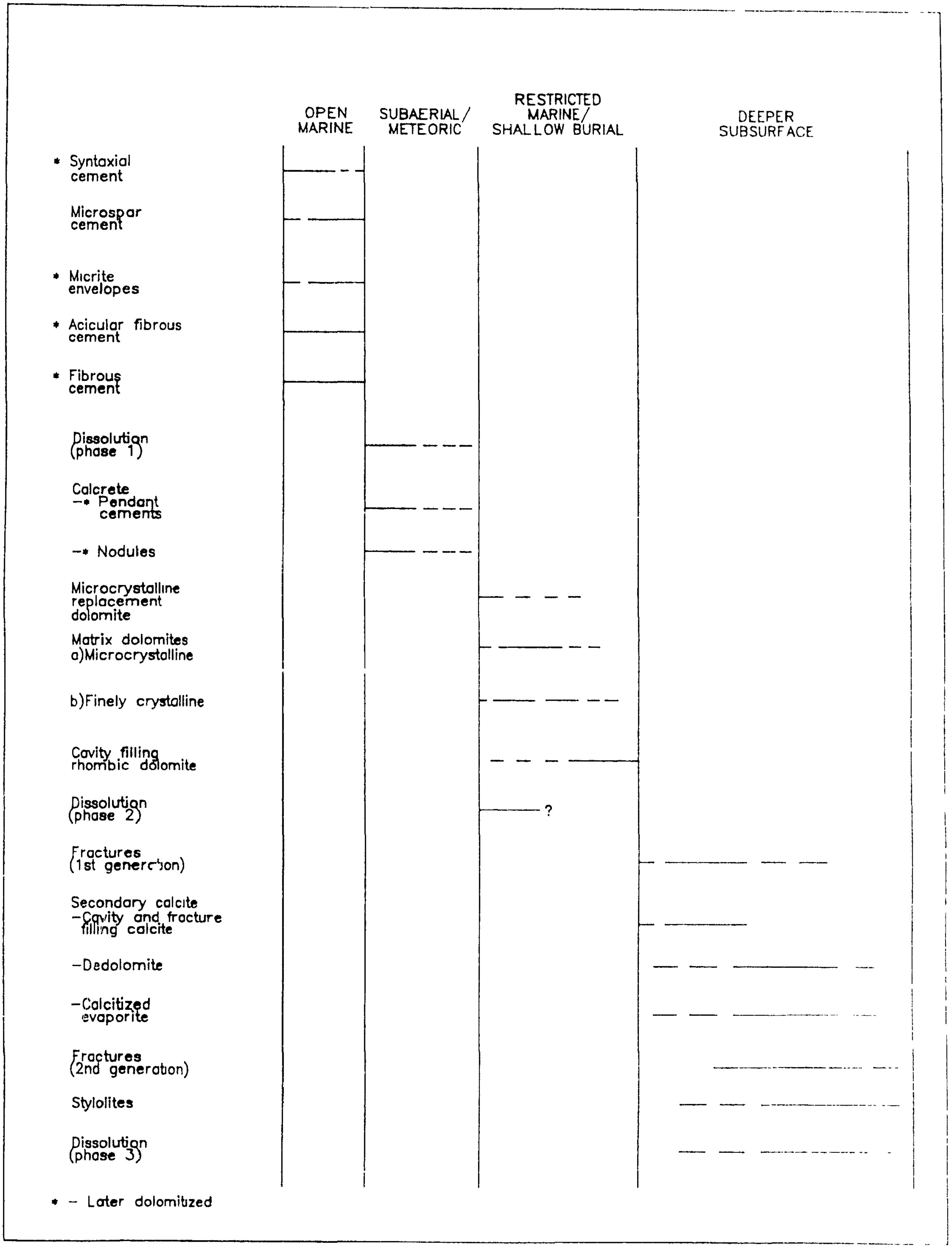


Fig. 13 Paragenesis of Winnipegosis buildups

isotopic data, staining and cathodoluminescence are discussed and interpreted. At the end of the chapter, a general discussion of the textural and geochemical data investigates the diagenetic processes involved in the early submarine cementation of buildup sediments, the contemporaneity of subaerial and submarine diagenetic processes, the evidence for restricted marine and shallow burial dolomitization, possible mechanisms for dolomitizing fluid flow, the dissolution porosity in the buildups, and the late stage cementation, calcitization and dedolomitization of buildup and basin sediments.

3.2 OPEN MARINE DIAGENESIS

The diagenetic features assigned to open marine diagenesis are syntaxial cementation, microspar cementation, micritization, and acicular fibrous and fibrous cementation.

3.2.1 Syntaxial Cement

Dolomitized syntaxial cements occur around echinoid ossicles in mud supported wackestones (Plate 11A).

3.2.2 Microspar Cement

The bulk of the wackestones and packstones in the lower Gunnlaugson limestone buildup and platform sediments consists of grey and brown skeletal debris in a brown mud matrix. The matrix is comprised of a mosaic of micrite and microspar. The constituent crystals are anhedral, cloudy, and range in size from 3 to 5 μm (Plate 11B). It is not certain that this cement mosaic is a primary fabric, but rather a neomorphic fabric. On the basis of petrographic data alone therefore, it is not clear whether these textures formed on the seafloor or later in a deeper burial diagenetic environment. However, geochemistry indicates that these fabrics were formed early from marine waters. These cements are the only cements preserved as calcite. In other buildups, matrix cements, acicular fibrous and fibrous cements are all dolomitized.

3.2.3 Micrite Envelopes

The evidence for micritization of carbonate grains throughout the buildups has been largely obscured by fabric destructive matrix dolomitization, and is only preserved in the stromatolite cap facies (Fig. 9). Dolomitized micritic envelopes form black and grainy films, 5 to 10 μm thick, which outline the circular to ellipsoidal shape of original host grains (0.5 to 1.0 mm diam.), possibly peloids and oncolites (Plate 11C). The interior cavities within the envelopes are filled by dolomitized fibrous cements or cavity filling rhombic dolomite. This textural relationship suggests that the micritization of carbonate grains was one of the very earliest diagenetic processes to have occurred, predating grain interior solution and fibrous cement pore filling.

3.2.4 Acicular Fibrous Cement

Dolomitized acicular fibrous cement can only be identified in thin section, and is minor in occurrence comprising less then 5% of all cavity filling cement types. Commonly, it occurs in shelter porosity and sheet cavities in the flank facies, and fills the corallites of coralline debris distributed throughout the interior and flank facies. Rarely, the cement separates parallel laminations that encrust peloids and oncolites in the stromatolite cap facies.

Acicular fibrous cement consists of inclusion-rich crystals which vary from 75 to 200 μm in length and 5 to 10 μm in width. The sweeping extinction pattern across a single generation of cement suggests that the constituent crystals are radiaxial. Inclusion-rich banding is parallel to the cement substrate. In shelter porosity and sheet cavities, the cement occurs as fans of distally diverging crystals (Plate 11D). In intraskeletal porosity, it occurs as an isopachous rim cement which may partially or completely infill the cavities (Plate 12A). Up to four generations of the cement are concentrically arranged around the perimeters of some oncolites, grapestones and relict sponge debris (Plate 12B).

Acicular fibrous cement is probably the earliest fibrous cement because: 1) it predates the more coarsely crystalline bladed fibrous cement; 2) it is overlain by carbonate muds in intraskeletal cavities; 3) reworked fragments of oncolites and grapestones encrusted by the cement are recemented by coarsely crystalline fibrous cement (Plate 12C).

3.2.5 Fibrous Cement

Dolomitized fibrous cement represents 5% of all cement fabrics, and 35% of cavity filling cements in the interior and flank facies. The distribution of these brown and cream coloured cements is facies controlled commonly occurring as intergranular cements in the cemented subfacies (Plate 12D) (Fig. 10). It also occurs as a cavity filling spar in shelter porosity and sheet cavities along bedding planes in the flank facies. It is partially preserved as a minor cement in the reworked storm deposits of the stromatolite cap facies.

Fibrous cement is characterized by crystals which are 275 to 500 μm long, 25 to 75 μm wide, inclusion-rich, banded, and arranged normal to the substrate (Plate 13A). Undulose extinction across individual crystals indicate that they display a radiaxial split crystal growth fabric (Plate 13B). Otherwise, intercrystalline boundaries and crystal tips have been destroyed by neomorphic processes. The cement most frequently occurs as a single generation precipitate, but can occur as two generations. Both generations may contain internal banding. In a cavity containing two generations of fibrous cement, the later generation displays a dense concentration of inclusions that appears black (Plate 13C). In addition, an unusual pattern of irregular internal "fractures" ramifies across the black, inclusion-rich fibrous crystals (Plate 13D). These "fractures" tend to be normal, sub-normal or parallel to the substrate. They are 5 to 10 μm wide and up to 400 μm long, often extending the length of the host crystals. Their orientation is not necessarily determined by the intercrystalline boundaries of the host crystals. They are filled by a highly birefringent microspar which may be related to the next generation of cement, cavity filling rhombic dolomite. This texture in the cement is stratigraphically restricted to a 50 m interval above the platform in the cemented subfacies (Figs. 10, 11).

Fibrous cement postdates acicular fibrous cement. Locally, it is observed on a substrate of acicular fibrous cement (Plate 11D); and fragments of grapestones encrusted by acicular fibrous cement are frequently reworked and recemented by fibrous cement. The timing of formation of the internal "fractures" in the fibrous cements predates the subsequent precipitation of the cavity filling rhombic dolomite on the fibrous cement substrate.

3.3 SUBAERIAL/METEORIC DIAGENESIS

The following diagenetic features are assigned to subaerial/meteoric diagenesis: dissolution (phase 1), and calcrete formation (pendant cements, glaebules).

3.3.1 Dissolution (Phase 1)

Phase 1 dissolution of the cortices of peloids and oncolites is restricted to the stromatolite cap facies. The rims of these allochems are preserved as micritic envelopes that are filled by fibrous marine cements (Plate 11C). The timing of Phase 1 dissolution postdates the deposition of the peloids, and predates the precipitation of the cements in the peloidal cortices.

3.3.2 Calcrete

Horizontal intervals (10 to 25 cm) of calcrete are interbedded with thicker peloid-oncolite grainstones (50 to 75 cm) in the upper 4 m of the stromatolite cap facies exposed in the Steeprock Bay dome outcrop. Evidence for calcrete development in drill core is limited to a single well (M-4-87) on Salt Point. Calcrete is comprised of brown and cream bands containing a chaotic jumble of dolomitized crenulated laminations and glaebules (Plate 10A). Considerable porosity is preserved in the voids of the crenulated fabric.

Calcrete contains two characteristic diagenetic fabrics: 1) pendant cements; 2) glaebules.

3.3.2.1 Pendant Cements

Dolomitized pendant cements represent less than 5% of all cavity filling cements. They line the ceilings of voids in the calcrete horizons (Plate 14A). These cements appear blocky with rectangular crystals, 75 to 150 μm long and 50 μm wide, arranged parallel to void ceilings. Successive cement phases develop downward into the underlying cavities. Internal sedimentation in the cavities is hard to identify because of modification by dolomitization.

3.3.2.2 Glaebules

Severely modified circular to ellipsoidal dolomitized glaebules (0.2 to 0.4 mm diam.) are distributed throughout the calcrete-related matrix dolomites (Plate 14B). Generally, they are structureless, although vague concentric laminations are rarely preserved in the glaebule walls. Invariably, the glaebules contain central cavities which outline the shape of original host grains. These cavities indicate that the glaebules were subjected to a phase of dissolution prior to their recementation by cavity filling rhombic dolomite.

The relationships between the various textural features and cements in these calcretes indicate that pendant cementation was contemporaneous with or postdated calcrete formation.

3.4 RESTRICTED MARINE/SHALLOW SUBSURFACE DIAGENESIS

Microcrystalline replacement dolomite, matrix dolomites, and cavity filling rhombic dolomite are interpreted to have precipitated in the restricted marine/shallow subsurface diagenetic environments.

3.4.1 Microcrystalline Replacement Dolomite

Fabric retentive microcrystalline replacement dolomite mimetically replaces and preserves delicate structures such as micritic envelopes, laminated oncolites and grapestones, and calcareous algae (Plate 14C). It is only clearly resolved under the scanning electron microscope, and is comprised of anhedral to subhedral crystals less than 5 μm in size (Plates 15A, 15B). It occurs most commonly in the uppermost interior and organic rim facies. It is rarely preserved in the platform and the lowermost interior facies.

Where more coarsely crystalline matrix dolomites have not completely obliterated the original diagenetic fabrics, this fabric retentive type of dolomite has preserved textures such as fibrous and pendant cements. Although intercrystalline boundaries may be obliterated by neomorphic fabrics, sweeping undulose extinction define the width and length of mimetically replaced radiaxial fibrous and acicular fibrous crystals (Plates 12A, 13A). Similarly, the dolomitized blocky crystals of the pendant cements are clearly delimited by their unit extinction (Plate 14A).

Mimetic replacement of radiaxial submarine and pendant vadose cements indicates that this generation of dolomitization postdated the early cementation, and subsequent subaerial exposure of the buildup sediments.

3.4.2 Matrix Dolomites

Matrix dolomites are widespread throughout the buildup, basin and platform sediments, and represent 60% of all Winnipegosis textural fabrics. They occur in a variety of colours and textures. White matrix dolomite is chalky, and constituent allochems are poorly preserved. Light to dark brown matrix dolomite is not chalky, and the cream coloured allochems and early diagenetic fabrics are better preserved. The platform sediments are characterized by yellow, chalky mottles surrounded by a distinctly different brown matrix.

In the basin sediments, thin (<50 μm), light to dark brown intervals of matrix dolomite are intercalated with the black, laminated, bituminous mudstones of the Brightholme Member. In the Ratner Member, 3.0 to 5.0 mm thick, brown intervals of the dolomite are interbedded with bituminous laminites.

Matrix dolomite is divided into two categories based on crystal size: 1) microcrystalline matrix dolomite (<20 μm; commonly 5 to 10 μm); and 2) finely crystalline matrix dolomite (20 to 50 μm; commonly 30 to 40 μm) (Plate 15C and D). Both types of matrix dolomite are inclusion rich.

In buildup sediments, microcrystalline matrix dolomite is comprised of poorly defined anhedral crystals that form an interlocking mosaic associated with submicroscopic pin-point porosity. Under plane light, it most often appears black and grainy giving the matrix a poorly defined, clotted appearance.

In the buildups, the occurrence of finely crystalline matrix dolomite ranges from a dense mosaic of tightly interlocking, euhedral to subhedral rhombic crystals (Plate 15C) to a very porous fabric of poorly preserved rhombs. The crystal edges of these rhombs are often solution pitted and rounded.

Platform sediments are comprised exclusively of finely crystalline matrix dolomite. The distinctive chalky mottles are characterized by individual rhombs surrounded by considerable porosity. The brown, non-chalky mottles contain a less porous, dense mosaic of the matrix dolomite.

In basin sediments, finely crystalline matrix dolomite occurs as a dense mosaic (Plate 15D). In upper Ratner beds, some of the dolomite was dedolomitized during the calcitization of associated evaporite beds.

The fabric destructive nature of finely crystalline matrix dolomite affects allochems and early diagenetic fabrics throughout the buildups. In particular, allochem peripharies and marine cement intercrystalline boundaries are often the sites of neomorphic replacement fabrics by the dolomite (Plate 16A and B).

The distribution of the various types of matrix dolomite does not appear to be facies controlled. However, the platform, basin and lowest buildup sediments are characterized by the dense finely crystalline matrix dolomite, whereas most of the overlying buildup sediments contain the whole range of matrix dolomite crystal types and fabrics.

Matrix dolomites neomorphically replace micritic sediments and mimetically dolomitized fibrous cements. These textural relationships suggest that matrix dolomitization postdated both early sediment cementation, and dolomitization by the fabric retentive replacement dolomite.

3.4.3 Cavity Filling Rhombic Dolomite

Light brown to white cavity filling rhombic dolomite represents 20% of all replacement and cement fabrics, and 40% of the various cavity filling cements in the buildups. It is difficult to distinguish from other replacement fabrics in hand specimen. It forms the primary intergranular cement in the peloid oncolite grainstones of the stromatolite cap facies. Cavity filling rhombic dolomite occurs as a minor cement in shelter porosity and sheet cavities in the flank facies, and rarely in intraskeletal cavities of skeletal debris throughout the buildup. In addition, the dolomite forms a void filling cement in cavities of uncertain origin in Ratner sediments and in horizons of calcrete which occur intermittently in the buildup cap.

Crystals of cavity filling rhombic dolomite are anhedral to euhedral. In the intergranular porosity of the peloid oncolite grainstones, crystal sizes vary from 5 to 20 μm (Plate 16C). In larger intergranular, intraskeletal and calcrete cavities or shelter porosity, they range in size from 25 to 200 μm (Plates 16D and 17A). In cavities originally lined by fibrous cement, the dolomite cement inherits an undulatory extinction pattern from its fibrous cement substrate. More commonly, the dolomite develops directly on a matrix or allochem substrate and expresses unit crystal extinction. In general, the crystals are cleaner than the dusty matrix dolomites. Where present, primary intergranular and shelter porosity is either partially or completely infilled by the cement. In Ratner sediments, cavity filling rhombic dolomite is observed as well formed rhombs with dusty nuclei, clean rims and sharp crystal tips indicating at least two periods of crystal growth (Plate 17B).

Locally in the buildup sediments, rhomb cores have been removed by dissolution (Plate 17C). The preserved rims vary in thickness from 5 to 25 μm, display unit extinction and are relatively clean. Although the rim tips and boundaries are poorly defined, their general shape, size and other textural characteristics resemble modified crystals of cavity filling rhombic dolomite.

Where fibrous cements and cavity filling rhombic dolomite occur together in the same cavity, the dolomite cement always postdates the fibrous cement. Cavity filling rhombic dolomite infills voids in calcrete horizons, forms intergranular cements in the peloid-oncolite grainstones that are interbedded with the calcrete, and occurs as a cement in varved Ratner laminites. These textural relationships indicate that the dolomite cement postdates open marine cementation, buildup exposure, and Ratner sedimentation.

3.5 DEEPER SUBSURFACE DIAGENESIS

Dissolution (phase 2), two fracture generations, cementation by cavity and fracture filling calcite, dedolomitization, calcitization of evaporites, and pressure solution are assigned to the deeper subsurface diagenetic realm.

3.5.1 Dissolution (Phase 2)

In hand specimen, most of the Winnipegosis carbonates contain small to coarse vugs, and are extremely porous. The coarse vugs (1.0 to 1.5 cm) are often enlarged moldic pores of skeletal grains. Fine vuggy porosity (0.2 to 0.5 mm (after Choquette and Pray, 1970)) is abundant in the matrix dolomites.

In thin section, intercrystalline porosity in all dolomite types is greatly enhanced by dissolution; for example, the dissolved cores of cavity filling rhombic dolomite and the well rounded crystal tips of finely crystalline matrix dolomite. However, it is unlikely that this porosity can be attributed to a single dissolution event as Winnipegosis sediments were probably subjected to more than one period of dissolution during geologic time; therefore, constraining the timing of this event is somewhat problematic. Also, the extent of dissolution due to present day exposure is uncertain.

3.5.2 Fractures

In outcrop, cliff faces exhibit vertical to subvertical fractures and joints. A major disruption of the flank sediments occurs at the southwest end of Rock Island where undisturbed southwesterly dipping flank beds are juxtaposed along a fracture next to a house-sized block containing northeasterly dipping flank beds.

In core, at least two generations of fractures are observed. The earlier, and most common, generation is infilled by secondary cavity and fracture filling calcite cement (Plate 17D); whereas the later generation of fractures are open.

Fracture orientation is generally vertical to subvertical, although it is sometimes random. Where orientation is random, the rock is slightly brecciated, and all interclastic cavities are filled with the calcite cement (Plate 18A). Rarely, first generation fractures are cross cut by stylolites. In one instance, a second generation fracture is truncated by a stylolite (Plate 18B). Fractures of both types cross cut all facies in both limestone and dolostone buildups.

Some small cavities and all first generation fractures contain calcite cement and predate stylolitization. The textural relationship between both generations of fractures and the stylolites indicates that these rocks were fractured prior to significant burial.

3.5.3 Cavity and Fracture Filling Calcite

Cavity and fracture filling calcite cement represents about 15% of all Winnipegosis cement types, and about 15% of cavity filling cements in the buildups. It fills moldic, vuggy, intercrystalline, and intraskeletal porosities, and first generation fractures. In very large cavities (2.0 to 3.0 cm diam.), grey, euhedral, calcite crystals several millimetres in size are observed. In thin section, the cement is readily identified by its large (0.5 to 1.0 mm), euhedral crystals with rhombohedral cleavage (Plat 18C).

The calcite cement is the last cement to be precipitated in the buildups. It fills, and therefore postdates, the first generation fractures. It predates the development of second generation fractures that lack cement.

3.5.4 Dedolomite and Calcitized Evaporite

Dedolomite occurs within a 0.5 to 8.0 m interval of the top of some buildups in the Dawson Bay area (e.g., Steeprock Bridge Dome, drill core S-5-75). The original carbonate precursor is often completely obliterated by the very coarse crystalline, brown and grey, sugary calcite. In upper Ratner sediments, laminations of calcitized evaporite contain anhedral calcite crystals that cross cut and preserve thin dusty units that were associated with the precursor evaporite (Plate 18D). In these basinal sediments, the original textures of the dedolomites resemble finely crystalline matrix dolomite

3.5.5 Stylolites

Rare stylolites are observed in both buildup and basin sediments. In the buildup sediments, horizontal stylolites are restricted to the Gunnlaugson limestone buildup and the limestone intervals which cap the dolomitized buildups. Similarly, stylolites have developed in the dedolomitized intervals of the Ratner Member. In addition, microstylolites occur along the bituminous partings contained by the calcitized and dedolomitized intervals of the basin sediments. Significantly, stylolites are not observed in any dolomitized Winnipegosis carbonates in the Dawson Bay area. However, they are observed in the more deeply buried dolomitized carbonates in Saskatchewan. In both buildup and basin settings, the lateral extent of stylolites is uncertain as they are only observed in core.

In buildup and dedolomitized sediments, stylolites have amplitudes which vary from a few microns to 1 to 2 cm, and wavelengths which vary from a few microns to 0.5 cm. They often contain a black, petroliferous, insoluble residue most probably comprised of clays and organic matter (Plate 19A). In the Gunnlaugson limestone buildup, first generation fractures containing cavity and fracture filling calcite cements are truncated by a horizontal stylolite. In the Bell River Bay dolostone buildup, stylolites also cross cut first generation fractures and an interval of dedolomite.

Along bituminous partings in the basin sediments, microstylolite amplitudes and wavelengths vary from 25 to 500 µm. Microstylolites are heavily stained with a red-brown black insoluble residue acquired from the original bituminous partings. In the limestone intervals of the Ratner Member, calcitized evaporite (calcite crystals >250 µm) are often abruptly juxtaposed against finely crystalline dedolomites (<100 µm) along stylolites.

Stylolites cross cut and, therefore, post date calcitized evaporite and dedolomite cement fabrics in all dolomitized buildup and basin sediments. Furthermore, the textural relationship between fractures, calcite cements and stylolites in the Gunnlaugson limestone buildup indicates that stylolitization postdated fracturing and calcite cement precipitation.

3.5.6 Dissolution (Phase 3)

The timing of the dissolution events is highly problematic. The Winnipegosis carbonates in Dawson Bay were undoubtedly subjected to at least one, if not many, different phases of dissolution late in their diagenetic history. However, it is hard to differentiate between the evidence for dissolution caused during the removal of the overlying Prairie Evaporite and similar effects caused by present day ground waters. There are several possible episodes during which the buildups were exhumed and subjected to dissolution, the Mississippian, the Permian/Triassic boundary, the Lower Cretaceous, and the Tertiary (Fig. 14). In the Dawson Bay area, all traces of the Prairie Evaporite Formation have been completely removed by one or more solution events that caused the collapse of

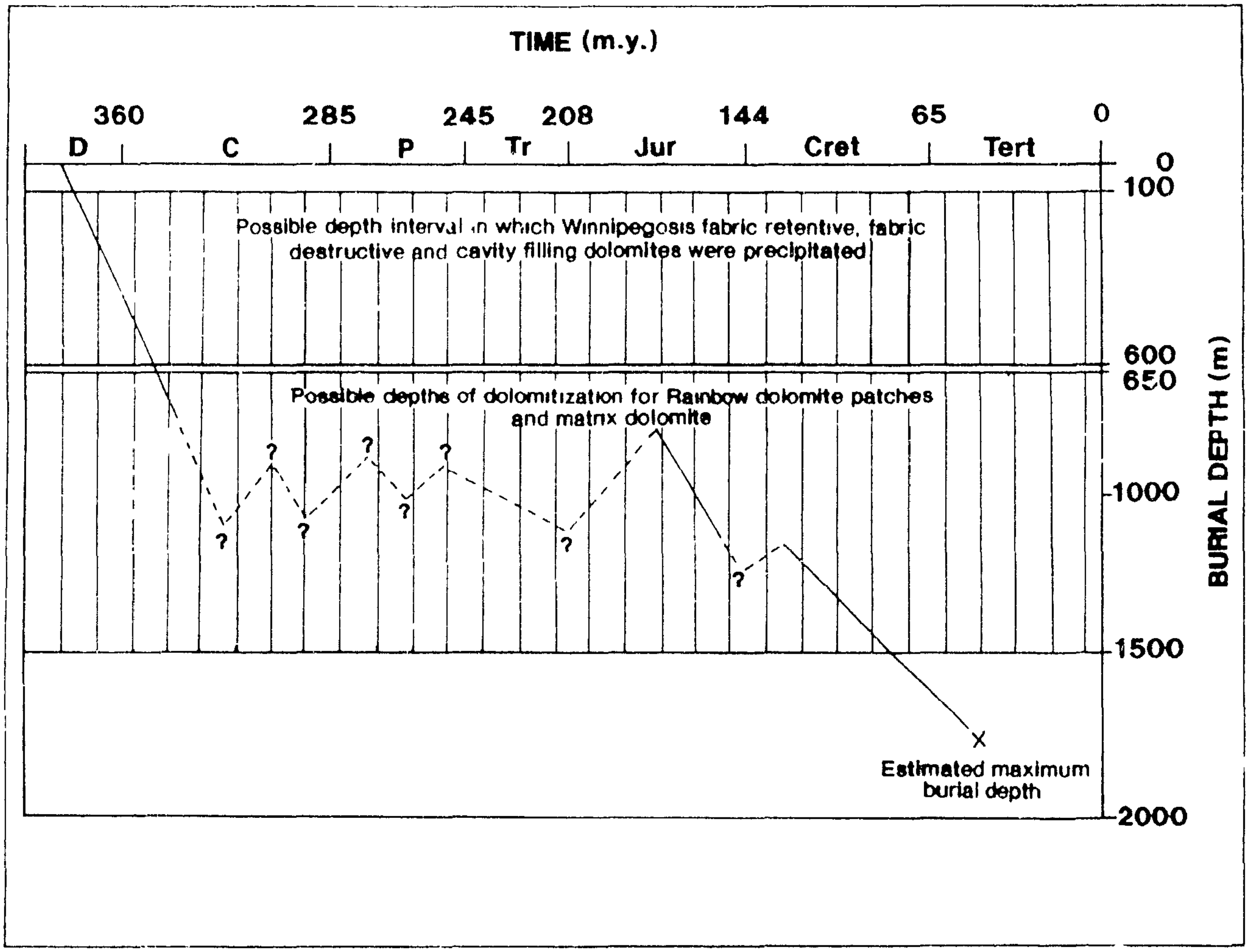


Fig 14 Burial history of Winnipegosis buildups. Solid lines represent preserved rock record, and cut lines represent rock record that was later eroded Although the exact amount of erosion and extent of uplift is not known, the buildups were probably subjected to dissolution during the Mississippian, the Permian/Triassic boundary, the Lower Cretaceous, and the Tertiary From stable isotope data, fabric destructive matrix dolomite and cavity filling rhombic dolomite were probably formed between 100 and 600 m burial. Textural evidence suggests that fabric retentive dolomitization may have started on or just below the seafloor.

younger Paleozoic stratigraphy over underlying Winnipegosis carbonates.

3.6 SUMMARY

The various stages of diagenesis are summarized below in their order of occurrence:

3.6.1 Open Marine Diagenesis

1. Rare syntaxial cementation of monocrystalline echinoid ossicles.
2. Cementation and neomorphic replacement of lime muds by microspar cements.
3. Micritization of carbonate grains to form micrite envelopes
4. Precipitation of rare acicular cements.
5. Precipitation of fibrous cements in cemented subfacies.
6. Development of internal "fractures" in inclusion rich generations of fibrous cements.

3.6.2 Subaerial/Meteoric Diagenesis

1. Phase 1 dissolution of carbonate allochems in stromatolite cap facies
2. Development of calcrete in uppermost stromatolite cap facies
3. Precipitation of pendant cements and calcrete glaebules in calcrete horizons.

3.6.3 Restricted Marine/Shallow Subsurface Diagenesis

1. Precipitation of fabric retentive microcrystalline replacement dolomite throughout all buildup facies.
2. Precipitation of fabric destructive microcrystalline and finely crystalline matrix dolomites in buildup, basin and

platform sediments.

3. Precipitation of cavity filling rhombic dolomite in stromatolite cap facies, calcrete horizons, Ratner sediments, and locally in buildup sediments.

3.6.4 Deeper Subsurface Diagenesis

1. Phase 2 dissolution of all dolomite fabrics generating uncertain amount of observed porosity in buildups; e.g., the dissolved rhomb cores of cavity filling rhombic dolomite.
2. First generation fracturing.
3. Local precipitation of cavity and fracture filling calcite cement.
4. Calcitization of uppermost buildup dolomites and Ratner evaporites and dolomites.
5. Second generation fracturing.
6. Stylolitization of limestones, calcitized evaporites and dedolomites.
7. Extensive phase 3 dissolution of dolomites generating most of observed porosity.

3.7 GEOCHEMISTRY

3.7.1 Radiogenic Isotopes

The results of the $^{87}Sr/^{86}Sr$ radiogenic isotopic analyses are summarized in Appendix 1. They are all 0.7080 for Dawson Bay and Saskatchewan limestones and dolomites. They plot on the Burke et al. (1982) curve for $^{87}Sr/^{86}Sr$ variations in Phanerozoic seawater (Fig. 15) suggesting that: 1) the primary carbonates were precipitated in chemical equilibrium with Middle Devonian marine waters; and 2) the dolomitizing fluids were derived from Middle Devonian marine waters.

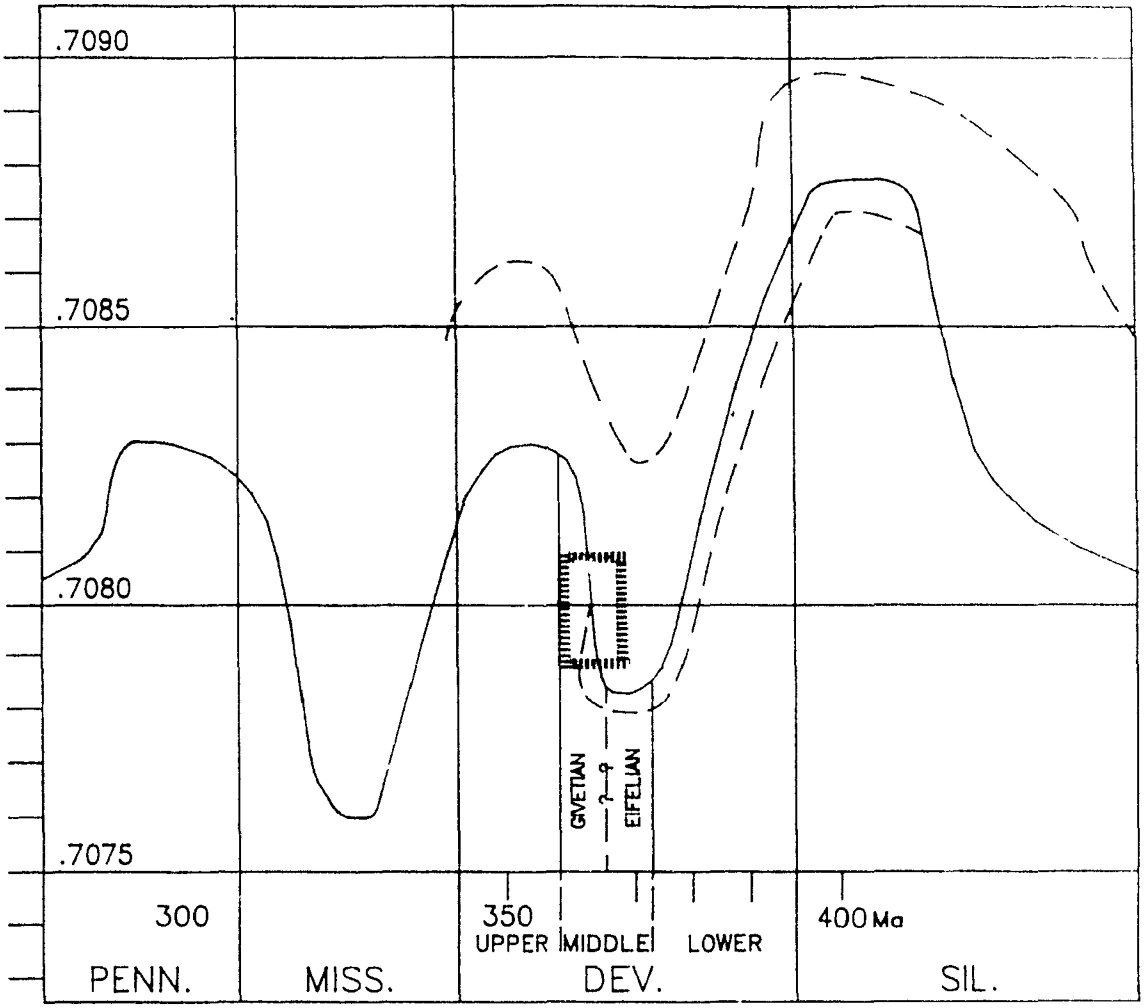


Fig. 15 $^{87}Sr/^{86}Sr$ compositions (0.7080 plots inside box) of Givetian Winnipegosis carbonates plot on the sea level curve that represents the estimated variations of $^{87}Sr/^{86}Sr$ in Paleozoic marine waters The solid line indicates the generally accepted curve, the dashed lines define the outer limits (modified after Burke et al , 1982)

3.7.2 Stable Isotopes

3.7.2.1 Dolomites

The results of the $\delta^{18}O$ and $\delta^{13}C$ stable isotopic analyses for all Dawson Bay and Saskatchewan dolomites are summarized in Appendix 2, and plotted in Figure 16 according to diagenetic texture and host grain type. All measurements are reported in permil (‰) PDB values.

The $\delta^{18}O$ of the dolomitized fibrous cements, allochems, finely crystalline matrix dolomites and cavity filling rhombic dolomites selected from both Dawson Bay and Saskatchewan buildup interior, buildup platform, buildup flank and basin sediments ranges from -4.1 to -6.4‰ . The $\delta^{13}C$ ranges from +0.5 to +2.9‰. Although the dolomite types can be differentiated petrographically, their isotopic compositions are all quite similar and are therefore discussed together.

An original marine $\delta^{18}O$ signature (-4.3‰) for the Dawson Bay limestones was determined by averaging the isotopic compositions of low-Mg calcite brachiopods. In general, the brachiopods contained little evidence of neomorphism, and were better preserved texturally than other shelly constituents as revealed by petrography and cathodoluminescence. Therefore, this value is interpreted to represent the isotopic composition of primary biogenic calcite precipitated in equilibrium with Middle Devonian marine waters. It corresponds to isotopic values proposed for Middle and Upper Devonian marine waters, for example $\delta^{18}O$ -4.5‰ (Lohmann, 1985), $\delta^{18}O$ -3.7‰ (Popp *et al.*, 1986), $\delta^{18}O$ -5.1‰ (Qing and Mountjoy, 1989). The heaviest value (-3.7‰) is probably the most representative for the Middle Devonian.

As the matrix dolomites formed from the neomorphic replacement

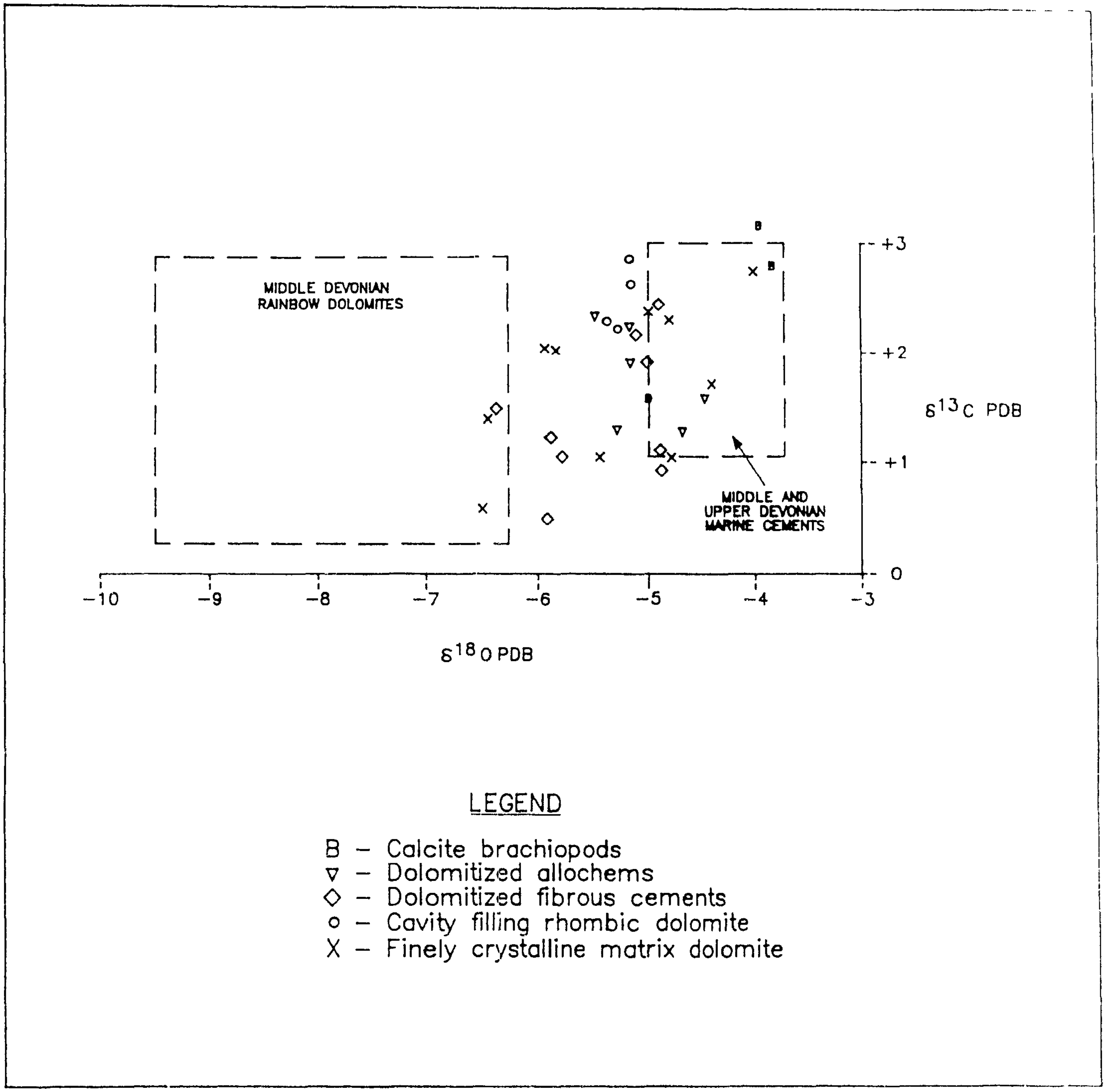


Fig. 16 Carbon and oxygen isotope compositions of Winnipegosis dolomites Fields outline plots for other Devonian carbonates for comparison (Lohmann, 1985; Popp et al., 1986; Hurley and Lohmann, 1988, Carpenter and Lohmann, 1989, Qing and Mountjoy, 1989)

of limestones, their isotopes represent some combination of the isotopic compositions of the dolomitizing fluids and the limestones, reaction temperatures, and water/rock ratios (after Land 1980, 1983).

The influence of evaporation on the isotopic compositions of Winnipegosis dolomitizing fluids is uncertain. Dolomites formed from hypersaline evaporative sea water are typically enriched in δ^{18}O (e.g. McKenzie, 1981; Botz and van der Borch, 1984). However, the relatively depleted δ^{18}O isotopes of the Winnipegosis dolomites might suggest that the original dolomitizing fluids were not derived from evaporative waters, although hypersaline brines were available for dolomitization in the Elk Point Basin following buildup deposition. Alternatively, the lack of enriched δ^{18}O that might be derived from hypersaline Elk Point brines may be attributed to the limitations of sampling fabric retentive microcrystalline replacement dolomite with crystal sizes less than 5 μm (see later discussion).

The effect of mixing fresh and marine waters on the isotopic composition of the resultant dolomitizing fluid has been well documented for both modern and ancient rocks (Land, 1973; Margaritz *et al.*, 1980; Ward and Halley, 1985; Given and Lohmann, 1986; Coniglio *et al.*, 1988;). Carbonate sediments that are dolomitized in mixed solutions of meteoric and sea water are characterized by depleted δ^{18}O and relatively light and often variable δ^{13}C values. Although δ^{18}O (mean -5.2‰) for Winnipegosis dolomites are deplete by 1‰ compared to the δ^{18}O (mean -4.3‰) for non-dolomitized marine fossils and might indicate a meteoric influence, the very narrow range of δ^{13}C in Winnipegosis buildup dolomites does not represent dolomitization in CO_2-rich meteoric waters. The unlikelihood of a meteoric water influence on Winnipegosis dolomitization is further supported by the limited amount of vadose textures and meteoric cements in the buildups.

Dolomite depleted by more than $\delta^{18}O$ 2‰ compared to its precursor may have formed at elevated temperatures (Land, 1980, 1983). In Upper Devonian buildups, Mattes and Mountjoy (1980) and Machel (1985) interpreted a 2 to 3‰ $\delta^{18}O$ depletion in dolomites to represent shallow burial dolomitization at elevated temperatures. Similarly, Qing and Mountjoy (1989) interpreted a 5 to 8‰ $\delta^{18}O$ depletion in Middle Devonian Rainbow dolomites to represent dolomitization at shallow to intermediate burial depths. For Winnipegosis dolomites, the $\delta^{18}O$ of Middle Devonian marine waters was about -4.0‰, and the range of $\delta^{18}O$ for the dolomites varied from -4.1 to -6.4‰. $\delta^{18}O$ SMOW (-2.5‰) for Middle Devonian marine waters was determined from:

$$10^3 \ln \alpha_{cal-water} = 2.78 \times 10^6 T^{-2}(^\circ K) - 2.89$$ (Friedman and O'Neil, 1977)

and:

$$\delta^{18}O \text{ SMOW} = 1.03\ \delta^{18}O \text{ PDB} + 30.4$$ (Hudson, 1977)

From the Middle Devonian $\delta^{18}O$ SMOW and Winnipegosis dolomite $\delta^{18}O$ PDB, a temperature range of 45 to 65°C for dolomitization was determined (after Land, 1980, 1983, 1985) (Fig. 17) from:

$$10^3 \ln \alpha_{dol-water} = 2.78 \times 10^6 T^{-2}(^\circ K) + 0.91$$

Using an average surface temperature of 30°C and a geothermal gradient of 33°C/km, the calculated temperatures correspond to burial depths of about 600 m. If average surface temperatures in the Elk Point Basin approached the higher value of 40 C recorded for modern day Persian Gulf waters, the calculated temperatures indicate that dolomitization may have started at even shallower (< 200 m) burial depths. In conclusion, the isotopes suggest that the $\delta^{18}O$ of the dolomitizing fluids were

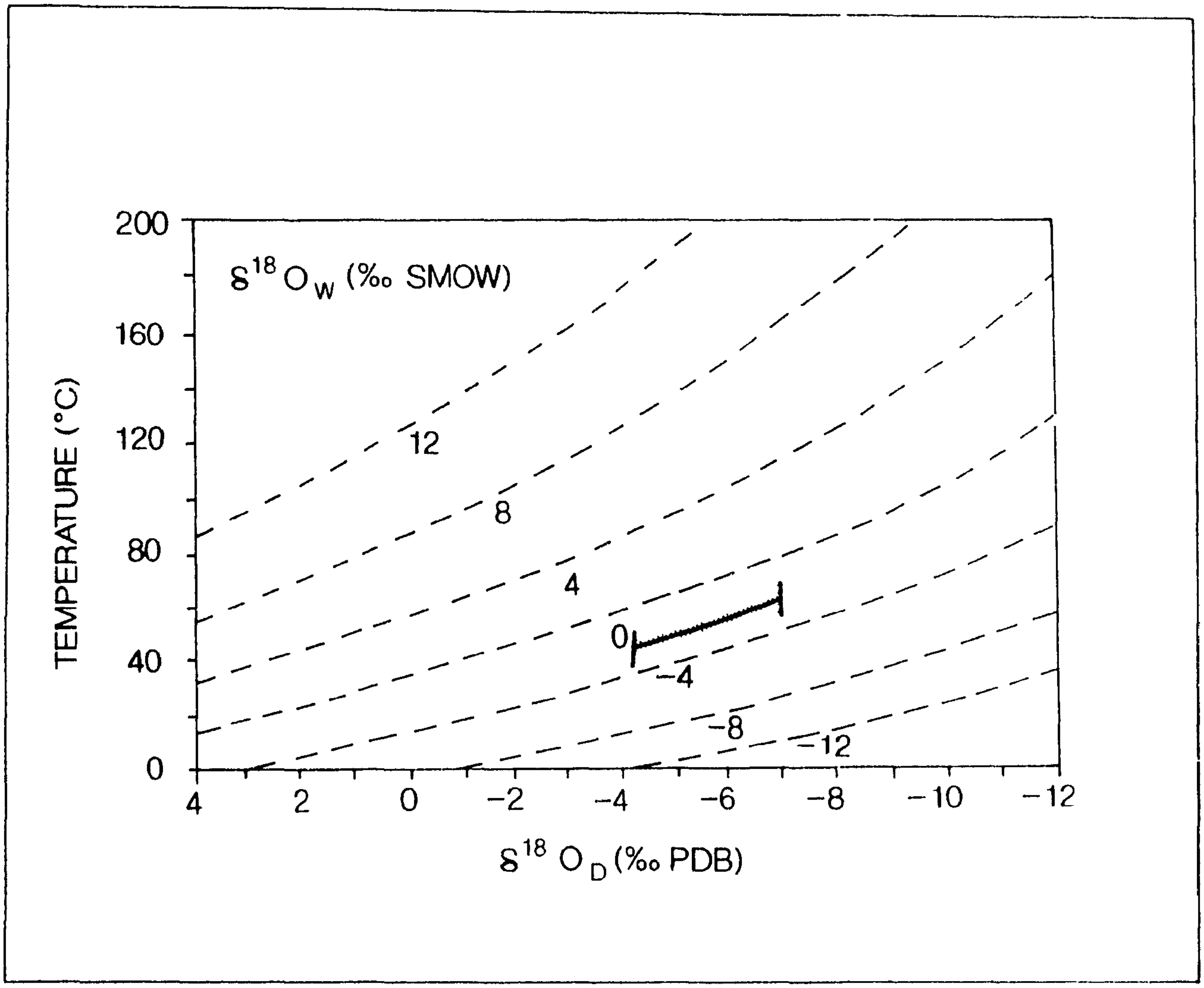


Fig. 17 Temperature (°C) versus $\delta^{18}O_{dolomite}$ (^{0}/oo PDB) for a range of $\delta^{18}O_{water}$ (^{0}/oo SMOW) values If $\delta^{18}O$ (SMOW) of the dolomitizing fluids was -2.5^0/oo, the range of temperatures within which the Winnipegosis dolomites (with $\delta^{18}O$ ranging from -4.1 to -6.4^0/oo PDB) precipitated was 45 to 65°C.

modified by elevated temperatures at very shallow burial depths.

3.7.2.2 Calcites

The results of the $\delta^{18}O$ and $\delta^{13}C$ isotopic analyses for all calcite specimens are summarized in Appendix 2, and plotted in Figure 18. The cavity and fracture filling calcite cements range in $\delta^{18}O$ from -7.2 to -10.0‰, and in $\delta^{13}C$ from -6.0 to -8.2‰. $\delta^{18}O$ of calcitized evaporites and dedolomites in basinal Ratner sediments ranges from -3.2 to -6.6‰, and $\delta^{13}C$ ranges from -3.3 to -7.7‰.

Both $\delta^{18}O$ and $\delta^{13}C$ of the calcite cements are significantly depleted relative to normal marine waters. The $\delta^{18}O$ compositions indicate that the cements were probably precipitated from either fresh waters or at elevated temperatures. The range of depleted $\delta^{13}C$ values may be due to light carbon derived from either soil-gas reactions during periods of subaerial exposure, bacterial reduction of organic matter under reducing conditions during burial (Hudson, 1977; Anderson and Arthur, 1983), or hydrocarbons (e.g. Budai _et al._, 1984).

The isotopic compositions of the dedolomites and calcitized evaporites are also significantly depleted relative to normal marine waters. The $\delta^{18}O$ suggests that dedolomitization and calcitization of evaporites occurred in either fresh waters or at elevated temperatures; the $\delta^{13}C$ indicates that these processes took place under the influence of either sulphate reducing bacteria, soil-gas reactions, or during hydrocarbon maturation and migration.

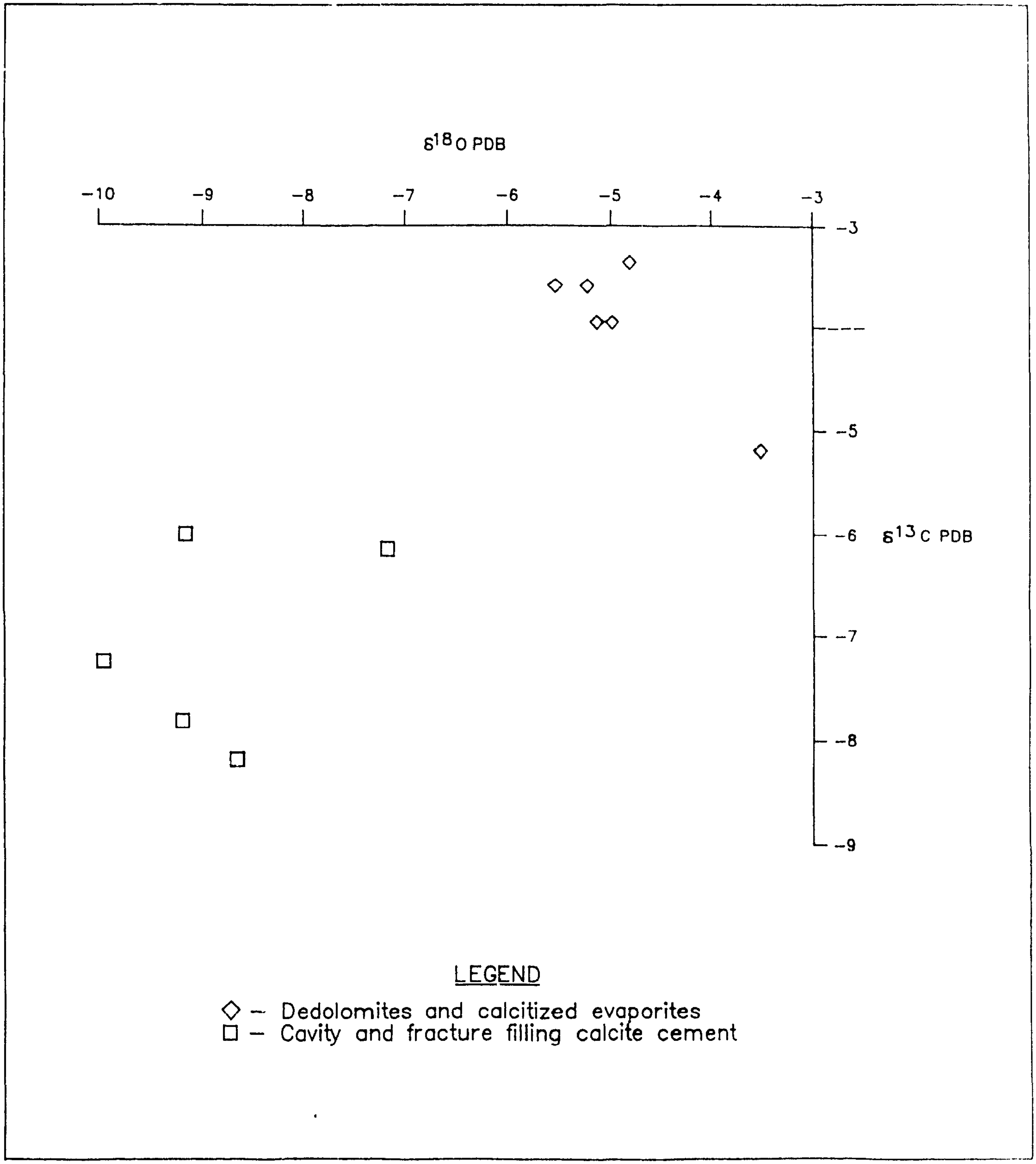


Fig. 18 Carbon and oxygen isotope of Winnipegosis calcite cements, dedolomites and calcitized evaporites.

3.6 SUMMARY

1. The mean $^{87}Sr/^{86}Sr$ value (0.7080) for the analyzed Dawson Bay and Saskatchewan limestones and dolomites indicate that: 1) the primary carbonates were precipitated in equilibrium with Middle Devonian marine waters; and 2) the dolomitizing fluids were derived from the same Middle Devonian marine waters.

2. The mean $\delta^{18}O$ composition (-4.3‰) for unaltered Winnipegosis brachiopods represents the isotopic composition of primary biogenic calcites precipitated in equilibrium with Middle Devonian marine waters.

3. The relatively depleted oxygen isotopic compositions of the Winnipegosis dolomites suggest that the dolomitizing fluids were not derived from evaporated waters. However, the isotope data may reflect a sample bias due to the impossibility of accurately sampling microcrystalline replacement dolomite crystals (< 5 μm)

4. The very narrow range of enriched carbon isotopic compositions of the dolomites suggests that freshwater probably did not influence the isotopic compositions of the dolomitizing fluids.

5. The depleted oxygen isotopic compositions of both Dawson Bay and Saskatchewan dolomites suggest that Winnipegosis dolomitization occurred at very shallow to shallow burial depths and elevated temperatures.

6. The significantly depleted isotopic compositions of cavity and fracture filling calcite cements, calcitized evaporites and dedolomites represents cementation and calcitization either in a near-surface diagenetic environment under the

influence of fresh waters and soil-gas reactions or at depth under the influence of elevated temperatures, sulphate reducing bacteria and hydrocarbon generation.

3.9 DISCUSSION

The petrographic and isotopic investigation of the Winnipegosis carbonates reveals that: 1) the original sediments were cemented in an open marine environment during and shortly after their deposition; 2) the upper parts of the buildups were modified by subaerial and meteoric diagenetic processes; 3) three general types of dolomitization occurred - fabric retentive, fabric destructive and cavity filling; 4) the buildup, platform and basin sediments were locally modified by relatively deeper burial diagenetic processes.

3.9.1 Early Submarine Cementation

Although considerable evidence for early submarine cementation by microspar has been documented for modern and ancient carbonates (e.g., James et al., 1976; Walls et al., 1979; Marshall, 1983; Kerans et al., 1986; Aissouai et al., 1986), it is difficult to determine the extent of this type of cementation in Winnipegosis buildups due to the limited amount of preserved limestone in the study area. It is clear from the isotopes and cathodoluminescence that the limestones were precipitated from Middle Devonian marine waters. However, destructive neomorphic processes have rendered the relationship between the fine textured microspar and later stages of submarine cement difficult or impossible to identify.

The occurrence of aragonitic acicular fibrous cements in the growth chambers of corals and gastropods in modern reefs (James et al., 1976; Marshall, 1983) might suggest that the original mineralogy in similar Winnipegosis cements was aragonite. However, Sandberg (1983) and James and Choquette (1983) proposed that so-called 'calcite seas' prevailed during the Devonian in which aragonitic cements would not be expected to predominate. In addition, square-ended fibrous crystals representing the orthorhombic crystal habit of aragonite were not observed (e.g. Sandberg, 1983); however, these may have been obliterated by later neomorphic processes especially dolomitization. Furthermore, microdolomites were not identified in the calcite textures indicating that the original mineralogy of the primary carbonates was probably not high-Mg calcite (e.g. Lohmann and Meyers, 1977). Due to the lack of distinctive criteria, the original mineralogy of Winnipegosis cements remains uncertain.

Unfortunately, undolomitized fibrous calcite cements were not preserved in the study area. Although the isotopic signatures of the dolomitized cements indicate that the dolomitizing fluids were derived from Middle Devonian marine waters, the textural similarity between these cements and other Mg-calcite cements observed in Devonian carbonates (e.g. Walls et al. 1979, Playford, 1980; Machel, 1985, Carpenter and Lohmann, 1989) suggest that they were not precipitated as primary dolomitic cements.

In both modern and ancient marine settings, a facies specific distribution of fibrous cements has been observed along the seaward margins of modern and ancient carbonate platforms and buildups exposed to prevailing wind and current activity (e.g., James et al., 1976; Playford, 1980; Lighty, 1985; Machel, 1985; Marshall, 1985; Aissouai et al., 1986; Kerans et al., 1986). Similarly, the distribution of fibrous cements in the Winnipegosis cemented subfacies may represent the exposed seaward margin of these carbonate buildups.

How the internal "fractures" in fibrous cements formed is uncertain. It is unlikely that they represent desiccation features as they occur well below the estimated extent of sea level draw down as defined by evidence for subaerial exposure. Similar internal "fractures" that cut across several generations of submarine cements in Silurian reef platform rocks were identified by Savard and Bourque (1989). They proposed that this type of fracturing may be induced by mechanical readjustments associated with physical compaction. The internal fracturing of Winnipegosis cements may have formed in a similar manner.

3.9.2 Subaerial/Meteoric Diagenesis

The local dissolution of peloids and oncolites and the development of calcrete in the uppermost few metres of some buildups suggests that meteoric diagenesis modified Winnipegosis carbonates during a period of subaerial exposure at the end of buildup construction. In particular, pendant cements, calcrete glaebules and the thin crenulated laminations are distinct diagenetic characteristics of subaerially exposed carbonates (Esteban, 1974; Esteban and Klappa, 1983). Subsequent episodes of dolomitization appears to have erased freshwater isotopic signatures from these pendant cements.

Diagenetic and sedimentological evidence indicates that all Winnipegosis sediments were deposited in marine waters. At the end of Winnipegosis time, only thin intervals (< 1 m thick) of the uppermost stromatolite cap facies represent sediment modification by calcrete during periods of subaerial exposure. The presence of acicular fibrous cements around many oncolites and grapestones, and the subsequent precipitation of fibrous cements between reworked oncolite clasts in these facies represents cementation in marine waters. These textural relationships show that the oncolites, grapestones and other related allochems such as peloids were deposited as grainstones in agitated marine waters. Furthermore, depositional and erosional textures such as cross laminated and graded bedding, grainstones, sand to boulder sized rip-up clasts (teepee structures), laterally extensive truncation surfaces, and hardgrounds represent marine processes. Capping the buildups, fenestral textures, oncolites, and grapestones indicate that water depths shallowed (possibly with intermittent periods of non deposition), and that sedimentation occurred in intertidal waters. As waters shallowed further, the bands of calcrete were formed by vadose diagenesis during intermittent periods of subaerial exposure. Thus both subaerial and submarine diagenetic and depositional processes were inextricably linked and contemporaneous during late Winnipegosis time.

The evidence of submarine sedimentological and diagenetic processes in the stromatolite cap facies challenges the proposal by Kendall (1989) that these uppermost sediments are travertine deposits derived from subaerial springs. One of several important controls that strongly influence the delicate balance between the physio-chemical and/or biochemical processes that precipitate calcium carbonate to form travertine is water turbulence (Julia, 1983). In travertine, water turbulence is carefully controlled by walls, dams and dykes to create a relatively quiet environment suited to the maintenance of algal colonies and other organisms involved in travertine formation. In Winnipegosis stromatolite cap sediments, the boulder-sized rip-up clasts, erosional truncation surfaces, and grainstone textures represent strongly agitated, high energy waters in which travertine would not form. It is therefore unlikely that the stromatolite cap facies represents travertine deposition.

3.9.3 Dolomitization

Interpretation of the origin of the pervasive Winnipegosis dolomites is made difficult by complex petrography and isotope geochemistry, especially the wide range of fabric retentive and fabric destructive types of dolomite. In their review of possible models for dolomitization, Machel and Mountjoy (1986) ascribed the origin of dolomites to: 1) freshwater and seawater mixing zone fluids; 2) hypersaline brines derived from evaporated waters in sabkha environments; 3) subtidal marine to hypersaline brines; 4) a wide variety of subsurface fluids. Machel and Mountjoy (1986) discussed the improbability of the mixing zone hypothesis due to reaction kinetic constraints and the very limited evidence for dolomitization in modern freshwater/seawater mixing zone environments. They demonstrated that these fluids were more suitable agents for carbonate dissolution than carbonate precipitation. The pervasive character of Winnipegosis dolomites, their isotope compositions, and the lack of extensive textural evidence for freshwater diagenesis in these rocks preclude the possibility of significant freshwater influence on Winnipegosis dolomitization. Although marine waters were probably hypersaline at the end of Winnipegosis time, a lack of diagenetic and sedimentary evidence for buildup exposure and sabkha deposition suggests that the dolomitization of Winnipegosis sediments did not occur under evaporated sabkha conditions. Furthermore, the limited areal extent of modern sabkha-related dolomites does not adequately account for thick sequences of pervasively dolomitized carbonates (Machel and Mountjoy, 1986)

Fabric retentive dolomitization of Winnipegosis fabrics (e.g. fibrous cements) by microcrystalline replacement dolomite possibly occurred in normal to slightly hypersaline subtidal waters shortly after the end of buildup development. Although the $\delta^{18}O$ data tend not to represent an evaporative influence on the original dolomitizing fluids, the difficulties of accurately sampling these extremely small (< 5 μm) crystals may account for a sample bias toward the more depleted $\delta^{18}O$ coarsely crystalline matrix dolomites that were probably precipitated at depth. Early subtidal dolomitization by restricted marine hypersaline waters has been suggested for similarly well preserved textural detail in carbonates throughout the rock record (e.g. Morrow, 1982; Sass and Katz, 1982; Coniglio et al., 1988). Although $^{87}Sr/^{86}Sr$ compositions (mean 0.7080) for all Winnipegosis dolomites represent fluids derived from Middle Devonian waters, $\delta^{18}O$ compositions (-4.1 to -6.4‰) are depleted compared to normal marine limestone values (-4.0‰), and may not be affected by evaporation. Subsurface dolomitization at slightly elevated temperatures (45 to 65°C) may account for the depleted $\delta^{18}O$ as the narrow range of $\delta^{13}C$ (+0.5 to +2.9‰) rules out any significant meteoric influence. If these temperature data are valid, they suggest that subsurface dolomitization occurred at about 600 m depth or less. By comparison, the more depleted $\delta^{18}O$ compositions of Middle Devonian Rainbow matrix dolomites represent burial dolomitization at depths between 650 to 1500 m (Fig. 14) (Qing and Mountjoy, 1989).

In the Winnipegosis buildups, the distribution of the fabric retentive and fabric destructive types of matrix dolomites appears to be stratigraphically controlled. In upper buildup sediments, the fabric retentive microcrystalline replacement dolomite preserves delicate biological and cement textures, and the fabric destructive matrix dolomites only occur locally in patches. Lower in the buildup sediments and throughout the platform and basin sediments, finely crystalline matrix dolomite predominates obliterating most of the original textures and non-skeletal allochems. This stratigraphically controlled distribution of the dolomite types suggests that the more deeply buried lower parts of the Winnipegosis Formation were exposed to the fluids that precipitated the matrix dolomites for longer than the upper less buried parts in which the fabric retentive microcrystalline replacement dolomite was preserved.

The corollary of these geochemical, textural and stratigraphic relationships is that the dolomitization of the Winnipegosis sediments started with the microcrystalline replacement of organic allochems and early diagenetic fabrics in normal to hypersaline waters on or just below the sea floor. As the buildups were buried, dolomitization continued at elevated temperatures as slightly more coarsely crystalline matrix dolomites (N.B., the crystal size of finely crystalline matrix dolomite rarely exceeds 50 µm) replaced the earlier microcrystalline replacement dolomites (< 5 µm) from the bottom of the buildups upward (see section 3.9.4 for possible subsurface fluid flow mechanisms).

Cavity filling rhombic dolomite is the third and latest type of Winnipegosis dolomite. Rhombs of this dolomite cement are texturally distinct from the other dolomite types, and are characterized either by zonation or by hollow rhombs (rhombs with dissolved cores). Isotopically, the depleted oxygen signature of cavity filling rhombic dolomite (-5.4‰) indicates that it was precipitated at shallow burial depths. ^{87}Sr/^{86}Sr isotopic values (0.7080) support that it was also derived from Middle Devonian marine waters. Rhomb zones, comprised of dusty, inclusion-rich nuclei and clear epitaxial rims, may represent dolomitization by two fluids of distinct chemical composition. Similarly, the hollow rhombs may have formed in at least two distinct phases, an earlier, less stable, inclusion and calcian-rich phase that formed the original rhomb cores, and a later, magnesian phase that formed the rhomb rims (e.g. Ward and Halley, 1985; Coniglio _et al._, 1988).

3.9.4 Subsurface Fluid Flow Mechanisms

In the shallow burial environment, mechanical compaction of the carbonates and overlying evaporites may have provided Winnipegosis dolomitizing fluids of marine origin. Illing (1959) and Jodry (1969) proposed that differential compaction, such as off-reef compaction exceeding reefal compaction, will expel large volumes of fluid into the less compacted reefal strata. Machel and Mountjoy (1986) demonstrated that compaction fluids are capable of dolomitizing carbonates, provided the reaction kinetics are suitable for dolomitization. Machel and Anderson (1989) demonstrated that all petrologic and geochemical characteristics, and mass balance calculations show that the dolomitization of Upper Devonian Nisku buildups by burial compaction is a plausible dolomitization model for these carbonates. Similarly, Qing and Mountjoy (1989) proposed that some early dolomite rhombs and patches in the Keg River buildups were precipitated from solutions derived from mechanical compaction. Although fabric retentive replacement dolomitization probably started on or just below the seafloor, the distribution of fabric destructive matrix dolomites in the lower Winnipegosis sediments suggests that this phase of dolomitization began in fluids derived from the mechanical compaction of surrounding sediments as soon as the buildups were encased in evaporites at very shallow depths.

Various workers have investigated dolomitization by fluids generated by the dehydration of gypsum. Morrow (1978) determined that the brines from which Muskeg sulphates were precipitated had high Mg/Ca ratios, and would be suitable dolomitizing fluids for nearby Keg River buildups. During the conversion of gypsum to anhydrite at elevated temperatures and pressures, significant volumes of water of crystallization is released and pore pressure is increased (Blatt et al., 1980; Sonnenfeld, 1984). Qing and Mountjoy (1989) suggested that this increase in pore pressure may have caused microfracturing that would facilitate the mobilization of the diluted brines into the Keg River carbonates. The typical association between anhydrite caps and Saskatchewan Winnipegosis buildups (Martindale and Orr, 1987, Kendall, 1989) indicates that the Dawson Bay buildups were probably encased by similar anhydrite caps prior to extensive dissolution. However, it is unlikely that waters of crystallization derived from gypsum dehydration influenced Winnipegosis dolomitization because· 1) the dolomites do not have an evaporative $\delta^{18}O$ signature, and 2) mass balance constraints indicate that the volume of dolomitizing fluid required to pervasively dolomitize Winnipegosis buildup and basin carbonates (after Machel and Mountjoy, 1986; Machel, 1989) vastly exceeds the overall volume of the locally distributed anhydrite caps.

Some dolomitization of Devonian carbonate sequences has also occurred by the funnelling of intermediate or deeper burial subsurface fluids up fault and fracture systems (e.g., Barss et al., 1970; Machel, 1986; Halim-Dihardja, 1986; Qing and Mountjoy, 1989). However, the marine isotopic signatures of Winnipegosis dolomites do not represent fluids derived from significant burial depths. Therefore, it appears unlikely that deeper burial fluids influenced Winnipegosis dolomitization.

Kendall (1989) proposed that dolomitization may have occurred in Mg-bearing fluids derived from the mixing of formation waters and marine brines. These fluids migrated beneath a desiccated Elk Point basin and flowed up through the Winnipegosis to emerge at the top of the buildups to form travertine. In the Dawson Bay area, there is limited evidence for travertine deposits above and on the flanks of

Winnipegosis buildups. However, the upward movement of dolomitizing fluids through the buildups could explain the distribution of the two main types of dolomite present, the fabric retentive replacement dolomite and the fabric destructive matrix dolomite. The pervasive distribution of the matrix dolomites in lower Winnipegosis sediments may be due to the continuous exposure of these sediments to dolomitizing formation waters that funnelled into the bases of the buildups from the underlying older Paleozoic carbonates. Higher in the buildups, these fluids may have preferentially selected more permeable upward flow paths that avoided sediments previously dolomitized on or just below the sea floor by the fabric retentive replacement dolomite.

If the distribution of matrix dolomites can be explained by this model of fluid flow, their isotope signatures then become more difficult to explain. Carbonates dolomitized by fluids derived from depth should be more deplete in $\delta^{18}O$ (e.g. Qing and Mountjoy, 1989) than the recorded Winnipegosis values (mean $\delta^{18}O$ -5‰). Furthermore, the isotopic signatures of fluids exposed to deeper Paleozoic carbonates may have re-equilibrated to assume the isotopic signatures of the older rocks. If these contaminated fluids then dolomitized Winnipegosis rocks, their $\delta^{18}O$ would no longer represent the isotopic composition of Devonian marine waters and further problems of interpretation would ensue.

In summary, there were at least two phases of Winnipegosis dolomitization. Phase one was the precipitation of the fabric retentive dolomites that probably began in normal to slightly hypersaline marine waters on or just below the seafloor. Phase two was the precipitation of the fabric destructive matrix dolomites that occurred at shallow burial. Cavity filling rhombic dolomite was also precipitated at this time. Phase two dolomite fluids were possibly derived from either mechanical compaction of surrounding carbonates and evaporites or the upward passage of formation waters derived from beneath the buildups.

3.9.5 Later Diagenetic Events

Dissolution has probably affected Winnipegosis rocks during the Mississippian, at the end of the Permian, during the Lower Cretaceous, and since the Tertiary. It is largely responsible for the considerable porosity observed in the buildup and platform sediments. However, the regional extent of dissolution related fabrics and their relative timing of formation is unknown. Thus the distribution of porosity and permeability in deeper subsurface Winnipegosis reservoir rocks can not be predicted with accuracy.

The relative timing of first and second generation fracturing is poorly constrained by cavity and fracture filling calcite cementation and stylolitization. Fracturing may be related to the solution and collapse of the overlying Prairie Evaporite Formation. Isotopic data indicate that the calcite cement precipitated in either a near-surface or deeper diagenetic environment. The original calcite-bearing fluids may have travelled up the fracture system from depth and precipitated out the cement thereby infilling the fractures.

Limited $\delta^{13}C$ isotopic data indicate that the calcitization of evaporites and dedolomitization may have occurred under reducing conditions in the presence of sulphate reducing bacteria, or in the presence of hydrocarbons. The association between organic-rich sediments, sulphate reducing bacteria, and calcitized evaporites and dedolomties has been recognized throughout the rock record (e.g., Kirkland and Evans, 1981; Pierre and Rouchy, 1988). However, the spread of depleted $\delta^{13}C$ derived from methanogenesis in most of these documented cases is far greater than that observed for Dawson Bay Ratner sediments. Budai et al. (1984) proposed that depleted $\delta^{13}C$ (-2 to -6‰) in stylolite and bitumen related Mississippian dedolomites may be attributed to a light carbon source associated with hydrocarbon migration. The depleted $\delta^{18}O$ (-6 to -11‰) in Ratner rocks represent dedolomitization at higher temperatures. Although the evidence for hydrocarbon generation is limited in the Dawson Bay Ratner sediments, the bituminous residue that lines the stylolites may have provided the source for light carbon in these rocks. As Brightholme bituminous mudstones are thermally immature, light carbon may be derived from hydrocarbons generated from older source rocks. Further isotopic and petrographic work is required before the influence of sulphate-reducing bacteria on Ratner evaporites and dolomites is understood.

3.10 DIAGENESIS PLATES

PLATE 11

A) Syntaxial Cement (C). A poorly preserved echinoid ossicle is outlined by the syntaxial cement overgrowth. Scale bar, 0.61 mm.. Cross nicols. Mason Island, S-30.

B) Microspar Cement (M). The original lime mud matrix of this fossiliferous wackestone was neomorphosed to microspar. Scale bar, 2.78 mm.. Plane light. Gunnlaugson limestone buildup, M-2-87 (4). 120 ft..

C) Micritic Envelopes (M). The rims of allochems, possibly peloids or oncolites, were micritized and preserved while the cortices of allochems were dissolved. The cavities were later infilled by early submarine fibrous cements (C). Scale bar, 0.69 mm.. Plane light. Inco 635-48 (24), 103 ft..

D) Acicular Fibrous Cement (A). A sheet cavity is partially occluded by fans of distally diverging acicular crystals. The fans provide a substrate for a later generation of more coarsely crystalline radiaxial fibrous cement (F). All cements are preserved by fabric retentive microcrystalline replacement dolomite. Scale bar, 0.78 mm.. Plane light. Mason Island, S-48 (3).

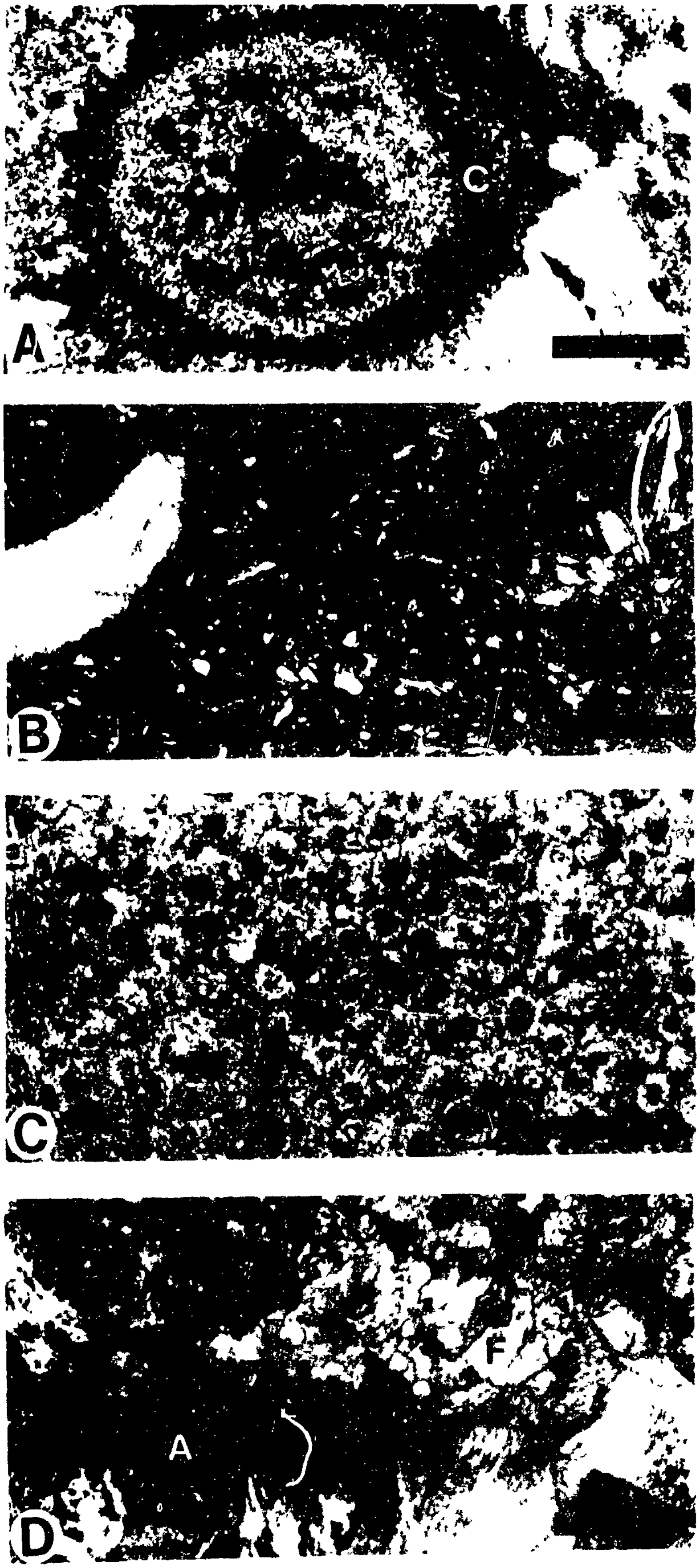

C
A
B
C
F
A
D

PLATE 12

A) Acicular Fibrous Cement (A). Isopachous rims of dolomitized acicular fibrous cement form in the intraskeletal cavities of Thamnopora coralline debris. Scale bar, 1.17 mm.. Cross nicols. Simons Island, S-81 (2).

B) Acicular Fibrous Cement (A). Several generations of isopachous acicular fibrous cement encrust peloids, oncolites, and composite grains. Each generation is separated by a lamination of uncertain origin, possibly algal, that is parallel to the original allochem substrate. Note the brecciated allochems (B) with cement rims representing evidence for early submarine cementation prior to brecciation by hydraulic processes. All textures are preserved by fabric retentive microcrystalline replacement dolomite. Scale bar, 2.69 mm.. Plane light. Salt Point, SPB-4B.

C) Acicular Fibrous Cement (A) and Fibrous Cement (F). Dolomitized radiaxial fibrous crystals (note undulose extinction pattern) cement brecciated clasts with isopachous rims of dolomitized acicular fibrous cement. This textural relationship indicates that fibrous cements postdate acicular fibrous cements. Scale bar, 2.0 mm.. Cross nicols. 635-48 (28). 96 ft..

D) Fibrous Cement (F). At least two generations of brown and cream coloured, dolomitized fibrous cement infill the intergranular porosity of these Udoteacean grainstones that occur in the cemented subfacies of the buildup flank. M-18-77 2(27). 123 ft..

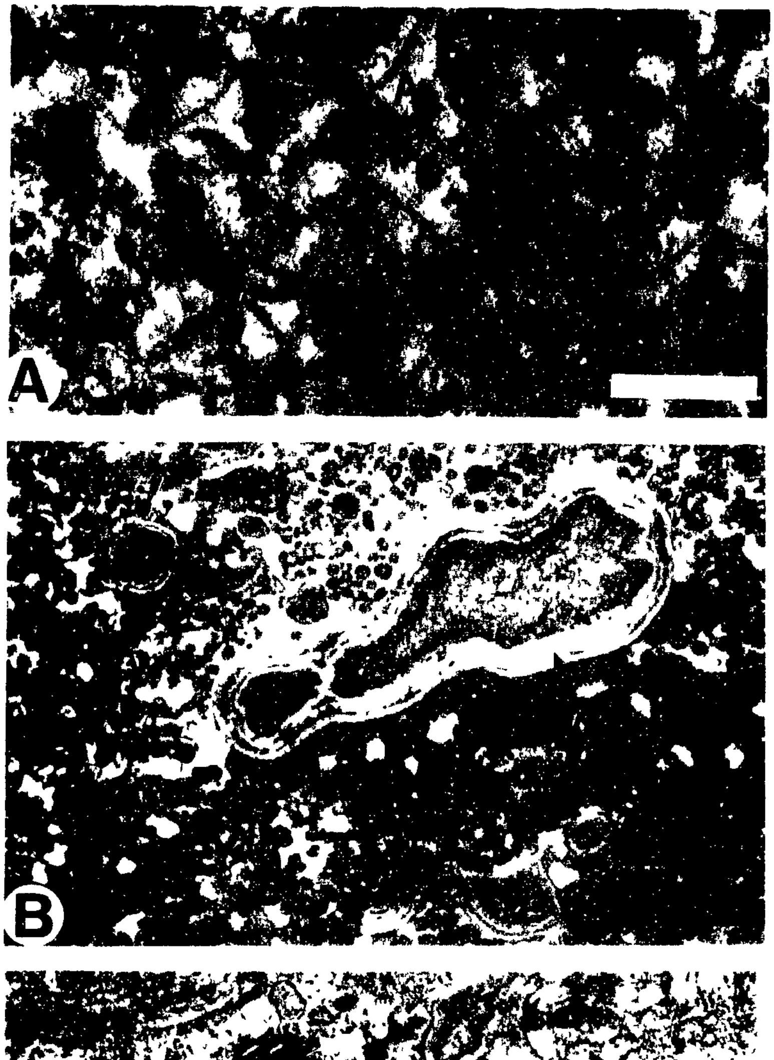

A
B
F
A
F
C
D

PLATE 13

A) Fibrous Cement (F). A single generation of inclusion-rich and banded fibrous cements occurs as an isopachous rim around poorly preserved remnants of Udoteacean calcareous algae (A). The cements were dolomitized by fabric retentive microcrystalline replacement dolomite. Scale bar, 0.95 mm.. Plane light. M-18-77 87(2). 293 ft..

B) Fibrous Cement (F). Undulose extinction across individual crystals of dolomitized fibrous cement indicate that they exhibit a radiaxial split crystal growth fabric. Scale bar, 2.69 mm.. Cross nicols. M-18-77 2(27). 123 ft..

C) Fibrous Cement (F). The first generation of fibrous cements (F1) provides a substrate for the second generation of inclusion-rich fibrous cements (F2). All cements are dolomitized. Scale bar, 1.39 mm.. Plane light. M-18-77 (7). 294 ft..

D) Internal "Fractures" (I). A pattern of internal "fractures" are arranged across a generation of inclusion-rich fibrous cements. Note how the "fractures" do not extend across the substrate surface of the calcareous alga fragment (A) or across the next generation of relatively clear cavity filling rhombic dolomite (C). Scale bar, 0.95 mm.. Plane light. M-18-77 2(22). 178 ft..

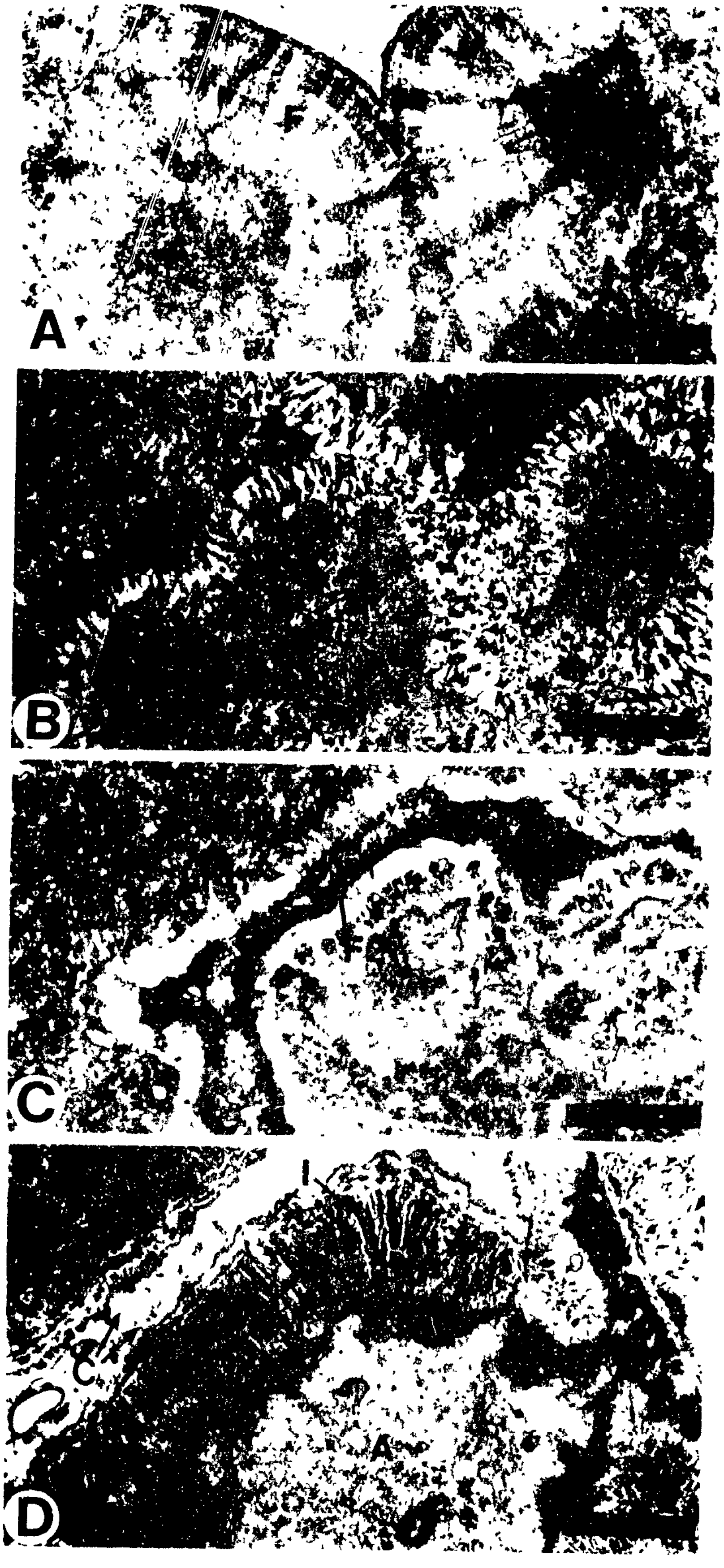

A
B
C
I
C
A
D

PLATE 14

A) Pendant Cement (P). Blocky, rectangular crystals of pendant cements line the ceilings of voids in a calcrete horizon. All cements are preserved by microcrystalline replacement dolomite. Scale bar, 0.69 mm.. Cross nicols. Steeprock Bay Dome Cliffs.

B) Calcrete Glaebules (G). Dolomitized circular to ellipsoidal calcrete glaebules are distributed throughout the calcrete horizons in the stromatolite cap facies. The hollow glaebule centres outline dissolved host grains. Scale bar, 1.13 mm.. Steeprock Bay Dome Cliffs.

C) Microcrystalline Replacement Dolomite. The fine textural detail of the calcareous alga, Tentaculites, is well preserved by fabric retentive microcrystalline replacement dolomite. Scale bar, 1.25 mm.. Plane light. Mason Island, S-41.

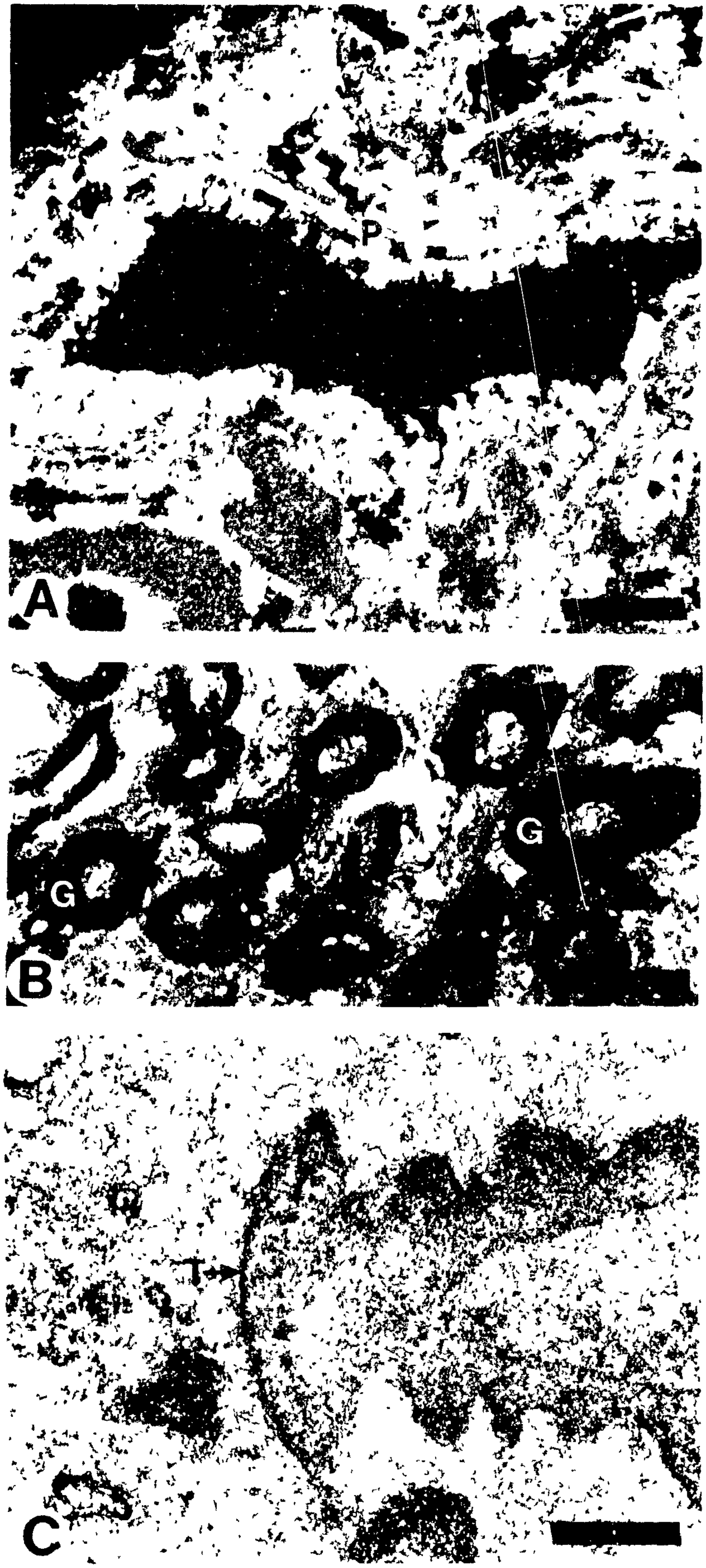

P
A
G
G
B
T
C

PLATE 15

A) Microcrystalline Replacement Dolomite (M). High magnification photomicrograph (X 1.5K) of the fabric retentive microcrystalline replacement dolomite. Scale bar, 5 μm.. S.E.M.. Mason Island, S-41.

B) Microcrystalline Replacement Dolomite (M). Very high magnification photomicrograph (X 5.0K) of fabric retentive microcrystalline replacement dolomite. Scale bar, 5 μm.. S.E.M.. Mason Island, S-41.

C) Finely Crystalline Matrix Dolomite (F). The matrix of the carbonate platform crinoidal wackestones is completely replaced by tightly interlocking crystals of this fabric destructive type of dolomite. Scale bar, 2.69 mm.. Cross nicols. M-18-77 (2). 319 ft..

D) Finely Crystalline Matrix Dolomite (F). The non dedolomitized carbonate mudstones that are interbedded with bituminous laminations (B) in basinal Ratner beds contain finely crystalline matrix dolomite. Scale bar, 1.35 mm.. Cross nicols. M-3-73 87(8). 71 ft..

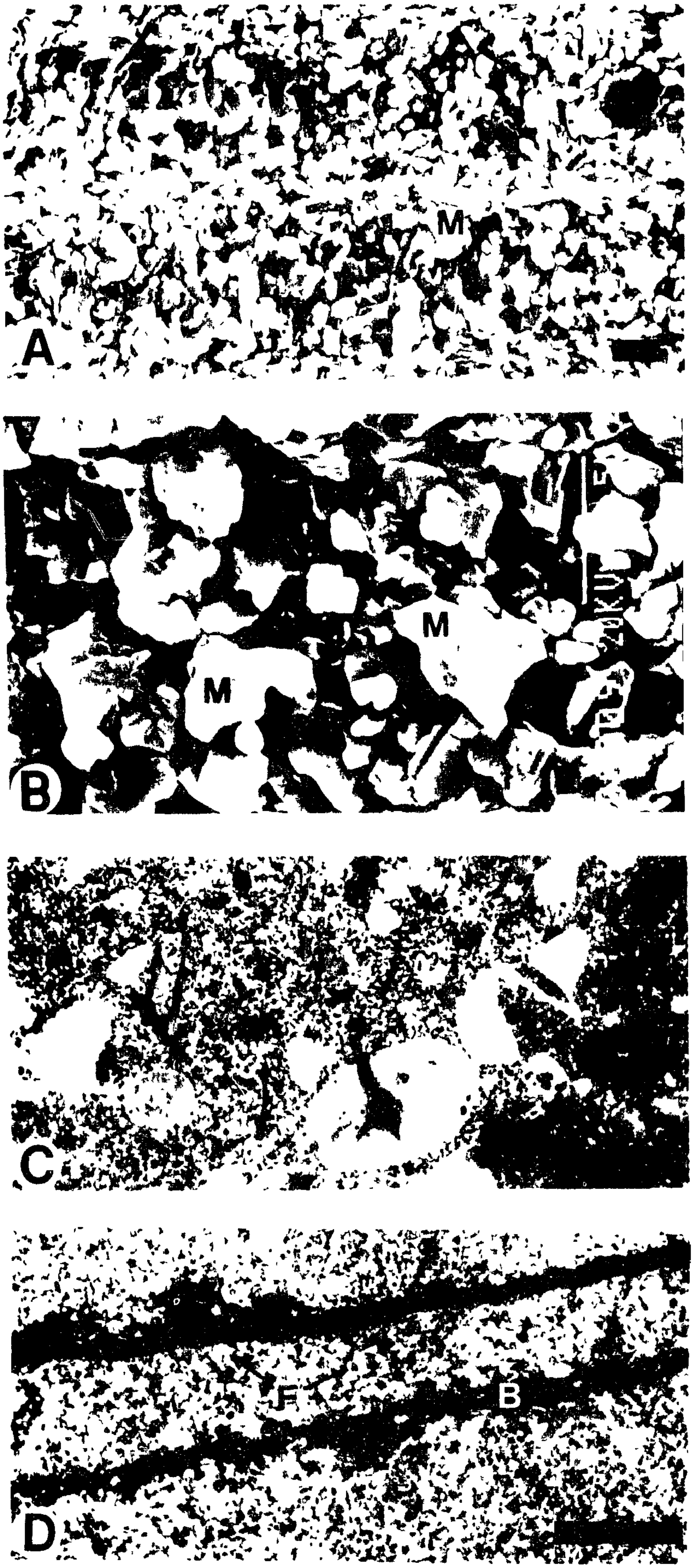

M
A
M
M
B
C
F
B
D

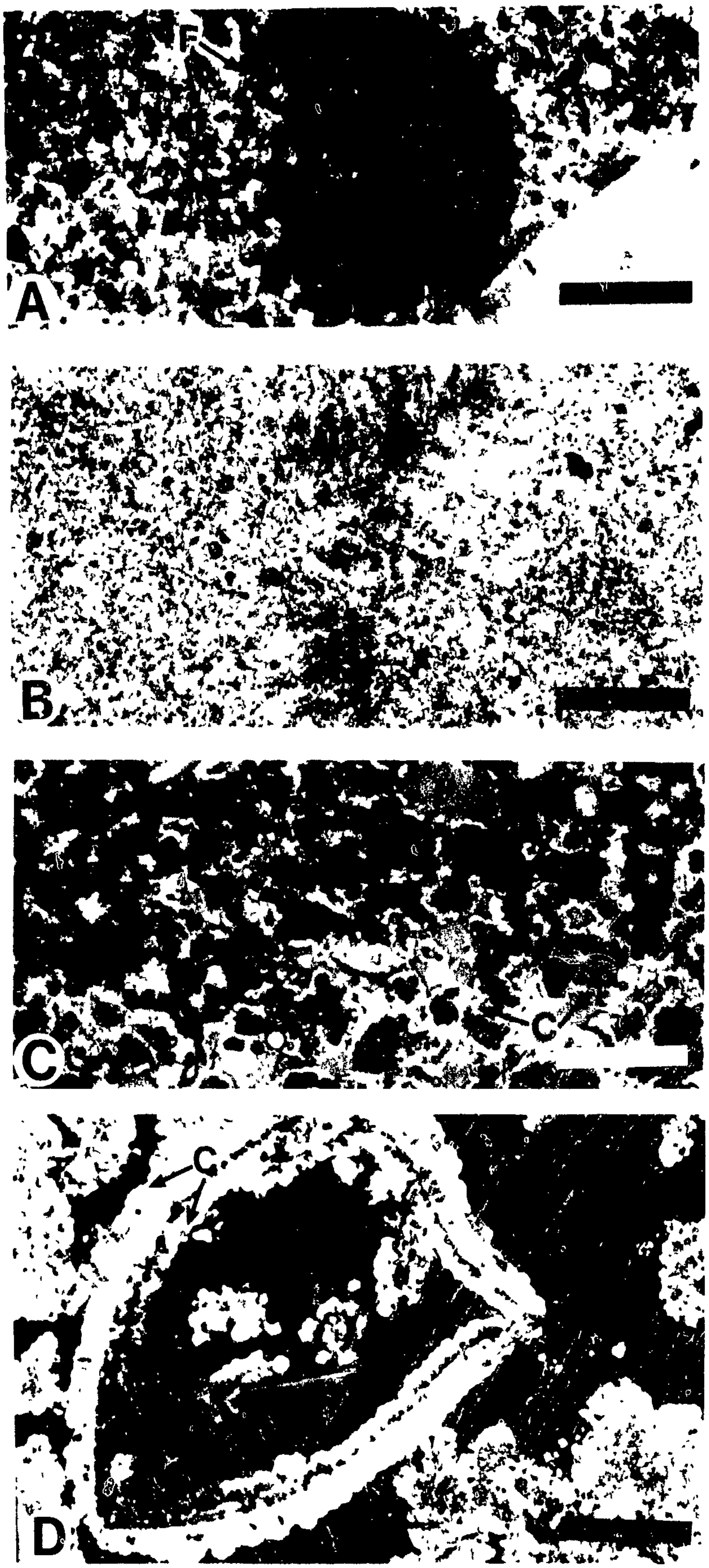
PLATE 16

A) Finely Crystalline Matrix Dolomite (F). A crinoid ossicle is gradually replaced by this type of fabric destructive dolomite. Scale bar, 0.61 mm.. Cross nicols. M-18-77 (2). 310 ft..

B) Finely Crystalline Matrix Dolomite (F). Radiaxial fibrous cements, dolomitized by microcrystalline replacement dolomite, are later partially replaced by the fabric destructive matrix dolomites. Scale bar, 0.69 mm.. Cross nicols. M-3-85 (49-2). 78 ft..

C) Cavity Filling Rhombic Dolomite (C). The relatively clear primary dolomite cement partially occludes the intergranular porosity (P) in peloid oncolite grainstones. Scale bar, 1.39 mm.. Plane light. M-3-84 (23). 55 ft..

D) Cavity Filling Rhombic Dolomite (C). A single generation of this dolomite cement forms isopachous rims inside and outside an ostracod and around other poorly preserved allochems. Scale bar, 0.95 mm.. Cross nicols. M-3-84 (23). 55 ft..


F
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D

PLATE 17

A) Cavity Filling Rhombic Dolomite (D). This finely crystalline dolomite forms a void-filling primary cement in calcrete horizons. Scale bar, 1.39 mm.. Cross nicols. Steeprock Bay Dome. SBD-1 (1).

B) Cavity Filling Rhombic Dolomite (C). Well formed rhombs of this dolomite cement partially infills cavities in non dedolomitized basinal Ratner carbonates. Note the dusty rhomb nuclei (N) and their relatively clean epitaxial rims (E) indicating at least two periods of crystal growth. Scale bar, 0.30 mm.. Plane light. M-3-73 (7). 69 ft..

C) Cavity Filling Rhombic Dolomite (C). The cores of the cement rhombs have been preferentially dissolved. The preserved rims (R) retain unit extinction inherited from their host nucleii (N). Scale bar, 0.30 mm.. Cross nicols. Mason Island. S-59.

D) First Generation Fracture (F1). These fractures are distinguished from other generations of fractures by the grey, secondary calcite cement (C) that fills all first generation fractures. 635-47 (22). 63 ft..

1

PLATE 18

A) First Generation Fractures (F1). Fracture orientation is often random resulting in the brecciation of the rock and cementation of the clasts by cavity and fracture filling calcite (C). M-5-76 (3). 274 ft..

B) Second Generation Fractures (F2). The F2 fracture cross cuts the F1 fracture filled by cavity and fracture filling calcite cement. The F2 fracture is also truncated by the stylolite (S). M-5-76 (2). 294 ft..

C) Cavity and Fracture Filling Calcite Cement (C). The cement, characterized its by coarse crystal size and rhombohedral cleavage, completely infills a cavity. Scale bar, 1.17 mm.. Cross nicols. M-5-76 (6). 255 ft..

D) Calcitized Evaporite (C). Laminations of calcitized evaporite contain anhedral calcite crystals that cross cut and preserve thin dusty units (D) that were probably associated with the precursor evaporite. Scale bar, 0.61 mm.. Plane light. M-5-76 (6). 255 ft..

1

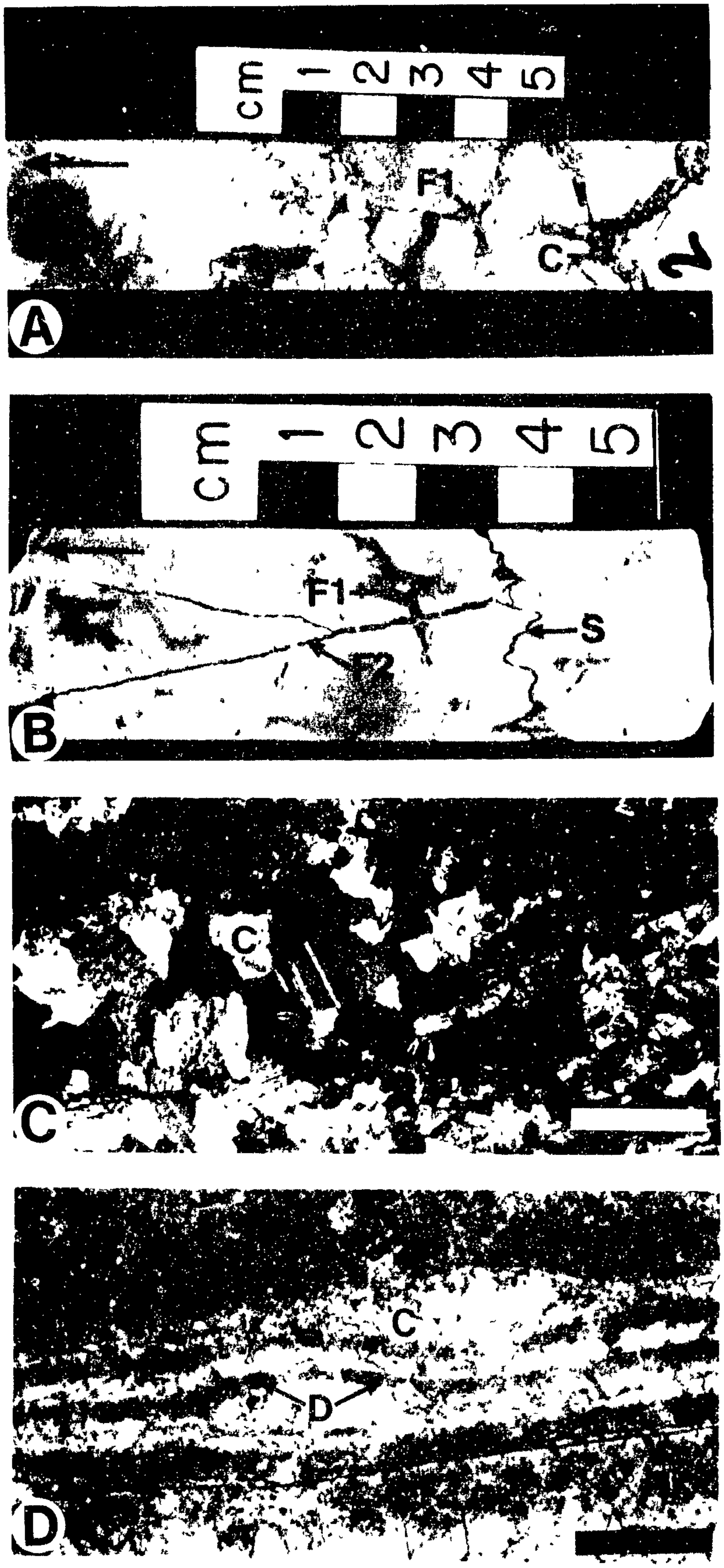


PLATE 19

A) Stylolite (S). Stylolites are pressure solution features that are observed in Winnipegosis limestones, calcitized evaporites and dedolomites. Typically, a black residue (R), most probably comprised of clays and bituminous organic matter, is preserved along the stylolite. Scale bar, 0.75 mm.. Plane light. M-8-86 (19). 182 ft..


A

CHAPTER 4. SUMMARY AND CONCLUSIONS

1. The Winnipegosis reef complexes in the Dawson Bay area are comprised of individual carbonate buildups that probably coalesced during their development to form larger composite reef structures. The buildups are local in extent and range in thickness from 75 to 100 m; they are located on regionally extensive platform sediments of relatively uniform thickness, 10 to 15 m. Basin sediments, 10 m thick, are situated between the reef complexes and on the carbonate platform. These carbonate sediments were initially deposited in shallow water that increased to a maximum depth of about 95 m at the end of buildup development.

2. Six environmental facies are identified in the Winnipegosis carbonates. They are: 1) platform (Lower Winnipegosis Member); 2) interior, 3) flank, 4) organic rim, and 5) stromatolite cap (Upper Winnipegosis Member); and 6) basin (Brightholme and Ratner Members). The platform facies is subdivided into lower and upper platform subfacies. The flank facies is subdivided into bioturbated, cemented, and laminated subfacies. The basin facies consist of two subfacies, the Brightholme Member bituminous mudstones, and the Ratner Member varved mudstones, dedolomites and calcitized evaporites.

3. Winnipegosis carbonates in the Dawson Bay area are almost exclusively dolomitized with the exception of some locally distributed dedolomites and one limestone buildup at Gunnlaugson's Farm.

4. At least twenty phases of diagenesis are identified in the Winnipegosis carbonates. They are interpreted to have occurred in four principal diagenetic environments: 1) open marine, 2) subaerial/meteoric, 3) restricted marine/shallow subsurface, and 4) deeper subsurface.

5. Open marine diagenetic processes modified the carbonate sediments during the deposition of platform, basin and buildup sediments. Although all textures are dolomitized, many are preserved: syntaxial cement, microspar cement, micritic envelopes, and acicular fibrous and fibrous cements.

6. The crests of the buildups were modified by dissolution, minor pendant cement precipitation, and calcrete formation during periods of subaerial exposure and meteoric diagenesis at the end of Winnipegosis time. The calcrete horizons are also dolomitized, but textures such as the crenulated laminations, pendant cements, and glaebules are preserved.

7. Three types of dolomite occur: 1) fabric retentive microcrystalline replacement dolomite that replaces and preserves delicate algal and skeletal forms and fibrous cements, 2) fabric destructive matrix dolomites (microcrystalline and finely crystalline matrix dolomites) that tend to obliterate all original textures, 3) cavity filling rhombic dolomite, a primary dolomite cement, that partially occludes intergranular, intraskeletal and moldic porosity. The matrix dolomites obliterate textures previously dolomitized by the fabric retentive dolomites, and are therefore considered to postdate the earlier dolomite phase.

8. The $\delta^{13}C$ (+2.5‰), $\delta^{18}O$ (-4.3‰), and $^{87}Sr/^{86}Sr$ (0.7080) isotopic signatures of Winnipegosis limestones suggest that the carbonates were originally deposited in normal marine Middle Devonian waters.

9. The range of $\delta^{18}O$ (-4.1 to -6.4‰), $^{87}Sr/^{86}Sr$ (0.7080) and related temperature/burial depth data of Saskatchewan and Dawson Bay Winnipegosis dolomites suggest that dolomitization occurred in fluids derived from normal to slightly hypersaline marine waters either under the influence of fresh water or

elevated temperatures at depth. However, the narrow range of $\delta^{13}C$ (+0.5 to +2.9‰) and the limited textural evidence for meteoric diagenesis do not favour dolomitization by freshwater mixing. Therefore, elevated temperatures at depths of 600 m or less are considered the most likely influence on the $\delta^{18}O$. This interpretation does not preclude the possibility that dolomitization, particularly fabric retentive dolomitization, occurred in marine waters during or very shortly after Winnipegosis deposition and prior to shallow burial. The problems inherent of sampling crystal sizes of less than 5 μm prevents accurate isotope analysis of the fabric retentive dolomites to establish under what conditions this type of dolomite formed. However, the unusually well preserved fabrics of this type of dolomite may represent dolomitization at sedimentary temperatures on or just below the seafloor.

10. The exact source of dolomitizing fluids is not clear. $^{87}Sr/^{86}Sr$ isotopes indicate that all Winnipegosis dolomitization occurred in fluids derived from marine waters. The fabric retentive microcrystalline dolomite may have precipitated on or just below the seafloor in normal to slightly hypersaline waters. However, $\delta^{18}O$ isotopes indicate that the matrix and cavity filling rhombic dolomites were precipitated at slightly elevated temperatures. Therefore, these slightly modified dolomitizing fluids derived from marine waters may have: 1) funnelled into the carbonates by the early mechanical compaction of the evaporites that encase the buildups, 2) sank by gravity into underlying platform sediments, or 3) funnelled upward through the buildups as formation waters from older Paleozoic carbonates.

11. The textural relationships between fractures and stylolites, and the $\delta^{18}O$ isotopes (-7.2 to -10.0‰) of late cavity and fracture filling calcite cements suggest that all these diagenetic phenomena took place at intermediate burial

depths. However, extensive dissolution in the Dawson Bay Winnipegosis dolomites may have occurred later in the subsurface or near ground level.

12. The $\delta^{13}C$ (-2.0 to -6.0‰) of Winnipegosis dedolomites and calcitized evaporites was possibly derived from a light carbon source associated with the bituminous residue along through-going stylolites. The $\delta^{18}O$ (-6.0 to -11.0‰) suggests that dedolomitization and calcitization of evaporites occurred at elevated temperatures during shallow to intermediate burial.

REFERENCES

Aissaoui, D.M., Coniglio, M., James, N.P., and Purser, B.H., 1986, Diagenesis of a Miocene reef platform: Jebel Abu Shaar, Gulf of Suez, Egypt: in Schroeder, H.H., and Purser, B.H., eds., Reef Diagenesis, Springer-Verlag, New York, 455p.

Anderson, T.F., and Arthur, M.A., 1983, Stable isotopes of oxygen and carbon and their application to sedimentologic and paleoenvironmental problems: in Stable Isotopes in Sedimentary Geology: Soc. Econ. Paleontologists Mineralogists Short Course, no. 10, p. 1-1 - 1-151.

Andrichuk, J.M., 1956, Cooking Lake and Duvernay (late Devonian) sedimentation in Edmonton area of central Alberta, Canada: Am. Assoc. Petroleum Geologists Bull., v.42, p. 2189-2222.

Assereto, R.L., and Kendall, C.G. St. C., 1977, Nature, origin and classification of peritidal teepee structures and related breccias. Sedimentology, v.24, p. 153-210.

Baillie, A.D., 1951, Devonian geology of Lake Manitoba - Lake Winnipegosis area, Manitoba: Manitoba Mines Branch, Publication 49-2.

________, 1953, Devonian names and correlations in the Williston Basin area: Am. Assoc. Petroleum Geologists Bull., v. 37(2), p. 444-447.

________, 1955, Devonian System of Williston Basin: Am. Assoc. Petroleum Geologists Bull., v. 39(5), p. 575-629.

Barss, D.L., Copland, A.B., and Ritchie, W.D., 1970, Geology of the Middle Devonian reefs, Rainbow area, Alberta, Canada: in Halbouty, M.T., ed., Geology of Giant Petroleum Fields: Am. Assoc. Petroleum Geologists Mem. 14, p. 19-49.

Blatt, H., Middleton, G., and Murray, R., 1980, Origin of Sedimentary Rocks: New Jersey, Prentice-Hall, 628p.

Botz, R., and von der Borch, C.C., 1984, Stable isotope study of carbonate sediments from the Coorong area, South Australia: Sedimentology, v. 31., p. 837-849.

Brooks, P.W., Osadetz, K.G., and Snowdon, L.R., 1988, Geochemistry of Winnipegosis discoveries near Tablelands, Saskatchewan; in Current Research, Part D, Geological Survey of Canada, Paper 1-88D, p. 11-20.

Budai, J.M., Lohmann, K.C., and Owen, R.M., 1984, Burial dedolomite in the Mississippian Madison Limestone, Wyoming and Utah Thrust Belt: Jour. Sed. Petrology, v. 54 (1), p. 276-289.

Burke, C.A., 1976, The Chad Basin: an active intracontinental basin: Tectonophysics, v. 36, p. 197-206.

Burke, W.H., Denison, R.E., Hetherington, E.A., Koepnick, R.B., Nelson, H.F., and Otto, J.B., 1982, Variation of seawater ^{87}Sr/^{86}Sr throughout Phanerozoic time: Geology, v.10, p. 516-519.

Carpenter, S.J., and Lohmann K., 1989, δ^{18}O and δ^{13}C variations in Late Devonian marine cements from the Golden Spike and Nevis reefs, Alberta, Canada, Jour. Sed. Petrology, v. 59, p. 792-814.

Choquette, P.W., and Pray, L.C., 1970, Geologic nomenclature and classification of porosity in sedimentary carbonates: Am. Assoc. Petroleum Geologists Bull., v. 54, p. 107-250.

Coniglio, M., James, N.P., and Aissaoui, D.M., 1988, Dolomitization of Miocene carbonates, Gulf of Suez, Egypt: Jour. Sed. Petrology, v. 58(1), p. 100-119.

Cuffey, R.G., 1977, Bryozoan contributions to reefs and bioherms through geologic time: in Reefs and related carbonates - ecology and sedimentology: Am. Assoc. Petroleum Geologists, Studies in Geology, no. 4.

Davies, G.R., and Ludlam, S.D., 1973, Origin of laminated and graded sediments, Middle Devonian of western Canada: Geol. Soc. America Bull., v. 84, p. 3527-3546.

Dickson, J.A.D., 1965, A modified staining technique for carbonates in thin section: Nature, v. 205, p. 587.

Dunham, R.J., 1962, Classification of carbonate rocks according to depositional texture: in Classification of Carbonate Rocks, Ham, W. E., ed: Am. Assoc. Petroleum Geologists, Mem. 1, p. 108-121.

Ehrets, J.R., and Kissling, D.L., 1987, Winnipegosis platform margin and pinnacle reef reservoirs, northwestern North Dakota, in Fischer, D.W., ed.: Fifth International Williston Basin Symposium Core Workshop Volume, Grand Forks, North Dakota, p. 1-32.

Embry, A.F., and Klovan, J.E., 1971, A late Devonian reef tract on northeastern Banks Island, Northwest Territories: Bull. Canadian Petroleum Geology, v. 19, p. 730-781.

Esteban, M., 1974, Vadose pisolite and caliche: Am. Assoc. Petroleum Geologists Bull., v.60, p. 2048-2057.

_____ _______, and Klappa, C.F., 1983, Subaerial exposure, in Scholle, P.A., Bebout, D.G., and Moore, C.H., eds.: Am.Assoc. Petroleum Geologists Mem. 33, p. 1-54.

Flugel, E., 1982, Microfacies Analysis of Limestones. Springer-Verlag, New York. 633p

Folk, R.L, Chafetz, H.S., and Tiezzi, P., 1985, Bizarre forms of depositional and diagenetic calcite in hot-spring travertines: in Schneidermann, N., and Harris, P.M., eds., Carbonate Cements: SEPM Spec. Paper No. 36, p. 185-220.

Fowler, C.M.R., and Nisbet, E.G., 1985, The subsidence of the Williston Basin: Can. Jour. Earth Sciences, v. 22, p. 408-415.

Friedman, G.M., and O'Neill, J.R., 1977, Compilation of stable isotope fractionation factors of geochemical interest: U.S. Geol. Survey Prof. Paper 440K, 12p

Fuller, J.G., and Porter, J.W., 1969, Evaporites and carbonates; two Devonian basins of western Canada: Bull. Canadian Petroleum Geologists, v. 17, p. 182-193.

Gill, D, 1985, Depositional facies of Middle Silurian (Niagaran) pinnacle reefs, Belle River Mills gas field, Michigan Basin, southeastern Michigan; in Roehl, P.O., and Choquette, P.W., eds., Carbonate Petroleum Reservoirs: Berlin, Springer-Verlag, p. 141-160

Given, R.K., and Lohmann, K.C., 1986, Isotopic evidence for the early diagenesis of the reef facies, Permian reef complex of west Texas and New Mexico: Jour. Sed. Petrology, v. 56, p. 183-193.

Grayston, L.D., Sherwin, D.R. and Allan J.F., 1964, Middle Devonian in McCrossan, R.G., and Glaister, R.P., eds.,: Geological History of Western Canada. Alberta Soc. Petroleum Geologists, ch. 5, p. 49-59.

Halim-Dihardja, M.K., 1986, Diagenesis and sedimentology of the late Devonian (Fammenian) Wabamun Group in the Tangent, Normandville, and Eaglesham fields, north-central Alberta [unpub. M.Sc. thesis]: Montreal, McGill University, 173p.

Haxby, W.F., Turcotte, D.L., and Bird, J.M., 1976, Thermal and mechanical evolution of the Michigan Basin: Tectonophysics, v. 36, p. 57-75.

Heckel, P.H., and Witzke, B.J., 1979, Devonian world paleogeography determined from distribution of carbonates and related lithic paleoclimatic indicators: Special Papers in Paleontology, no. 23, p.99-123.

Horowitz, A.S., and Potter, P.E., 1971, Introductory Petrography of Fossils. Springer-Verlag. 302p

Hudson, J.P., 1977, Stable isotopes and limestone lithification: Jour. Geol. Soc. London, v. 133, p. 637-660.

Illing, L.V., 1959, Deposition and diagenesis of some upper Paleozoic carbonate sediments in western Canada: 5th World Petroleum Congress, New York, Proc., sec. 1, p. 23-52.

James, N.P., 1983, Reef environments: in Scholle, P.A., Bebout, D.G., and Moore, C.H., eds., Carbonate Depositional Environments: Am. Assoc. Petroleum Geologists Mem. 33, p. 345-463.

__________, and Choquette, 1983, Diagenesis 6. Limestones - The sea floor diagenetic environment: Geoscience Canada, v.10, p. 161-194.

__________, Ginsburg, R.N., Marszalek, D.S., and Choquette, P.W., 1976, Facies and fabric specificity of early subsea cements in shallow Belize (British Honduras) reefs: Jour. Sed. Petrology, v. 46, p. 523-544.

Jodry, R.L., 1969, Growth and dolomitization of Silurian reefs, St Clair County, Michigan: Am. Assoc. Petroleum Geologists Bull., v.52, p. 957-981.

Johnson, J.G., Klapper, G., and Sandberg, C.A., 1985, Devonian eustatic fluctuations in Euramerica: Geol. Soc. America Bull., v. 96, p. 567-587.

Johnson, M.E., and Lescinsky, H.L., 1986, Depositional dynamics of cyclic carbonates from the Interlake Group (Lower Silurian) of the Williston Basin: Palaios, v. 1(2), p. 111-121.

Jones, J.L., 1964, The stratigraphy of Middle Devonian Winnipegosis Formation in Saskatchewan: 3rd International Williston Basin Symposium, Regina, Saskatchewan, Saskatchewan Geological Society, North Dakota Geological Society, Billings Geological Society, p. 73-91.

__________, 1965, The Middle Devonian Winnipegosis Formation of Saskatchewan: Saskatchewan Department of Mineral Resources, Report 98.

Julia, R., 1983, Travertines: in Scholle, P.A., Bebout, D.G., Moore, C.H., eds., Carbonate Depositional Environments: Am. Assoc. Petroleum Geologists Mem. 33, p. 64-72.

Kendall, A.C., 1975, The Ashern, Winnipegosis and Lower Prairie Evaporite Formations of the commercial potash areas: Saskatchewan Geological Survey, Summary of Investigations, p.61-65.

_______________, 1984, Evaporites: in Walker, R.G., ed., Facies Models, Geoscience Canada, Reprint Series 1, Ainsworth Press.

_______________, 1989, Brine mixing in the Middle Devonian of western Canada and its possible significance to regional dolomitization, Sedimentary Geol., v. 64, p. 271-285.

Kerans, C., Hurley, N.F., and Playford, P.E., 1986, Marine diagenesis in Devonian reef complexes of the Canning Basin, Western Australia: in Schroeder, J.H., and Purser, B.H., eds., Reef Diagenesis, Springer-Verlag, New York, 455p.

Kinsman, D.J., 1966, Gypsum and anhydrite of Recent age, Trucial coast, Persian Gulf: in Second Symposium on Salt, v. 1, Cleveland, Ohio, Northern Ohio Geol. Soc., p.302-326.

_______________, 1969, Models of formation, sedimentary associations, and diagnostic features of shallow water and supratidal evaporites: Am. Assoc. Petroleum Geologists, v. 53, p. 830-840.

Kirkland, D.W., and Evans, R., 1981, Source-rock potential of evaporitic environments: Am. Assoc. Petroleum Geologists, v. 65, p. 181-190.

Land, L.S., 1973, Phreatic versus vadose diagenesis of limestones: Evidence from a fossil water table: Sedimentology, v. 14, p. 175-185.

____________, 1980, The isotopic and trace element geochemistry of dolomite: the state of the art, in Zenger, D.H., Dunham, J.B., and Ethington, R.L., eds., Concepts of Models of Dolomitization: Soc; Econ: Paleontologists Mineralogists Spec. Publ., v. 28, p.87-110.

____________, 1983, The application of stable isotopes to studies of the origin of dolomite and to problems of diagenesis of clastic sediments, in Stable Isotopes in Sedimentary Geology: Soc. Econ. Paleontologists Mineralogists Short Course No. 10, p. 4-1-4-22.

____________, 1985, The origin of massive dolomite: Jour. Geol. Educ., v. 33, p.112-125.

Langton, J.R., and Chin, G.E., 1968, Rainbow Member facies and related reservoir properties, Rainbow Lake, Alberta: Bull. Canadian Petroleum Geology, v. 16(1), p. 104-143.

Lenz, A.C., 1982, Ordovician to Devonian sea-level changes in western and northern Canada: Can. Jour. Earth Sciences, v. 19 (10), p. 1919-1933

Lighty, R.G., 1985, Preservation of internal reef porosity and diagenesis sealing of submerged early Holocene barrier reef; southeast Florida shelf: in Carbonate Sediments: Soc. Econ. Paleontologists Mineralogists Spec. Publ. 36,

p. 123-151.

Lohmann, K.C., 1985, Application of carbon and oxygen isotopes, in Diagenetic History of Carbonate Sequences, Short Course Notes.

______________, and Myers, W.J., 1977, Microdolomite inclusions in cloudy prismatic calcites: Jour. Sed. Petrology, v. 47(3), p. 1078-1088

Machel, H.G., 1985, Facies and diagenesis of the Upper Devonian Nisku Formation in the subsurface of central Alberta [Ph.D. dissert.]: McGill University, Montreal, 392p.

____________, 1986, Early lithification, dolomitization, and anhydritization of Upper Devonian Nisku buildups, subsurface of Alberta, Canada, in Schroeder, J.H., and Purser, B.H., eds., Reef Diagenesis: Berlin, Springer-Verlag, p.336-356.

____________, 1989, Nisku Oil and Sour Gas Play, Subsurface of Central Alberta, in Bloy, G.R., Hadley, M.G., and Curtis, B.V., eds., The Development of Porosity in Carbonate Reservoirs: Canadian Soc. Petroleum Geologists Continuing Education Short Course Notes.

_____________, and Anderson, J.H., 1989, Pervasive dolomitization of the Nisku Formation in Central Alberta, Jour. Sed. Petrology, v. 59 (6), p. 891-911.

_____________, and Mountjoy, E.W., 1986, Chemistry and environments of dolomitization - a reappraisal: Earth Sci. Rev., v. 23. p. 175-222.

Maiklem, W.R., 1971, Evaporative drawdown - a mechanism for water level lowering and diagenesis in the Elk Point Basin: Bull. Canadian Petroleum Geology, v. 19, p. 487-503.

Margaritz, M., Goldenberg, L., Kafri, U., and Arad, A., 1980, Dolomite formation in the seawater-freshwater interface. Nature, v. 287, p. 622-624.

Marshall, J.F., 1983, Submarine cementation in a high energy platform reef: One Tree Reef, southern Great Barrier Reef: Jour. Sed. Petrology, v. 53, p. 1133-1149.

_______________, 1985, Cross-shelf and facies related variations in submarine cementation in the central Great Barrier Reef: Fifth International Coral Reef Cong. (Proc.), v. 3, p. 221-226.

_______________, and Davies, P.J., 1981, Submarine lithification on the windward reef slopes: Capricorn-Bunker group, Southern Great Barrier Reef: Jour. Sed. Petrology, v. 51, p. 953-960.

Martindale, W., and Orr, N.E., 1987, Middle Devonian Winnipegosis reefs of the Tablelands area, S.E. Saskatchewan: Second International Symposium on the Devonian System (Abst.).

_______________, and MacDonald, R.W., 1989, Sedimentology and diagenesis of the Winnipegosis Formation, Tableland area, S.E. Saskatchewan, <u>in</u> Bloy, G.R., Hadley, M.G., Curtis, B.V., eds., The Development of Porosity in Carbonate Reservoirs: Canadian Soc. Petroleum Geology Cont. Ed. Short Course Notes, sec. 7, p. 1-18.

Mattes, B.W., and Mountjoy, E.W., 1980, Burial dolomitization of the Upper Devonian Miette buildup, Jasper National Park, Alberta, in Zenger, D.H., Dunham, J.B., Ethington, R.L., eds., Concepts of Models of Dolomitization: Soc. Econ. Paleontologists Mineralogists Spec. Publ. 28, p. 259-297.

McCabe, H.R., 1967, Field guide to Devonian outcrops of southwestern Manitoba: First International Symposium on the Devonian System (Field Trip).

_____________, 1986. Devonian stratigraphy of the southwestern Manitoba outcrop belt: Canadian Soc. Petroleum Geology (Field Trip).

McKenzie, D.P., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25-32.

McKenzie, J.A., 1981, Holocene dolomitization of calcium carbonate sediments from the coastal sabkhas of Abu Dhabi, U.A.E.: A stable isotope study, Jour. Geology, v. 89, p. 185-198.

McKerrow, W.S., 1979, Ordovician and Silurian changes in sea level: Geol. Soc. London, v. 136, p. 137-145.

Mesolella, K.J., Robinson, J.D., McCormick, L.M., and Ormiston, A.R., 1974, Cyclic deposition of Silurian carbonates and evaporites in Michigan Basin: Am. Assoc. Petroleum Geologists Bull., v. 58, p. 34-62.

Morrow, D.W., 1978, The influence of the Mg/Ca ratio and salinity on dolomitization in evaporite basins: Bull. Canadian Petroleum Geology, v. 26, p. 389-392.

________, 1982, Diagenesis 11. Dolomite - part 11: Dolomitization models and ancient dolostones. Geosci. Canada, v. 9, p. 95-107.

Mountjoy, E.W., 1980, Some questions about the development of Upper Devonian carbonate buildups (reefs), western Canada: Bull. Canadian Petroleum Geology, v. 28(3), p. 315-344.

Neumann, A.C., and Macintyre, I, 1985, Reef response to sea level rise: keep-up, catch-up or give-up, in Proc. of the fifth international coral reef congress, Tahiti, v. 3, p. 105-110.

Norris, A.W., Uyeno, T.T., and McCabe, H.R., 1982, Devonian rocks of the Lake Winnipegosis - Lake Manitoba outcrop belt, Manitoba: Geological Survey Canada Mem. 392.

Perrin, N.A., 1982, Environments of deposition and diagenesis of the Winnipegosis Formation (Middle Devonian), Williston Basin, North Dakota: in Christopher, J., and Kaldi, J., eds., Fourth International Williston Basin Symposium, Saskatchewan Geological Soc. Spec. Publ. #4, p. 51-66.

Pierre, C., and Rouchy, J.M., 1988, Carbonate replacements after sulphate evaporites in the Middle Miocene of Egypt: Jour. Sed. Petrology, v. 58(3), p. 446-456.

Playford, P.E., 1980, Devonian "Great Barrier Reef: of Canning Basin, western Australia: Am. Assoc. Petroleum Geologists Bull., v. 64, p. 814-840.

______________, and Cockbain, A.E., 1976, Modern algal stromatolites at Hamelin Pool, a hypersaline barred basin in Shark Bay, Western Australia: in Walter, M.R., ed., Stromatolites, Amsterdam, Elsevier Science Publication, p. 389-413.

Popp, B.N., Anderson, T.F., and Sandberg, P.A., 1986, Textural, elemental and isotopic variations among constituents in Middle Devonian limestones, North America: Jour. Sed. Petrology, v. 56, p. 715-727.

Precht, W.F., 1987, Exploration for Winnipegosis pinnacle reefs in southern Saskatchewan and North Dakota: Second International Symposium on the Devonian System, (Abst.)

Qing, H., 1986, Diagenesis and sedimentology of Rainbow F and E buildups (Middle Devonian), northwestern Alberta: M.Sc. thesis (unpub.), McGill University.

Qing, H., and Mountjoy, E.W., 1989, Multistage dolomitization in Rainbow buildups, Middle Devonian Keg River Formation, Alberta, Canada: Jour. Sed. Petrology, v. 59(1), p. 114-126.

Quinlan, G.M., and Beaumont, C., 1984, Appalachian thrusting, lithospheric flexure, and the Paleozoic stratigraphy of the Eastern Interior of North America: Canadian Jour. Earth Sciences, v. 21, p. 973-996.

Rhodes, D., Lantos, E.A., Lantos, J.A., Webb, R.J., and Owen, D.C., 1984, Pine Point orebodies and their relationship to the stratigraphy, structure, dolomitization, and karstification of the Middle Devonian barrier complex: Econ. Geol., v. 79, p. 991-1055.

Rosenthal, L.R., 1988, The Winnipegosis Formation (Middle Devonian) of the northeastern margin of the Williston

Basin, Canada; McMillan, N.J., Embry, A.F., Glass, D.J., eds., in Devonian of the World, Proc. of the Second International Symposium on the Devonian System, Calgary, v. 1, p. 463-477.

Sandberg, P.A., 1983, An oscillating trend in Phanerozoic non-skeletal carbonate mineralogy: Nature, v. 305, p. 19-22.

Sass, E., and Katz, A., 1982, The origin of platform dolomites: new evidence: Am. Jour. Science, v. 282, p. 1184-1213.

Savard, M., and Bourque, P-A., 1989, Diagenetic evolution of a Late Silurian reef platform, Gaspe Basin, Quebec, based on cathodoluminescence petrography: Can. Jour. Earth Sciences, v. 26, p. 791-806.

Schlager, W., 1981, The paradox of drowned reefs and carbonate platforms: Geol. Soc. America Bull., v. 92, p. 197-211.

Schmidt, V., McILearth, I.A., and Budwill, A.E., 1985, Middle Devonian cementation reefs encased in evaporites, Rainbow field, Alberta, Canada: in Roehl, P.O., and Choquette, P.W. eds., Carbonate Petroleum Reservoirs, Springer-Verlag Inc., p.141-160.

Scholle, P.A., 1979, A colour illustrated guide to carbonate rock constituents, textures, cements, and porosities: Am. Assoc. Petroleum Geology Mem. 27. 241p

Shearman, D.J., and Fuller, J.G., 1969, Anhydrite diagenesis, calcitization and organic laminites, Winnipegosis Formation, Middle Devonian, Saskatchewan: Bull. Canadian Petroleum Geology, v. 17, p. 496-525.

Sleep, N.H., and Snell, N.S., 1976, Thermal contraction and flexure of Mid Continent and Atlantic marginal basins: Geophysical Jour. Royal Astronomical Soc., v. 45, p. 125-154.

Sloss, L.L., 1963, Sequences in the cratonic interior of North America: Geol. Soc. America Bull., v. 74, p. 93-113.

Sonnenfeld, P., 1984, Brines and Evaporites: Academic Press Inc., Florida, 581p.

Stoakes, F.A., 1980, Nature and control of shale basin fill and its effect on reef growth and termination: Upper Devonian Duvernay and Ireton Formations of Alberta: Bull. Canadian Petroleum Geology, v. 28(3), pp. 345-410.

Teare, M.R., 1987, The sedimentology of carbonate mounds of the Middle Devonian, Winnipegosis Formation, Manitoba: Canadian Soc. Petroleum Geologists Second International Symposium on the Devonian System, Calgary (Abst.)

Tyrrell, J.B., 1892, Report on Northwestern Manitoba with portions of the adjacent District of Assiniboia and Saskatchewan: Geological Survey of Canada Annual Report, 1981, pt.E, p. 1-240.

Vail, P.R., Mitchum, R.M., Jr., Todd, R.G., Widmier, J.M., Thompson, S., III, Sangree, J.B., Bubb, J.B., and Hatleid, W.G., 1977, Seismic stratigraphy and global changes of sea level: Am. Assoc. Petroleum Geologists Mem. 26, p. 49-212.

Walls, R.A., Mountjoy, E.W. and Fritz, P., 1979 Isotopic composition and diagenetic history of carbonate cements in Devonian Golden Spike reef, Alberta, Canada: Geol.

Soc. of America Bull., v. 90, p. 963-982.

____________, and Burrowes, G., 1985, The role of cementation in the diagenetic history of Devonian reefs, western Canada: in Schneidermann, N., and Harris, P.M., eds., Carbonate Cements, Soc. Econ. Mineralogists Paleontologists Spec. Publ., No. 36, p. 185-220.

Ward, W.C., and Halley, R.B., 1985, Dolomitization in a mixing zone of near-seawater composition, late Pleistocene, northeastern Yucatan Peninsula: Jour. Sed. Petrology, v. 55, p. 407-420.

Wardlaw, N.C., and Reinson, G.E., 1971, Carbonate and evaporite deposition and diagenesis, Middle Devonian Winnipegosis and Prairie Evaporite Formations of south-central Saskatchewan: Am. Assoc. Petroleum Geologists Bull., v. 55(10), p. 1759-1786.

Wendte, J., and Stoakes, F., 1982, Evolution and corresponding porosity distribution of the Judy Creek reef complex, Upper Devonian, Central Alberta, in Cutler, W.G., ed.: Canada's Giant Hydrocarbon Reservoirs; Am. Assoc. Petroleum Geologists Core Conference, p. 63-81

Whiteaves, J.F., 1892, The fossils of the Devonian rocks of the islands, shores or immediate vicinity of Lakes Manitoba and Winnipegosis: Geological Survey of Canada, Separate Report 445, Contributions to Canadian Palaeontology, v. 1(part 4, no. 6), p.255-359.

Williams, G.K., 1984, Some musings on the Devonian Elk Point Basin, western Canada: Bull. Canadian Petroleum Geology, v. 32(2), p. 216-232.

Wilson, J.L., 1975, Carbonate Facies in Geologic History. Springer-Verlag, New York, 471p

Wilson, N., 1984. The Winnipegosis Formation of south-central Saskatchewan, in Lorsong, J.A., and Wilson, M.A., eds.: Oil and gas in Saskatchewan; Saskatchewan Geological Soc. Spec. Pub. 7, p. 13-15.

Wray, J.L., 1977, Calcareous Algae, Developments in Paleontology and Stratigraphy, 4, Elsevier, 185p.

APPENDICES

APPENDIX 1

$^{87}Sr/^{86}Sr$ radiogenic isotope analyses

Appendix 1. $^{87}Sr/^{86}Sr$ radiogenic isotopes

Sample No.	Sample	Description	$^{87}Sr/^{86}Sr$
M-18-77 2(23)	DOL	Dol. fib. cmt	0.70795
M-18-77 87-26	DOL	Dol. fib. cmt	0.70800
M-2-87 24	CAL	Brachiopod	0.70804
M-8-86 20	DOL	FCMD	0.70804
635-46 13	DOL	FCMD	0.70795
Sask. 87-9	DOL	FCMD	0.70800

APPENDIX 2

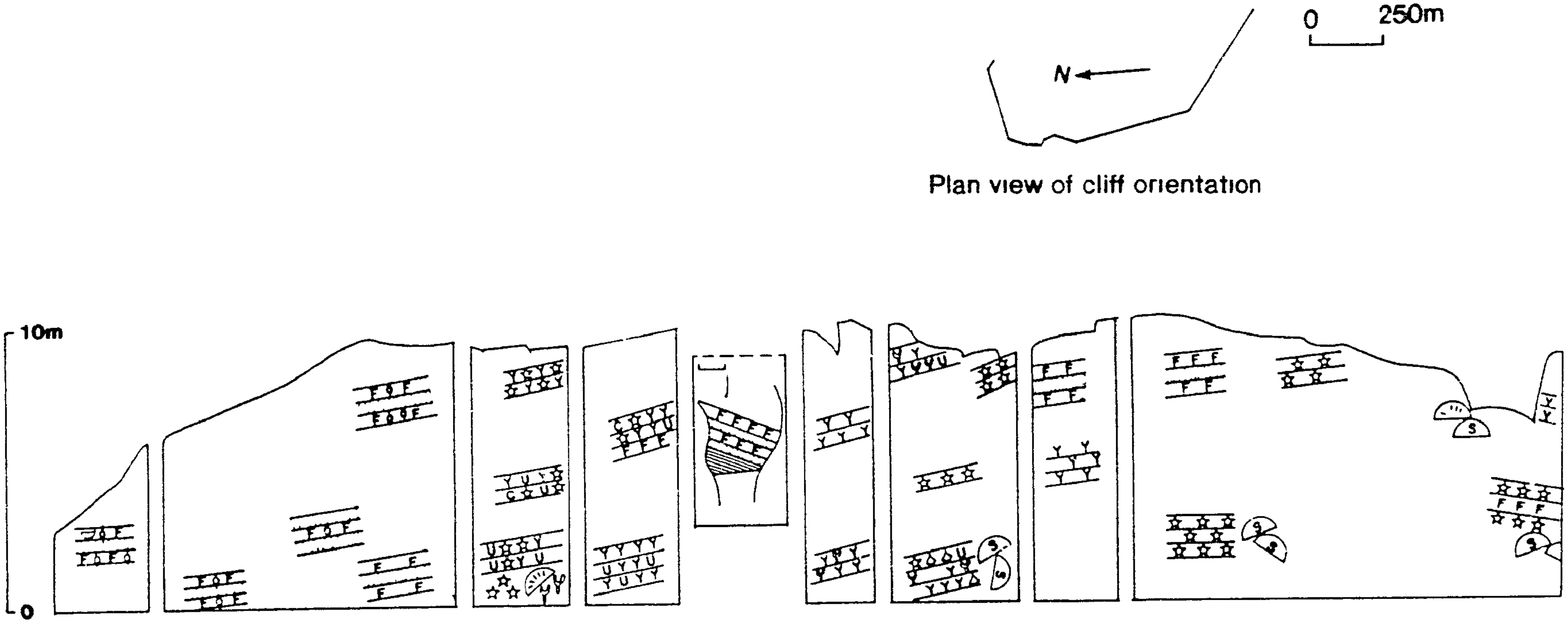
C and O stable isotope analyses

Appendix 2. C and O stable isotope analyses

Sample No.	Sample	Description	Location	O	C
M-2-87 20	CAL	Brachiopod		-5.0	+1.5
M-2-87 23	CAL	Brachiopod		-3.9	+2.8
M-2-87 25	CAL	Brachiopod		-4.0	+3.2
M-17-81 1	DOL	Crinoid grn		-4.5	+1.5
M-3-84 9	DOL	Crinoid grn		-5.2	+2.2
M-3-85 22	DOL	Crinoid grn		-5.5	+2.3
SB 3	DOL	Crinoid grn		-5.2	+1.9
M-18-77 2(20)	DOL	Brachiopod		-5.3	+1.3
635-48 36	DOL	Peloid		-4.6	+1.3
M-18-77 11	DOL	Dol. fib. cmt		-6.3	+1.5
M-18-77 11	DOL	Dol. fib. cmt		-5.9	+1.2
M-18-77 14	DOL	Dol. fib. cmt		-4.9	+2.4
M-18-77 14	DOL	Dol. fib. cmt		-5.2	+2.1
M-18-77 23	DOL	Dol. fib. cmt		-4.9	+0.9
M-18-77 23	DOL	Dol. fib. cmt		-5.8	+1.0
M-3-85 26	DOL	Dol. fib. cmt		-4.9	+1.1
635-46 22	DOL	Dol. fib. cmt		-5.0	+1.9
635-46 22	DOL	Dol. fib. cmt		-5.9	+0.5
M-18-77 23	DOL	MMD		-5.9	+2.1
47-76-14 9	DOL	FCMD		-5.4	+1.0
M-18-77 3	DOL	FCMD		-4.4	+1.7
M-3-84 9	DOL	FCMD		-4.8	+2.2
M-3-85 14	DOL	FCMD		-6.4	+1.4
M-3-85 26	DOL	FCMD		-4.8	+1.0
M-7-86 23	DOL	FCMD		-4.1	+2.7
Sask. WM 87-9	DOL	FCMD		-6.4	+0.6
Sask. WM 1	DOL	FCMD		-5.8	+2.1
Sask. WM 2	DOL	FCMD		-5.0	+2.3
47-76-2 S1	DOL	CFRD		-5.2	+2.9
M-5-87 36	DOL	CFRD		-5.4	+2.2
SBD1 1	DOL	CFRD		-5.2	+2.5
SB 2	DOL	CFRD		-5.3	+2.2
S-5-75 24	CAL	Sec. cal		-7.2	-6.2
M-3-85 26	CAL	Sec. cal		-9.2	-6.0
635-46 22	CAL	Sec. cal		-8.7	-8.2
635-46 32	CAL	Sec. cal		-10.0	-7.2
M-3-73 (87)8	CAL	Sec. cal		-9.2	-7.8
M-3-73 4	CAL	Dedol		-6.2	-3.5
M-3-73 7	CAL	Dedol		-6.1	-3.9
M-3-73 7	CAL	Dedol		-6.0	-3.9
M-3-73 (87)6	CAL	Dedol		-3.9	-5.2
M-5-76 13	CAL	Dedol		-5.8	-3.3
M-5-76 13	CAL	Calcit. evap		-6.6	-3.5

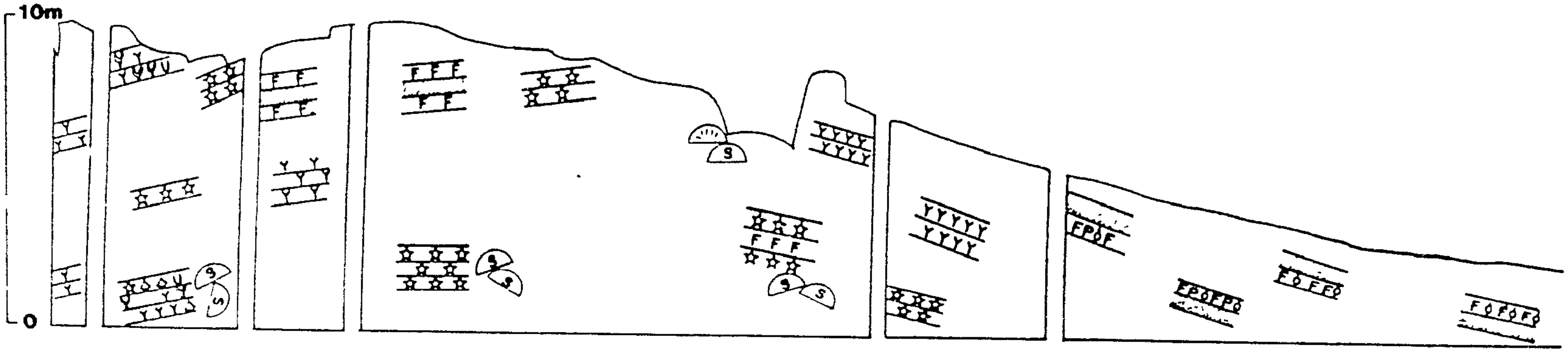
APPENDIX 3

Outcrop cross sections showing distributions of fauna, sedimentary features and diagenetic textures for Mason Island, Rock Island, Simons Island, The Bluff, and the Steeprock Bay Dome Cliffs. A legend for all symbols used appears at the end of the appendix.

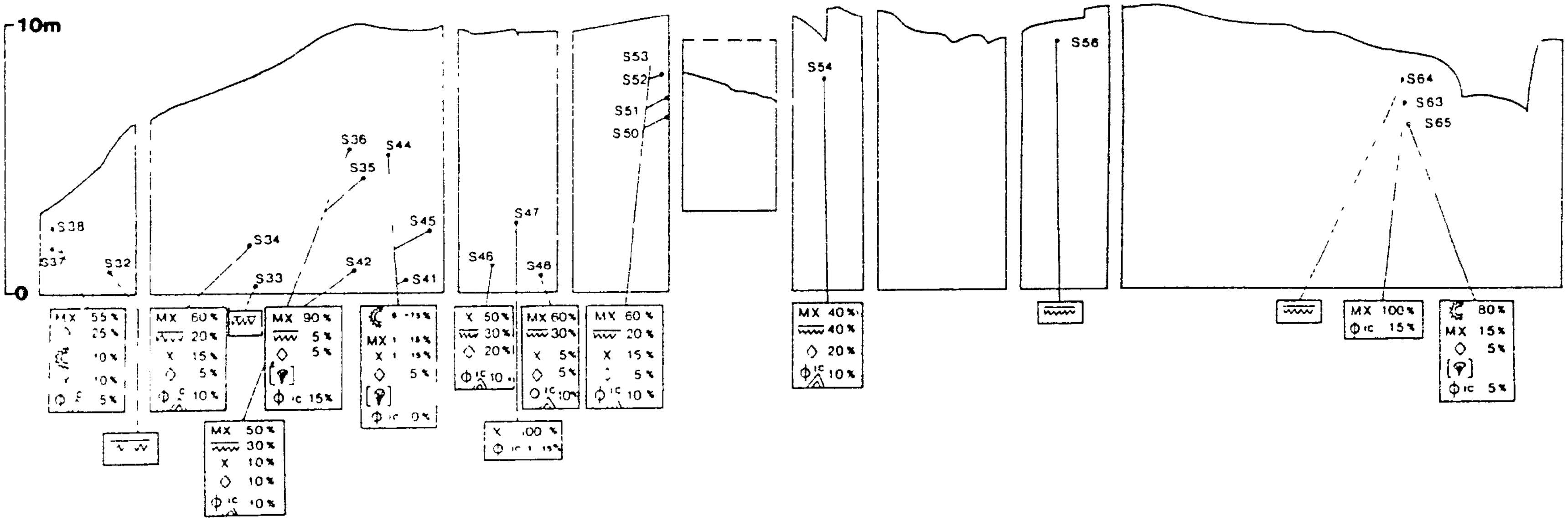


APPX. 3. FIGURE 1. Mason Island, northern exposure. Buildup interior facies containing a vertical series of well bedded shoals of crinoidal, bryozoan, coralline and calcareous algal floatstones. Scattered massive stromatoporoids are distributed throughout. Note that bedded sediments dip northward away from buildup core at north end of the exposure.

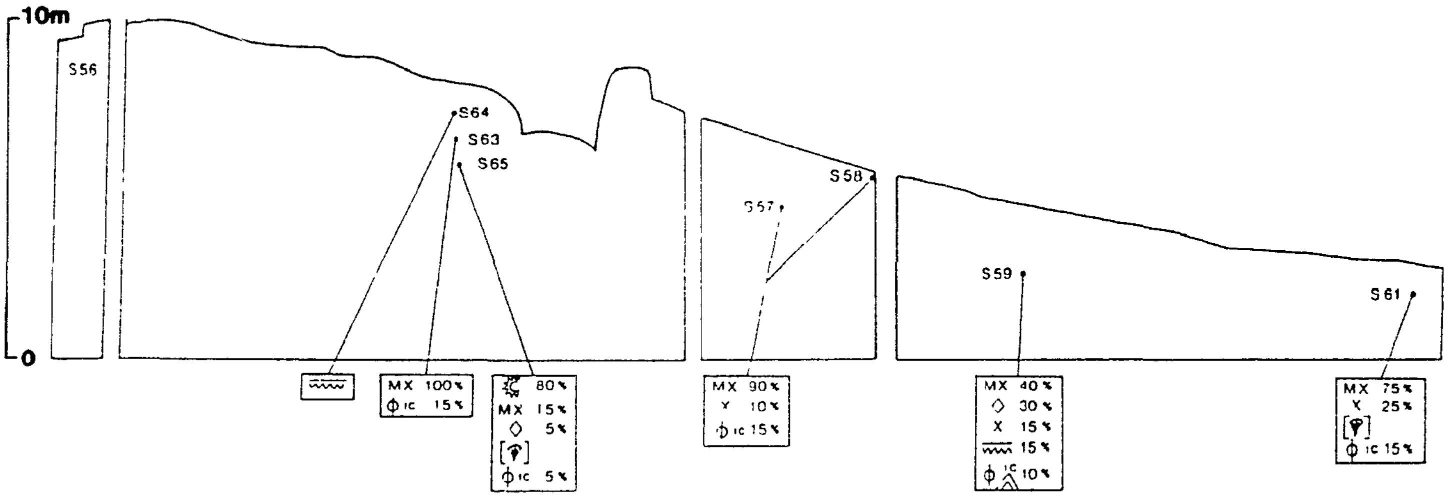
Plan view of cliff rim orientation



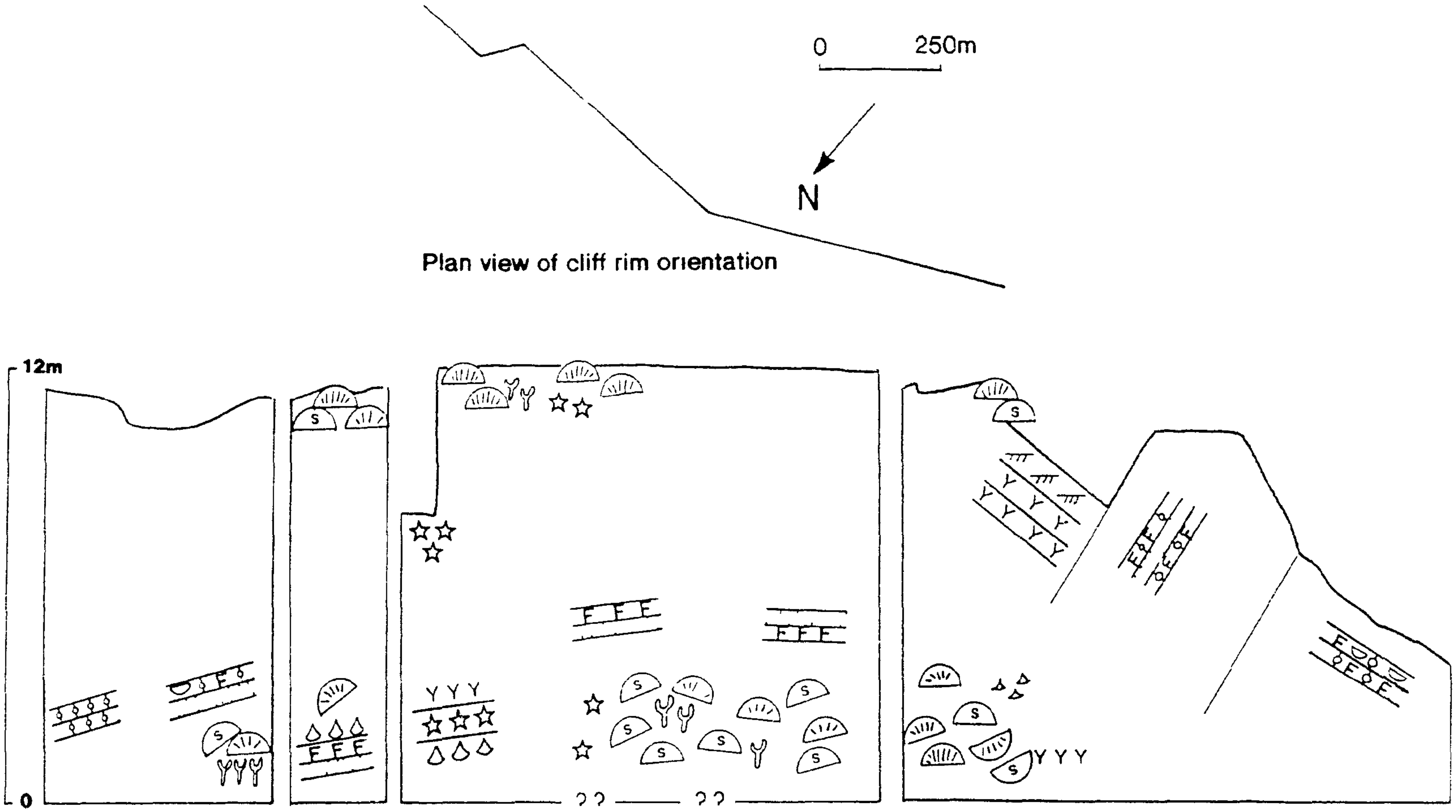
APPX. 3 FIGURE 2. Mason Island, southern exposure. Build up interior facies containing a vertical series of well bedded shoals of crinoidal, bryozoan, coralline and calcareous algal floatstones. Note that bedded sediments dip southward away from buildup core at south end of exposure.



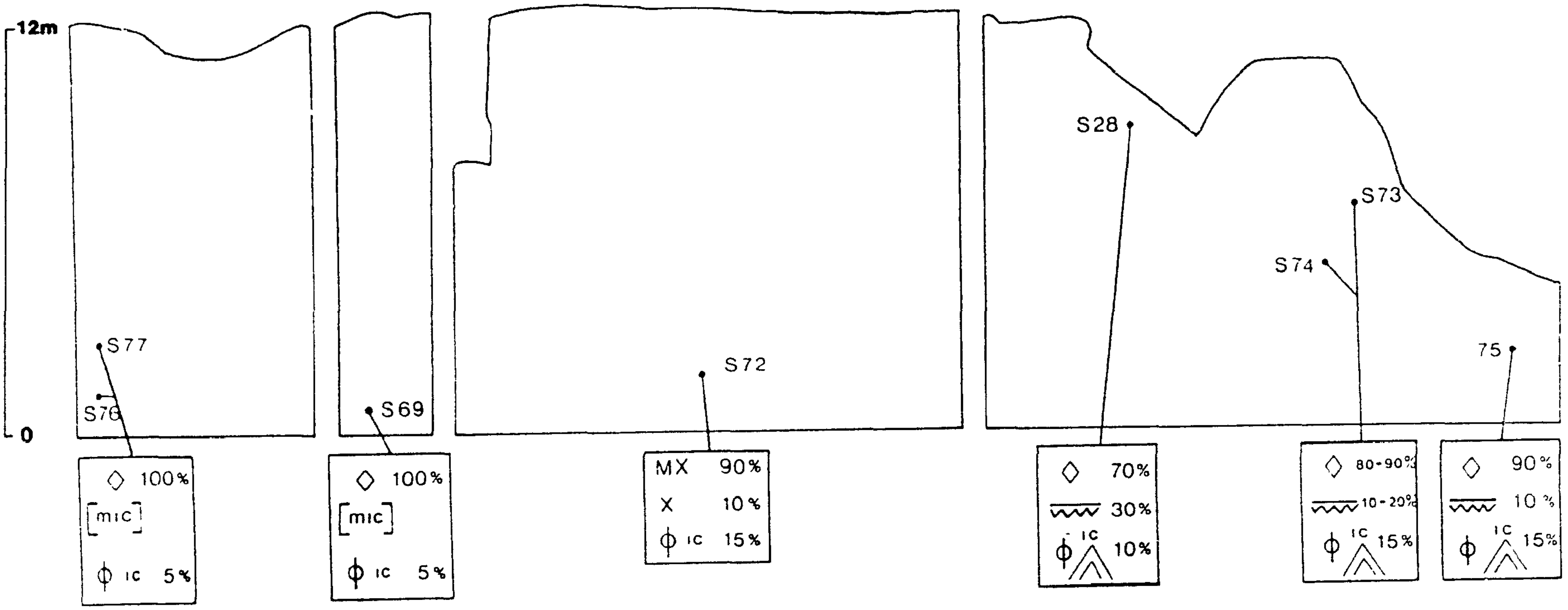
APPX. 3. FIGURE 3. Mason Island, northern exposure. Relative amounts (by percentage) of various dolomite and cement types observed petrographically in collected outcrop specimens. Dolomitized submarine cements and fabric retentive dolomites are common at this stratigraphic interval. Fabric destructive and cavity filling rhombic dolomites occur in lesser amounts.



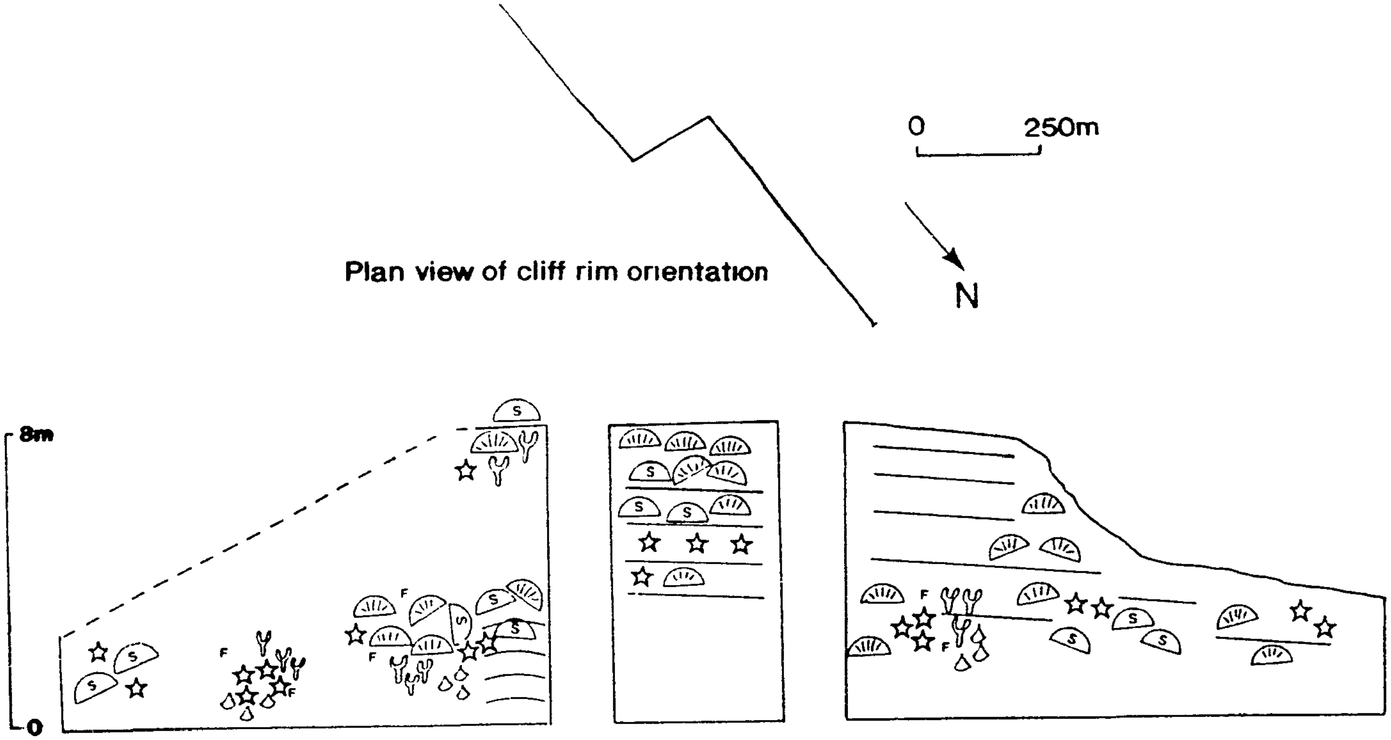
APPX. 3. FIGURE 4. Mason Island, southern exposure. Relative amounts (by percentage) of various dolomite and cement types observed petrographically in collected outcrop specimens. Dolomitized submarine cements and fabric retentive dolomites are common at this stratigraphic interval. Fabric destructive and cavity filling rhombic dolomites occur in lesser amounts.



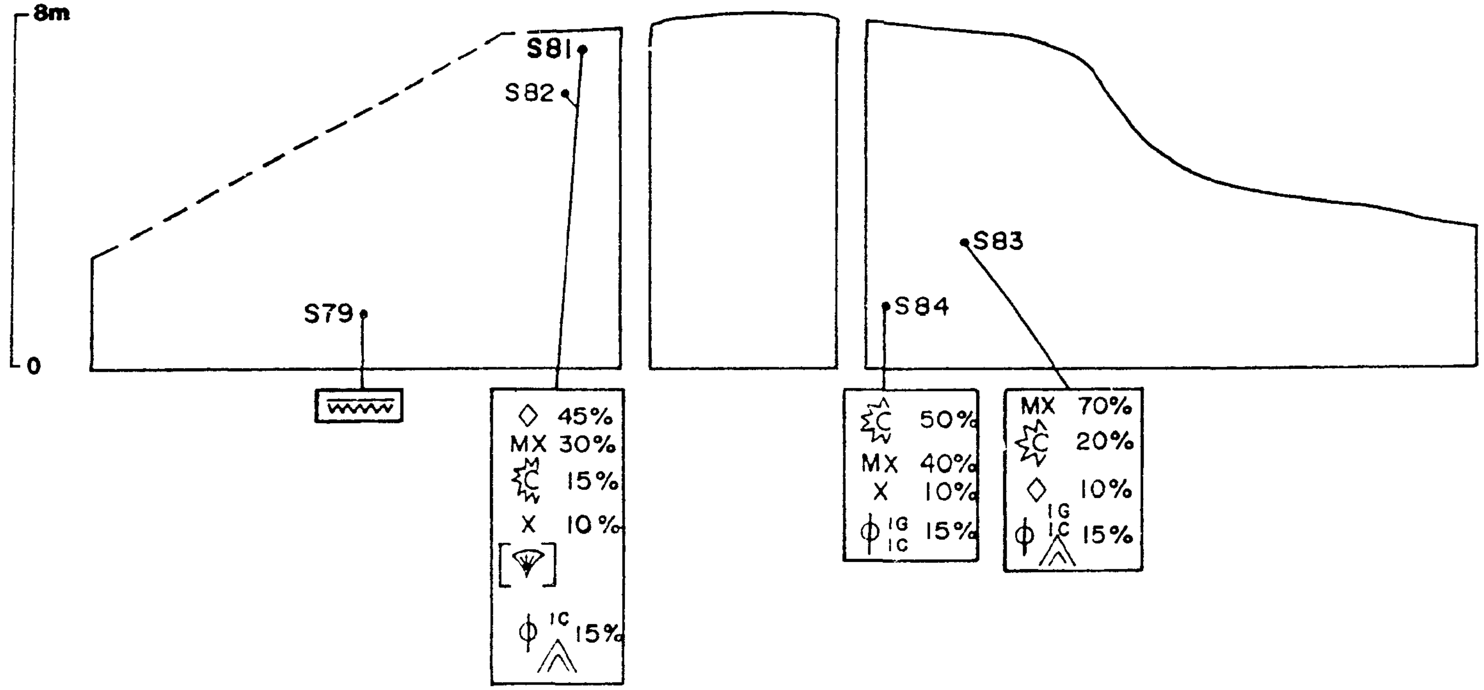
APPX. 3 FIGURE 5 Rock Island. Buildup interior facies contain a vertical series of well bedded shoals of crinoidal, bryozoan, and calcareous algal floatstones. Pebble to boulder-sized massive coralline and stromatoporoid debris is commonly scattered throughout these sediments. Toward the top of the outcrop exposure, the enigmatic sponge/coral, Chaetetes, massive corals and stromatoporoids are preserved in situ, and represent the early development of the organic rim facies. The poorly defined beds of comminuted skeletal debris and peloidal wackestones and mudstones on the outcrop flanks represent the buildup flank facies. Note how these beds dip east and west away from the buildup core. Also note the upturned block of sediments on the east flank of the outcrop.



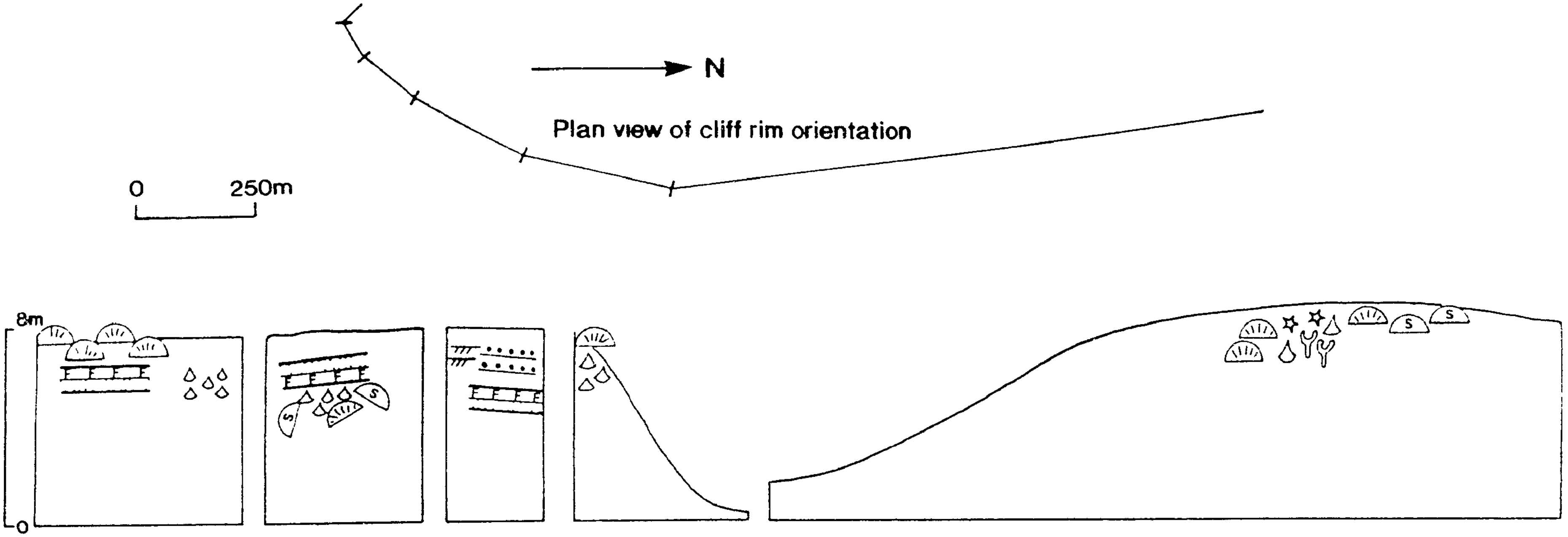
APPX. 3. FIGURE 6. Rock Island. The relative amounts (by percentage) of various dolomite and cement types observed petrographically in collected outcrop specimens. Submarine cements and other textures preserved by the fabric retentive microcrystalline replacement dolomites are common. The high occurrence of cavity filling rhombic dolomite may represent a sample bias as this dolomite cement type was not observed in significant amounts in core



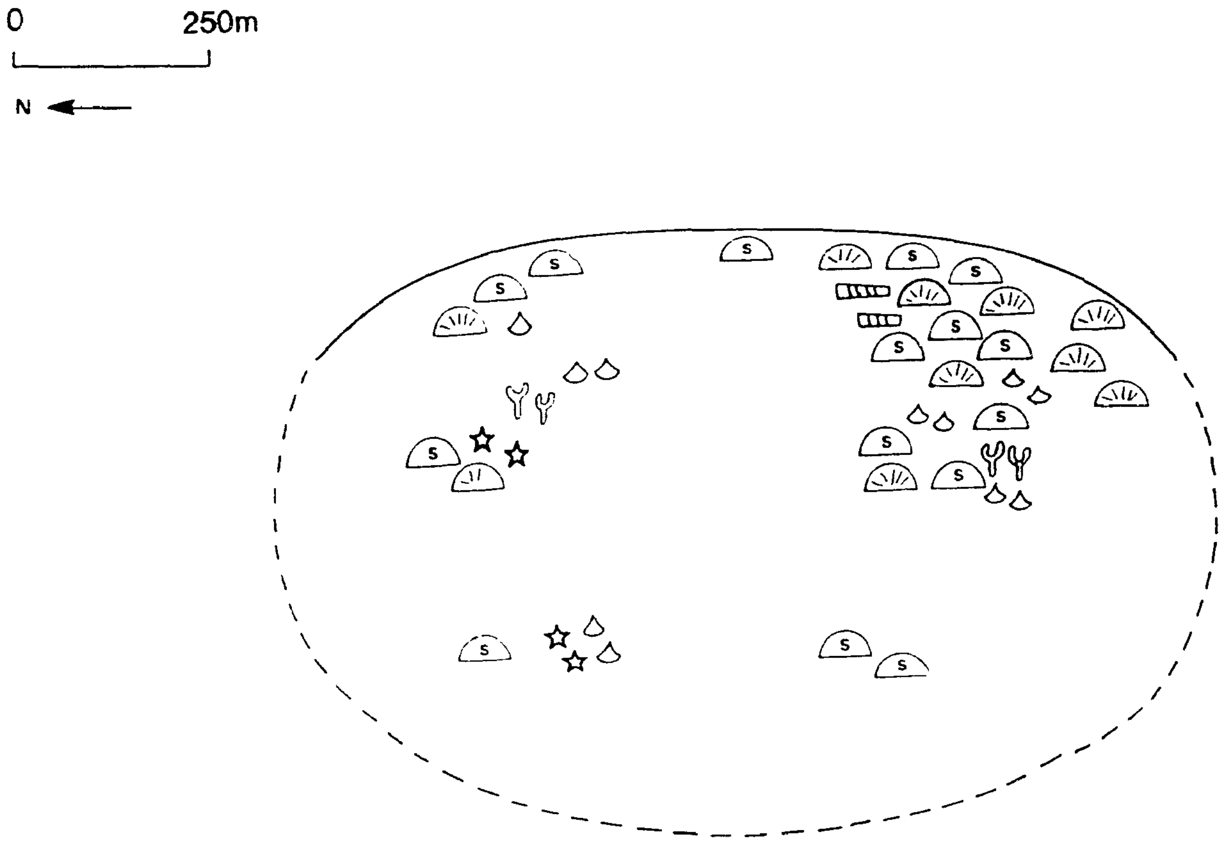
APPX. 3. FIGURE 7. Simons Island. The organic rim facies contains *in situ* and disturbed massive corals, stromatoporoids and the enigmatic sponge/coral, *Chaetetes*, echinoderms, branching and tabulate corals, brachiopods and a plethora of non-framebuilding organisms. Large volumes of skeletal debris and muds are interbedded with the framebuilders. The apparent doming of the beds may represent the exposed core of the buildup.



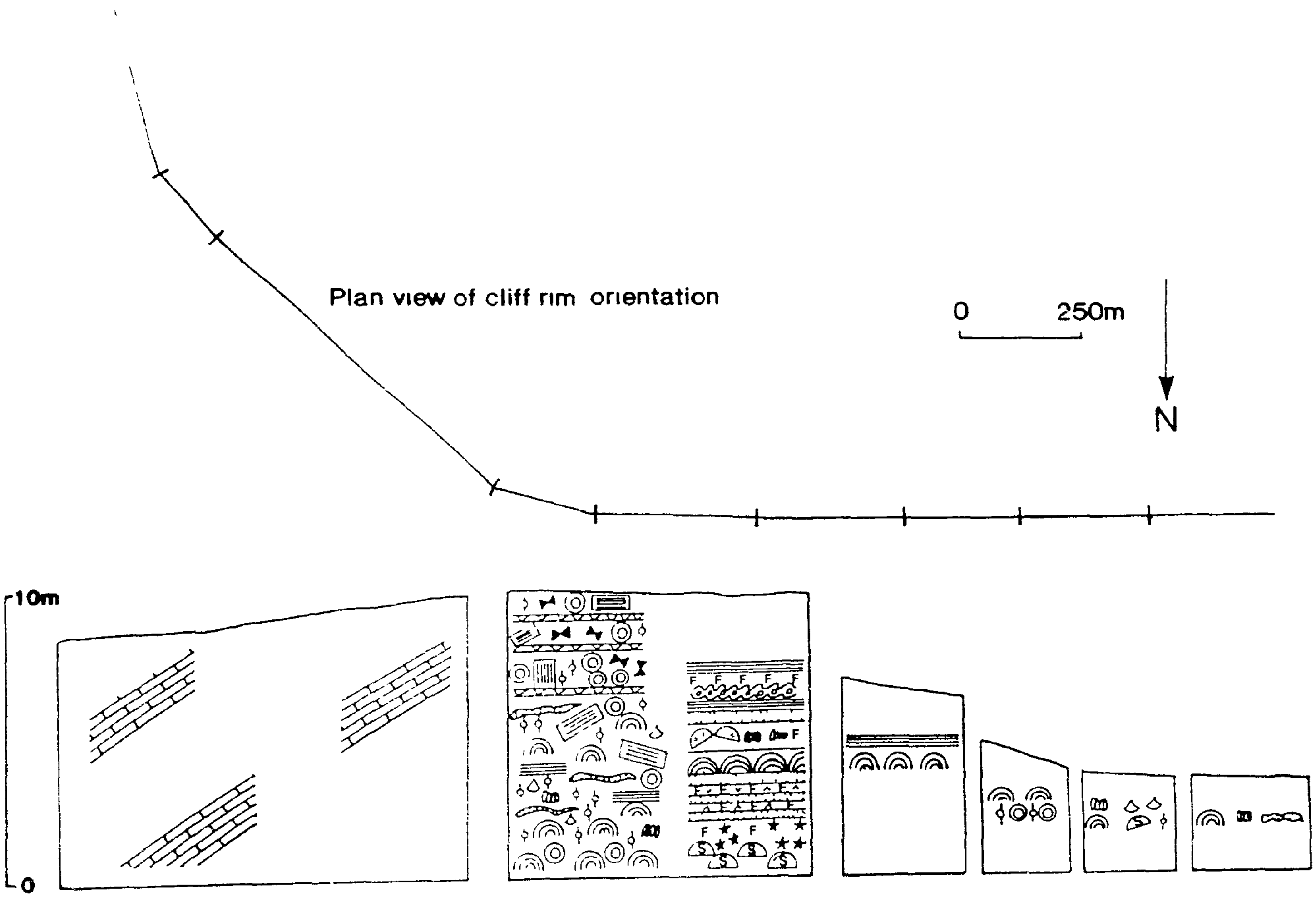
APPX. 3. FIGURE 8 Simons Island The relative amounts of the various cement and dolomite types observed petrographically in collected specimens are recorded by percentage. Submarine cements and other textures are preserved by the microcrystalline replacement dolomite. Cavity filling rhombic dolomite commonly occurs as primary dolomite cement in various porosity types Fabric destructive matrix dolomites occur in small amounts only



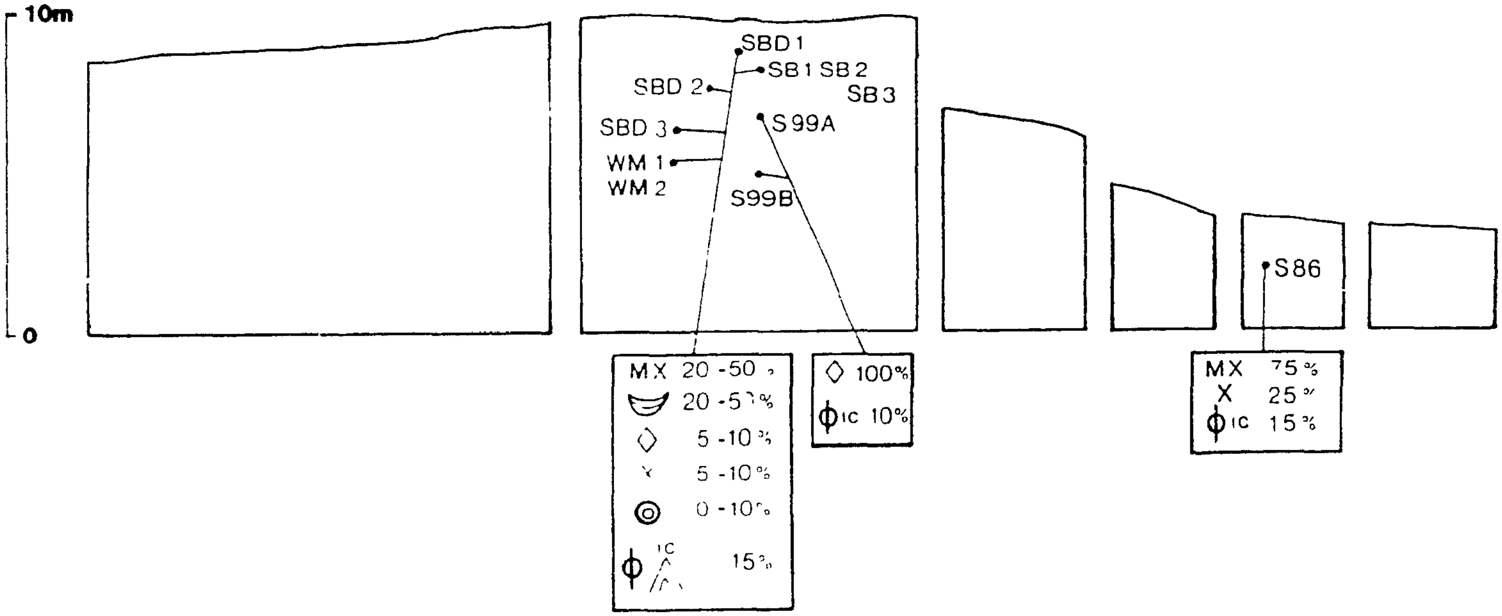
APPX. 3. FIGURE 9. The Bluff. The organic rim facies contains *in situ* and disturbed massive corals, stromatoporoids and the enigmatic sponge/coral, *Chaetetes*, echinoderms, branching and tabulate corals, brachiopods and many non-framebuilding organisms. Fossiliferous wackestones and cross laminated mudstones are interbedded with the framestones.



APPX 3 FIGURE 10. Knob One, The Bluff A plan view of the distribution of frame and non-framebuilding organisms in the organic rim facies.



APPX. 3. FIGURE 11. Steeprock Bay Dome Cliffs. The stromatolite cap facies represents peritidal sedimentation accompanied by intermittent periods of subaerial exposure, meteoric diagenesis and calcrete development. These sediments are predominantly coated grain grainstones with a well developed fenestral fabric throughout. Bioclastic debris is interbedded with the fenestral grainstones. Laterally extensive truncation surfaces, boulder-sized teepee clasts and green shale stringers represent intense erosional activity possibly during storms. Cross laminated mudstones, elongated mud lobes, coated grain grainstones, and laminated pisolites all represent submarine depositional processes. Thin (< 0.5m) horizons of banded calcrete occur within the fenestral grainstones representing periods of subaerial exposure during which calcrete plates, crusts, and glaebules were formed.



APPX. 3. FIGURE 12. Steeprock Bay Dome Cliffs. The relative amounts of the various freshwater and submarine cements and dolomite types observed petrographically in collected outcrop specimens are given by percentage. Dolomitized freshwater pendant cements are common in calcrete horizons. Cavity filling rhombic dolomite is very common as an intergranular cement in the coated grain grainstones The fabric retentive and fabric destructive dolomite types may occur more commonly in the cap facies that extend over the buildup flanks

LEGEND

Diagenetic Fabrics

Symbol	Description
MX	Microcrystalline replacement dolomite (fabric retentive)
X	Matrix dolomites (fabric destructive)
◇	Cavity filling rhombic dolomite
⋀⋀⋀	Radiaxial fibrous cement (shelter porosity)
✲	Radiaxial fibrous cement (intergranular porosity)
⩛	Radiaxial acicular fibrous cement
MIC	Micritic envelope
◡	Pendant cement
◎	Calcrete glaebule
[ ]	Minor quantity
ϕ	Porosity
IC	Intercrystalline
⋀	Dissolved nuclei of cavity filling rhombic dolomite rhombs
IG	Intergranular

Inorganic/indeterminant Components

Symbol	Description
ϕ	Peloid
⊚	Pisolites
∾	Oncolites

Biogenic Components

☆	Echinoderm
Y	Bryozoan
U	Udoteacean calcareous algae
◇	Brachiopod
Ψ	Branched coral
◓	Massive coral
⊕	Solitary coral
S	Massive stromatoporoid
⌒	Fenestral Algae/Cyanobacterial
∞	Gastropod
▭	Orthocone
◡	Ostracod

Sedimentary Structures

▨	Interbedded wackestones/ floatstones with mudstones
⁄⁄⁄⁄	Rippled sediments
• • • •	Normal graded bedding
⩘	Calcrete
≡	Erosional surface
≡	Finely laminated muds

APPENDIX 4

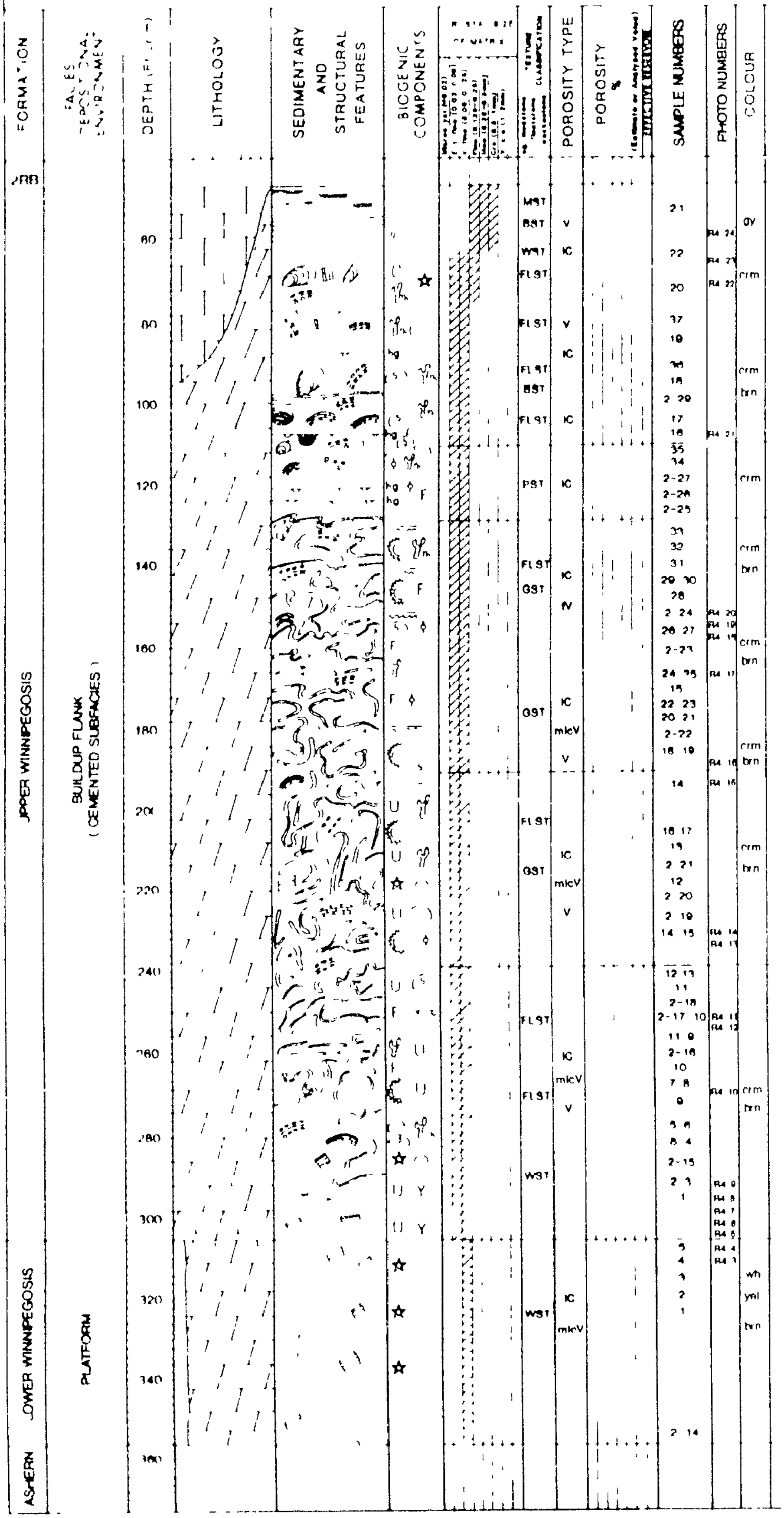
Locations of wells, and logs for all cores described in Dawson Bay and surrounding areas. All cores logged in Imperial units (ft). A legend for the log symbols appears at the end of Appendix 3.

Locations of wells with logged cores

M-18-77	03-17-45-25W1M
M-10-72	08-17-45-25W1M
47-76-14	14-12-45-26W1M
47-76-2	10-11-45-26W1M
M-17-81	08-14-44-25W1M
M-8-86	08-14-44-25W1M
M-7-86	05-13-44-25W1M
S-5-75	03-01-44-25W1M
M-5-87	06-17-44-24W1M
635-48	Salt Point
M-4-87	06-21-44-24W1M
635-47	Salt Point
635-46	Salt Point
M-2-84	16-33-43-24W1M
M-3-84	09-33-43-24W1M
M-3-85	09-33-43-24W1M
M-6-78	13-21-30-17W1M
M-12-71	12-07-48-25W1M
M-3-73	09-15-46-22W1M
M-2-87	05-35-24-10W1M
M-5-76	10-22-30-16W1M

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME M-18-77
LOCATION RED RIVER
FORMATION WINNIPEGOSIS
CORE INTERVAL 47-356 ft
K B ELEVATION 270 m
LOGGED BY MARK TEARE
DATE JUNE 15, 1986
PAGE 1 OF 1



COMMENTS

DEDOL crud lam grn sh incorp in mtx, ?algal bst, pr pres of prim texs, com vug ϕ/crs xtl calc cmt

DEDOL crm col fos wst flst obsc by dedol and v crs xtl calc cmt lrge frags strom deb

DOL rm fos/crls *Thamnopora*, *Alveolites*, *Favosites* deb, occ hdgrnds, v calc l/p dedol oblit prim texs

DOL fos, crl and strom deb, hdgrnds trnct skel deb pel intcl commin skel deb pst mtx

DOL fos deb pst ?algal lams, hdgrnds ic micvug ϕ

DOL shelt lg ϕ cmtd by 2(min) gens of acic and radiax fib cmts, com strom & crl deb pel brach pst glt rip up md clsts cln, soln micvug vug ϕ, occ pres prim ϕ

DOL fos flsts/com udoteacean calc algae (*Paralitonale*), pel fos gsts, mas tab strom deb com crin & brach, micvug vug ϕ, v com fib cmts brn crm gens of acic & radiax cmts in prim lg intskel shelt ϕ

DOL fos flsts crl tab strom udot calc algae, shel lg ϕ/2 3gens fib cmt, soln micvug vug ϕ pel & commin skel deb pst mtx bd slope dip (?calcturb deps) 13 15

DOL crin, udot bry deb wsts flsts cln bcmg calc

DOL six yel wh mtls in lt gy brn v fn grn mtx crm crin brach wsts, com bit prtgs in mtx micvug vug ϕ stylonod tex

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME M-10-72

LOCATION RED DEER RIVER

FORMATION WINNIPEGOSIS

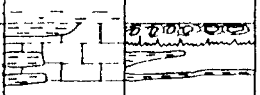
CORE INTERVAL 62-72 ft

K B ELEVATION 259m

LOGGED BY MARK TEARE

DATE JULY 7, 1986

PAGE 1 OF 1



FORMATION	FACIES/ DEPOSITIONAL ENVIRONMENT	DEPTH (Ft or m)	LITHOLOGY	SEDIMENTARY AND STRUCTURAL FEATURES	BIOGENIC COMPONENTS	CRYSTAL SIZE OF MATRIX	TEXTURAL CLASSIFICATION	POROSITY TYPE	POROSITY %	SAMPLE NUMBERS	PHOTO NUMBERS	COLOUR	COMMENTS
2RB		60										red	SH
UPPER WINNIPEGOSIS							BREC					gy gn	BREC gy mic clsts in con of lam grn sh
							MST	fr				gy	DEDOL gy mic mst prim texs & strcs oblit intbd grn sh
		80											

1235 08/81

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME 47-76-14

LOCATION RED DEER RIVER

FORMATION WINNIPGOSIS

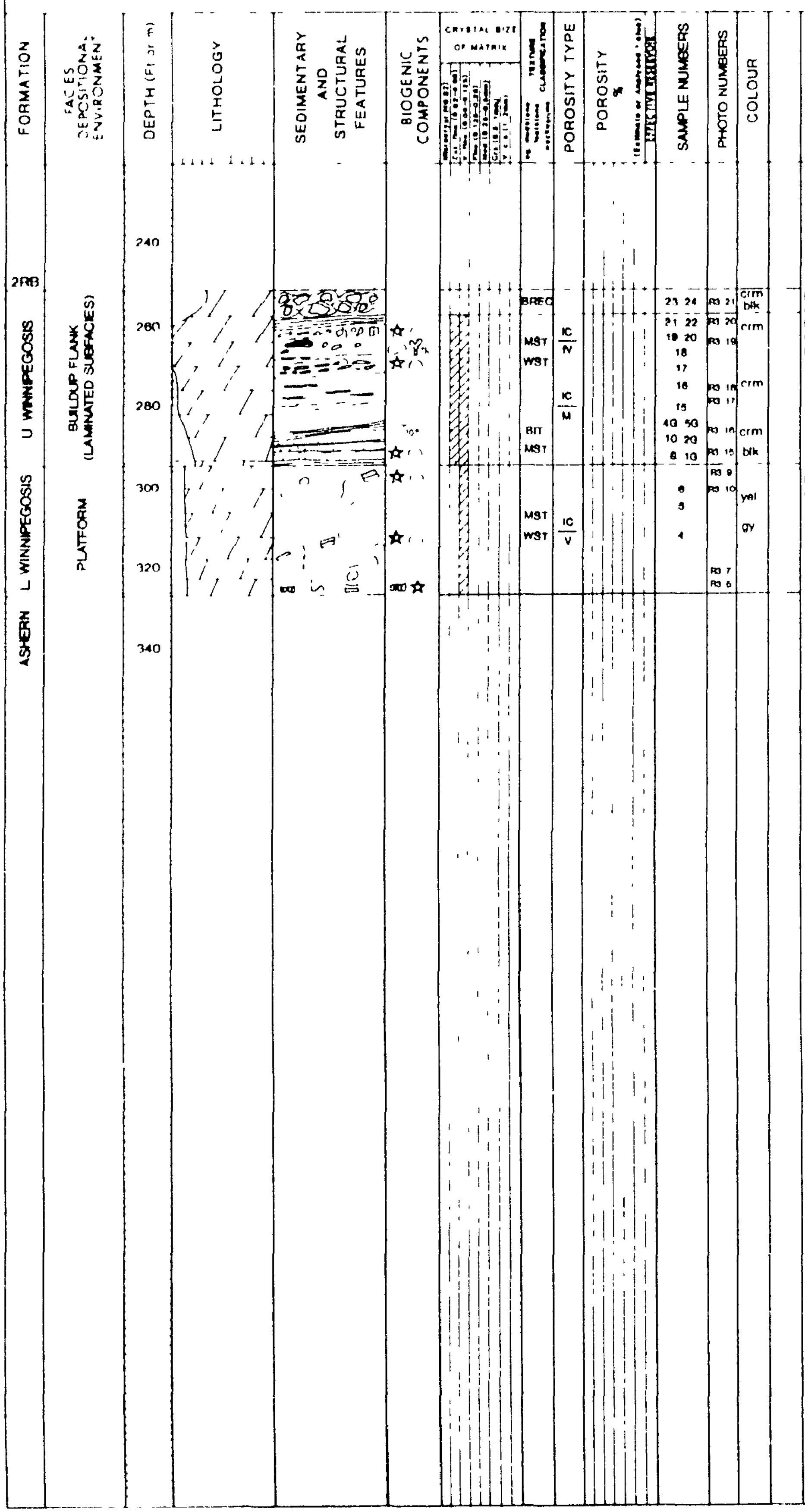
CORE INTERVAL 235-340 ft

K B ELEVATION 265 m

LOGGED BY MARK TEARE

DATE JUNE 10, 1986

PAGE 1 OF 1



COMMENTS

BREC dol mst clsts in gy blk sh mtx, chaot convol text, calc

DOL ? skel fab, lam, vug, crin brach wst mnr crl deb, occ bit prtg, bd, slope dip, prim texts oblit by dol mold vug ϕ, calc/gy calc cmt,

DOL fos mst wst intbd/blk bit lams, dip 10 microstyl sed slump struc

DOL mst wsts, yel sug mtls in gy brn fn grn mtx, com crin deb, vug ϕ/mold ϕ, com bit prtgs

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME 47-76-2

LOCATION RED DEER RIVER

FORMATION WINNIPEGOSIS

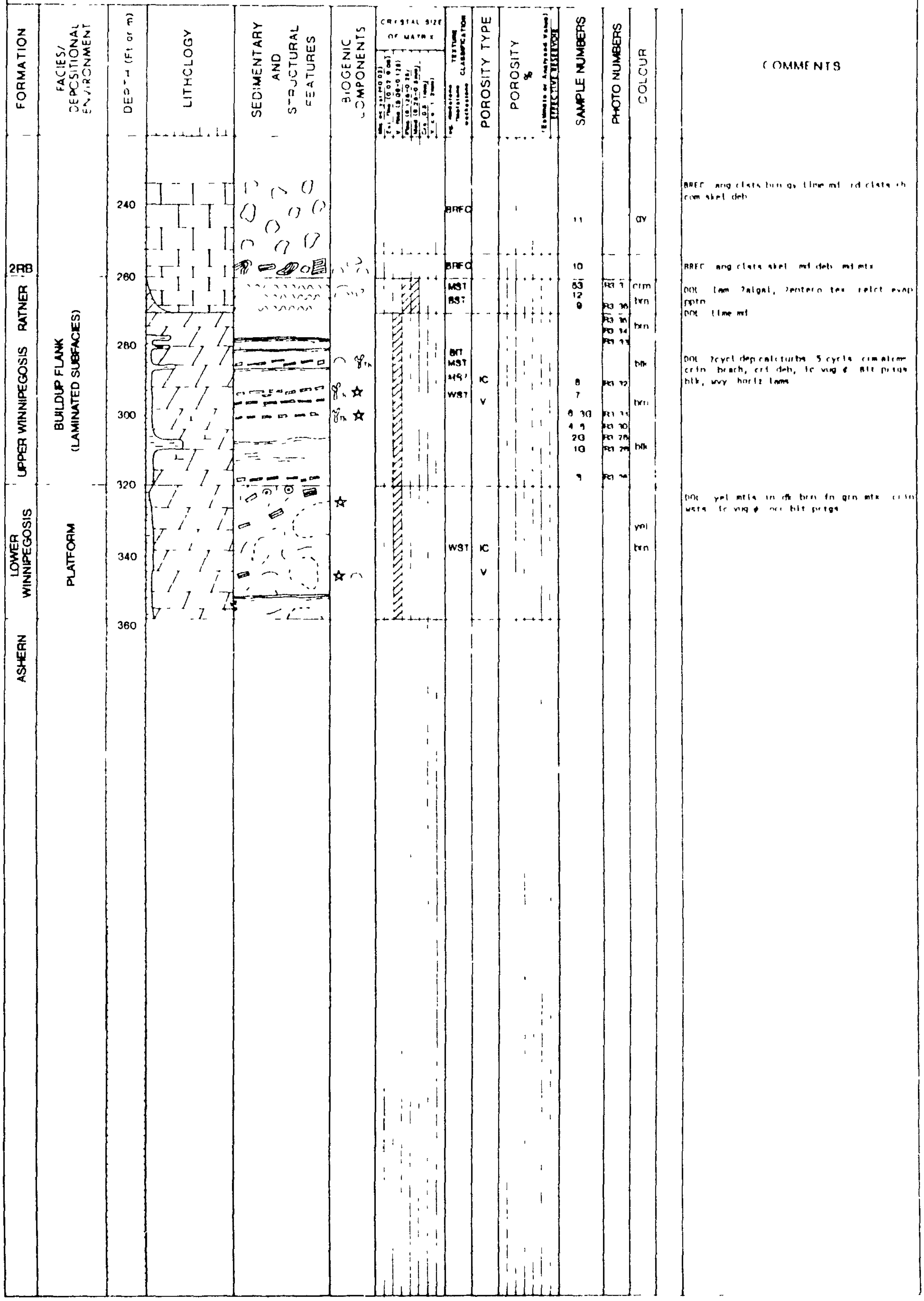
CORE INTERVAL 230-357 ft

K B ELEVATION 265 m

LOGGED BY MARK TEARE

DATE JUNE 13, 1986

PAGE 1 OF 1



BREC ang clsts brn gy llme mf rd clsts ch com skel deb

BREC ang clsts skel mf deb mf mtx

DOL lam ?algal, ?entero tex relct evap pptn

DOL llme mf

DOL ?cycl dep calcturbs 5 cycls crm alcme crin brach, crl deb, lc vug ϕ Blt prtgs blk, wvy horiz lams

DOL yel mtls in dk brn fn grn mtx crin wsts lc vug ϕ occ blt prtgs

1 '15 08/81

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME M-17-81

LOCATION STEEPROCK BRIDGE DOME

FORMATION WINNIPEGOSIS

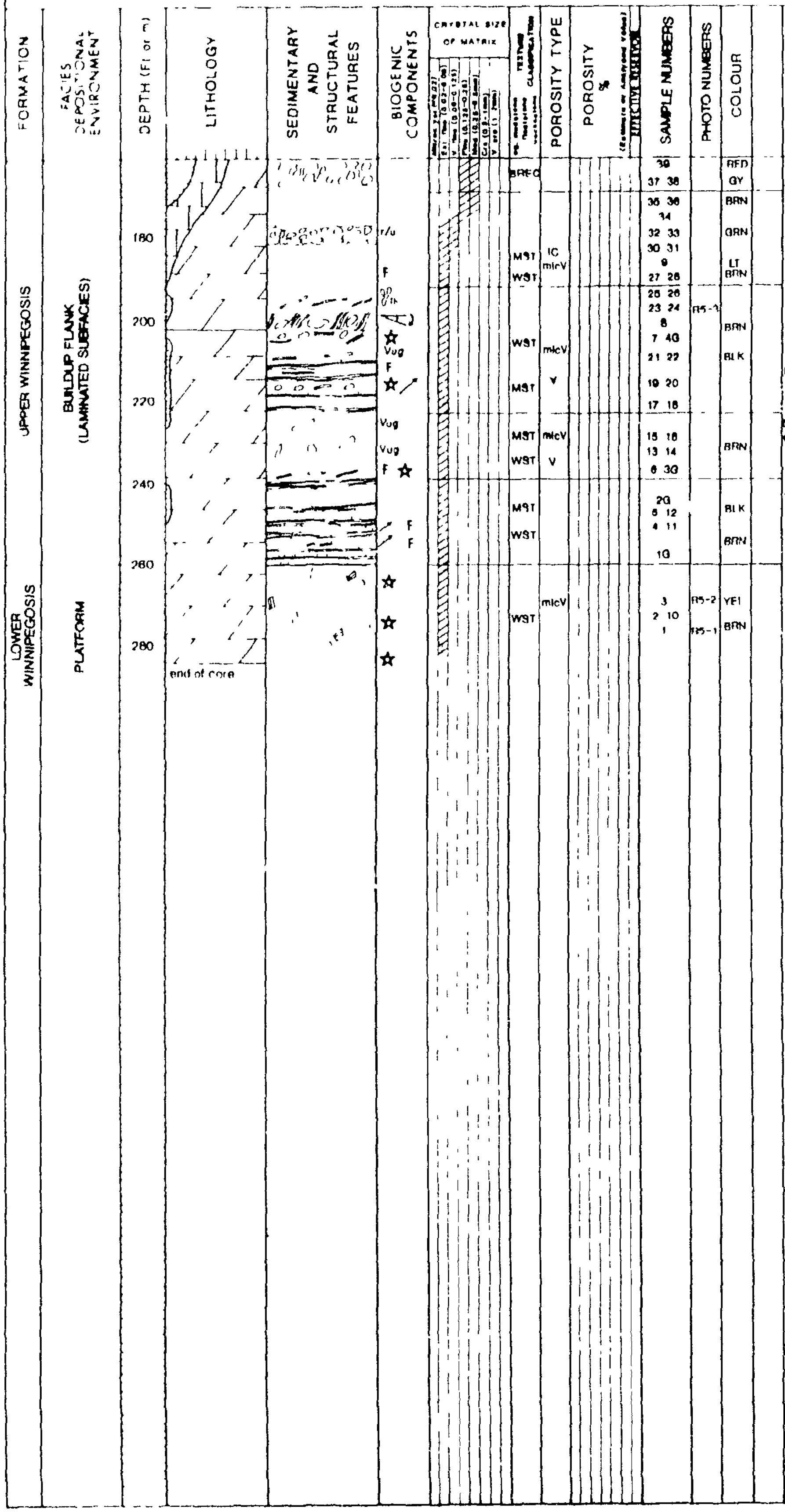
CORE INTERVAL 170-280'

K B ELEVATION 254 m

LOGGED BY MARK TEARE

DATE JUNE 24, 1988

PAGE 1 OF 1



COMMENTS

BREC ang clsts, gy, homog in rd calc arg mtx

DOL/DEDOL gy lt brn mst occ styl

BREC rip up clsts in grn sh mtx, styl

DOL mnr fos deb, cln, chlky mtx

DOL p pres crl deb, slope dip, sed def, bit lams, vug ϕ

DOL bit lams intbd/brn mst wst, crud grdg, fng up seqs

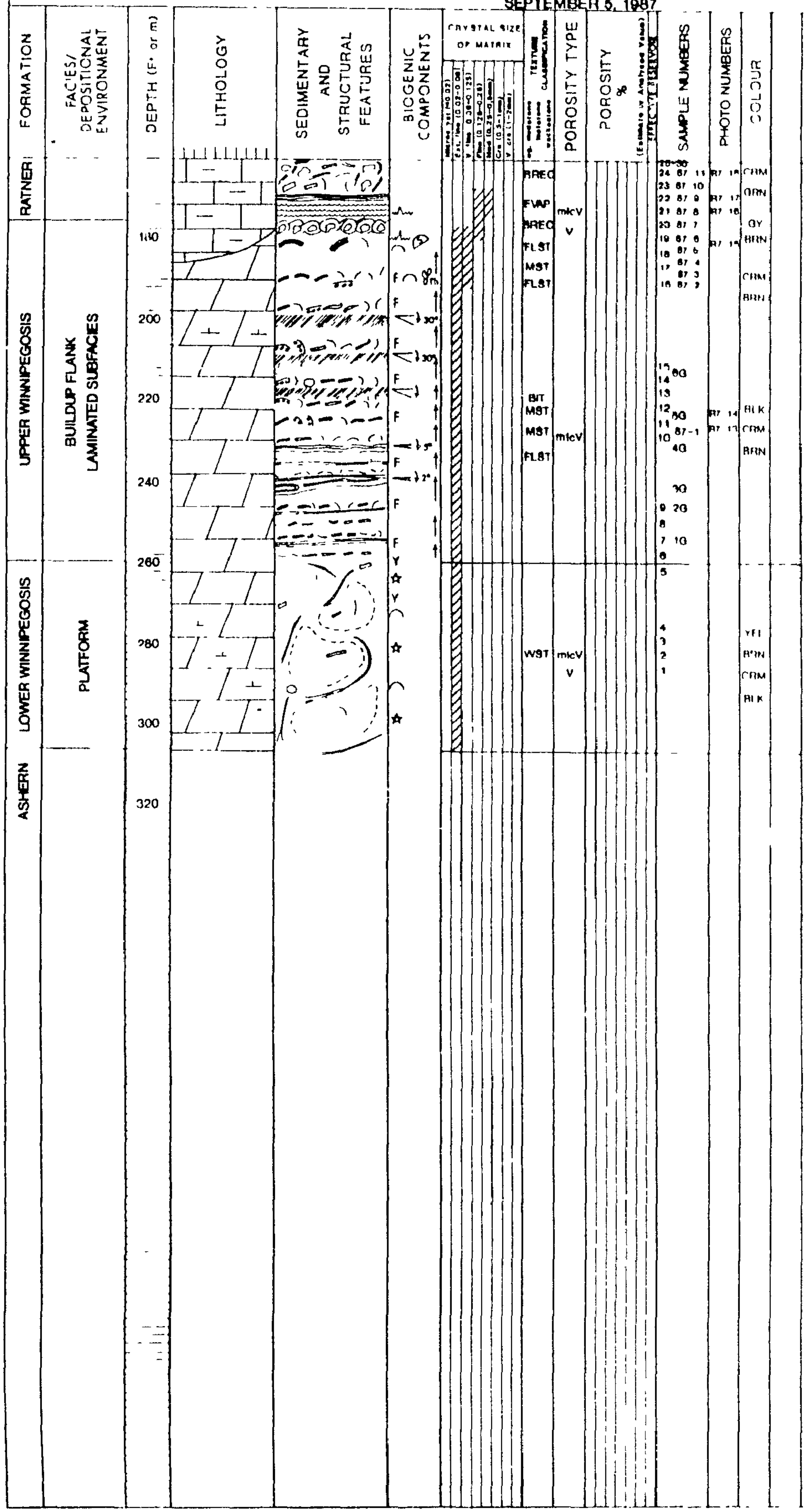
DOL homog mst, occ bit prtg, mtld, lrg vug ϕ

DOL brn mst wst, fng up seqs cap by bds bit lams

DOL yel mtls in lt brn crln rich mtx, com bit prtgs

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME M-8-86
LOCATION STEEPROCK BRIDGE
FORMATION WINNIPEGOSIS
CORE INTERVAL 160-312 ft
K B ELEVATION 254 6 m
LOGGED BY MARK TEARE
DATE JULY 2, 1986
SEPTEMBER 5, 1987
PAGE 1 OF 1



COMMENTS

BREC crm dol clsts in grn sh mtx

SH grn horiz lams, calc
DEDOL pos relict entero txt/dedol mat, calc cmt
BREC crm clst brec in grn sh mtx
DEDOL strom flat/mf mtx styl
DOL cycl deposn calciturbs foss deb defn bases of fin up seqs

DOL blk bit prtgs intbd/brn dol mat, skel deb dip bds 30 fract/calc cmt, overall fin up seq/fos deb at base grdg into mats

DOL increasing dip of lam mats bed thickness increasing skel deb ints 0 5 m/mat ints 0 6 m/bit lam mat 0 3 0 6 m
DOL fin up seqs capped by horiz at dip (2 5) bds bit lams crud grd

DOL cycl calciturbs skel deb bds 0 1 0 3 m thick mat bds 0 1 0 3 m thick, bit lams 0 02 0 06 m

DOL yel mtls in brn mtx suc, crin brach bry wsts bioturb seds, bit wisps incorp in mtx vug cavities loc developed/calc cmt

1235 08/81

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME M-7-86

LOCATION STEEPROCK BRIDGE

FORMATION WINNIPEGOSIS

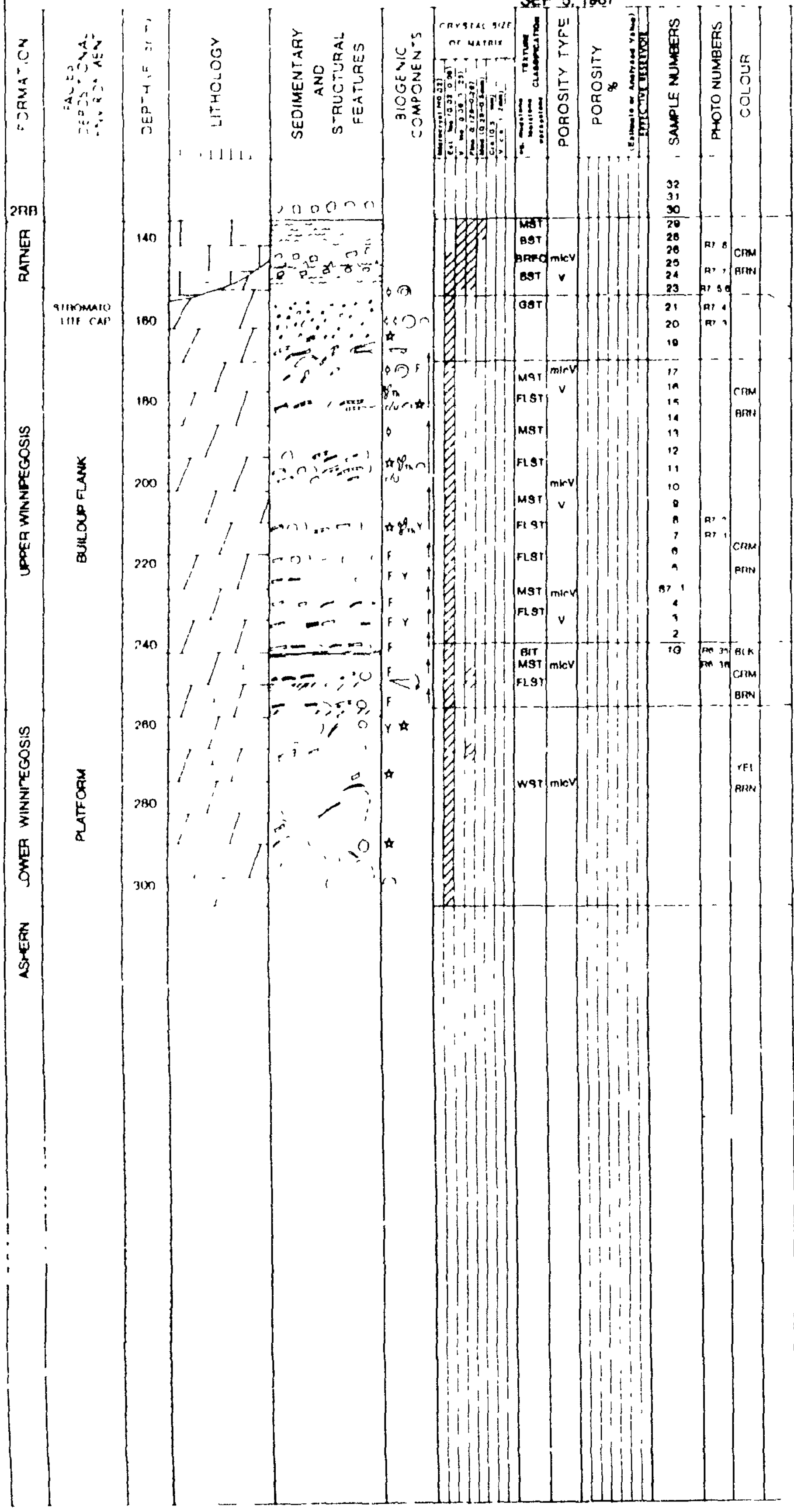
CORE INTERVAL 135-305 ft

K B ELEVATION 254 5 m

LOGGED BY MARK TEARE

DATE JULY 2 1986
SEP 5, 1987

PAGE 1 OF 1



COMMENTS

BREC varicol clsts in grn/rd sh mtx

DEDOL undisturb mdst, occ grn sh prtg, ?algal fab, prob relict entero txt
BREC varicol clsts in grn sh mtx, chaot, styl
DEDOL ?algal fab, pel onc gst mtx, grn sh

DOL pel onc gst skel deb crin crl deb fib cmts

DOL series of crud grd fin up seqs, cmn skel deb at bases of each calcitürb cycle fin up into msts, occ scat skel deb in msts rip up clsts md lcl/deb crm col clsts in brn nod mtx bioturb, bry crin, crl, brach

DOL calciturb cycles capped by dip bit lams mnr calc cmt distrib thro micv ϕ

DOL yel chlky mrtx in brn mtx, foss rich i edom crins, b y brachs bit m prtgs feather thro mtx bioturb mnr calc cmt

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME S-5-75

LOCATION STEEPROCK BRIDGE DOME

FORMATION WINNIPEGOSIS

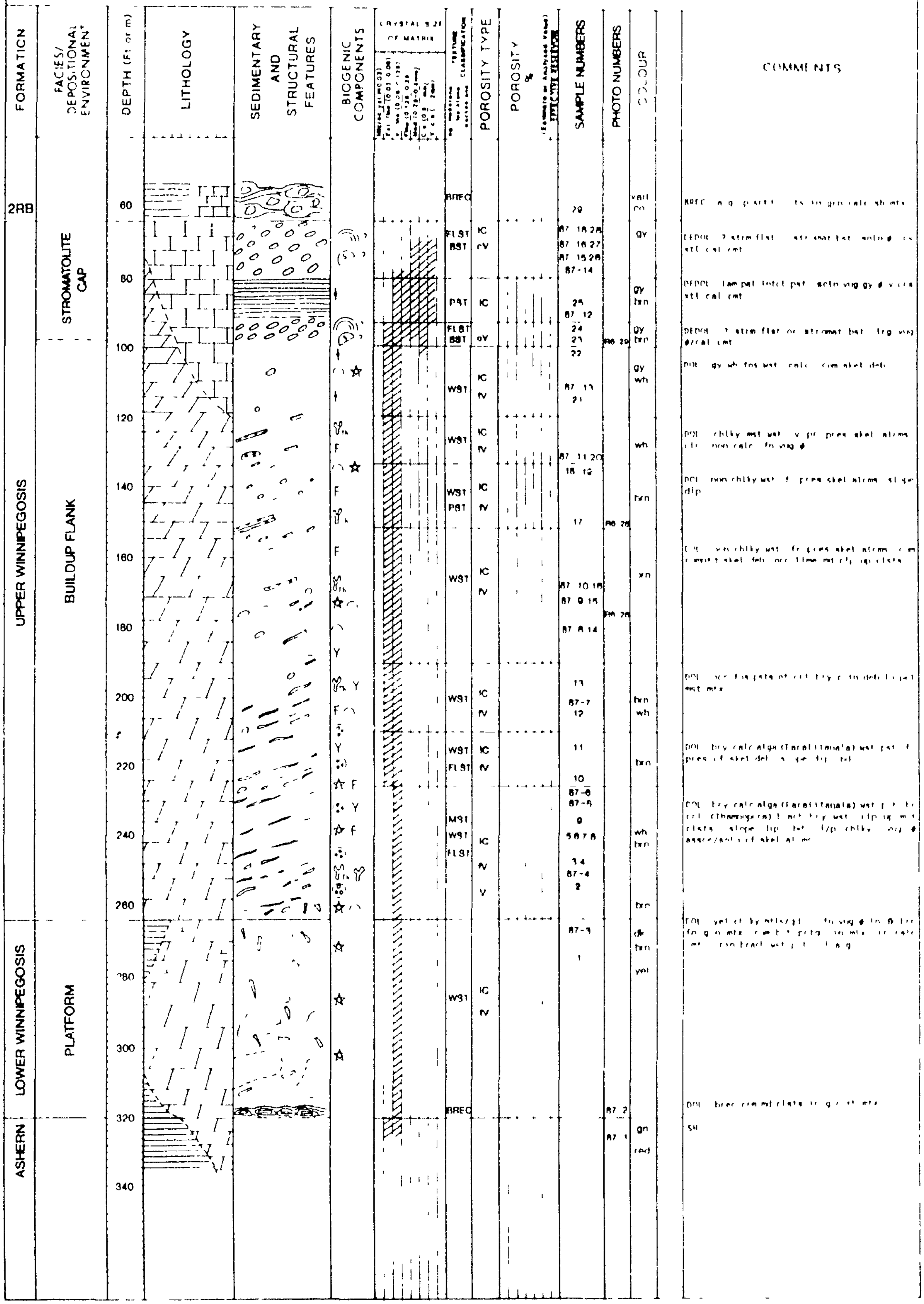
CORE INTERVAL 54-325 ft

K B ELEVATION 255m

LOGGED BY MARK TEARE

DATE JULY 3, 1986

PAGE 1 OF 1



GRAPHIC LOGGING FORM - CARBONATES

WELL NAME M-5-87

LOCATION SALT POINT WEST

FORMATION WINNIPEGOSIS

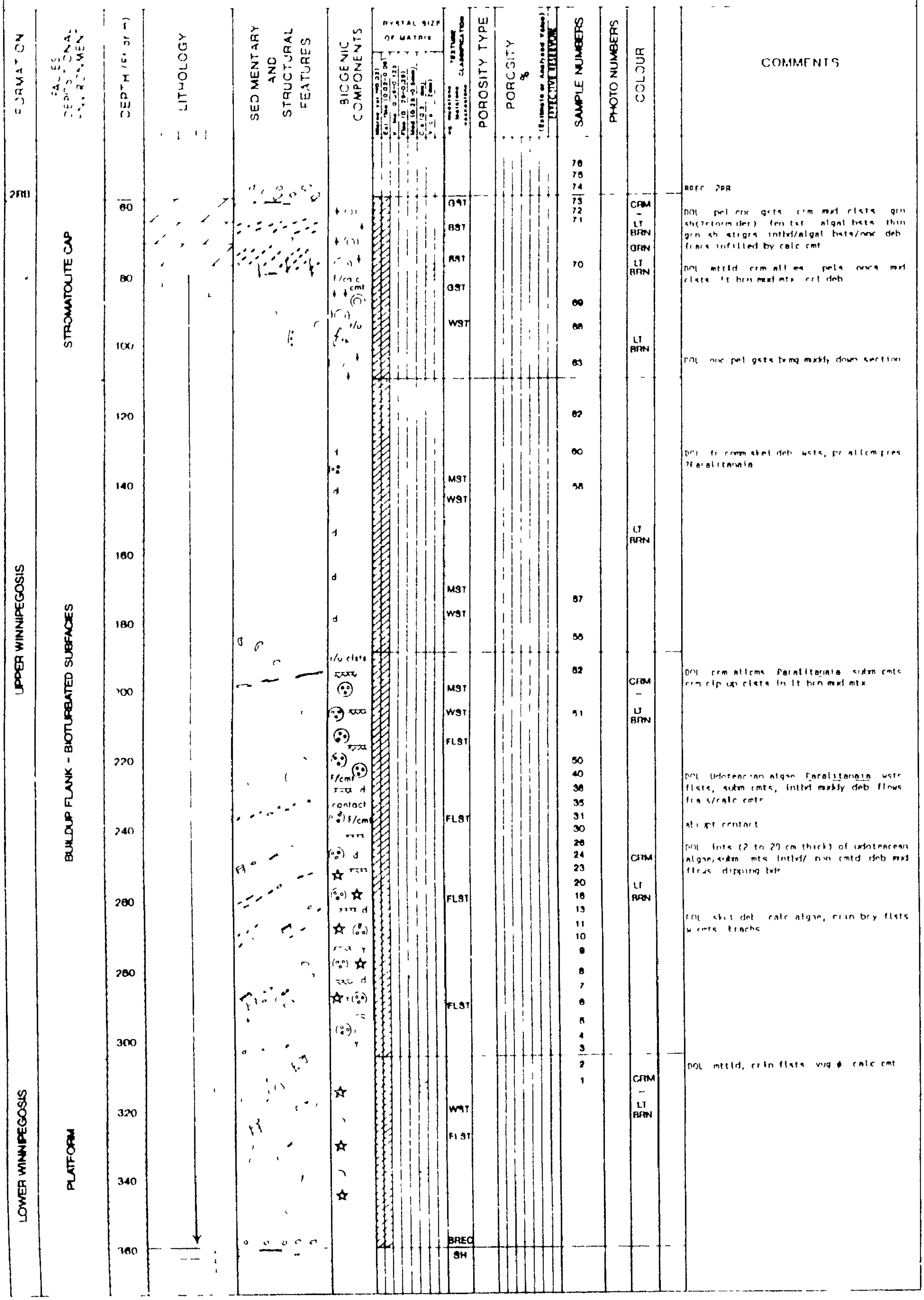
CORE INTERVAL 60-360 ft

K B ELEVATION 274 m

LOGGED BY MARK TEARE

DATE SEPTEMBER 6, 1987

PAGE 1 OF 1



RDEC 2RR

DOL pel onc gsts crm mud clsts grn sh(?storm dep) fen txt algal bsts thin grn sh strgrs intbd/algal bsts/onc deb fracs infilled by calc cmt

DOL mttld crm all ms pels oncs mud clsts lt brn mud mtx crl deb

DOL onc pel gsts bcmg muddy down section

DOL fr comm skel deb wsts, pr allcm pres ?Paralitanaia

DOL crm allcms Paralitanaia subm cmts crm rip up clsts in lt brn mud mtx

DOL Udoteacean algae Paralitanaia wsts flsts, subm cmts, intbd muddy deb flows frs s/calc cmts

abrupt contact

DOL ints (2 to 20 cm thick) of udoteacean algae, subm mts intbd/ non cmtd deb mud flows dipping bds

DOL skel det calc algae, crin bry flsts w cmts trachs

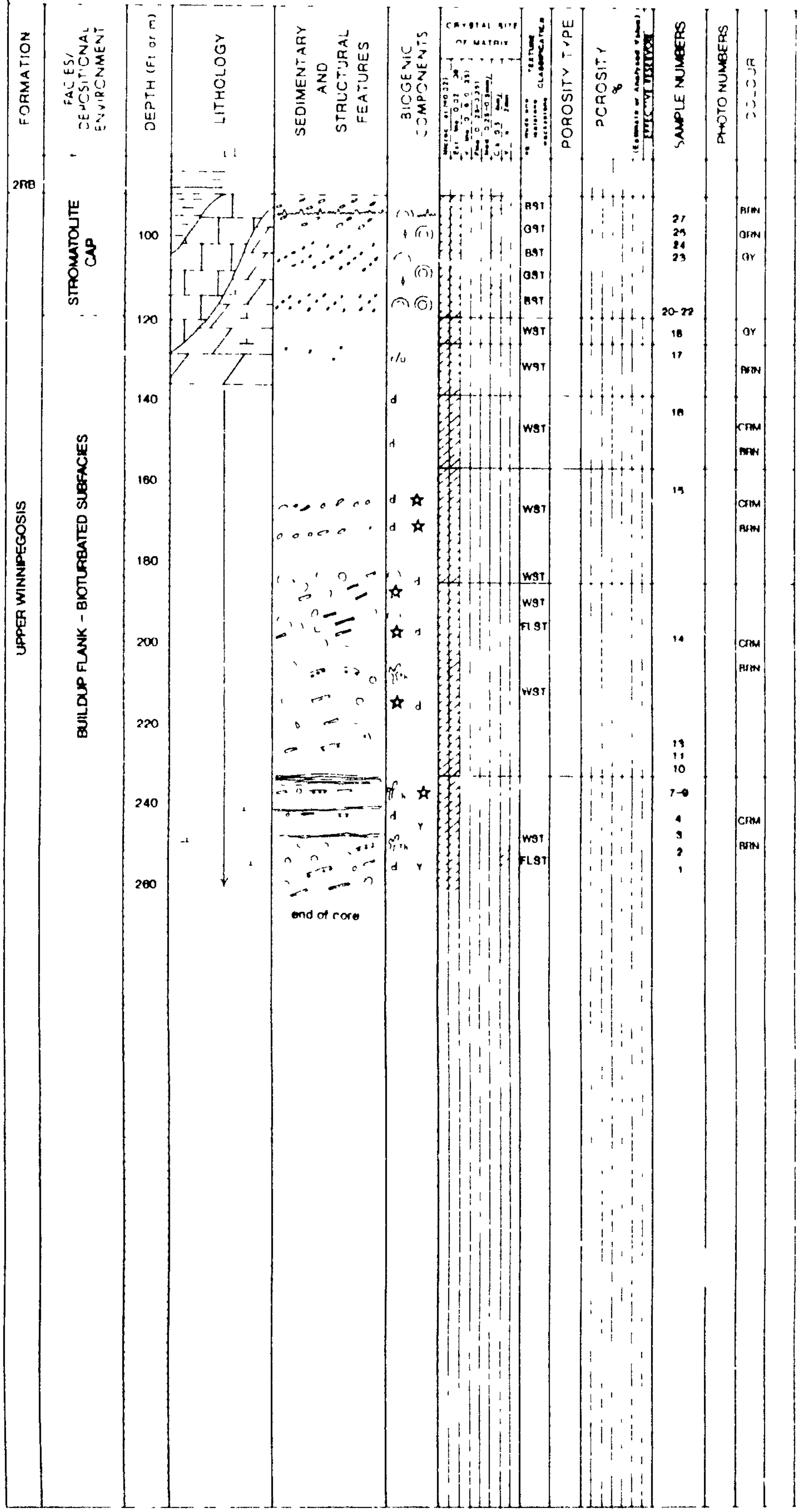
DOL mttld, crin flsts vug ϕ calc cmt

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME INCO 635-48 LOCATION SALT POINT

FORMATION WINNIPEGOSIS CORE INTERVAL 85-260 ft K B ELEVATION 270 m

LOGGED BY MARK TEARE DATE JULY 5, 1986 PAGE 1 OF 1



COMMENTS

SH grn lam to brec

F DOL fen grn sh prtgs [illegible] pel pk [illegible] grn gt mtx all fen ø filled by cal cmt

DOL fen algal bnt [illegible] pel [illegible] grn gsts grn sh prtg ø filled by calc cmt

abrupt contact
DOL gy dn mass no ø

DOL crm, lime mud intclsts pr pres crm allcms in lt brn mtx, fn vug ø anhy mtls crud lam
DOL homog lt brn mtx pr pres allcms ?debris flow txt no blt prtgs occ cav fn vug ø

DOL mtx bmg chlky wh v pr pres allcms crin brach loc concns of foss bt
DOL sparsely foss distrib throughout mtx occ crud lam blt prtgs

DOL brach crl det lt brn mtx chaot distrib of foss deb

DOL v foss flsts v comm crl det crin brach, bry bedding evident mttld mtx apparent cyclic or episodic depo of deb flows mnr calc cmt

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME M-4-87

LOCATION SALT POINT EAST

FORMATION WINNIPEGOSIS

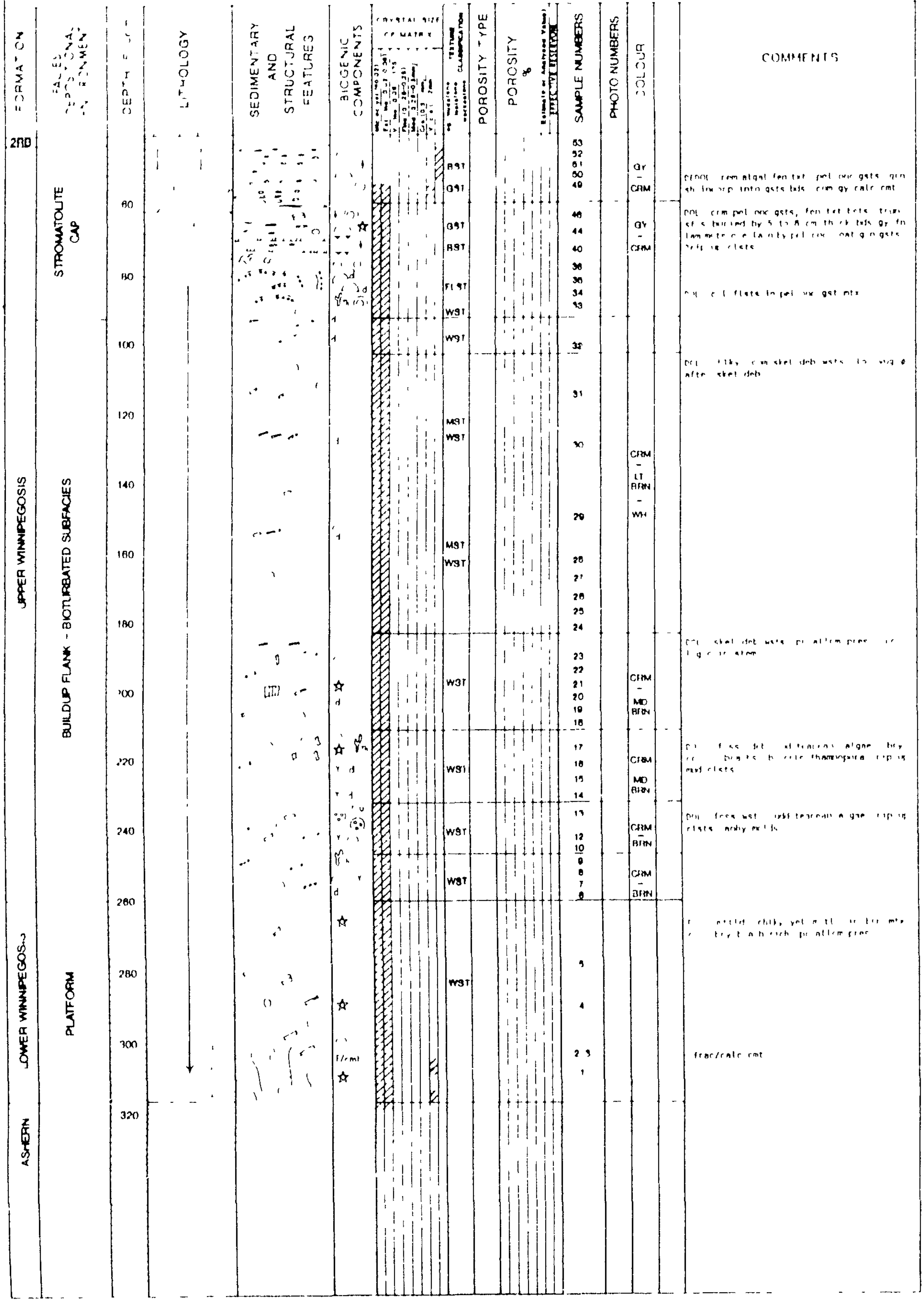
CORE INTERVAL 44-324 ft

K B ELEVATION 266 7 m

LOGGED BY MARK TEARE

DATE SEPTEMBER 5, 1987

PAGE 1 OF 1



GRAPHIC LOGGING FORM - CARBONATES

WELL NAME INCO 635-47

LOCATION SALT POINT

FORMATION WINNIPEGOSIS

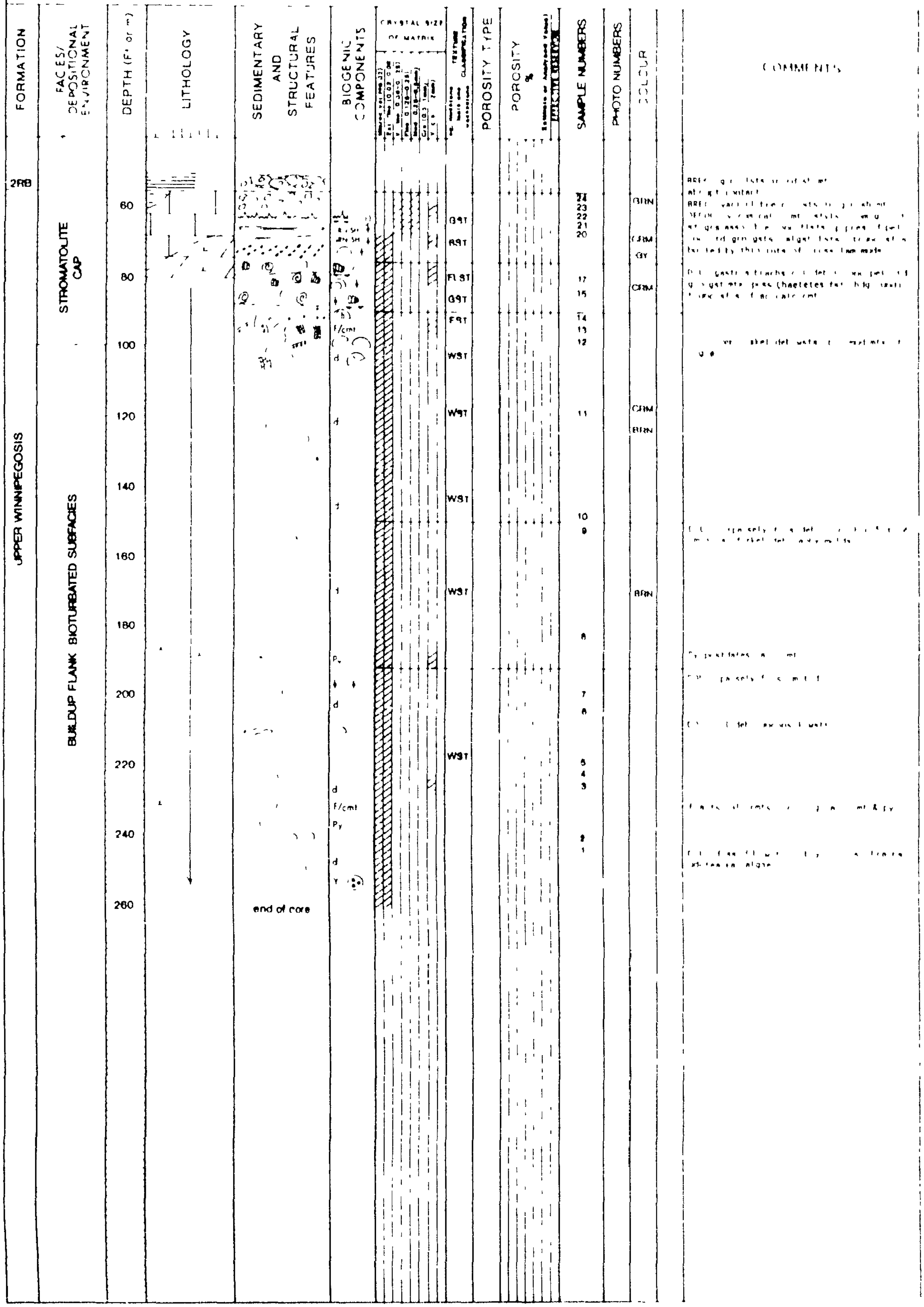
CORE INTERVAL 55-260 ft

K.B. ELEVATION 270 m

LOGGED BY MARK TEARE

DATE SEPTEMBER 4, 1987

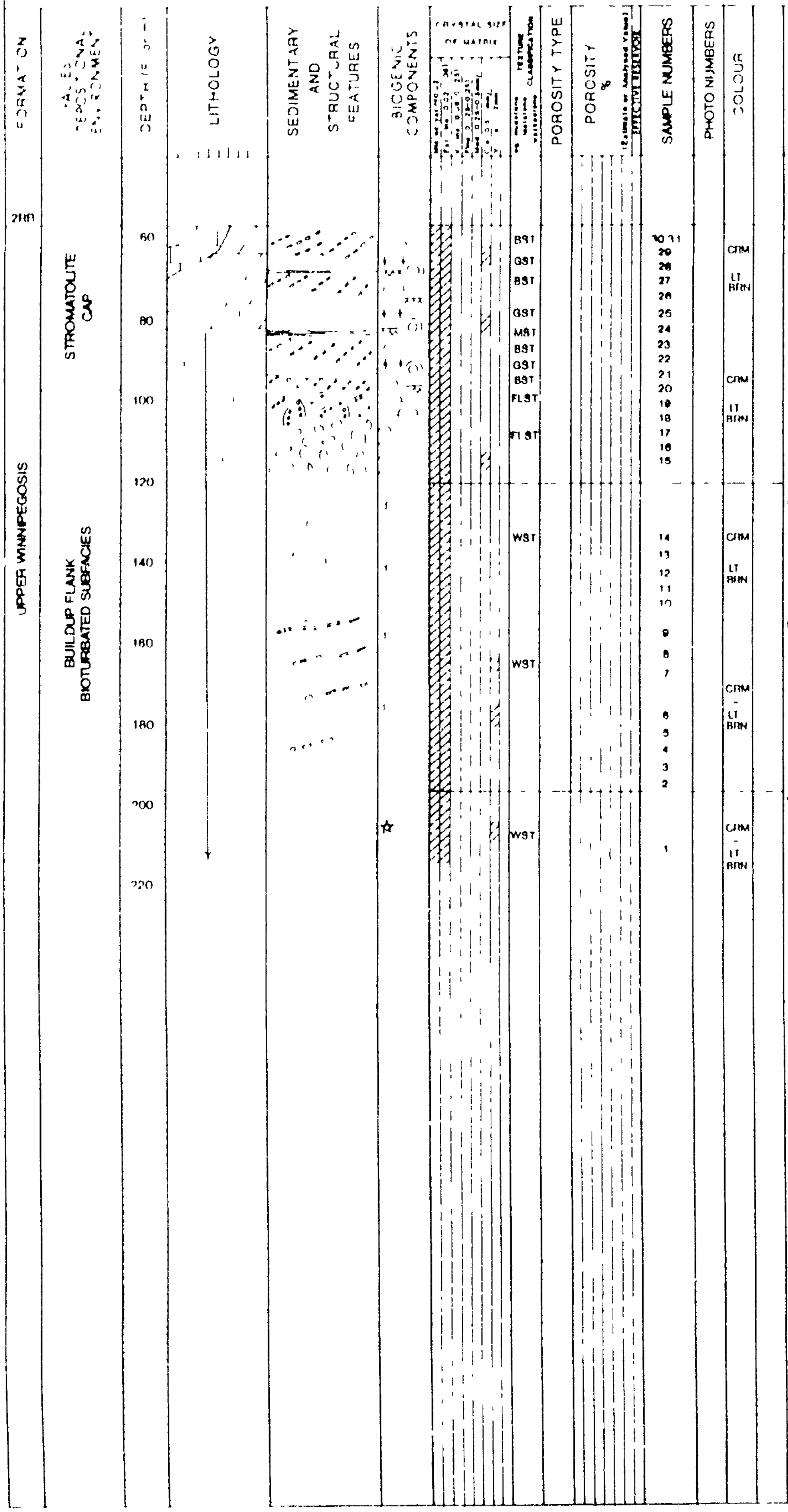
PAGE 1 OF 1



1235 08/81

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME **INCO 635-46**
LOCATION **SALT POINT**
FORMATION **WINNIPEGOSIS**
CORE INTERVAL **60-215 ft**
K B ELEVATION **270 m**
LOGGED BY **MARK TEARE**
DATE **JULY 5, 1987**
PAGE **1** OF **1**



COMMENTS

[illegible] lt brn mtx crm allcms pel onc grapst gsts, fen txt algal bsts, v comm g, calc cmt grn sh dis throughout subm cmts trunc sfcs buried by cross lam muds fn vug ∅

[illegible] crm allcms pel onc grapst gsts algal bsts crl deb flsts thin shelled brach psts

[illegible] widely scatt commin skel deb wsts in brn mud mtx p pres allcms fn vug mldic ∅ clean

[illegible] crl deb crin [illegible] poss deb flows lt brn mud mtx fn vug ∅

[illegible] chlky crumbly txt mttld lrg vugs lt brn mtx p pres allcm calc cmt

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME M-2-84

LOCATION BELL RIVER BAY

FORMATION WINNIPEGOSIS

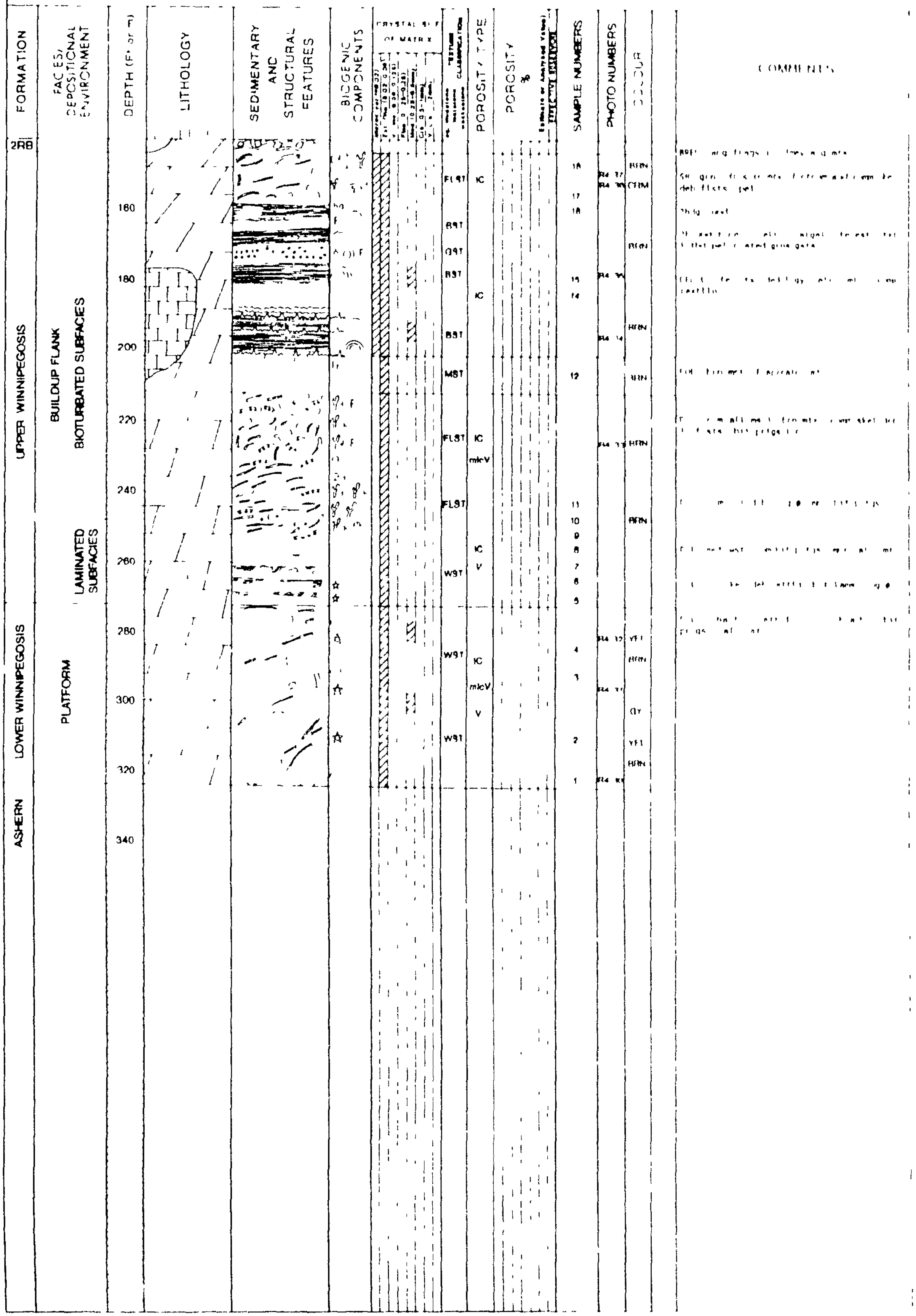
CORE INTERVAL 142-325 ft

K B ELEVATION 268.2 m

LOGGED BY MARK TEARE

DATE JUNE 22, 23, 1986

PAGE 1 OF 1



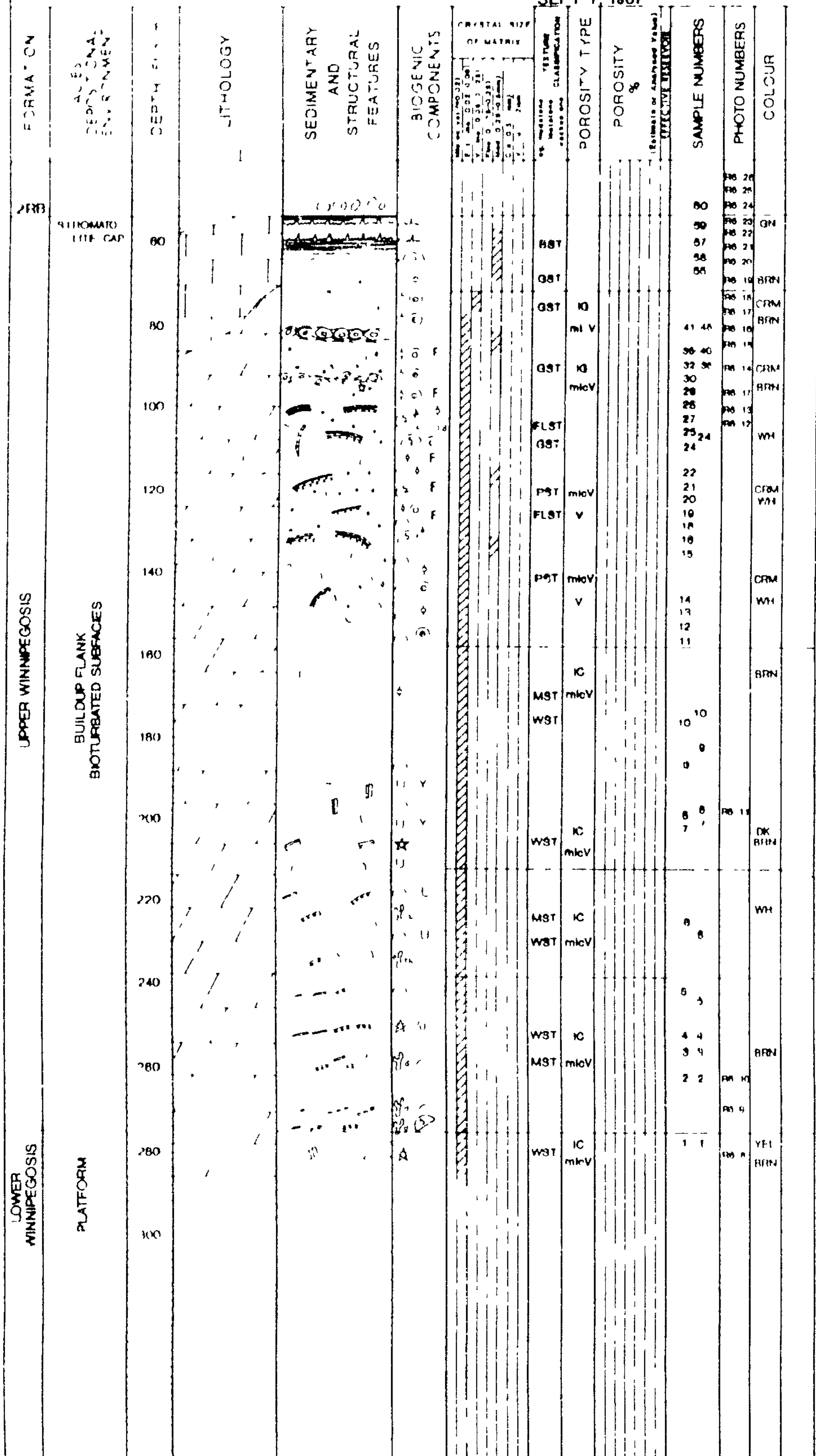
1235 08/81

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME M-3-84 LOCATION BELL RIVER BAY

FORMATION WINNIPEGOSIS CORE INTERVAL 58–284 ft K B ELEVATION 268 2 m

LOGGED BY MARK TEARE DATE JUNE 30, 1986 SEPT 7, 1987 PAGE 1 OF 1



COMMENTS

BREC varic l clsts in rd sh mtx
SH gry sh, calc, lam, lines interiors of cavities and intskel ϕ, ?storm derived
DEDOL ?fen txt/algal origin probable relict entero txt styl

DOL pel comp grn algal cyst, onc gsts, intgran micv ϕ, calc cmt
SH grn convol lam around crm clsts, ?storm derived
DOL gsts scatt skel deb, grn sh incorp in intskel ϕ, lrge encrus oncs, subm pisolites, loc bd gsts/lam msts

DOL lrg chunks mass crls, strms brach crin rich, pels, onc comp grns, chlky txt mttld vug calc cmt in vugs
DOL strm crl brach psts, red pres of allcms bcmg chlky

DOL r fos pel mtx homog txt

anhy needle mclds

DOL cln, dk brn, bry, calc alga (Parallitanaia), brach crin in brn md mtx gd pres of allcms

DOL v chlky int v pr pres of allcms Thamnopora, crin brach Parallitanaia

DOL crm skel allcms in brn mtx skel deb accums intbd/msts crud grd, ?cycl bdg of calciturbs, no bit matter
DOL deb flow deposn calciturbs, crud grd, skel deb at flow base fin up to msts

DOL yel sug mtls in brn mtx crin brach rich arg, bit wisps bcmg chlky wh pr pres allcms

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME M-3-85

LOCATION OVERFLOW BAY

FORMATION WINNIPEGOSIS

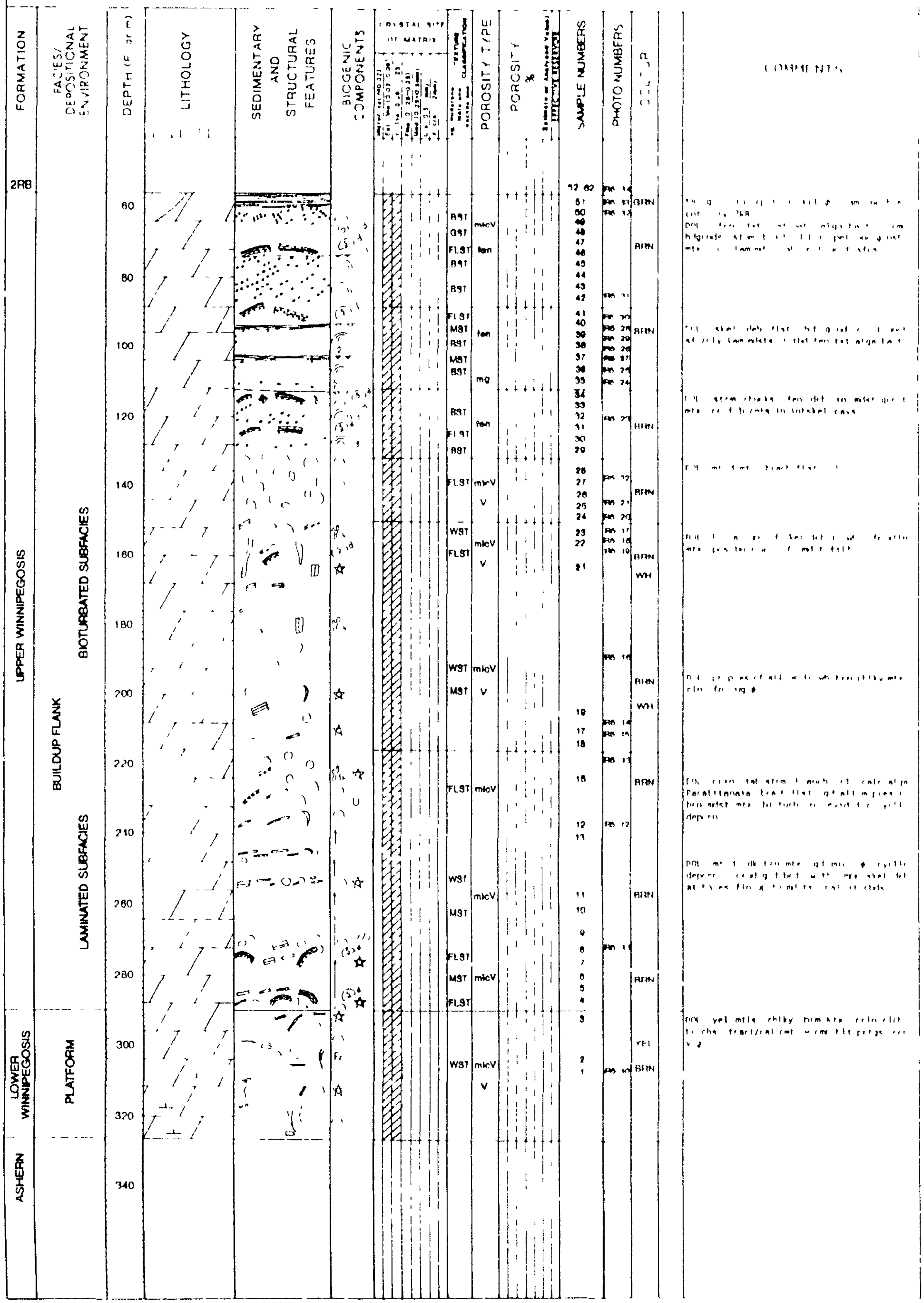
CORE INTERVAL 58-327 ft

K B ELEVATION 269 1 m

LOGGED BY MARK TEARE

DATE JUNE 28, 1986

PAGE 1 OF 1



1235 08/84

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME M-6-78

LOCATION OVERFLOW BAY

FORMATION WINNIPEGOSIS

CORE INTERVAL 51-239 ft

K B ELEVATION 259 m

LOGGED BY MARK 1EARE

DATE JUNE 19, 1986

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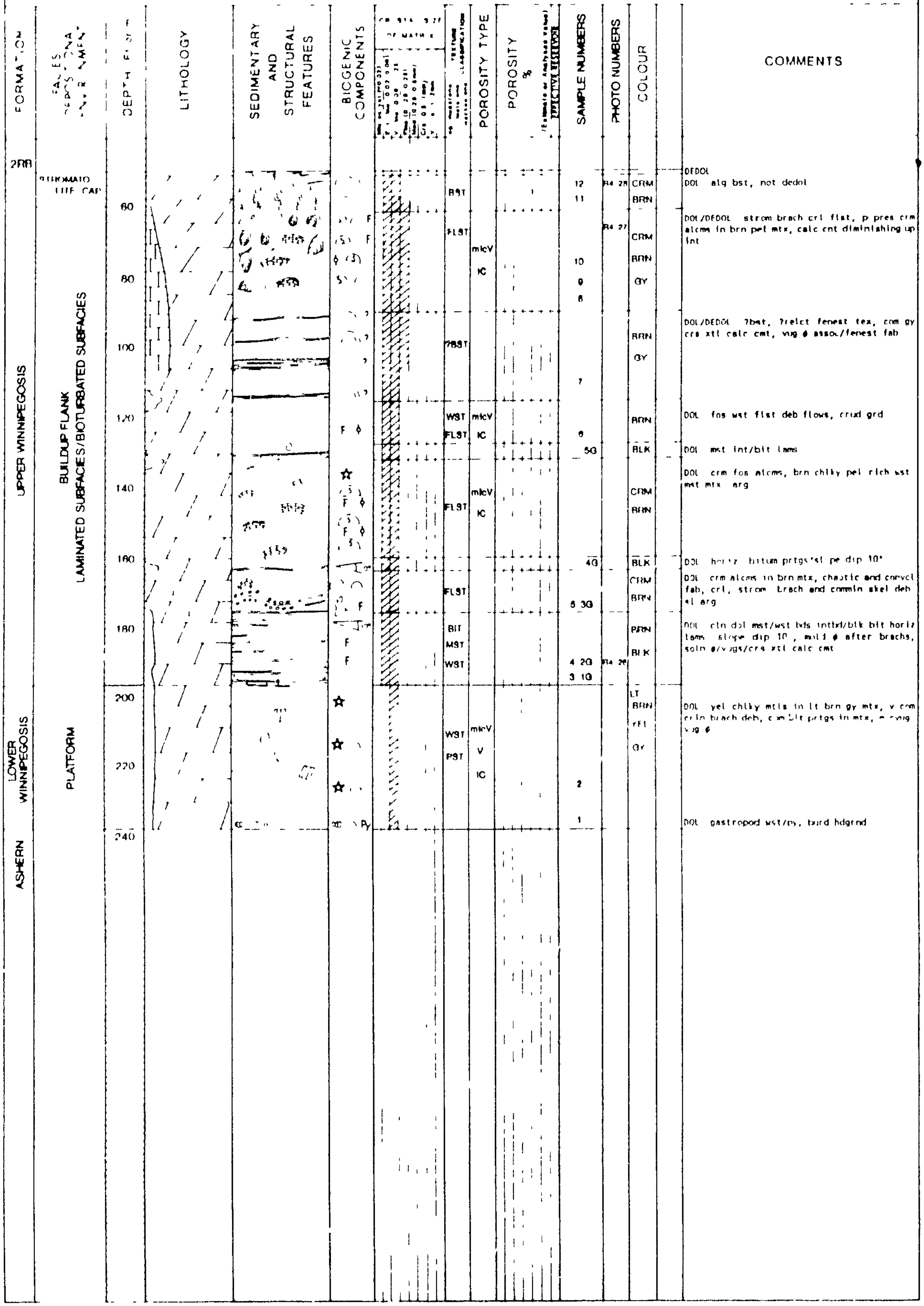


DFDOL

DOL alg bst, not dedol

DOL/DFDOL strom brach crl flst, p pres crm alcms in brn pel mtx, calc cnt diminishing up int

DOL/DEDOL ?bst, ?relct fenest tex, com gy crs xtl calc cmt, vug ϕ assoc/fenest fab

DOL fos wst flst deb flows, crud grd

DOL mst int/bit lams

DOL crm fos alcms, brn chlky pel rich wst mst mtx arg

DOL horiz bitum prtgs/sl pe dip 10°

DOL crm alcms in brn mtx, chaotic and convcl fab, crl, strom brach and commin skel deb sl arg

DOL cln dol mst/wst bds intbd/blk bit horiz lams slope dip 10 , mold ϕ after brachs, soln ϕ/vugs/crs xtl calc cmt

DOL yel chlky mtls in lt brn gy mtx, v com crin brach deb, com bit prtgs in mtx, ϕ vug vug ϕ

DOL gastropod wst/ps, burd hdgrnd

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME M-12-71

LOCATION DAWSON BAY

FORMATION WINNIPEGOSIS

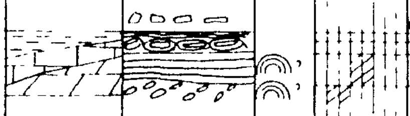
CORE INTERVAL 45-60 ft

K B ELEVATION 259m

LOGGED BY MARK TEARE

DATE JULY 7, 1986

PAGE 1 OF 1



FORMATION	FACIES/ DEPOSITIONAL ENVIRONMENT	DEPTH (Ft or m)	LITHOLOGY	SEDIMENTARY AND STRUCTURAL FEATURES	BIOGENIC COMPONENTS	CRYSTAL SIZE OF MATRIX	TEXTURE CLASSIFICATION	POROSITY TYPE	POROSITY % (Estimate or Analysed Value)	SAMPLE NUMBERS	PHOTO NUMBERS	COLOUR		COMMENTS
2RB UPPER WINNIPEGOSIS	? STROMATOLITE CAP	40 60					BREC BST BST	V				gy crm crm		BREC r f & grn clsts in grn sh mtx DEDOL lam BREC mic clsts in grn h mtx DOL lam ?algal b? fenst vug ϕ calc

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME M-3-73

LOCATION CAMERON BAY

FORMATION WINNIPEGOSIS

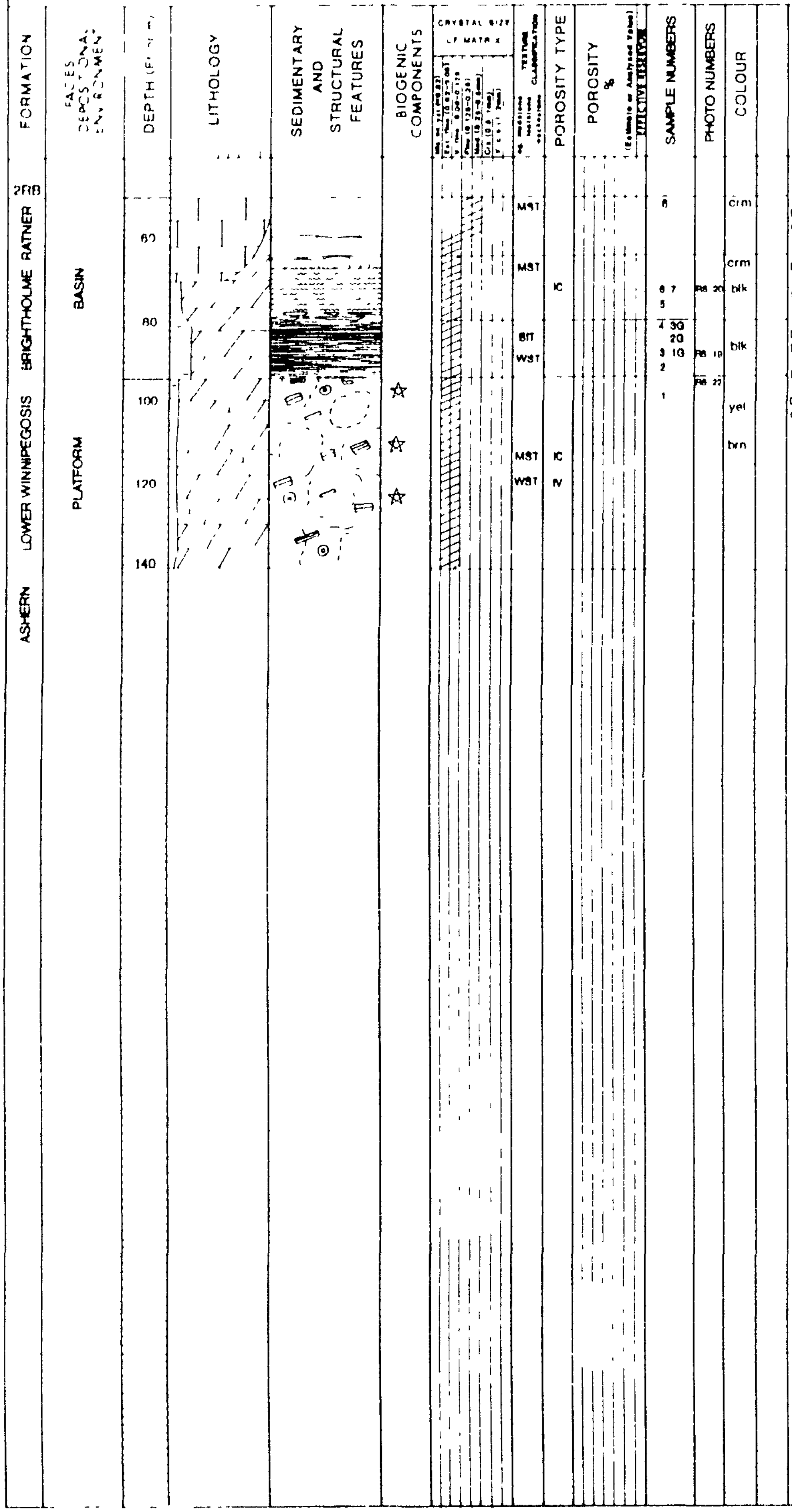
CORE INTERVAL 54-141 ft

K B ELEVATION 261 m

LOGGED BY MARK TEARE

DATE JULY 6, 1986

PAGE 1 OF 1



COMMENTS

DEDOL crud lam, prim texs oblit by dedol, crs xtl calc cmt, occ bit prtgs

DOL v fn lam bit prtgs, ?bit varvs interlam/cln dol mst prtgs, slump and flame strucs

DOL horiz bit lams/gy mst intbds, non bioturb

burrowed contact, ?hdground

DOL chlky yel mtls in gy brn fn grn mtx crin wsts, sl calc, bit prtgs in mtx

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME M-2-87

LOCATION GUNLAUGSON'S FARM

FORMATION WINNIPEGOSIS

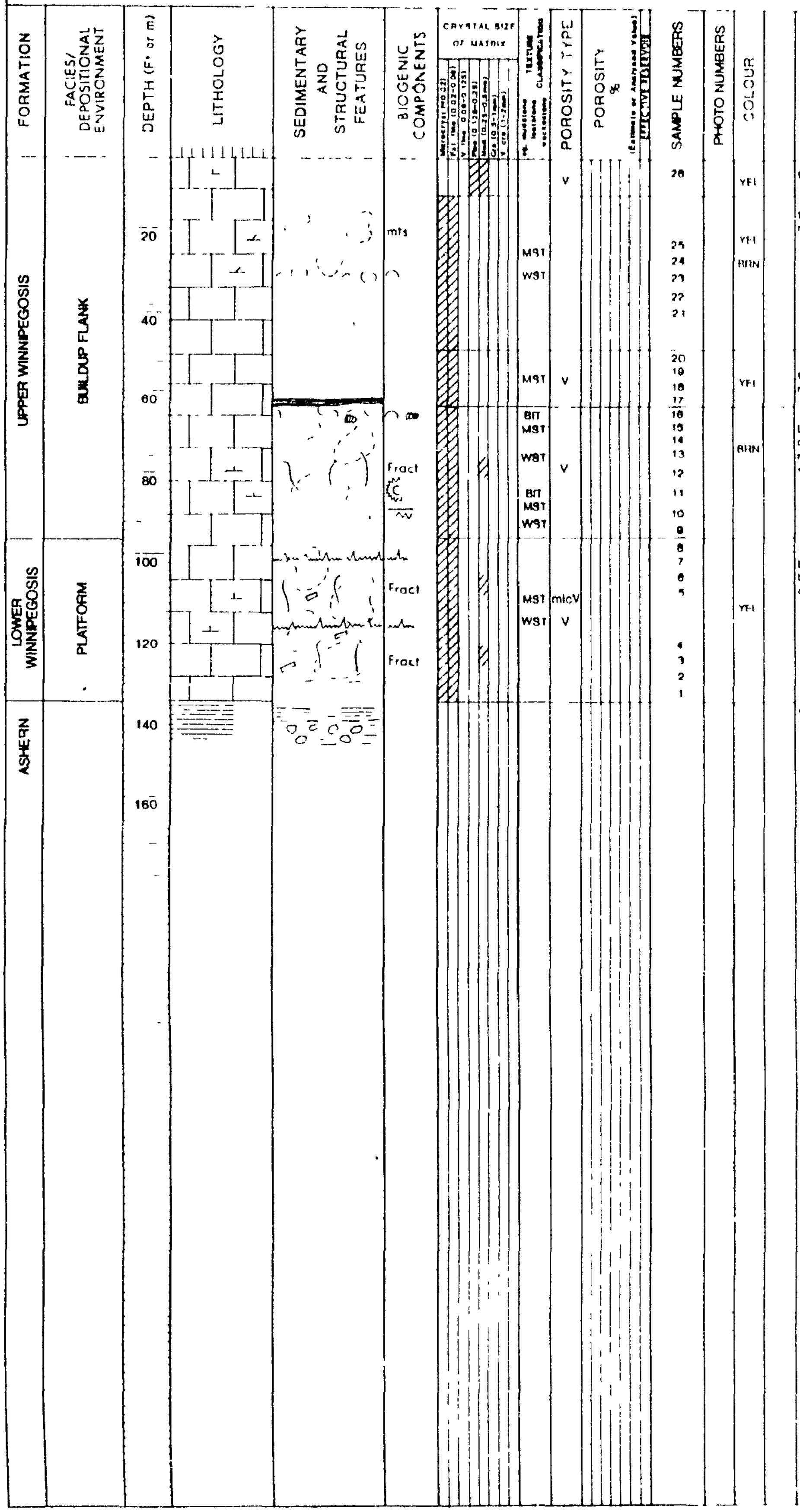
CORE INTERVAL 0-150 ft

K B ELEVATION 249 3 m

LOGGED BY MARK TEARE

DATE SEPTEMBER 3, 1987

PAGE 1 OF 1



COMMENTS

LS xtlln calc cmt soln ɸ after foss allcms

LS dk yel brn mlsts occ mttlg rr foss mic

LS no mttls, homog mlsts occ lam rr foss mnr vug ɸ

LS mttld mlsts/wsts, bioturb bit prtgs/foss deb, 5 10 cm ints of bit mm intbd/ lam mlsts, fract/alc cmt fib cmts in intskel shelter ɸ

LS yel suc mttls in v fn xtlln gy brn mtx brach crin rich bioturb styls fract/calc cmt

SH/BREC

1235 08/83

GRAPHIC LOGGING FORM - CARBONATES

WELL NAME M-5-76

LOCATION MEADOW PORTAGE

FORMATION WINNIPEGOSIS

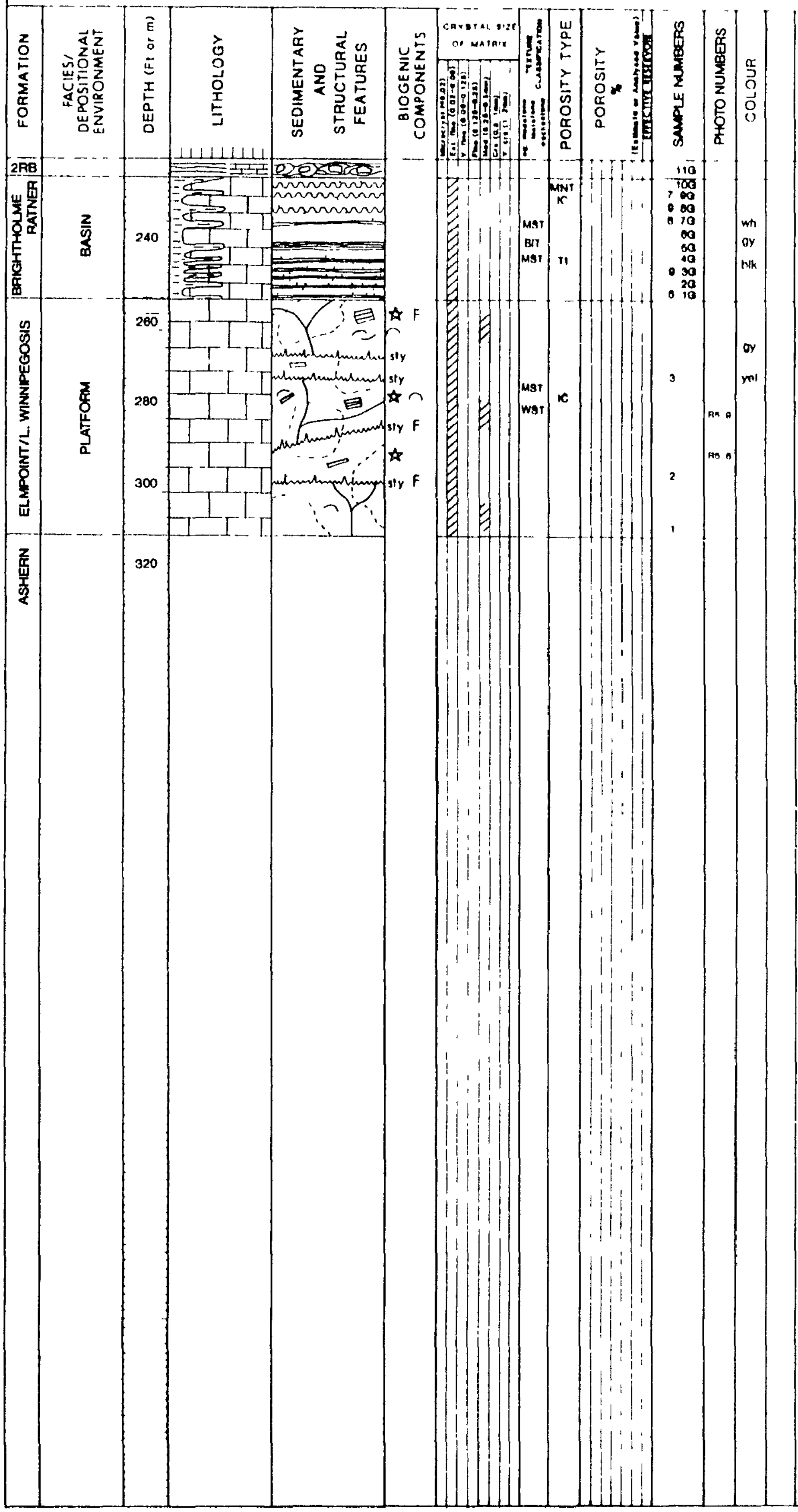
CORE INTERVAL 222-313 ft

K B ELEVATION 258 m

LOGGED BY MARK TEARE

DATE JUNE 25, 1986

PAGE 1 OF 1



COMMENTS

BREC mst clsts in grn sh mtx
LS entero tex relct evap ppln, blt lams
intlam/lime md

LS blk horiz blt lams/lime md ints, no relct
evap tex

LS yel mtls in gy mtx, crin brach wst, blk
blt prtgs assoc/styls fract/gy crs xtl calc
cmt, mnr IC ø