A STUDY OF THE DIAGENETIC HISTORY AND PROPOSED DEPOSITIONAL ENVIRONMENT OF THE MANITOULIN FORMATION IN SOUTHERN ONTARIO.

by

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Abstract

The transition from the Whirlpool Sandstone to the Manitoulin Dolomite represents a marine transgression. Within the Manitoulin Formation, the proportion of siliclastics to carbonates shows a marked upward decrease. The Manitoulin Formation consists of four main facies. The lower two facies indicate an inner shelf environment, while the upper two represent a middle to outer shelf environment.

These sediments have been almost totally dolomitized. Cathodoluminescent microscopy was employed to determine the diagenetic history of quartz, calcite, and dolomite cements. The petrographic characteristics of the dolomite using CL and normal light indicate a late stage (epigenetic) dolomitization.

Dolomitization is thought to have been a late diagenetic process brought about by Mg-rich fluids expelled during compaction of adjacent shales and supplemented by brines circulating through fracture systems.

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Chapter One

General Introduction

1.1 Overview

The Lower Silurian Manitoulin Formation consists predominantly of bioclastic dolomite and thin interbedded shales. These dolomites and overlying marine shales represent a marine transgressive sequence during the early Silurian period.

The underlying Whirlpool Formation ranges from 12-22 feet in thickness from Hamilton to the Nottawasaga River tributary and is dominantly orthoquartzite. The Whirlpool Formation has been interpreted as braided fluvial sands overlain by sands deposited in a shallow marine setting (Salas,1983).

The Manitoulin Dolomite is present in the subsurface under much of southwestern Ontario but thins to the S.E., and is overlain by the Whirlpool Sandstone.

The Cabot Head Formation conformably overlies the Manitoulin and represents the maximum southeastwards transgression of Lower Silurian seas in this region. It attains a maximum thickness of 140 ft. beneath West Central Lake Erie, and thins in a northwesterly direction towards the Michigan Basin.

The purpose of this study is to document the

Whirlpool-Manitoulin transition in the Hamilton and Lake Erie region. Facies descriptions and interpretations will be combined with petrography to determine the diagenetic history and propose a depositional environment for the Manitoulin Formation.

1.2 Previous Work

As early as 1821, Bigsby classified the rocks of Manitoulin Island as the "limestones of the Manitoulin Range"(Caley,1940). The term "Manitoulin Formation" was first proposed by Williams in 1913 from his studies on the calcareous rock on Manitoulin Island. Schuchert (1913) suggested the term "Cataract" as a stratigraphic term for the sediments between the Ordovician Queenston and the Lower Silurian Grimsby. He interpreted this sequence of sediments to represent a shallow marine environment. Bolton (1953) raised the "Cataract" to group status, including the Whirlpool, Manitoulin, Cabot Head, and Grimsby Formations. In 1954 Fisher concluded that the vertical succession of Whirlpool Sandstones, through Fish Creek shales into Manitoulin Dolomite recorded a minor transgression followed by a major regressive period represented by the Cabot Head and Grimsby Formations. Bolton (1957) did not recognize the Manitoulin Formation east of Stoney Creek, stating that it does not "persist" or retain its lithologic character. At this time the Fish Creek shale was renamed the Power Glen shales (Bolton, 1957). (see Fig 1.2). Martini (1971) conducted a detailed geologic study of the Medina Formation between Hamilton and Fulton, New York, in order to outline the local stratigraphy. This study concluded that the Medina Formation was formed in deltaic and shallow marine settings. This conclusion supported earlier works by Bolton (1957), Fisher (1954), and Martini (1966), which suggested that the Manitoulin and Cabot Head were sublittoral open marine muds and carbonates.

Sanford (1972), described early Silurian seas occupying the Michigan Basin, and the eastern shoreline transgressing towards the Taconics. This interpretation supports the vertical sequence of marine Manitoulin sediments overlying fluvial to marine Whirlpool sediments.

1.3 Regional Sedimentology

The Late Ordovician period was characterized by the deposition of the "Queenston Delta" which extended in a westward direction from the original position of the Appalachian Mountains. The close of the Ordovician marked the emergence of the region presently known as Ontario.

This area shows little evidence of any folding, faulting, or metamorphism due to the Taconic Orogeny, which affected most of eastern New York state.

Throughout Silurian time, Ontario formed a hingeline between two major sedimentary basins, the elongated Allegheny Basin to the south, and the Michigan Basin to the west. The Michigan Basin was dominated by the deposition of carbonates and evaporites while the Allegheny Basin consisted largely of clastics which thickened in a southeasterly direction.

1.4 Location

Field studies conducted in the summer of 1984 on the Manitoulin Formation were concentrated in two well exposed outcrop sections in the Hamilton region. These sections are referred to as 'Jolley Cut'and 'Flock Road'. Both occur along roadcuts through the Niagara Escarpment.

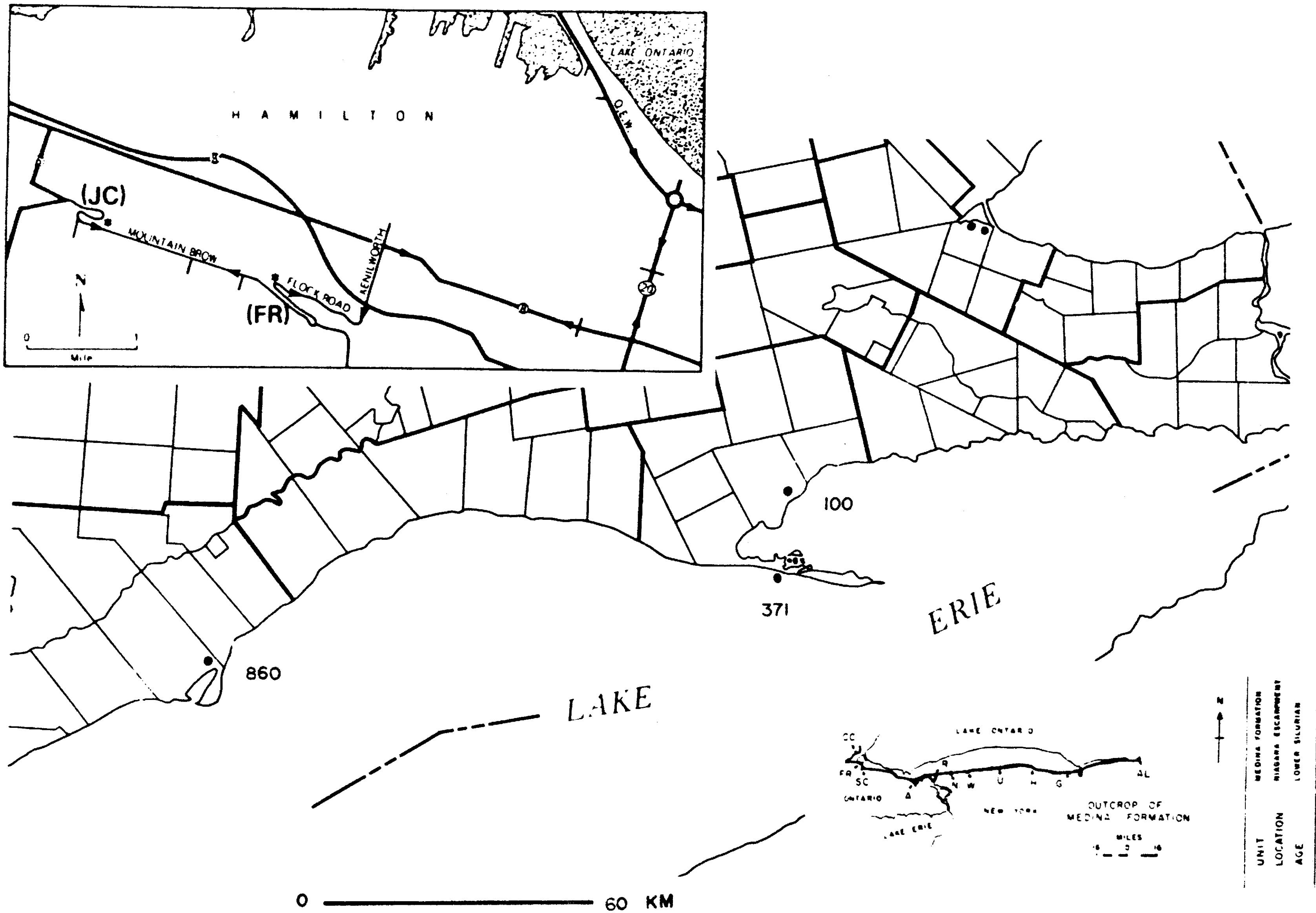
The transition from the Whirlpool Sandstone to the Manitoulin Dolomite is well exposed in both sections. However, the gradational upper contact of the Manitoulin with the Cabot Head is not well exposed due to shaley debris and vegetal cover.

Drill core made available by Consumer Gas Company and the Ontario Geological Survey was used in the drafting of vertical sections. Location of the core sections extends along the north shore of Lake Erie (see Fig 1.4).

Figure 1.2 Comparative table of stratigraphic names used for the formations in the "Cataract Group".

LOWER SILURIAN (ALEXANDRIAN SERIES)	CATARACT GROUP	Fisher (1954)	Bolton (1957)	Martini (1971)
		Cabot Head	Grimsby/Cabot Head	Cabot Head
			Power Glen	
		Manitoulin	Manitoulin	Manitoulin
		Fish Creek		
		Whirlpool	Whirlpool	Whirlpool

Figure 1.4 Location map of the study region, southern Ontario. Outcrop and drill core sites.


LAKE ONTARIO
HAMILTON
Q.E.W.
(JC)
MOUNTAIN BROW
FLOCK ROAD
KENILWORTH
(FR)
N
0 1
Mile
100
371
860
LAKE
ERIE
0 60 KM
OUTCROP OF
MEDINA FORMATION
MILES
NEW YORK
ONTARIO
LAKE ERIE
UNIT MEDINA FORMATION
LOCATION NIAGARA ESCARPMENT
AGE LOWER SILURIAN

Chapter Two

Facies Descriptions

2.1 Overview

Data collected from both field and drill core sections has resulted in a total of nine units identified on the basis of such features as lithology, sedimentary structures, and fossil content. These units have been further condensed into five facies. An attempt has been made to trace lateral facies variations in the Hamilton and Lake Erie region.

Figures 2-1 to 2-5 are stratigraphic sections detailing the position of facies. Figure 2-1 is a legend describing all symbols used. Figure 2-6 shows the lateral variation of Facies A at Flock Road.

2.2 Facies A

Units A1 and A2 constitute the lowest part of the transition from the Whirlpool Formation to the Manitoulin Formation. Unit A1 is a marine shale which is overlain by A2, a quartz rich sandstone. Both units are laterally continuous from the Jolley Cut outcrop eastwards to the Flock Road section (see plate 2.2.1.).

The shale (A1) unit is relatively uniform in

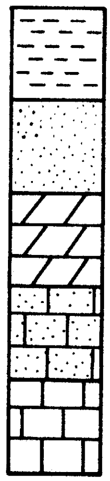
Figure 2-1: Legend for the stratigraphic sections, figures 2-2 to 2-5.

LEGEND

GRAIN SIZE

M	MUD
MG	MEDIUM GRAINED
FG	FINE GRAINED
FL	FINE LOWER
VFU	VERY FINE UPPER
VFL	VERY FINE LOWER

LITHOLOGY



SHALE

SANDSTONE

DOLOMITE

SANDY LIMESTONE

LIMESTONE

FOSSILS

BRACHIOPODS

CORALS

CRINOIDS

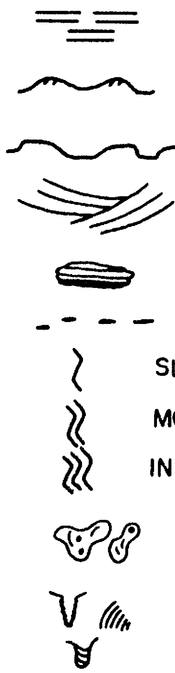
STROMATOPOROIDS

CHONDRITES

ACCESSORIES

S	SULPHIDES
C	CALCITE
G	GLAUCONITE
M	MICROSTYLOLITES & CLAY SEAMS

STRUCTURES



PLANE LAMINATION

WAVE RIPPLES

SCOUR & FILL

LOW ANGLE STRATIFICATION

LITHIFIED S.S. CLAST

MUD CLASTS

SLIGHT

MODERATE BIOTURBATION

INTENSE

FOSSIL FILLED BURROWS

BURROWS

Figure 2-2 : Stratigraphic section of the Jolley Cut outcrop. Refer to figure 1.4 for the location of the outcrop, and figure 2-1 for the legend describing all symbols used.

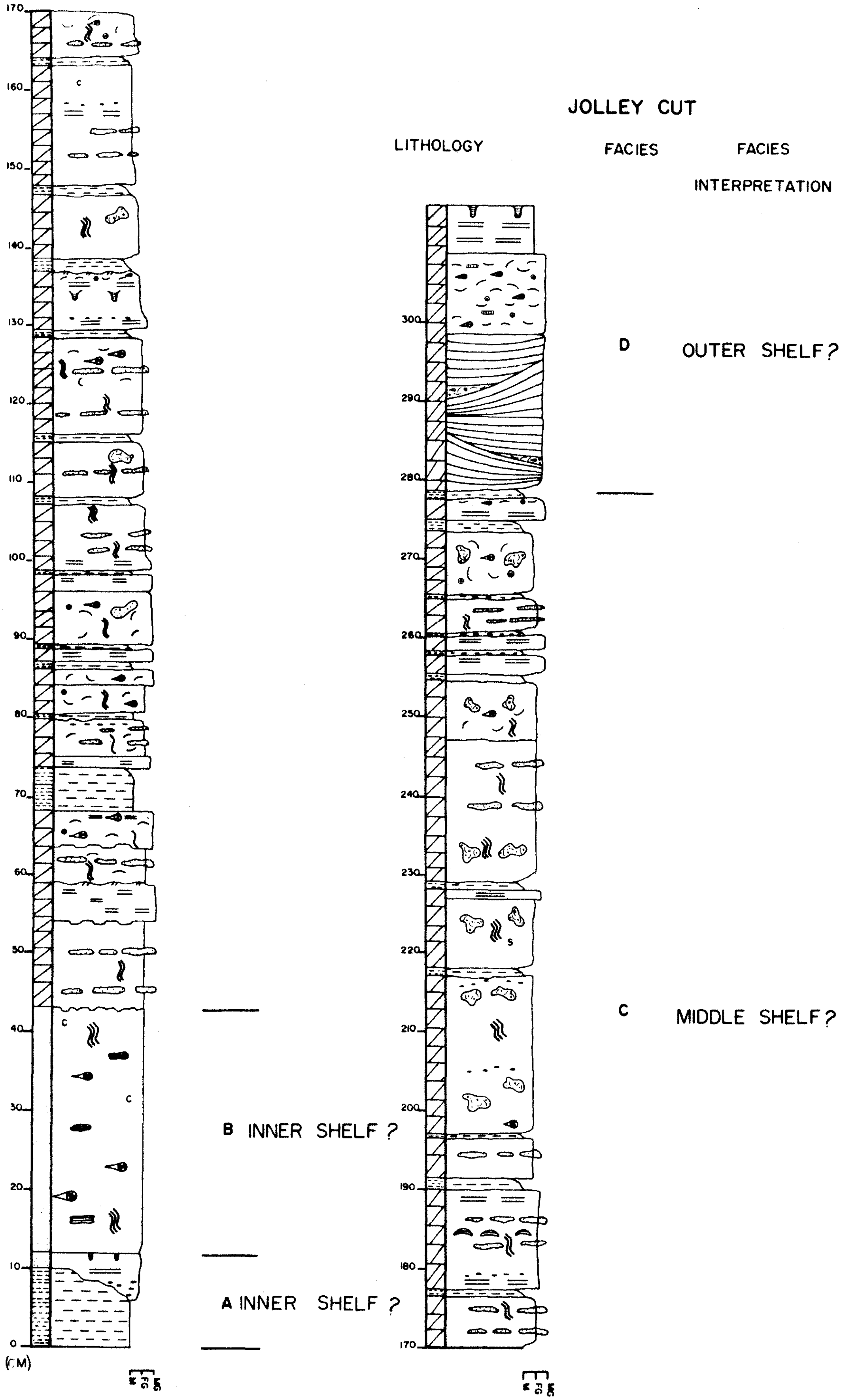

JOLLEY CUT
LITHOLOGY
FACIES
FACIES INTERPRETATION
D OUTER SHELF?
C MIDDLE SHELF?
B INNER SHELF ?
A INNER SHELF ?
(CM)

Figure 2-3 : Stratigraphic section for the OGS well no. 860. Refer to figure 1.4 for the location of the core, and figure 2-1 for the legend describing all symbols used.

OGS 82 2 CHATHAM HARWICH 25-IECR

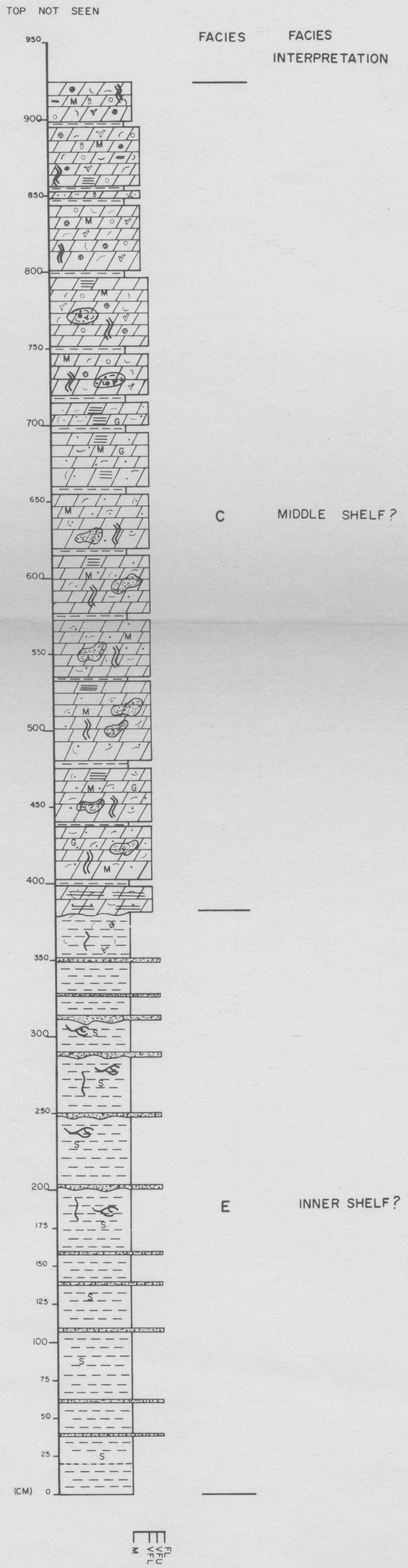
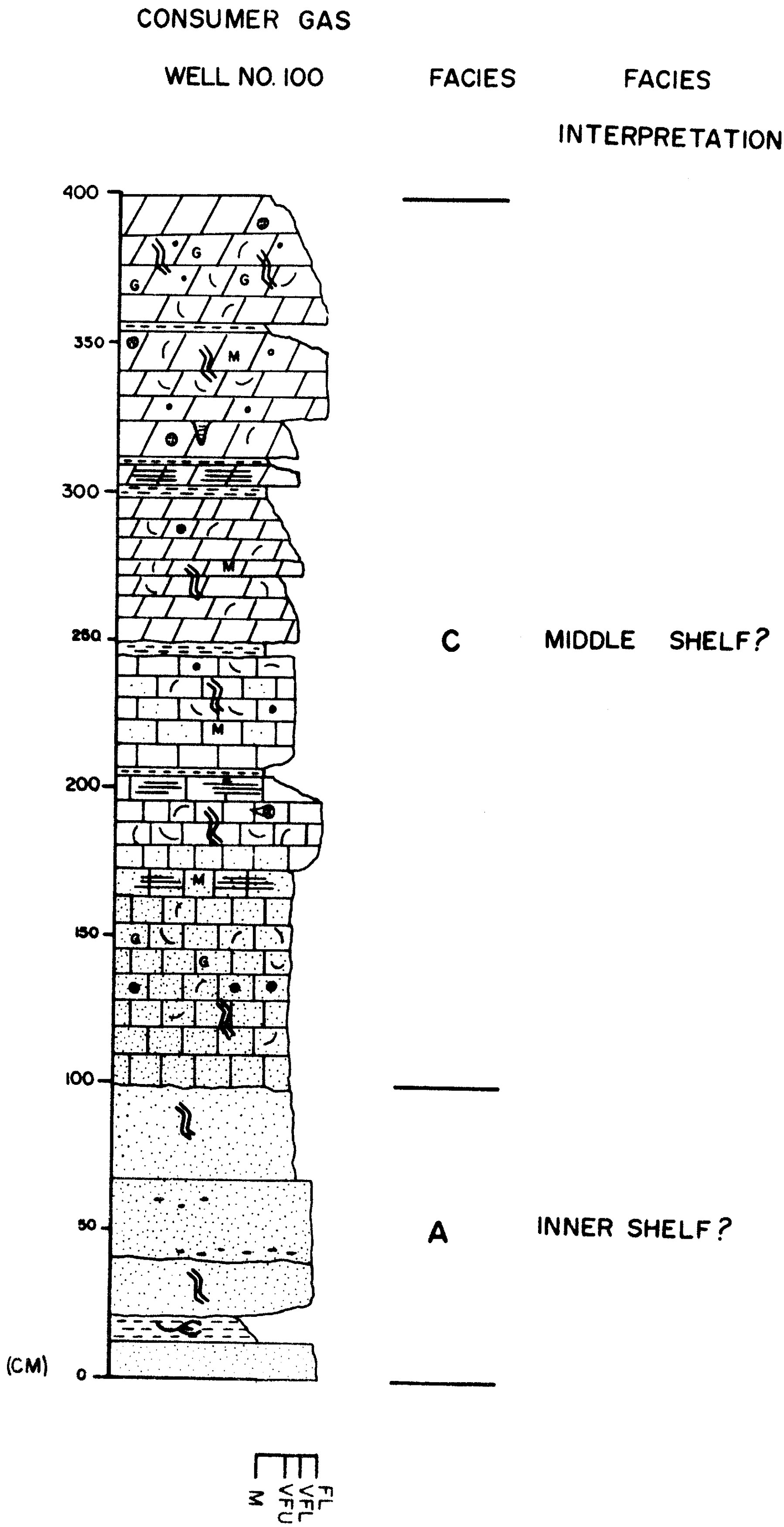


Figure 2-4 : Stratigraphic section for the Consumer Gas well no. 100. Refer to figure 1.4 for the location of the core and figure 2-1 for the legend describing all symbols used.



CONSUMER GAS
WELL NO. 100
FACIES
FACIES
INTERPRETATION
400
350
300
250
200
150
100
50
0
(CM)
G
M
C
MIDDLE SHELF?
A
INNER SHELF?
M
VFU
VFL
FL

Figure 2-5 : Stratigraphic section for the Consumer Gas well no. 371. Refer to figure 1.4 for the location of the core and figure 2-1 for the legend describing all symbols used.

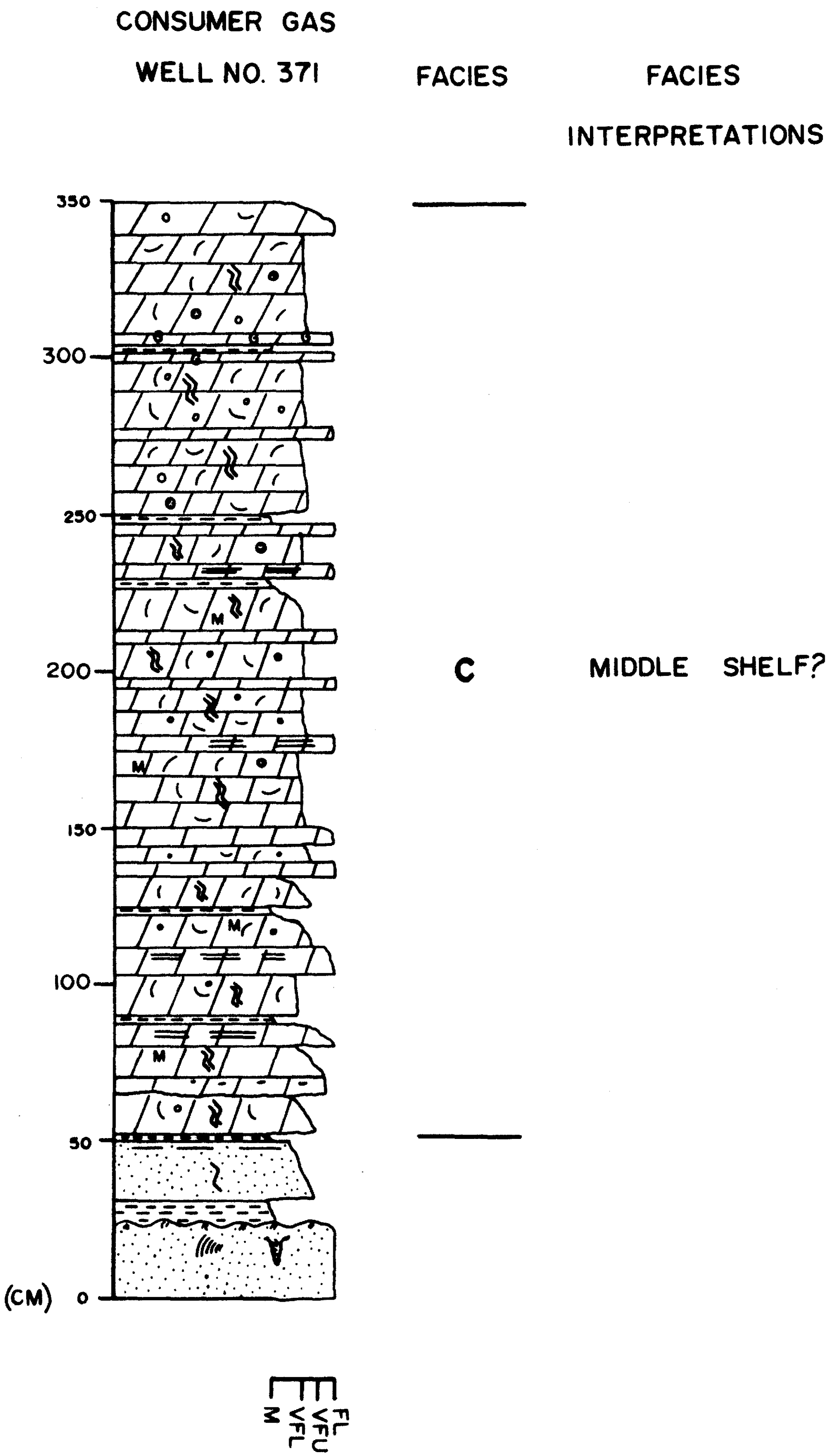
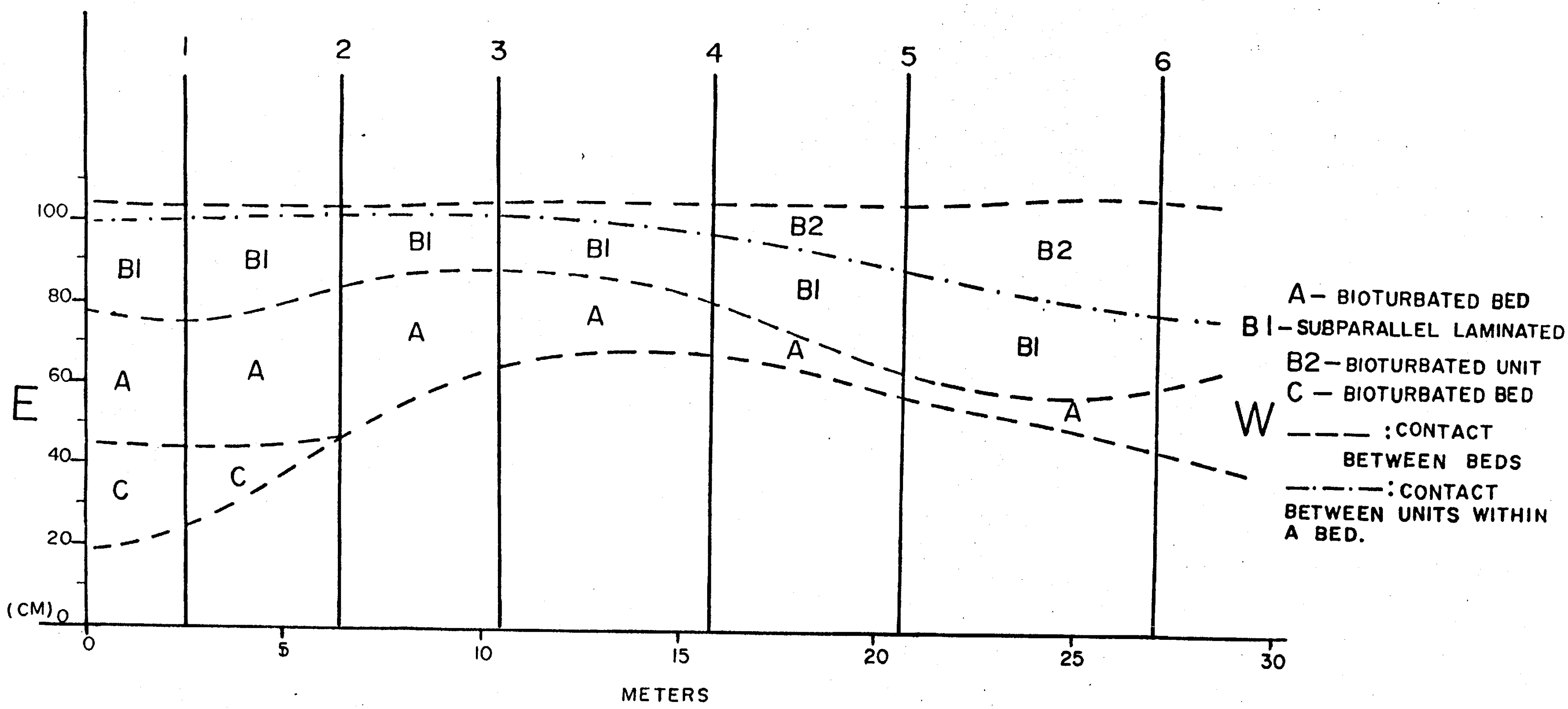

CONSUMER GAS
WELL NO. 371
FACIES
FACIES
INTERPRETATIONS
350
300
250
200
150
100
50
(CM) 0
C
MIDDLE SHELF?
M
M
M
M
M
FL
VFU
VFL
M

Figure 2.6 : Lateral variation diagram for Facies A at the Flock Road outcrop. HCS beds A,B, and C are shown. Beds A and C thin out to the West. Bed B increases in total thickness to the west. The sub-parallel laminated unit of bed B thins, as the bioturbated top unit thickens to the West. Facies A is much thicker at this location than at Jolley Cut indicating that scouring was more pronounced farther to the West.

FLOCK ROAD


1
2
3
4
5
6
100
80
60
40
20
(CM) 0
E
W
B1
A
C
B2
0
5
10
15
20
25
30
METERS
A– BIOTURBATED BED
B1–SUBPARALLEL LAMINATED
B2–BIOTURBATED UNIT
C – BIOTURBATED BED
: CONTACT BETWEEN BEDS
: CONTACT BETWEEN UNITS WITHIN A BED.

thickness, between 5-10 cm. The sandstone (A2) unit varies between 5-41 cm, thickening to the east. Facies A is not recognizable in the drill core sections.

The shale unit is massive, grey-green in color, and yielded no fossils.

The shale is erosively overlain by buff colored calcareous sandstones. The sandstone beds range in thickness from 7 to 41 cm and have sharp bases, while the tops show either a sharply erosive contact or irregularity due to bioturbation (see plate 2.2.2.). The term hummocky cross stratification could be used to classify this unit based on two criteria. First, the layers are composed of broadly curved hummocks and swales with wavelenghts ranging from 1-8 m, and amplitudes of 3-8 cm, showing regular periodicity. Secondly, individual laminae conform to the broad shape of the hummocks and swales, exhibiting low angle dips (Walker, 1982) (see plate 2.2.3.).

The sandstone units display a fining upwards sequence in grain size. Elongate pebbles and shale clasts .5-25 cm in length characterize the base of each sandstone unit. Fossil content includes solitary rugose corals 1-2 cm in diameter, and the trace fossils Planolites and Phycodes (M.Rutka pers. comm.).

Interpretation

The sharp base of the A2 unit implies that the sands were episodically deposited on the top of the shale (A1) unit. The presence of shale clasts and pebbles at the base of each sandstone unit indicates that the flow was competent enough to erode and transport pre-existing sediments. The base of the beds shows distinct scours into the underlying beds. Hummocky cross-stratification indicates reworking of sediments below fair weather wave base by large storm waves (Hamblin and Walker, 1979). Bioturbation at the tops of each of the HCS beds, is suggestive of increased burrowing activity during fair weather periods (Dott, 1983). It can therefore be concluded that Facies A was deposited below fair weather wave base but above storm wave base.

2.3 Facies B

Facies B consists of a calcite cemented sandstone 35 cm thick which appears to be extensively bioturbated. Grain size ranges from 2.5-3.0 phi (.17-.08 mm). The basal contact is sharp but undulatory, whereas the upper contact is horizontal and grades irregularly upwards into a 2 cm shale parting. Biogenic mottling has given the surface a variable light grey to green-grey color.

Distinct features common to this facies are fine grained, parallel laminated sandstone clasts, 2-5 cm in length. They are oriented parallel to bedding and were probably derived from the underlying sandstones. Calcite and celestite filled vugs, 2-4 cm in diameter are found throughout Facies B (see plate 2.3.).

Fossil content consists of calcified scattered solitary rugose corals and articulated brachiopods both randomly orientated. Trace fossils include Chondrites, Planolites, and possibly Skolithos (pers. comm. M.Risk).

Facies B is not recognized in drill core section.

Interpretation

Extensive bioturbation of facies B has obliterated any pre-existing sedimentary structures. The sharply scoured base indicates deposition by flows strong enough to scour into underlying sediments. This is also supported by large lithified sandstone clasts present within the base of the facies. The gradational upper contact suggests little sedimentation for a long period of time, during which extensive burrowing took place. Body and trace fossils found indicate a shallow marine environment, of normal salinity.

2.4 Facies C

This facies is characterized by a series of couplets, each of which consists of a lower sharp-based, parallel to sub-parallel laminated unit (C1), overlain by a bioturbated upper unit (C2) (see plate 2.4.1.). Facies C is 2.4 m in total thickness at the Jolley Cut outcrop.

The C1 units consist of arenaceous dolomite, ranging in thickness from 1-5 cm, with a grain size of 1.5-2.5 phi (.35-.17 mm). A light buff weathered surface and sharp erosional bases accentuate these beds. The upper contact is sharp, sometimes showing slight undulations. The overall bed geometry is tabular. Green-grey shale clasts, 1-5 mm in length, oriented parallel to bedding occur in the upper portion of the C1 units. Body and trace fossils are absent, except on the tops of some beds where mud covered brachiopods in the current-stable (convex-up) position are found.

The C2 units are composed of argillaceous dolomite ranging in thickness from 2-8 cm, with grain sizes of 3.0-3.5 phi (.125-.08 mm). The color of the beds is medium to dark grey varying in proportion to the amount of argillaceous material. Primary sedimentary structures , if previously present, have been obliterated by moderate to extensive bioturbation. The units are tabular, and upper and lower contacts are sharply bound by the C1 units. Fossil material is abundant, and includes solitary rugose corals, loose crinoid ossicles, articulated crinoid stems, articulated brachiopods, and the occasional bryzoans. Fossils are randomly orientated and no significant size changes occur through the succession. Large unidentified horizontally branching burrows are present in the C2 units towards the top of Facies C in outcrop, and throughout all C2 units in drill core. These burrows are infilled with coarse, silicified fossil hash material (see plates 2.4.2.and 2.4.3.).

At Jolley Cut two marker beds can be traced laterally for approximately 100 meters within Facies C. The first of these beds occurs along a bedding plane 46 cm from the base of Facies C , and is composed of closely packed silicified articulate brachiopods. The lower 1 cm of the bed is occupied by brachiopods 1-1.5 cm in diameter which show no trends in hinge line orientation. The second marker bed contains scattered 'ballstone' stomatoporoids, in the growth (convex-up) position, and is located in the upper part of the facies.

Interpretation

The cyclic nature of the deposits of facies C is common in middle shelf environments. The sharp based A1 units are distinctive of episodic deposition by storm currents (Mesolella et al,1974). These units are then overlain by argillaceous, bioturbated sediments which represent a period of quiescense during which burrowing by marine organisms took place. Fossils within this facies suggest an open marine shelf environment.

2.5 Facies D

Facies D can be informally subdivided into three units. The basal unit is composed of low angle cross stratified glauconite-rich dolomite, which is overlain by a massive fossiliferous unit, which fines upwards into a parallel laminated quartz rich unit.

The base unit consists of two sets of low angle cross stratification, 10 cm in total thickness (see plate 2.5.1.). The scours between each set have been infilled with coarse fossil debris (see plate 2.5.2.). Grain sizes range from 2.0-2.5 phi (.25-.17mm). The stratification is accentuated by contrasting colors of the green glauconite bands and the white dolomite rich bands.

The cross stratified unit grades upward into a massive fossiliferous dolomite, 10 cm in thickness. Grain size ranges from 3.0-3.5 phi (.125-.08 mm), with silicified fossils being the main constituent. No sedimentary structures are evident, but all fossil material shows horizontal alignment and no bioturbation. Fossils include well preserved brachiopods, bryzoans, solitary rugose corals, and crinoid ossicles. All fossil material is larger than in the underlying facies.

The fossiliferous unit rapidly fines upwards into a fine grained, sub-parallel to parallel laminated , quartz rich dolomite. This dark grey unit is 5 cm in thickness with grain sizes ranging from 3.5-4.0 phi (.088-.063 mm). Elongate 1-2 mm green shale clasts are oriented parallel to bedding throughout the unit. No fossils are seen, but the top surface shows distinct vertical burrows penetrating into a compact substrate.

Interpretation

Facies D represents deposition in a middle to outer shelf environment. This is supported by the abundance of glauconite which favours precipitation in a quiet offshore environment. The sequence of sediments is characteristic of one individual storm event. The overlying Cabot Head shales represent further transgression into a low energy deeper marine environment.

2.6 Facies E

Facies E consists of 3.5 meters of green laminated sulphide rich shale. It has a sharp contact with the underlying red Queenston shale but grades upwards into a parallel-laminated dolomite at the top (see plate 2.6.1.). The mudrock contains 1-5 mm laminae of fossil hash, which increase in thickness towards the top of the facies (see plate 2.6.2.). These laminae also show undulatory bases as they increase in thickness. This is possibly a small loading structure into softer sediments below. The upper part of facies E exhibits an increase in the size of the fossil hash material, a moderate degree of bioturbation, and the appearance of the trace fossil Chondrites (see plate 2.6.3.). Sulphide material is found throughout the facies, but is more concentrated in the fossil hash beds. Facies E is found only in the most westerly of the core sections examined. This is due to the fact that the Whirlpool Sandstones do not extend this far west, and therefore the basal contact of the Manitoulin Formation is with the Queenston Formation.

Plate 2.2.1.A: Facies A showing (A1) shale unit overlain by a small hummock, unit (A2). The contact between Facies A and Facies B is also evident. Photograph from the Jolley Cut outcrop.

Plate 2.2.2.B: The erosive contact between Facies A and the overlying Facies B, bioturbated unit. Note the fining upward laminations shown in the (A2) unit of Facies A. Photograph from the Jolley Cut outcrop.

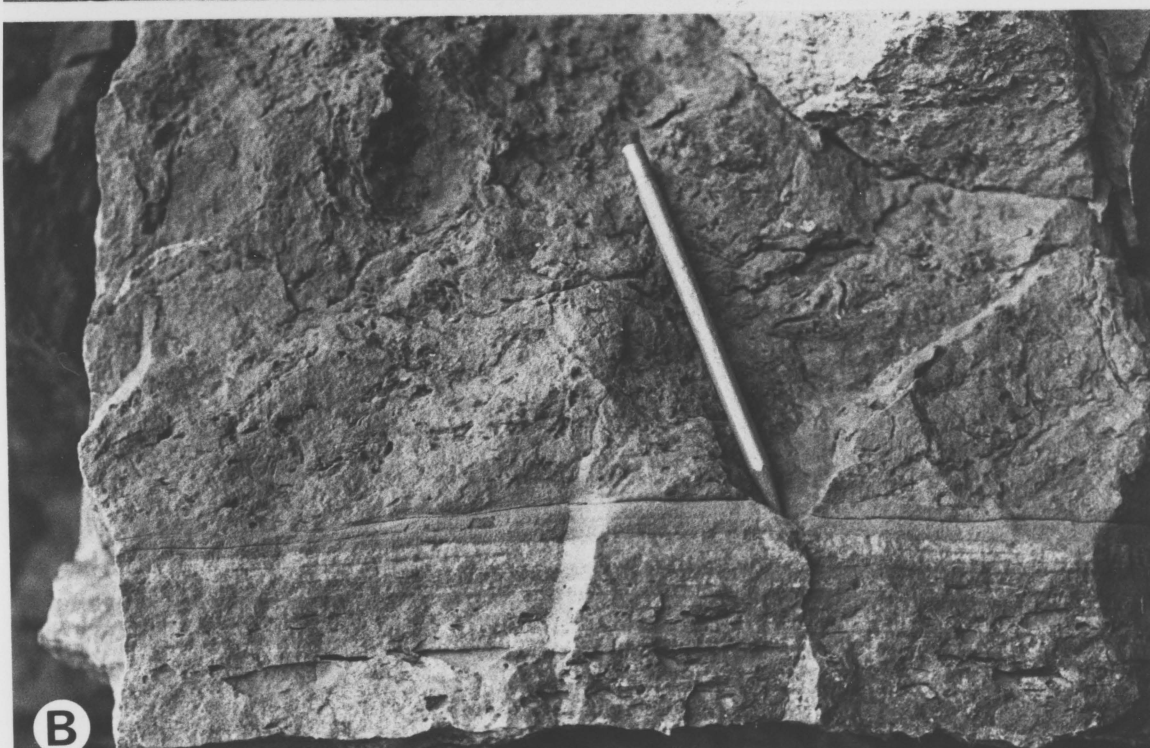


Plate 2.2.3.A: Facies A, broad hummocks and swales, with bioturbated tops which have been subsequently scoured into by the overlying HCS bed. Photograph from the Flock Road section.

Plate 2.3. B: Facies B showing extensive bioturbation, calcite vugs, and lithified, parallel laminated sandstone rip up clasts at the base. Photograph from the Jolley Cut outcrop.

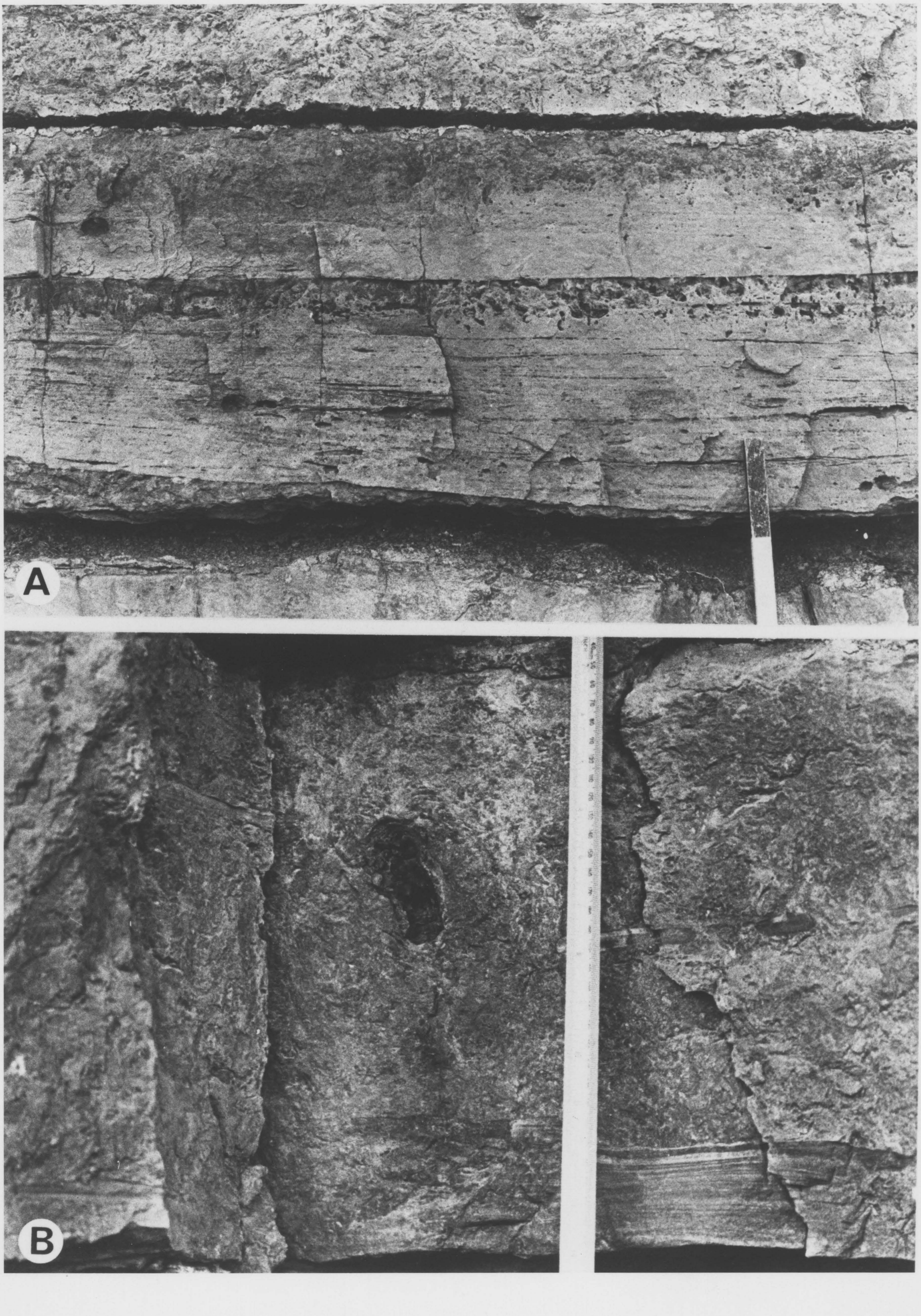

A
B

Plate 2.4.1.A: Facies C, a typical couplet set showing an argillaceous, fossil rich lower unit overlain by a parallel laminated, fining upward arenaceous dolomite. Photograph from the Jolley Cut outcrop.

Plate 2.4.2B: Light coloured horizontal burrows found in the upper section of Facies C. Photograph from Jolley Cut outcrop.

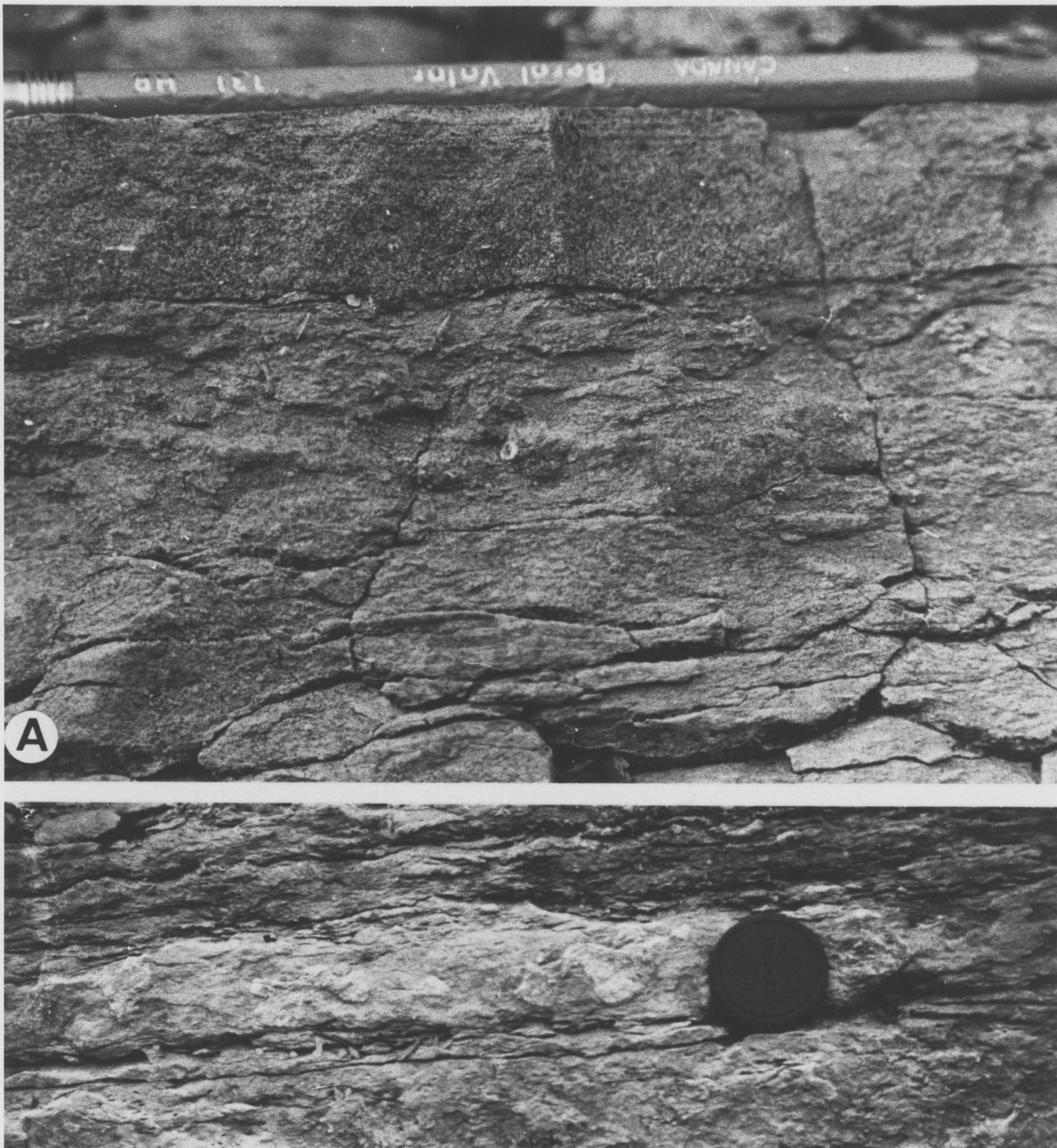

A
B

Plate 2.4.3. Acetate peel showing the texturally different appearance of the large fossil filled horizontal burrows.

Plate 2.5.1.A: Low angle cross stratified unit in the upper section of Facies D. The dark glauconite rich, and light dolomite rich bands accentuate the stratification. Photograph from the Jolley Cut outcrop.

Plate 2.5.2 B: Scours between cross bedded sets are infilled with weathered out coarse fossil material. Facies D, Jolley Cut location.

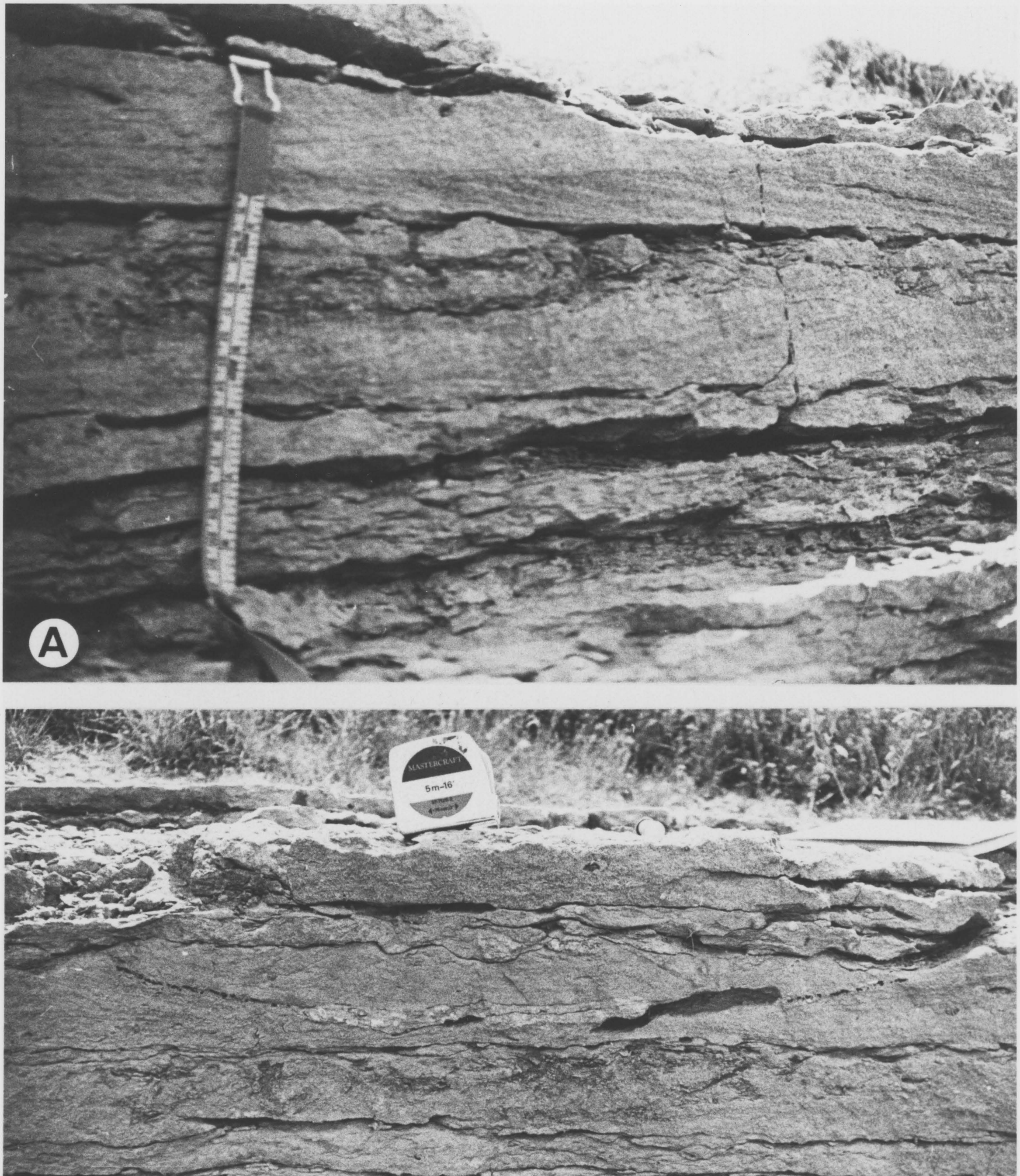
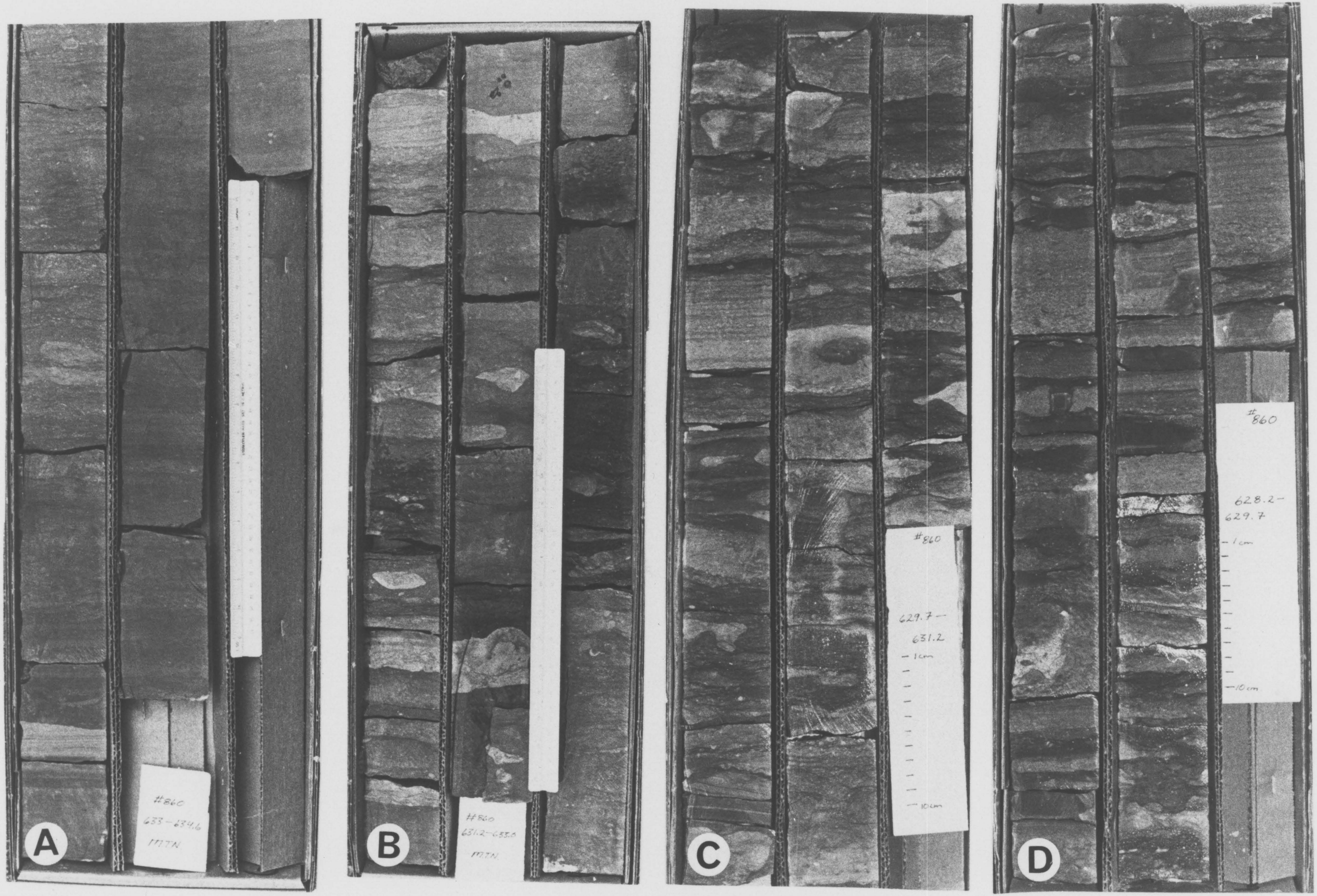

A
B
MASTERCRAFT
5m-16'

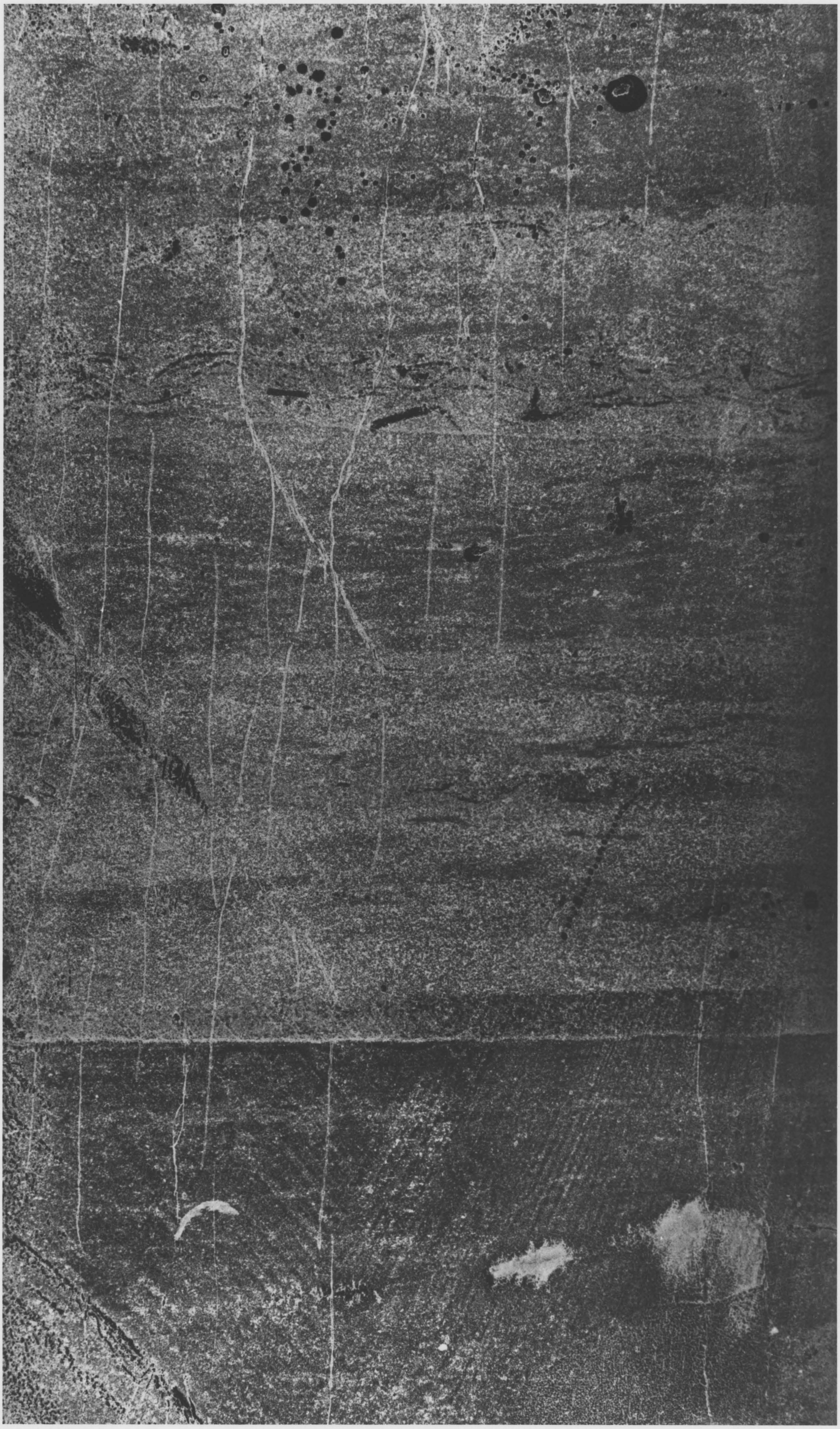
Plate 2.6.1. : A to D boxed core represents the base to the top of the Manitoulin Formation, OGS core no. 860.

A shows the erosive contact between the underlying Queenston shales and the overlying parallel laminated dolomite unit (C1). B to D boxes show light coloured horizontal burrows in unit C2, overlain by parallel laminated (C1) units of Facies C.



A
#860
633-634.6
MTN
B
#860
631.2-633.0
MTN
C
#860
629.7-
631.2
1cm
10cm
D
#860
628.2-
629.7
1cm
10cm

Plate 2.6.3. Acetate peel showing thin shell rich layers and the trace fossil Chondrites directly below the sharp based shell layer.



Interpretation

The red Queenston Shale defines the base of Facies E, while the upper section is representative of the transition between the Queenston shale and the Manitoulin Dolomite. The Queenston shale has been interpreted as a supratidal mudflat (Brogly,1983). Marine storm surge tides have produced the calcareous marine siltstone within this unit (Brogly,1983). Increased thickening of the fossil laminae and the appearance of the trace fossil Chondrites suggests that there was a rapid trangression at the time of deposition of Facies E. This is supported by the rapid increase in abundance of unbroken fossil material, which indicates a shallow marine environment, at the top of the facies. Directly above this is a parallel laminated unit (unit C1 of facies C) which scours into the shales below.

2.7 Carbon Determination

Carbon determination techniques can provide useful information about depositional environment, such as dissolved oxygen concentration, productivity of the overlying water, and indirectly the strenght of bottom currents (Gross, 1971).

Separation of organic matter from sediment is impossible therefore composition of organic remains depends on chemical analysis. Organic matter is derived from soft tissues or hard tissues (fossil remains).

Carbon determinations have been completed for representative samples from each facies at the Jolley Cut outcrop. The method used has been outlined by Krom and Berner (1982) (See Appendix 4).

Results have been graphically plotted (See Fig 2.7). Patterns which occur are summarized:

A. Low percentages of organic carbon occur at the base of the Whirlpool-Manitoulin transition (Facies A).

B. A slight increase in organic carbon is evident in Facies B.

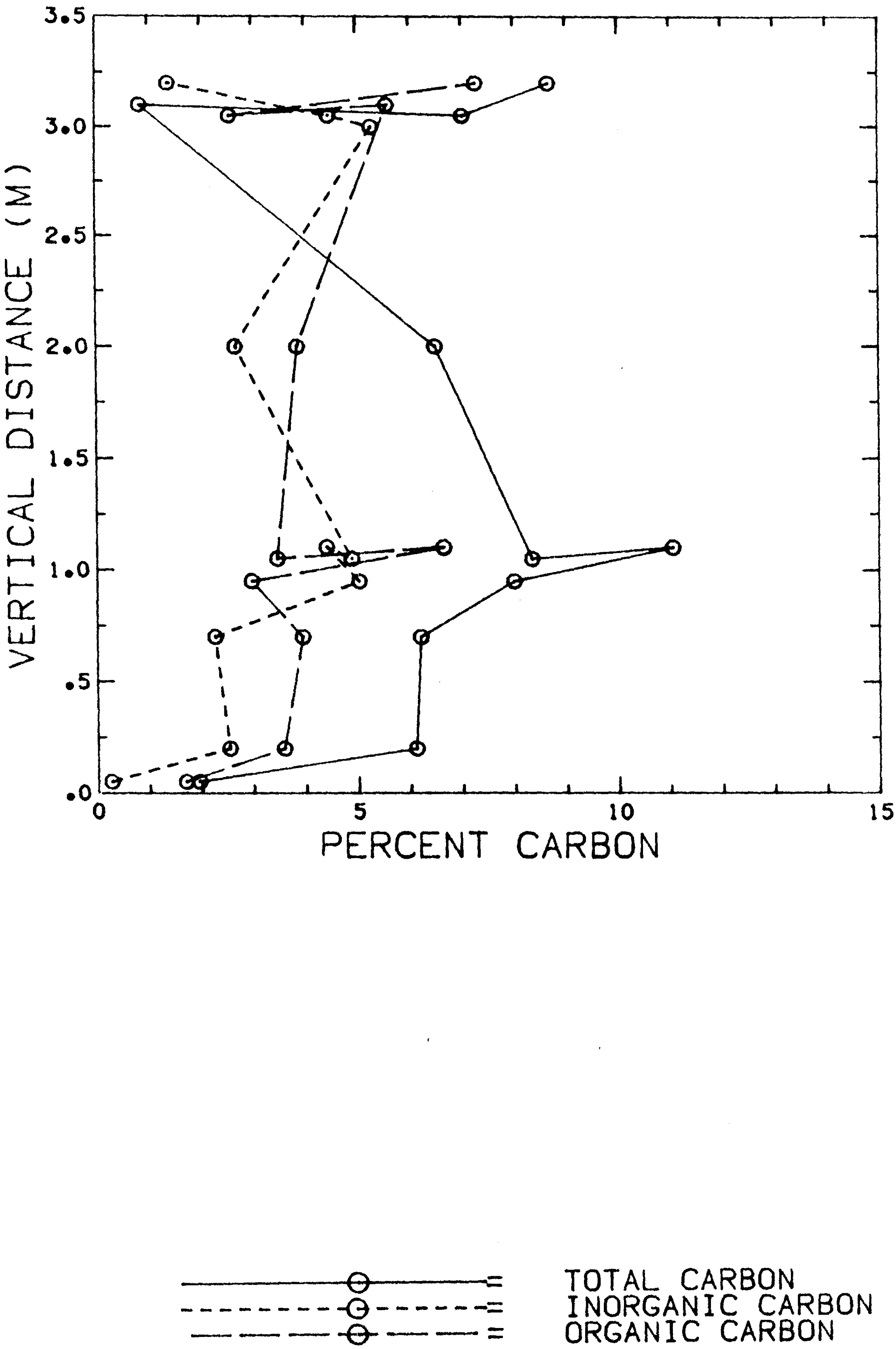
C. Sporadic increases and decreases characterize the percentage of organic carbon in Facies C.

D. The upper unit of Facies D contains the highest percentage of organic carbon.

The trends in percentages of organic carbon support previously discussed depositional environments, and sediment types. Facies A was episodically deposited and therefore had little time for extensive burrowing by marine organisms. This is confirmed by the small percentage of organic carbon. The small increase in organic carbon in Facies B is due to the increase in bioturbation, during which time marine organisms secreted small amounts of organics. Facies C shows sporadic high and low carbon percentages due to the cyclic nature of the sediments. Sharp based unfossiliferous units will contain less organic carbon than the overlying fossiliferous bioturbated units. The upper section of Facies D contains the highest percentage of organics, which is probably due to the thick shell lag.

The carbon determination study was useful in confirming ideas about depositional environment, as well being an interesting procedure to conduct.

Figure 2.7 Vertical Distance (m) vs. Carbon Percentage diagram showing the changes in total, organic, and inorganic carbon.



VERTICAL DISTANCE (M)
3.5
3.0
2.5
2.0
1.5
1.0
.5
.0
0
5
10
15
PERCENT CARBON
= TOTAL CARBON
= INORGANIC CARBON
= ORGANIC CARBON

Chapter 3

Petrography

3.1 Overview

A total of 17 thin sections were prepared from both outcrop and drill core sections. The sections were prepared slightly thicker, lightly polished on the bottom side and left uncovered in order to be analyzed by Cathodoluminescent Microscopy (See Appendix 1 for description of the technique).

All thin sections were stained for ferroan and non-ferroan calcite and dolomite using a method developed by Lindholm and Finkelman (1972) (see Appendix 2 for description of the staining technique). Results obtained from the staining were good for calcite and fair to good for dolomite.

After the Cathodoluminescence study and staining were completed, cover slips were fixed on the thin sections and they were analyzed under transmitted light. Petrographic compositions were determined by microscopic estimation of modal percentages for each mineral.

3.2 General Description

The mineral types and their modal percentages are recorded in Table 3.1. Minerals identified within the Manitoulin Formation as well as through the Whirlpool-Manitoulin transition include: quartz; present as detrital grains, authigenic overgrowths, and chalcedonic quartz replacement of fossils; feldspar; opaques (pyrite) and heavy minerals (tourmaline); chert, phosphatized fossil fragments and sedimentary rock fragments; non-ferroan calcite, present as both cement and fossil replacement; dolomite; present as cement and secondary replacement; detrital muscovite; glauconite; minor amounts of anhydrite and hematite cements.

Dolomite, in the form of secondary cement and replacement textures is the dominant mineral present in the samples. Quartz in the form of detrital grains and chalcedonic quartz replacement is second in abundance to dolomite.

3.2.1 Quartz

The detrital quartz grain population consists mainly of non-undulose and undulose monocrystalline quartz with minor amounts of polycrystalline quartz. Most grains in the thin sections from the Whirlpool-Manitoulin transition zone show well developed syntaxial overgrowths of silica cement. The overgrowths are generally easy to recognize, due to the presence of dust rims consisting of hematite and clay minerals, around the rim of the detrital grain (see Plate 3.2). Dust rims are formed in the pore space between the overgrowth and the detrital grain during cementation (Pittman, 1972). Overgrowths are not apparent on the detrital quartz grains within the middle to upper Manitoulin Formation.

Most of the monocrystalline quartz grains show undulose extinction and fractures, both indicative of a high degree of straining. Inclusions of sillimanite in some grains is evidence for a metamorphic source area. Chalcedonic quartz is present as a replacement of fossils. It is present as circular bundles of radiating fibres (see Plate 3.5). Most of the drill core thin sections contain length-slow chalcedony indicative of evaporatic conditions.

3.2.2. Dolomite

Dolomite is the main constituent mineral of the samples prepared for thin section. The dolomite crystals are stained blue, which distinguishes it from calcite. It appears as a coarse replacement of fossil material and in masses of tightly interlocked, medium grained "sucrosic" dolomite. Some crystals show pronounced zonation with respect to iron due to fluctuations in pore fluid concentrations. The relative size of the grains averages .1-.2 mm upwards through the vertical sections from both drill core and outcrop data. Larger grains, .2-.4 mm were often seen as a secondary replacement of fossil fragments (see Plate 3.3).

3.2.3. Feldspar

Trace amounts of the feldspar microcline were found through the transition zone. The grains display characteristic polysynthetic twinning, are well rounded, show some replacement by calcite, and average .05mm in diameter.

3.2.4. Mica (Muscovite)

Elongate mica flakes occur in trace amounts in drill core thin sections. They were slightly deformed and squeezed in the pore space between quartz grains.

3.2.5. Opaques and Heavy Minerals

The opaque mineral found in thin sections is pyrite which occurs as subhedral to euhedral crystals and is often associated with calcite or dolomite replacement of fossil material (See Plate 3.4). This may suggest that pyrite was precipitated at a late stage in response to Eh/pH conditions favourable to calcite precipitation.

Tourmaline was observed as rounded detrital grains and was detected in only a few thin sections within the Whirlpool-Manitoulin transition zone. It is a common heavy mineral in sediments due to its physical and chemical stability. It is found throughout the Whirlpool Sandstone (Calow, 1983).

3.2.6. Glauconite

Glauconite occurs as an authigenic replacement of echinoderm fragments, as well as appearing as a replacement of fecal pellets (see Plate 3.1). It is most commonly found in the basal unit of Facies D, but trace amounts are also found throughout drill core thin sections. Glauconite displays a characteristic green colour and a speckled green birefringence.

3.2.7. Collophane

Collophane is present as well rounded elongate clasts up to 1mm in length. It shows a typical brown colour in transmitted plane light, while it is virtually isotropic in polarized light. Collophane grains display fractures, slight bending, and internal lamination.

3.2.8. Chert and Rock Fragments

Well-rounded cryptocrystalline chert grains are found in trace amounts in all the thin sections. Most average .05-1.5mm in diameter.

Sedimentary rock fragments up to 4mm in length are found within Facies B and are often distinguished from the matrix by a thick hematite cemented rim (see Plate 3.2.8.). Small 1mm oval shaped shale clasts also occur throughout many thin sections and often display fracturing and bending.

3.2.9. Anhydrite

Anhydrite occurs as a pore filling cement in most of the drill core samples (see Plate 3.2). It displays both subequant crystals as well as small clusters of acicular crystals. Anhydrite is not seen in thin sections from outcrop presumably due to post-depositional leaching by ground water.

Plate 3.2.8. Micrograph of sample j.c.1
Quartz rich calcite cemented sandstone with a sedimentary rock fragment separated from the matrix by a thick hematite cemented rim.

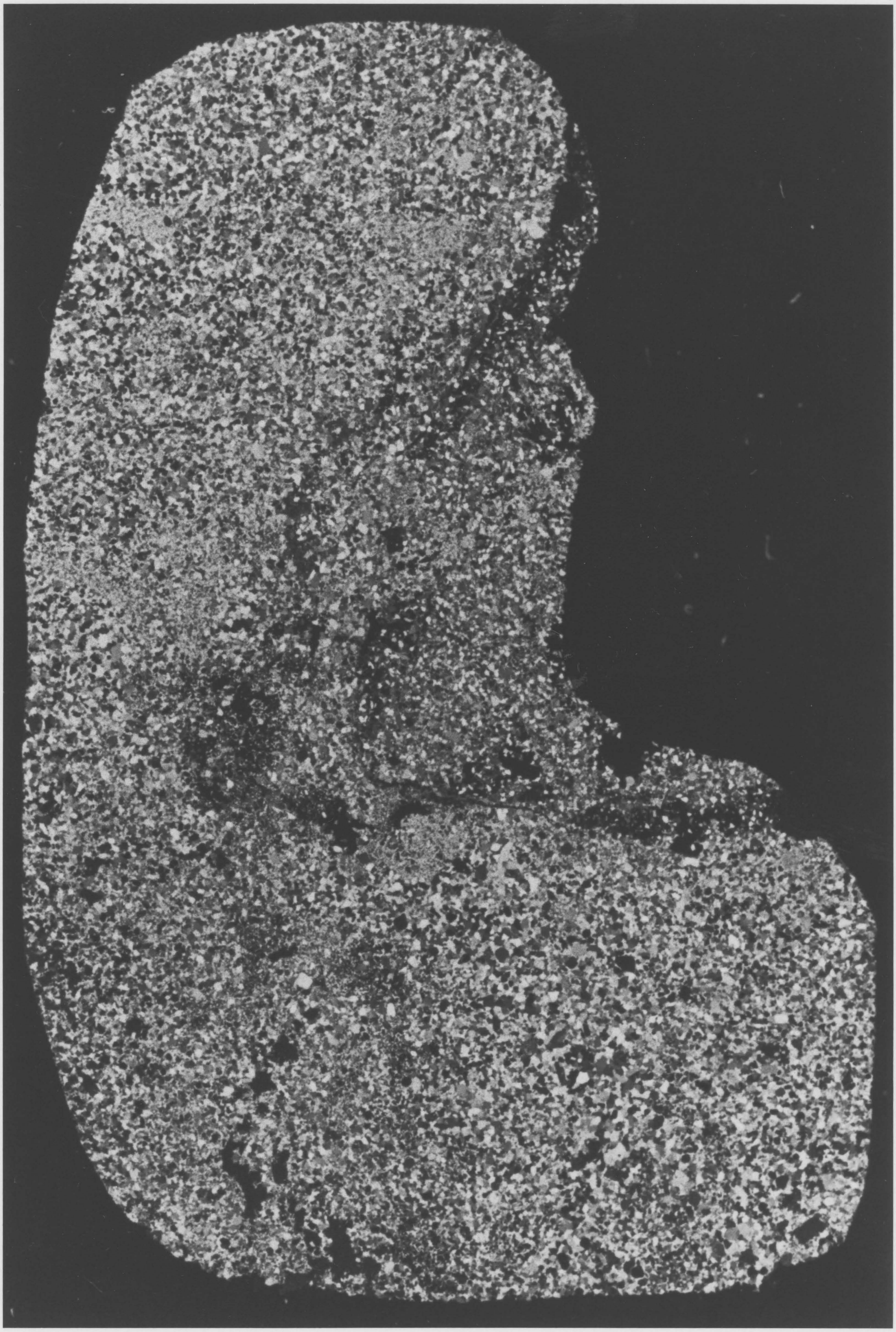
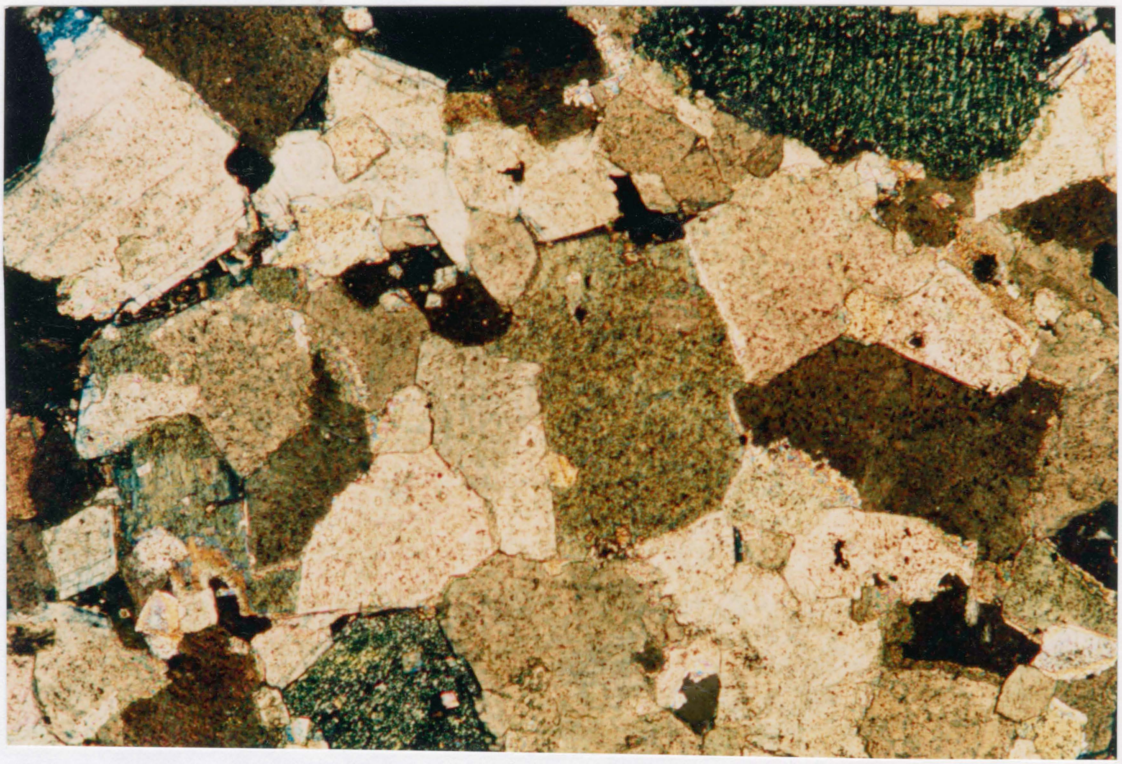


Plate 3.1: Coarse dolomite, with some individual rhombs shown. Echinoderm fragments show glauconite replacement Sample 7a, 630X magnification, XN.

Plate 3.2: Dust rims are shown surrounding detrital quartz grains. Calcite and anhydrite cements fill pore spaces. Sample 1290, 160X magnification, XN.



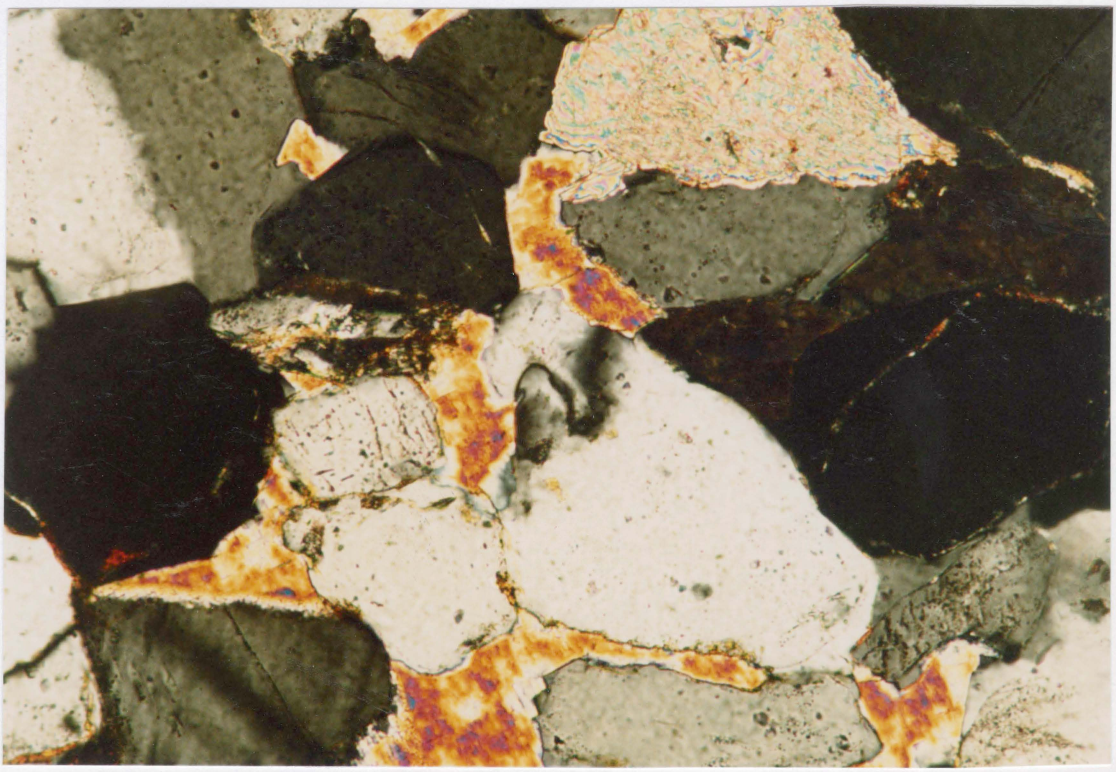
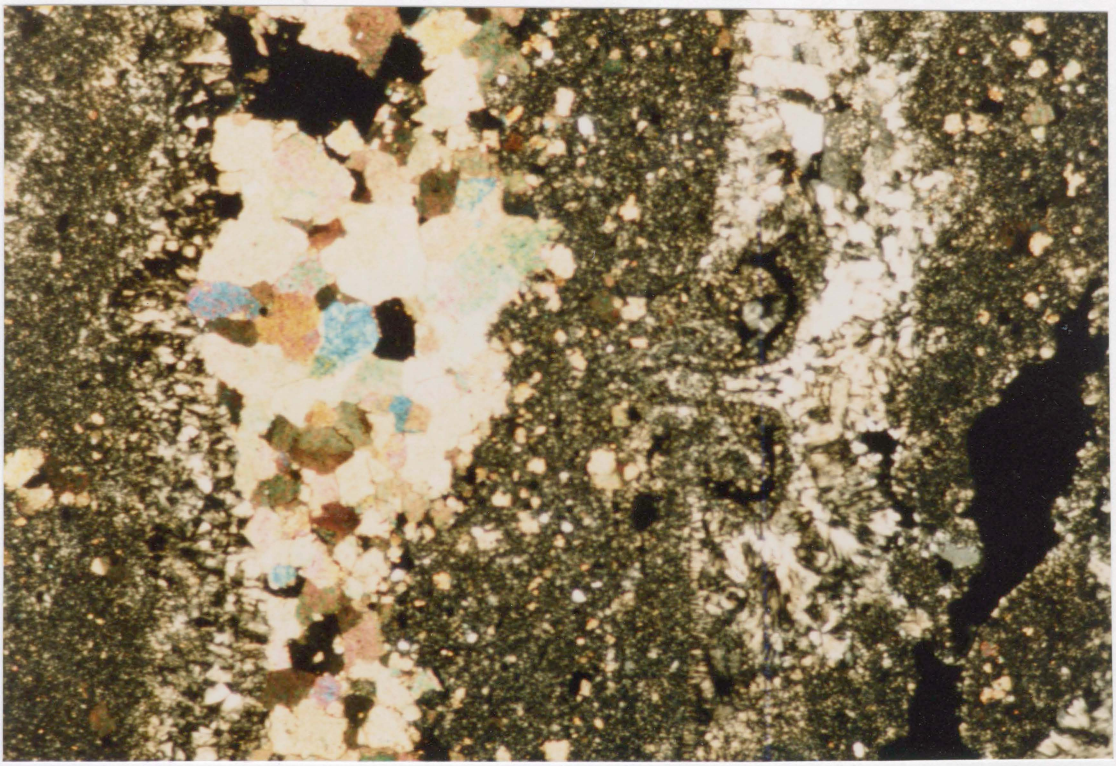


Plate 3.3: Coarse 'sucrosic' dolomite replacement of a fossil fragment. Also, chalcedonic quartz replacement of a brachiopod shell, preserving the original texture. Sample 7b, 250X magnification, XN.

Plate 3.4: Calcite cemented quartz grains. Calcite is undergoing replacement by dolomite. A large cluster of pyrite cubes is found in association with large patches of calcite. Sample j.c.1, 630X magnification, XN.



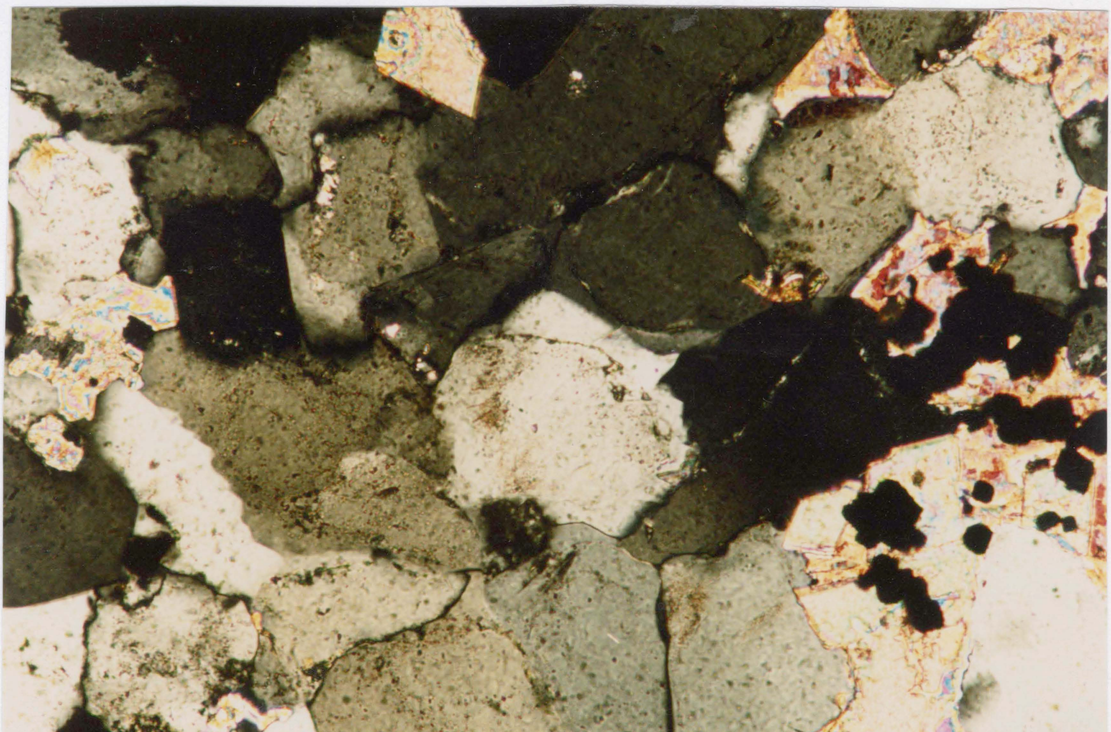
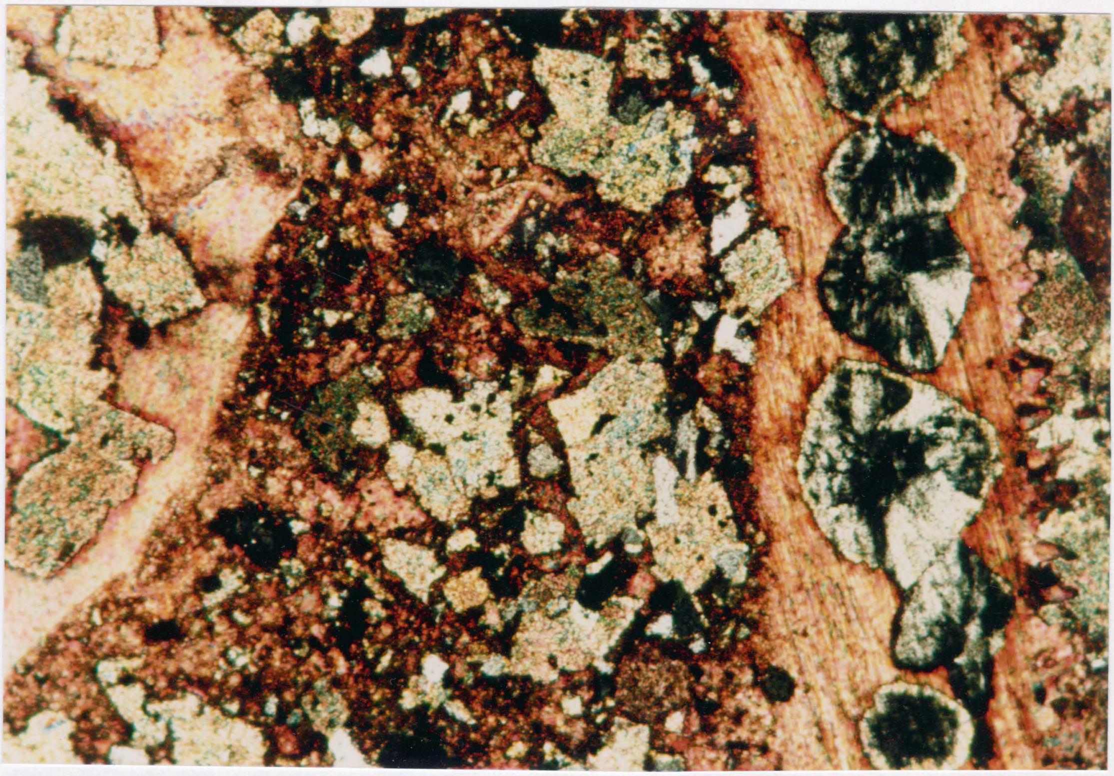


Plate 3.5 Bundles of radiating chalcedonic quartz replacing non-ferroan calcite within a brachiopod shell. Distinct dolomite rhombs shown replacing calcite within a fossil fragment. Sample 1281, 630X magnification, XN.

Plate 3.6 Coarse dolomite cement shown as a replacement of fossil fragments. This is surrounded by dark patches of hematite cement resulting from extensive bioturbation. Note the much smaller dolomite crystals associated with the patchy cement. Sample 1282, 250X Magnification, XN.



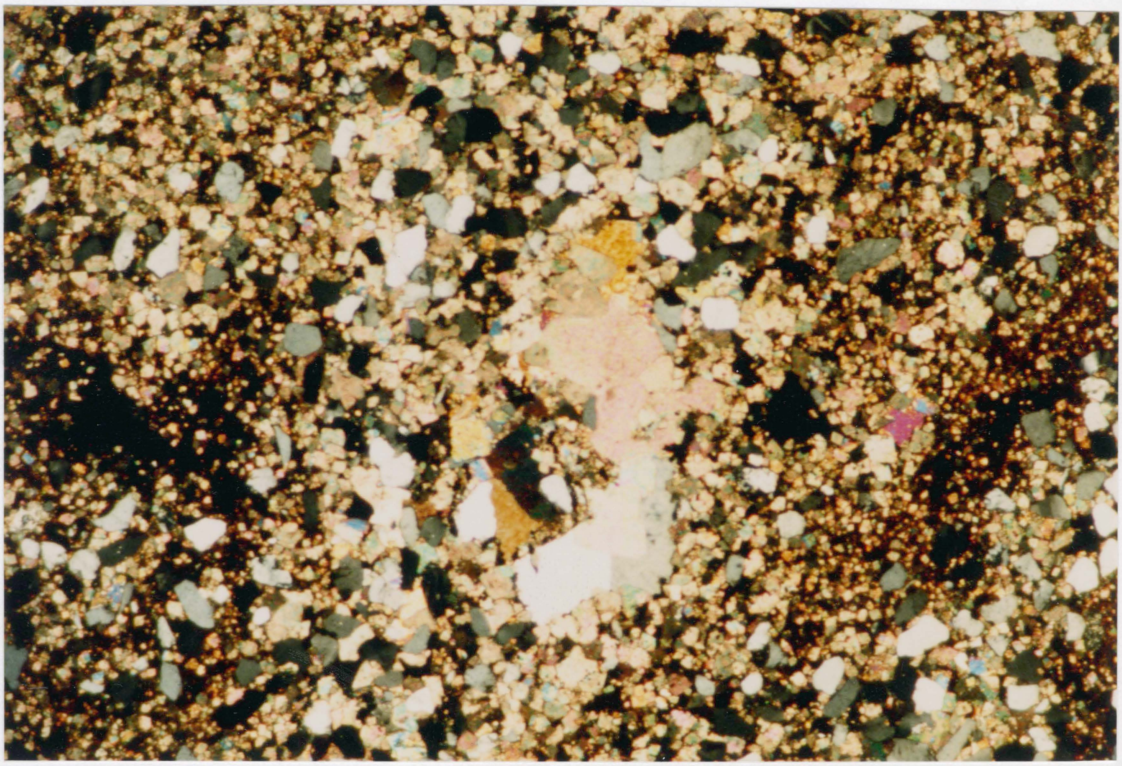


Table 3.1 Modal percentages of minerals identified in outcrop and drill core thin sections.

Sample No.	Quartz	Calcite	Dolomite	Feldspar	Phosphate
1276	25%	---	65%	trace	---
1277	2%	---	90%	---	---
1281	10%	50%	40%	---	---
1282	30%	---	60%	---	---
1284	2%	60%	30%	---	---
1289	55%	30%	10%	---	---
1290	90%	5%	---	trace	1%
1293	40%	---	55%	trace	---
j.c. 1	95%	2%	---	trace	---
sam 2	60%	35%	trace	1%	---
3a1	10%	---	80%	---	---
3a2	2%	---	95%	trace	---
sam 5	50%	---	40%	trace	trace
5a	5%	---	95%	---	---
7a	2%	---	90%	---	---
7b	20%	---	70%	---	---
8a	10%	---	85%	---	---

Sample No.	Glauconite	Mica	Opaques Heavies	Chert Rx Fr	Hematite Cement	Anhydrite Cement
1276	---	trace	trace	---	5%	trace
1277	---	---	---	2%	---	trace
1281	---	---	---	---	---	trace
1282	---	trace	trace	---	5%	trace
1284	2%	---	---	---	---	---
1289	2%	trace	trace	---	---	---
1290	---	---	---	---	trace	2%
1293	---	---	1%	2%	---	trace
j.c.1	---	---	trace	---	---	---
sam2	---	---	2%	---	---	---
3a1	---	---	trace	---	---	---
3a2	---	---	trace	---	---	---
sam5	---	---	trace	---	5%	---
5a	---	---	---	---	---	---
7a	1%	---	trace	---	---	---
7b	---	---	---	---	---	---
8a	---	---	1%	trace	---	---

3.3 Cathodoluminescence

3.3.1. General Description

Cathodoluminescence (C.L.) is visible light emitted by a material when it is subjected to the bombardment of electrons. This luminescence is clearly related to specific concentrations of transition elements such as Mg and Fe incorporated in a host mineral (Nickel, 1978). The process of cathodoluminescence involves the use of a luminoscope in which an electron beam is generated by applying a potential to a cold cathode in a partially evacuated tube. Electrons emitted from the cathode ionize any remaining gases in the tube and the positive ions produce more electrons on impact. This process leads to stable discharge, which is concentrated by magnets onto the sample (Kopp, 1981).

The CL colours and intensities result from both intrinsic and extrinsic factors. Intrinsic factors relate to the nature of the host lattice and the quenchers and activators it contains, while extrinsic factors include the degree of surface penetration and the voltage applied to the cathode. Activators are impurities in the mineral which are centers of excitement and lead to the development of luminescence. Quenchers, such as iron, produce excited states which emit radiation outside the visible region and "quench" the luminescence. The concentrations of quenchers and activators varies during different stages of growth, as shown by the dolomite zoning. Some common carbonate minerals and their reported CL colours are shown in Table 3.2. Table 3.3 indicates modal percentages obtained from the analysis of 6 thin sections by cathodoluminescent microscopy.

3.3.2. Quartz

Two different CL colours have been observed from the detrital quartz grains, red-brown and blue. These colour differences are due to varying amounts of activating and quenching substances. The red-brown quartz is the most abundant in the Whirlpool-Manitoulin transition where the total quartz percentage is high. It is likely derived from a metamorphic terrain (Zinkerhagel, 1978). The blue quartz is found throughout the Whirlpool-Manitoulin transition zone in minor quantities and is the only type of quartz detected in the middle to upper section of the Manitoulin Formation. It shows large detrital grains which are non-undulose and well rounded, and reflect the greater stability of this type of quartz, which is typical of higher temperature (>573°) plutonic origins.

Quartz overgrowths seen in the samples from the Whirlpool-Manitoulin transition are non-luminescent. This is due to their growth at low temperatures in which the lattice is unable to accomadate activators which cause them to luminesce (Kopp, 1981).

3.2.3. Dolomite

Dolomite appears as deep red to bright red, pseudo rhombs under CL and displays well developed zonation. Crystals often have deep red cores and bright red outer rims, similar to the 'natural' dolomites of N.Italy (Zinkernagel, 1978) (see Plate 3.9). Bright red inner cores followed by deep red outer rims or a series of bright and dark bands is also common (see Plate 3.1.0.). This growth banding or zonation is due to different quantities of activators and quenchers depending on the ions present in the depositing fluids, its temperature, pH, Eh, etc. (Kopp, 1981). An example is a first generation dolomite with Fe-poor fluids creating a zone of no CL colour (Amieux, 1982). Some crystals display bright orange calcitic cores followed by zoned dolomite (see Plate 3.1.1.). This probably reflects progressive dolomitization of the pre-existing calcite cement.

3.2.4. Calcite

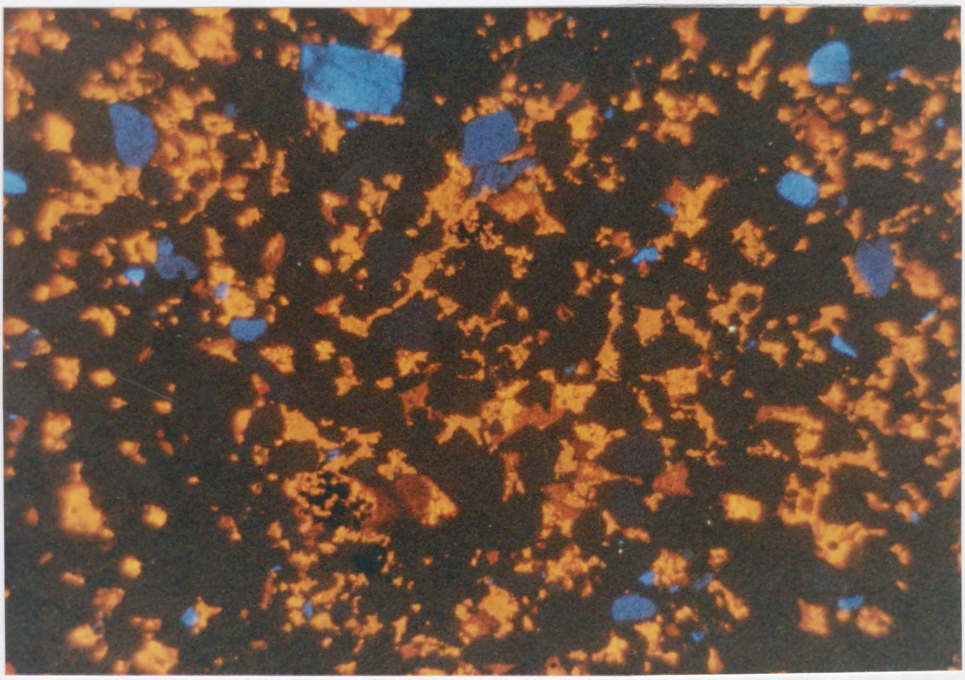
All calcite observed had a bright orange-red to orange CL colour. This reflects fluids with low Mg content (Nickel, 1978). Calcite appears as a pore filling cement, fracture infill, and fossil replacement (see Plate 3.1.2.).

3.2.5. Minor Constituents

A mauve to purple CL colour is displayed by chalcedonic quartz (See Plate 3.1.3.). Tourmaline grains display a yellow-green CL colour.

Plate 3.8 Large detrital quartz grains which luminesce bright blue indicating a plutonic source region. Dark red-brown grains are from a metamorphic source region. Calcite cement luminesces bright orange.

Plate 3.1.2 CL photograph showing calcite (bright orange) as a secondary pore filling cement and microfracture infill.



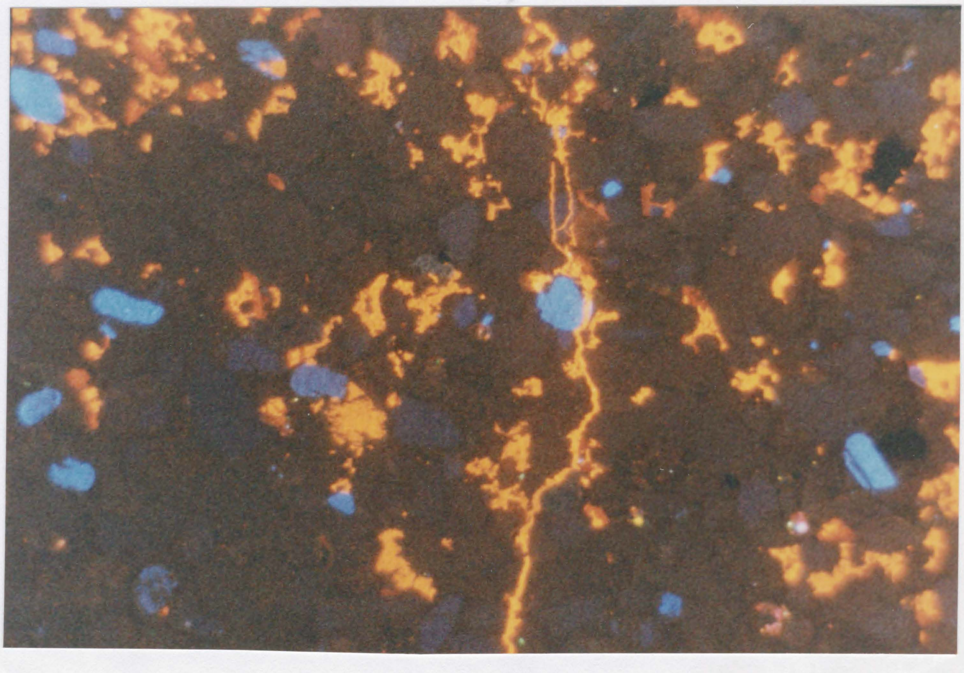


Plate 3.9 CL photograph showing zoned dolomite rhombs with deep red cores and bright outer rims replacing the inner section of a crinoid stem. The original preserved skeleton has been replaced by calcite, stained red in the upper PPL photo. Sample 1284, 280X magnification, top PPL, bottom CL.

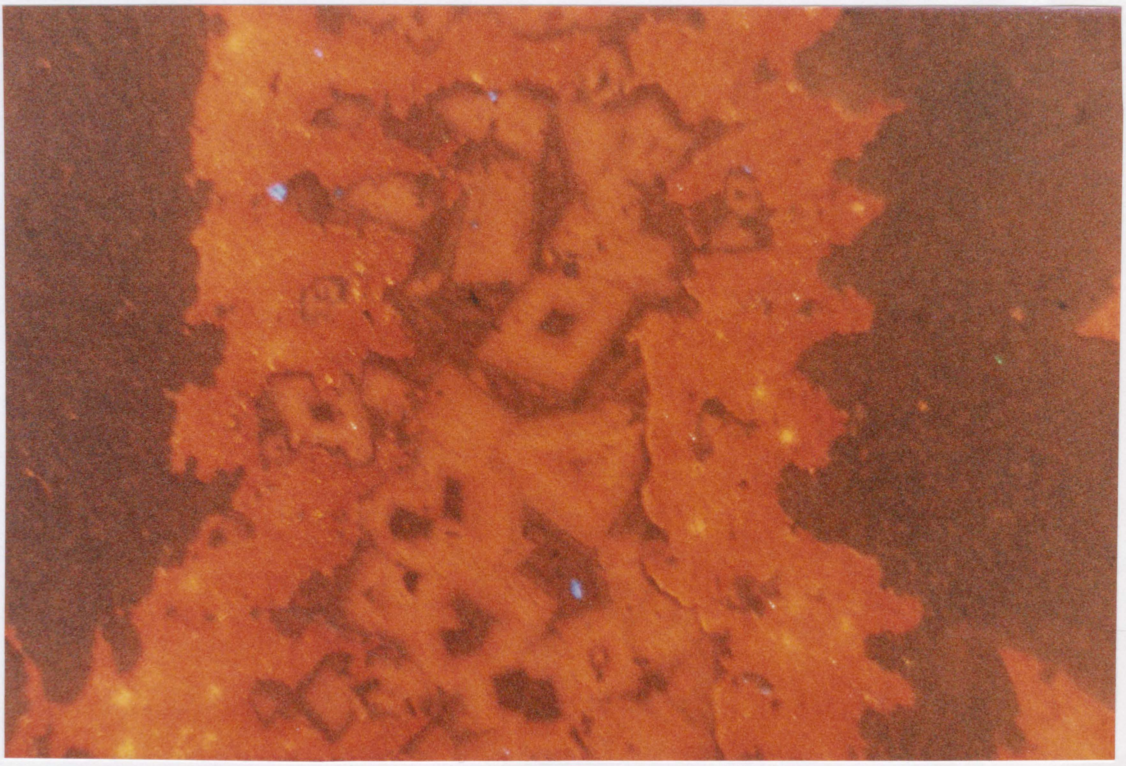
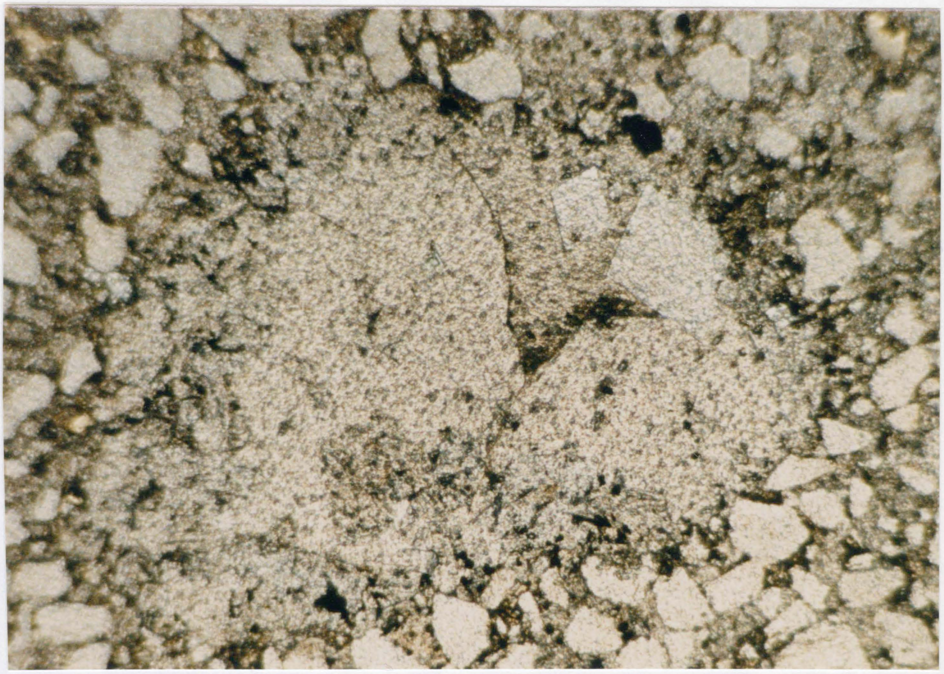


Plate 3.1.0. CL photograph showing the zonation of dolomite rhombs. Most of the dolomite shows either multiple banding or bright red inner cores followed by darker rims.
The dolomite shows a secondary replacement of a calcitic infilled fossil fragment. Sample 1281, 280 magnification, top PPL, bottom CL.



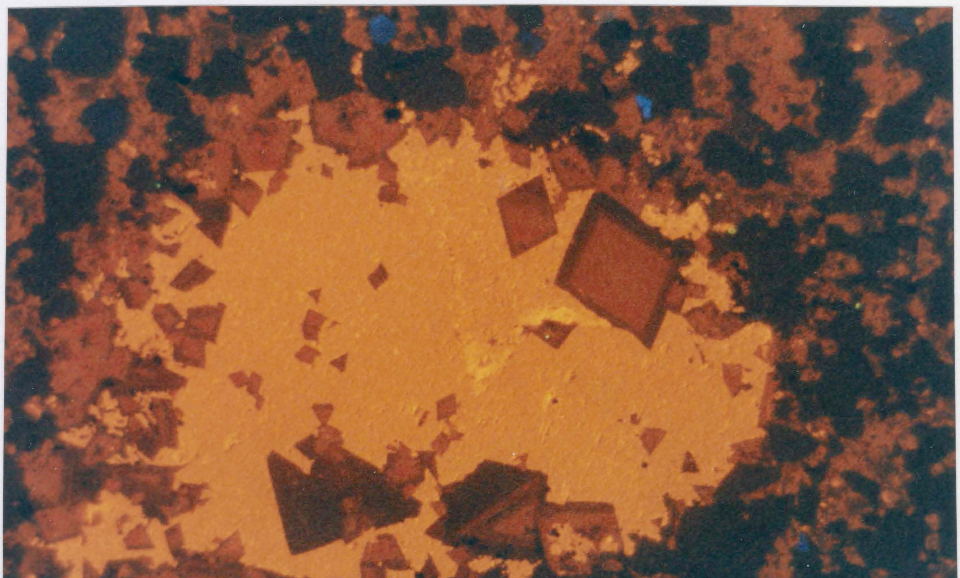
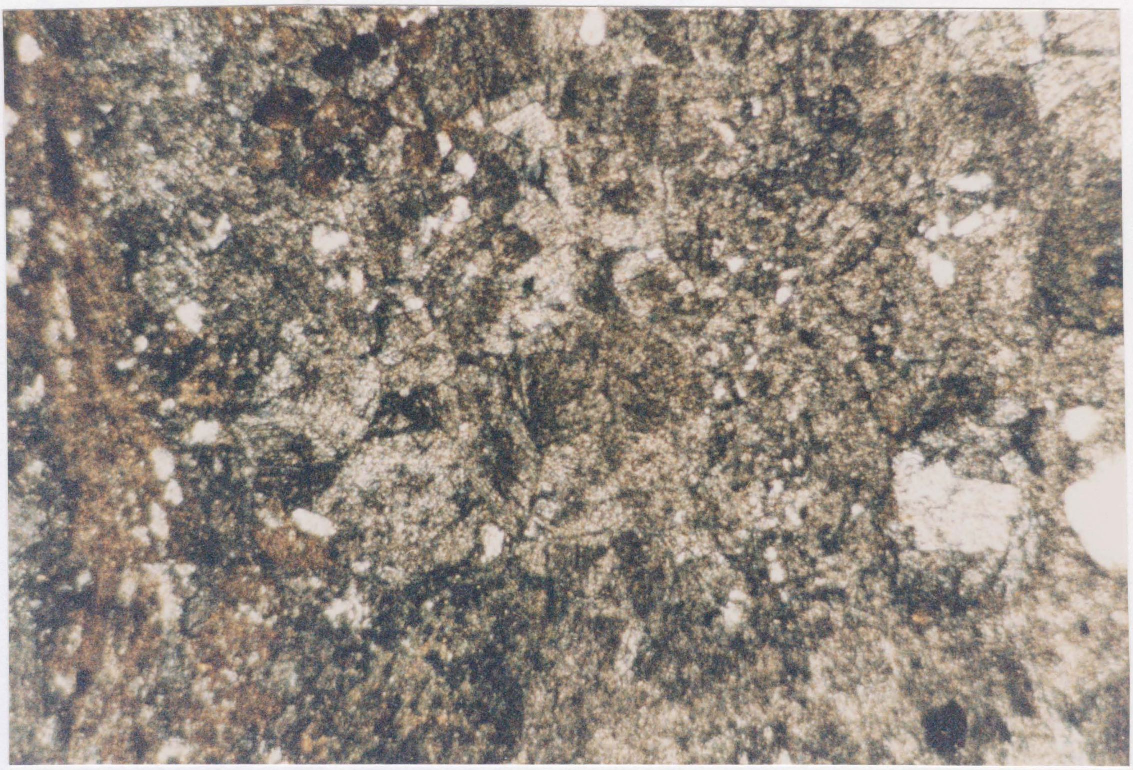


Plate 3.1.3. CL photograph shows mauve coloured bryzoans and a few blue quartz grains surrounded by a matrix of zoned dolomite rhombs. Sample 1281, 280X magnification, top PPL bottom CL.



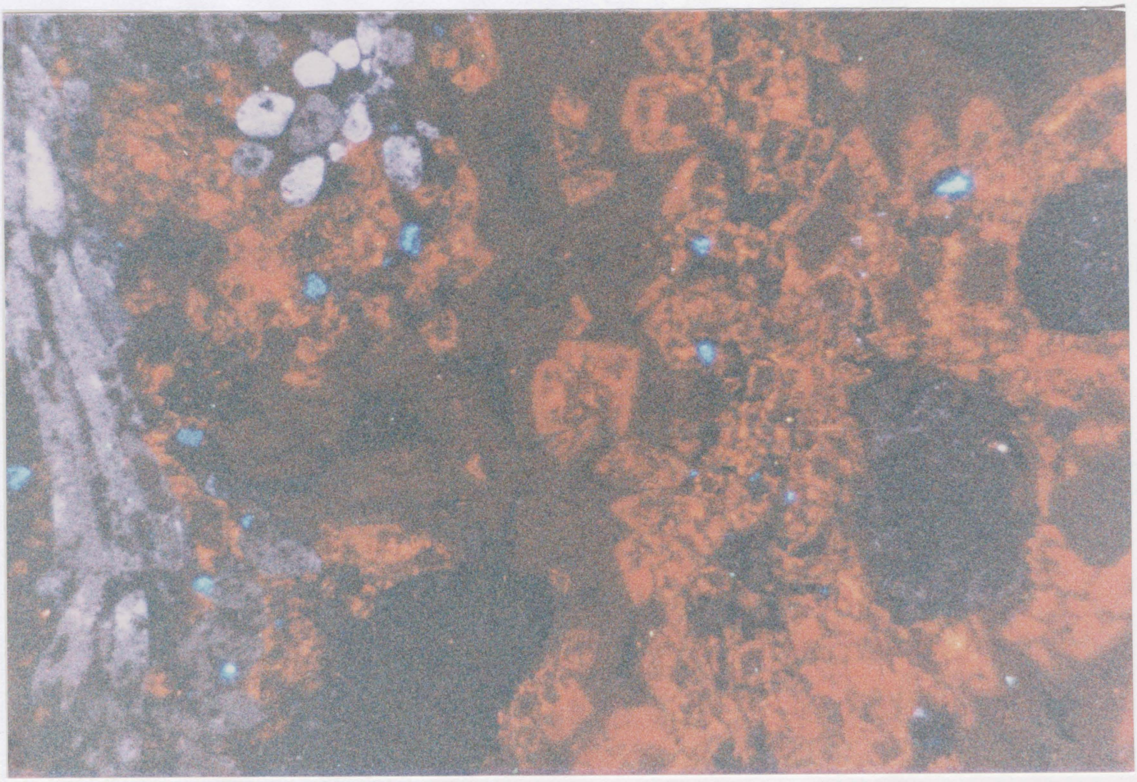


Table 3.2 Some common carbonate minerals and their reported CL colours.

Mineral	Luminescent Colour
Quartz from Verrucano sandstone N.Italy	red violet to light brown
detrital	dull blue - dull red
authigenic	no luminescence
hydrothermal quartz	bottle green to brown
plutonic and volcanic rocks (>573)	violet to violet-blue
low grade met-morphic (<573) quartz	brown
chalcedony	deep purple to mauve
calcite	
Low Mg	bright orange
High Mg	dull red
dolomite	
natural-N.Italy.	dark red outer core
	light red outer rim
Fe-rich	dark red and bright red
Tourmaline	bright green

Table 3.3 Modal percentages of minerals identified in thin section using CL technique.

Sample No.	Dolomite	Calcite	Quartz	Opaques Heavies	Glauconite
j.c.1	---	10%	85%	trace	---
sam 2	trace	60%	40%	---	---
3a2	90%	trace	5%	trace	---
7a	95%	trace	---	trace	trace
7b	80%	trace	20%	---	---
8a	85%	---	10%	---	---

Chapter 4

Diagenesis

4.1 Diagenetic Environments

Most cementation and dissolution in shallow marine carbonates occurs at relatively shallow depths in one of four major diagenetic environments: the vadose zone, meteoric phreatic zone, mixing zone, and the marine phreatic zone. These zones may be subdivided further on the basis of rate of water movement and the saturation of the water with respect to calcium carbonate (Longman,1980). Most carbonates are deposited and begin their diagenetic history in the marine phreatic environment. This environment can be subdivided into a zone of little water circulation in which micritization and minor intragranular cementation occur, and a zone of good water circulation near the sediment/water interface on shelf margins where extensive intergranular and cavity-filling cementation occurs. Zones of fresh and marine water mixing are often associated with subaerial exposure, fresh water replacing sea water in the pores of shallow water carbonates. Long-lived mixing zones with good water circulation and relatively low salinities often result in the formation of dolomite, whereas bladed Mg-calcite may form if the water is relatively saline. The freshwater phreatic environment may favour leaching in the zone of solution, and neomorphism of grains, accompanied by extensive intergranular calcite cementation in the active saturated zone. Neomorphism of grains without cementation may occur in the stagnant saturated zone. The freshwater vadose zone contains both air and meteoric water in the pores and can be subdivided into the zone of solution and zone of precipitation. Carbon dioxide from the atmosphere and biological activity in the soil contributes to solution which forms vugs, molds, and etched grains. Calcium carbonate saturated fluids which undergo evaporation precipitate fine, equant calcite in the form of pendant and meniscus cements. The interpretation of diagenesis in carbonates is complex due to the frequent changes in the diagenetic environment (Longman, 1980).

4.2 Diagenetic Processes

The principal diagenetic processes are cementation, diagenetic reorganization (authigenesis), diagenetic differentiation and segregation, diagenetic metasomatism, intrastratal solution, and compaction (Pettijohn,1975).

Cementation is the process of precipitating minerals into the pore space of a sediment. Many species of minerals are known to play the role of cement. The Manitoulin Formation exhibits three major cements: quartz, present as quartz overgrowths on detrital quartz grains; calcite; and dolomite. The textures of cements are of considerable importance. When the mineralogical composition of the cement is the same as that of the detrital grains, the cement is deposited in crystallographic optical continuity on the detrital grains. Calcite may show various textures related to conditions during cementation which can help in determining diagenetic history. Equant calcite cement is formed in freshwater phreatic environments whereas meniscus and pendant cements form in the freshwater vadose zone.

A definite order or paragenesis of cementing minerals is often determinable. The order of precipitation of several cementing minerals is often established on the principle that those minerals precipitated first will be more euhedral and attached to the walls of interstices. However, euhedralism of some minerals such as dolomite crystals means only that these are metacrysts formed during replacement. Origins of cementing material is another problem partially unresolved. Quartz overgrowths and chalcedonic quartz replacement of fossil material within the Manitoulin Formation is thought to have been derived from migrating pore fluids saturated in silica (Calow,1983). This silica was originally derived from the dewatering of surrounding compacted shales. The migrating pore fluids that originally formed quartz cement are thought to have become acidic in nature which then have resulted in the dissolution of detrital carbonate (Calow,1983). Reprecipitation of calcite pore-filling cement was then accomplished when Ca-rich fluids became static due to the buildup of quartz overgrowths and resultant loss of permeability. The Manitoulin-Whirlpool transition contains non-ferroan calcite cement suggesting reprecipitation close to the region of dissolution with little mixing with large quantities of pore fluids (Calow, 1983).

Authigenic processes occuring within a sediment attempt to establish an equilibrium assemblage by elimination of an unstable mineral species and its replacement by a stable species (Pettijohn, 1975). Processes involved include: a) reduction, especially of iron b) dehydration, eg. gypsum converting to anhydrite c) reaction between solid and liquid phases, eg. clay minerals take up potash to form glauconite or clay mica, calcium carbonate takes up magnesium to form dolomite (Pettijohn, 1957).

Calcite is the authigenic derivative of aragonite which is the chief constituent of some invertebrate shells and skeletal structures, eg. Aragonite is metastable, and inverts to calcite in a relatively short time (Pettijohn, 1975). Calcite may also appear as an overgrowth on detrital calcite, such as crinoid ossicles. Dolomite is mainly authigenic and shows rhombic euhedra transecting and replacing earlier structures such as fossils. Dolomite is distributed as scattered rhombs within the Manitoulin-Whirlpool transition, but forms an interlocking mosaic of crystals almost totally replacing calcite in the middle to upper section of the Manitoulin Formation.

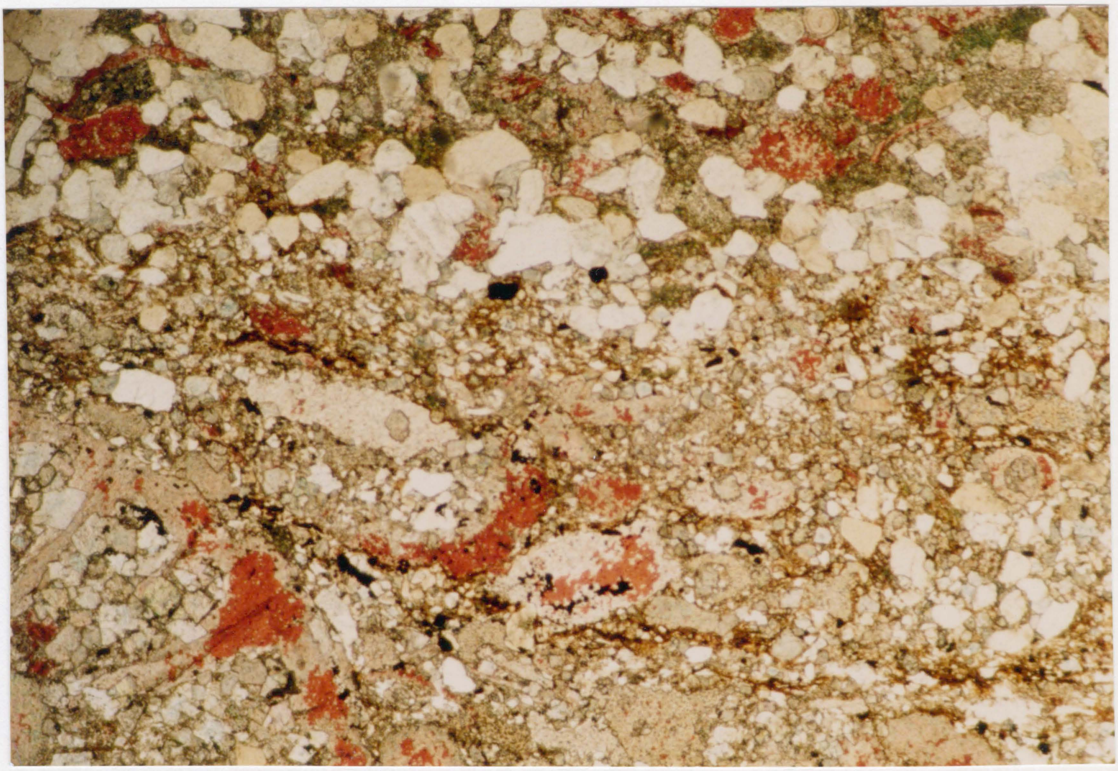
Authigenic anhydrite is common in sandstones as a minor cementing mineral. It is found in small quantities in the Whirlpool-Manitoulin transition of the drill core thin sections where it has not undergone leaching by groundwaters.

Authigenic pyrite is common in many sediments as scattered pyrite cubes, crystal aggregates, spherulites, and as a replacement of shells. The Manitoulin Formation contains scatered pyrite cubes as well as clusters of crystal aggregates associated with replaced fossil debris. Pyrite forms where bacteria can produce H_2S if there is available concentrations of dissolved sulphate and metabolized organic matter (Berner, 1971).

Diagenetic metasomatism involves introduction of materials from outside the system leading to replacement of one mineral for another with little volume change. The Manitoulin Dolomite represents large scale replacement of previous minerals. However, dolomitization does produce a significant increase in porosity through solution which could lead to a compactional decrease in volume if there was significant pressure from overlying sediments. Further study into the dolomitization processes will be discussed in the following section.

Intrastratal solution takes place within the sedimentary bed after deposition. This solution can lead to both the formation of secondary porosity and secondary replacement by precipitating minerals. Criteria useful in the recognition of intrastratal solution in the Manitoulin Dolomite includes clay seams, swarms of clay seams, and etched quartz grains (Barrett, 1964). Clay seams which skirt around around larger skeletal grains, and quartz grains which are truncated against but do not cross the seam indicate pressure solution following deposition (see Plate 4.1). Clay seams indicate pressure solution before dolomitization, shown by dolomite rhombs which protrude up through the clay seam. Factors critical in pressure solution include stress, nature of the pore fluid, local porosity and permeability, rate of fluid flow, temperature, and the concentration of clay in the rock (Bathurst, 1975).

Plate 4.1 Clay seams shown skirting around larger grains. Fine dolomite crystals concentrated near the seam.PPL 250X magnification.



Pressure solution is thought to be more important later in diagenesis under greater burial depths.

4.3 Dolomitization

Research on ancient dolomites has revealed two types. Primary, often characterized by peritidal rocks, and secondary, formed by the replacement of pre-existing limestone. Dolomitization is controlled by permeability, composition and particle size of the host, physiochemical parameters including temperature and pressure, and ionic concentration and composition of the pore fluid. Models for dolomitization include evaporative reflux, capillary concentration and evaporative pumping, fresh water-brine mixing, connate water expelled by shale compaction, and cannibalization of Mg-calcite sediments.
Variation and combinations of these models have also been suggested.

Dolomitization processes are either post depositional or diagenetic. Post depositional primary dolomite is of little significance in ancient dolomites and is often obscured by secondary replacement dolomite (Bathurst, 1975). Diagenetic dolomitization can be further subdivided into syngenetic (initial burial), anagenetic (compacted, maturation stage of lithification), and epigenetic (post orogenic). Syngenetic dolomitization passes beyond the depositional phase, and results from surficial solutions (Freeman, 1972). Syngenetic dolomitization forms under shallow burial, whereas epigenetic dolomites may form under shallow or deep burial.

The Manitoulin Dolomite contains the following petrographic features which support a late diagenetic or epigenetic stage of dolomitization:

1/ Idiomorphic rhombohedrons of dolomite with a nucleus and zonation common (Chilingar, 1979).

2/ The coarse grain size of dolomite (>100μ) is suggestive of late dolomitization (Chilingar, 1979).

3/ Dolomite focused along or truncating undulating clay seams or microstylolites, formed by pressure solution, implies epigenesis (Freeman, 1966).

4/ Dolomite crystals concentrated in or floating in secondary void fillings suggest epigenesis (Freeman,1966).

5/ Pervasive replacement of fragments and matrix alike. Fabric permeability exercises no control on the degree of dolomitization and therefore dolomitization must have occured after thorough cementation (Wilson, 1975).

Past theories presented to explain the dolomitization of the Manitoulin Formation have been suggested by Cameron (1975). He suggested seepage refluction (Adams and Rhodes, 1960 ; Deffeyes, 1965), or evaporative pumping (Hsu and

Siegenthaler, 1969), as possible models. However, both of these models are syngenetic and suggest shallow burial dolomitization which is contrary to the petrographic evidence.

The two major requirements for dolomitization of pre-existing limestone rock are: a sufficient source of Mg, usually expressed as an Mg:Ca ratio, to enable dolomitization to proceed; and a driving mechanism to flush a large volume of water through the rock to complete the process of dolomitization. These requirements must be met in any process suggested for dolomitization.

Illing (1959) and Jodry (1969) have presented arguements for the dolomitization of permeable reefal limestones by connate waters derived by compaction of adjacent or enclosing shales. The Mg:Ca ratio of connate waters in shales or other compactable sediments may be enriched by the precipitation of calcite cements, the release to the pore fluid of Mg from Mg-calcite bioclasts and mud by incongruent solution, and by exchange reactions with clays. Organic maturation processes affecting pH, and ionic concentrations may also enhance dolomitization. Further, the rate of dolomitization may be increased due to an increase in temperature and pressure in the subsurface. Mattes and Mountjoy (1980) have presented similar arguements in their theory of burial dolomitization, but have also included the process of mixing of near surface fluids with deep burial brines along fracture-controlled conduits. Both major requirements previously outlined are met in these suggested models.

Recent studies on the Whirlpool Sandstone, underlying the Manitoulin Dolomite suggest that the Whirlpool Formation acted as a conduit system for pore fluids expelled by surrounding shales and migrating up-dip from a depositional basin to the southeast. Calow (1983) uses this theory to explain the presence of authigenic quartz cement, patchy pyrite cement, the formation of authigenic illite, and the presence of ferroan/non-ferroan calcite and zoned dolomite cements in the upper marine beds. The previously mentioned shale dewatering deep burial dolomitization theories help justify Calow's hypothesis and support petrographic evidence of epigenetic dolomitization of the Manitoulin Dolomite. It is suggested that the Manitoulin Formation was dolomitized by Mg- rich pore fluids migrating up-dip from a basin in the south-east. This occured due to the compaction of surrounding shales and may have been aided by mixing of near surface fluids with deep burial brines along fractures.

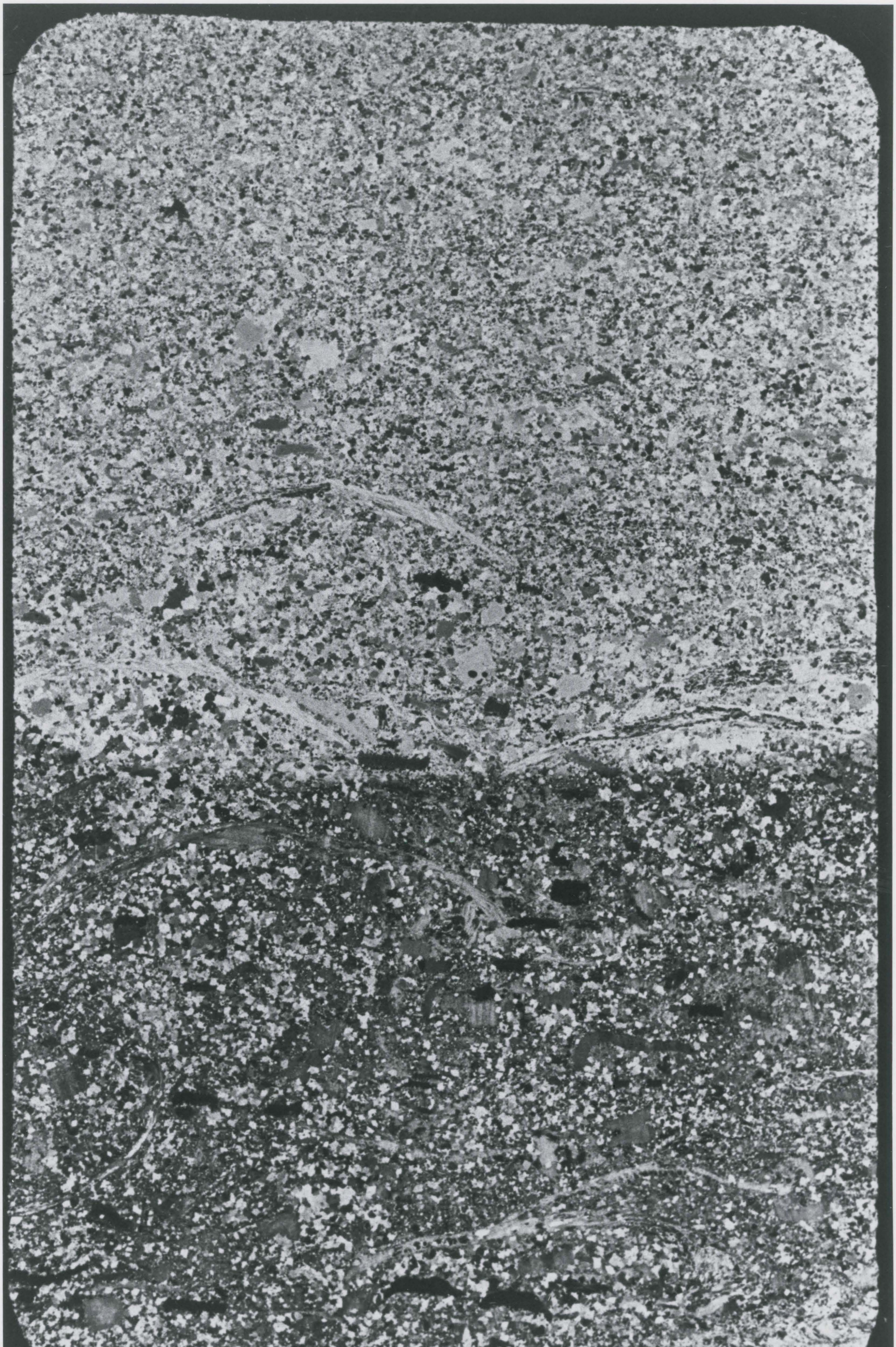
4.4 Palaeontology

The Manitoulin Formation contains an abundant marine fauna, which has been studied by Johnson (1934), Caley (1940), and Bolton (1953). The primary purpose of this study was not paleontological and therefore only the principle fossil groups have been identified. Patterns in abundance and occurance of fossil material is the main concern, which can help in affirming depositional environment. The main groups of fossils4 within the Manitoulin Formation are documented in Table 4.1.

General patterns are noticable in the Manitoulin Formation, which include an increase in abundance and variety of fauna towards the top of the formation. Many of the species found in the uppermost section are also common to the overlying Cabot Head shales. Fossil material is deposited in two different environments. High energy storm currents deposit fossils as randomly orientated shell lags, or as sparsely distributed fossils in the lower-most clastic beds of the Manitoulin Formation where marine fauna is not abundant.

Brachiopods are the most abundant species found throughout the section. They are concentrated in the marker bed within facies C and the shell lag of facies D. The brachiopods identified in thin section have been

Plate 4.4.1. : Micrograph of a shell lag deposit showing randomly orientated brachiopod shells, which tend to indicate higher energy deposition.



replaced by non-ferroan calcite which is then partially or fully replaced by chalcedonic quartz.

Rugose corals are found throughout the section and are orientated parallel to bedding. Usually the shell is partially dissolved around the outer edge, but well preserved in the inner portion due to silicification.

Crinoid ossicles are abundant in Facies C and Facies D. A few well preserved crinoid stems were found along bedding planes within Facies C.

Bryzoans are only found in abundance in the uppermost unit of Facies D. Some small bryzoan colonies are evident within the upper section of Facies C.

Echinoderms are abundant in the low angle cross stratified unit of Facies D. Most of them have undergone replacement by authigenic glauconite, but still show original internal texture. The large semi-confined environment within an echinoderm is favourable for the precipitation of glauconite (Odin and Matter, 1981).

Small 'ballstone' stromatoporoids have been identified within Facies C. Stromatoporoids are characteristic of clear water, and slow sedimentation rates, and could therefore indicate a time hiatus in deposition (Clarkson, 1979).

Other fauna which have been documented include gastropods, trilobites, and ostracods. The fauna which are present within the Manitoulin Formation reflect a normal shallow marine setting.

Table 4.1 Main groups of fossils within the Manitoulin Formation in the Hamilton region.

Group and Species

Stromatoporoidea

Clathrodictyon vesiculosum N. and M.

Anthozoa

Enterolasma
Neozaphrentis
Streptelasma

Crinoidea

gen.et sp.ind.

Bryozoa

H. cf. magnopora
Subretepora angulata
Fenestrellina tenuis
Helapora fragilis
P. ensiformis
P. expansa
P. punctata
Pachydictya crassa
P. turgida
Rhinopora verrucosa
Lichenalia concentrica

Brachiopoda

Dolerorthis flabellites
Hesperorthis cf. davidsoni
Glyptorthis fausta
Platystrophia biforata
R. cf. lepida savage
Plectatrypa marginalis
Dalmanella sp.
Leptaena rhomboidalis
Rhynchotreta sp.
Strophomena sp.
Rhipidomella sp.
Camarotoechia sp.

Gastropoda

Tentaculites minutus
Tentaculites bellulus

Trilobita

Calymene clintoni
Calymene niagarensis
Dalmanites cf. *limulurus*

Ostracoda

Leperditia sp.

(after Bolton, 1957 and Angold, 1955)

Chapter 5

Depositional Environments

The Manitoulin Formation in the Hamilton region represents a transgressive sequence from shallow marine inner shelf to deeper marine middle to outer shelf (see Fig 5.1). Environments are laterally intergradational, with the Manitoulin member forming a reef complex to the north-east, a shelf complex in the Hamilton region, and offshore deeper marine to the south-west in the Lake Erie region. The lower to middle Silurian was a period of reef developement with sea level changes producing the cyclic nature of the carbonates (Mesolella et al,1974).

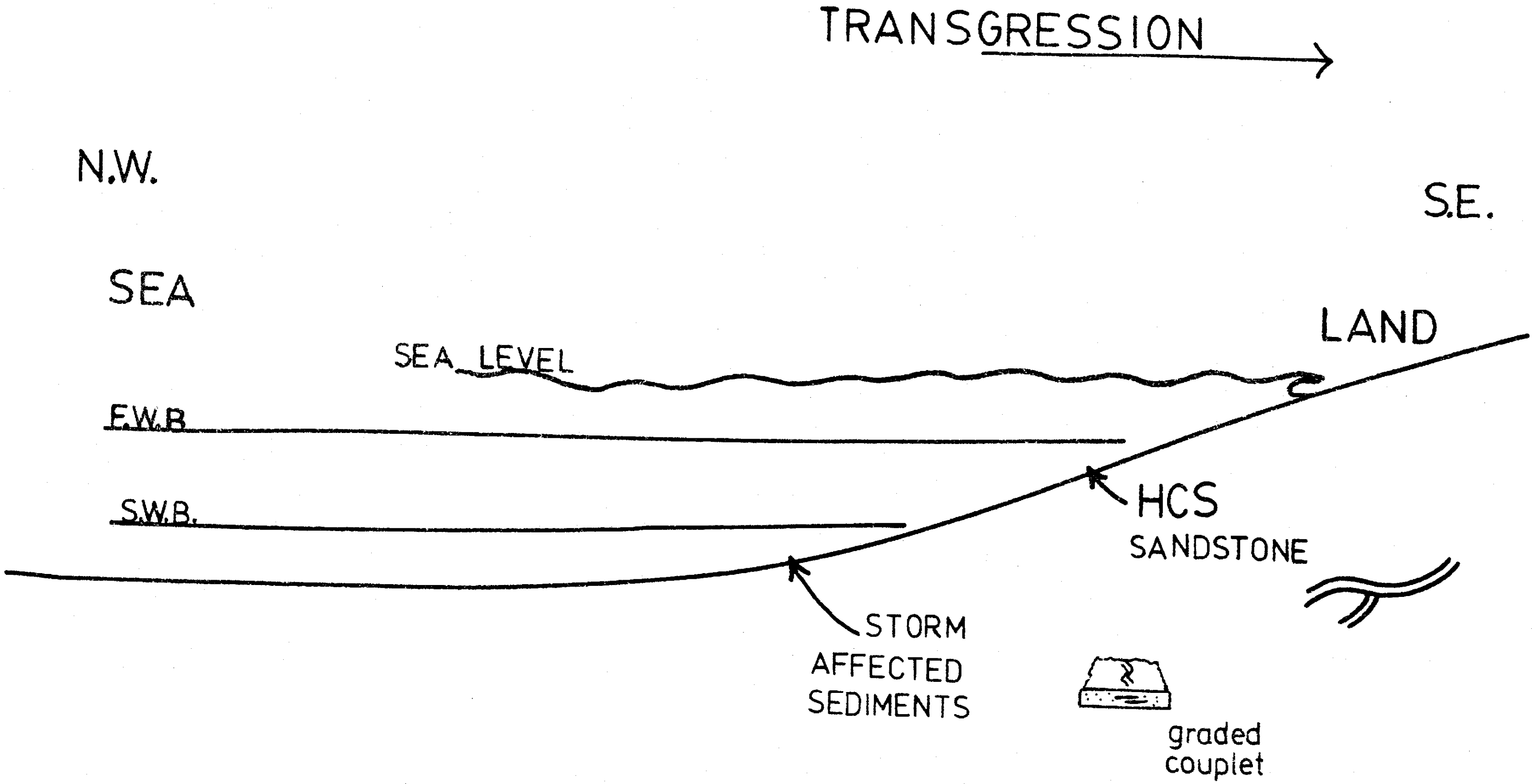
In the Hamilton region the base of the transgressive sequence is characterized by hummocky cross-stratified sandstones. These sandstones are considered to be the result of a combination of waning storm-generated unidirectional flows with superimposed oscillatory storm wave action (Swift et al,1983). The Flock Road section in Hamilton contains three sets of hummocky cross-stratified beds ranging in thickness from 25-41 cm. Each of the beds is characterized by a thin bioturbated layer at the top which has been subsequently scoured into by the overlying HCS beds (see Fig 2.6). The Jolley Cut section shows a 7 cm thickness of the HCS unit. The upper contact of the HCS unit with Facies B in both locations is erosive which suggests that the HCS bed at Jolley Cut has undergone more extensive scouring than the beds at Flock Road (G.Plint pers. comm.).

Facies B is characterized by extensive bioturbation, and represents deposition in a relatively low energy shallow marine environment. The base of the unit shows a sharp erosive contact with the underlying Whirlpool Sandstones. Large pebbles and lithified sandstone clasts within the base of the facies are indicative of high energy flows capable of eroding pre-existing, already lithified sediments from the underlying HCS beds. The presence of lithified clasts within Facies B also indicates a hiatus in deposition between Facies A and Facies B. The trace fossils Planolites, and Chondrites support the idea of a low energy shallow marine setting, while the presence of Skolithos indicates a higher energy environment (Frey and Pemberton,1984).

As previously mentioned, cyclic carbonates were characteristic of the Silurian time period in the Michigan Basin (Mesolella et al, 1974). Facies C is composed of numerous couplets, each of which consists of a quartz-rich, parallel laminated, unfossiliferous unit (C1) overlain by an argillaceous bioturbated fossiliferous unit (C2). The sharp based C1 unit is distinctive of episodic influxes of fine grained sediment rapidly falling out of suspension. This sediment was most likely derived from a distant storm surge event which was capable of carring suspended fine grained sediment out to the middle shelf (Wilson and Jordan, 1983). This was followed by a quiescent period depositing a thicker argillaceous unit which was thoroughly bioturbated. A slightly nodular texture was noted in this unit, possibly due to solution compaction along numerous tiny solution seams, concentrating clay layers between purer calcium carbonate lumps (Wilson and Jordan, 1983). Shale partings are common between units C1 and C2 and often form bedding planes, and represent periods of presumably low energy sedimentation. The fossils found within Facies C reflect a stenohaline shelf environment with open marine circulation and normal marine salinities (Wilson and Jordan, 1983). Fossils include the following groups: brachiopods, echinoids, and crinoids. The presence of stromatoporoids, and branching horizontal burrows towards the top of Facies C suggests quiet clear water conditions with little sedimentation. The large horizontal burrow traces are marked by colour and textural differences which is accentuated by dolomitization. The burrows are packed with coarse, well sorted, silicified fossil material which is characteristic of burrowing by crustaceans. (M.Risk pers. comm.)

The upper facies of the Manitoulin Formation represents an outer shelf open marine environment. Glauconite abundance in the basal unit is favoured by a quiet environment, as well as transgressive conditions (Odin and Matter, 1981). The low angle cross stratified appearance of the glauconite-rich sediments suggests reworking of bottom sediments by high energy storm waves which produced fossil-filled scours between the stratified sets. The cross stratified unit is overlain by a large unsorted shell lag bed which was probably emplaced by a bottom traction current. Immediately above this lies a fine grained parallel laminated bed which suggests that the flow quickly waned. All the sediments within facies D suggest rapid deposition in an otherwise quiet outer shelf environment. Fossil material within the shell lag is of the stenohaline type and includes the following: crinoids, brachiopods, gastropods, bryzoans, and echinoderms. The fossil material is unsorted, and randomly orientated suggesting rapid deposition. The top surface of the uppermost unit of Facies D contains small vertical burrows which penetrate fine grained sediment indicating that burrowing occured after deposition. This unit marks the top of the Manitoulin Formation and is directly overlain by a thick sequence of Cabot Head shales which represents a deep marine environment resulting from further marine transgression.

Figure 5.1 Diagrammatic sketch illustrating the depositional types and sequence of sediments seen in the Manitoulin Formation indicating a marine transgression.


TRANSGRESSION
N.W.
S.E.
SEA
LAND
SEA LEVEL
F.W.B
S.W.B.
HCS
SANDSTONE
STORM
AFFECTED
SEDIMENTS
graded
couplet

Chapter 6

Conclusions

1. The base of the Manitoulin Formation is a transgressive deposit, probably deposited on the inner shelf and was the result of a marine transgression that advanced towards the south-east. This was probably the result of a widespread eustatic sea level change during the early Silurian time (Mesolella et al,1974).

2. The middle section of the Manitoulin Formation represents a middle shelf environment characterized by alternations of argillaceous sediments deposited slowly during periods of fairweather, and sandy storm-related deposits.

3. Storm wave reworking of coarser sediments in the inner shelf region resulted in hummocky cross stratification. The tops of beds are commonly bioturbated and scoured by the succeeding HCS bed.

4. The mineralogy of the Manitoulin Formation in the study area includes: quartz, present as detrital grains, authigenic overgrowths, and chalcedonic quartz replacement; dolomite, present as cement and secondary replacement; calcite, present as cement and fossil replacement; feldspar; opaques (pyrite) and heavy minerals (tourmaline); chert, phosphatized fossil fragments, and sedimentary rock

fragments; detrital muscovite; glauconite; minor amounts of anhydrite, hematite, and clay cements.

5. Cathodoluminescent microscopy has proven very useful in determining the diagenetic history of the Manitoulin dolomite. The following diagenetic features have been identified:

1. Non-ferroan sparry calcite is seen as fossil replacement, pore filling cement, and cement within microfractures.

2. Secondary zoned dolomite crystals are seen partially or fully replacing sparry calcite.

3. The zoned dolomite crystals reflect fluctuations in pore water compositions.

5. CL microscopy distinguishes two quartz types, metamorphic and plutonic, indicating two source areas.

6. Detrital quartz grains and secondary overgrowths are easily distinguished.

6. The Manitoulin dolomite contains petrographic features which suggest epigenetic dolomitization. These are briefly summarized: zoned dolomite, coarse grain size of dolomite, dolomite concentrated along clay seams, dolomite crystals concentrated in secondary void fillings, and pervasive replacement of original grains and matrix alike.

7. A model suggested for the dolomitization of the

Manitoulin Formation combines a hypothesis suggested by Calow (1983) and a mechanism proposed by Mattes and Mountjoy (1980). It is suggested that the Manitoulin Formation was dolomitized by Mg-rich pore fluids migrating up-dip from a basin in the south-east. These fluids originated from the compaction of surrounding shales and may have been supplemented by mixing of near surface fluids with deep burial brines along fracture-controlled conduits.

8. The fauna of the Manitoulin Formation reflect a stenohaline environment with open marine circulation and normal marine salinities.

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APPENDIX 1

Cathodoluminescent Microscopy

Instrumentation:

Parameters associated with CL instrumentation have been adopted by Marshall (1977). Operating instructions have been supplied by the Nuclide Corporation.

Beam Energy: 12kv D.C.

Beam Current: 15 microamp

Spot Diameter: Focus set to 6

Gun type: Cold Cathode

Ambient Gas: Air

Instrument Type: Nuclide Luminoscope with Lietz petrographic microscope.

Sample preparation:

The thin sections have been cut slightly thicker than normal, lightly polished on the bottom and highly polished on the top. They were left uncovered until after use with CL at which time cover slips were affixed for examination under normal light.

Photography: Fugii 400 speed colour film was used with the following exposure times:

Plane light: 0.5 seconds

XN : 10.0 seconds

CL : 20.0,30.0,40.0 seconds

Varying CL light intensities was cause for experimentation with exposure times. It was determined that the 40.0 second exposure gave the brightest clearest print.

APPENDIX 2

Staining techniques

The method of staining developed by Lindholm and Finkelman (1971) was used in the identification of ferroan/non-ferroan calcite and dolomite. The calcite readily stained, while the dolomite partially stained on the edges of rhombohedrons. Non-ferroan calcite stains red, ferroan calcite mauve to purple, and dolomite blue.

Method:

1/ The solution consists of 1 gram of Alzarin Red-S and 5 grams of K-ferricyanide, dissolved in 1 litre of 0.2 HCL.

2/ The 0.2 solution of HCL was prepared by adding 2 ml of concentrated (12 normal) HCL to 998 ml of distilled water (always add acid to water).

3/ 0.5 g of Alzarin Red-S and 2.5 g of K-ferricyanide were dissolved in 500 ml of the 0.2 HCL solution.

4/ One half of the thin section was immersed in the 0.2 HCL etching solution for 30 seconds.

5/ The etched half was then immersed in the staining solution at room temperature for 2-4 minutes.

6/ After staining the sections were rinsed in distilled water and allowed to air dry.

The solution must be prepared fresh, since it gradually oxides, to ensure proper stain colouration.

APPENDIX 3

Acetate Peels

Preparation and procedure have been modified after McCrone (1963) and Katz and Friedman (1965).

Materials required for acetate peels:

Dilute hydrochloric acid (1)

Acetone

Single mat commercial acetate film (0.005 in. in thickness)

Procedure:

The technique requires cutting and polishing of a carbonate rock slab. After polishing, the specimen is washed and dried and the polished face is etched in dilute hydrochloric acid for 1 minute. The specimen is then washed and dried, making sure not to disturb the micro-relief on the etched surface. The etched surface is wetted with acetone and a piece of cellulose acetate is placed dull side down over the etched surface. Air bubbles are driven off by bending the acetate in a U-shape with the dull side down and then rolling the acetate onto the acetone-wetted surface. Adhesive forces keep the film pressed onto the rock slab without any pressure being applied to the surface. The acetate film was left on the slab for 1-5 minutes. Experimentation with the time period needed is recommended as some peels were to dry to remove while others did not preserve enough textural features. The peel can be removed by gently peeling away one corner, and then flattening out immediately between glass plates to prevent curling of the acetate film. Staining acetate peels was also attempted by the method outlined by Katz and Friedman (1965) but the stains did not successfully preserve on the peels.

APPENDIX 4

Carbon Determination Analysis

A combination of two methods have been used to determine the percentage of inorganic and organic carbon. An estimation of total carbon content was made by the use of a high-frequency induction furnace for combustion of sediment samples at temperatures exceeding 1500 C. An estimation of organic carbon was accomplished using ignition loss at 600 C.

Analytic Procedures

Total carbon determination using a high-frequency induction furnace.

1/ Samples are dried and finely ground using a mortar and pestle.

2/ 1 gram of each sample is weighed out while in porcelain crucibles.

3/ Prior to combustion in the CR-12 carbon analyzer a layer of quartz sand, previously determined to contain no carbon, is placed over the sample in the combustion boat. The quartz sand layer acts as a modifier, improving the accuracy of the system by inhibiting the escape of volatile organic compounds. The carbon analyzer is set to combust the sample at 1350 C in a stream of oxygen and the standard used to calibrate the system is analytic-grade calcium carbonate (Krom and Berner,1982). The total carbon content for the sample appears on the digital readout, which can then be converted to a percentage total carbon for the sample.

Organic Carbon Determination

1/ 1 gram of each of the finely ground samples is placed in porcelain crucibles.

2/ These samples are placed in a muffle furnace at 450 C and left overnight.

3/ The samples are removed the following morning, allowed to cool, and then analyzed for carbon in the C-12 carbon analyzer by the same procedure described above, only no quartz sand modifier is used.

4/ Percentages are then derived for total inorganic carbon, since all organic carbon has been lost due to ignition.

Tabulated results are made for total carbon and inorganic carbon percentages, the difference between the two being the organic carbon constituent. Two sample runs were made for the above procedures and the average computed. It should be noted that both sample run values were nearly identical for percentage of total, and inorganic carbon.