AN ICHNOLOGICAL AND SEDIMENTOLOGICAL STUDY OF DEVONIAN BLACK SHALES FROM THE LONG RAPIDS FORMATION, MOOSE RIVER BASIN, NORTHERN ONTARIO

AN ICHNOLOGICAL AND SEDIMENTOLOGICAL STUDY OF DEVONIAN BLACK SHALES FROM THE LONG RAPIDS FORMATION, MOOSE RIVER BASIN, NORTHERN ONTARIO

by

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ABSTRACT

The Long Rapids Formation in the Moose River Basin of northern Ontario is Upper Devonian in age and can be correlated with similar shale deposits in the Michigan, Appalachian, and Illinois Basins. The southern Ontario equivalent to the Long Rapids Formation is the Kettle Point Formation.

The Long Rapids Formation is a marine black shale deposited predominantly under depleted oxygen conditions. Large amounts of marine organic matter from the water column and from terrestrial sources accumulated in reducing bottom waters with little recycling to produce brown to black, organic-rich sediments. The depositional basin was stratified, and anoxic bottom waters and oxic surface waters were separated by a pycnocline. The position of the pycnocline (or the absence of it) dictated the type of sediment deposited, and the relative depth of the pycnocline to the sediment-water interface was more important than the absolute depth of the water column. The Moose River Basin in Late Devonian times was located on the Laurasian Continent in an area experiencing tropical conditions and was affected by a period of transgression following the Acadian Orogeny. The black shales in the Long Rapids Formation represent a period of transgression of the large epicontinental Catskill Sea, whereas the green-grey mudstones and carbonates represent periods of minor eustatic changes.

Dark-coloured facies with abundant bioturbation are overlain by lighter-coloured facies. Bioturbation is variable in the less abundant green-grey mudstone and carbonate facies, and were also low in organic matter. The ichnofauna suite *Chondrites-Planolites-Zoophycos-Alcyonidiopsis-(?Teichichnus)* represents an oxygen-minimum ichnofacies found predominantly in dark shale facies. As more oxygen was introduced to the sediment-water interface, more permanent burrow structures were constructed such as *Teichichnus, Terebellina, ?Cylindrichnus, Skolithos,* and Ichnogenus "A" in the green-grey mudstones and carbonates. As well, body fossils were more commonly found in those facies. The *Leiorhynchus* brachiopod fauna in the dark-coloured shales probably represents a sparse epifauna living in poorly oxygenated or temporarily oxic conditions in a basinal or open-shelf environment.

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CHAPTER 1:

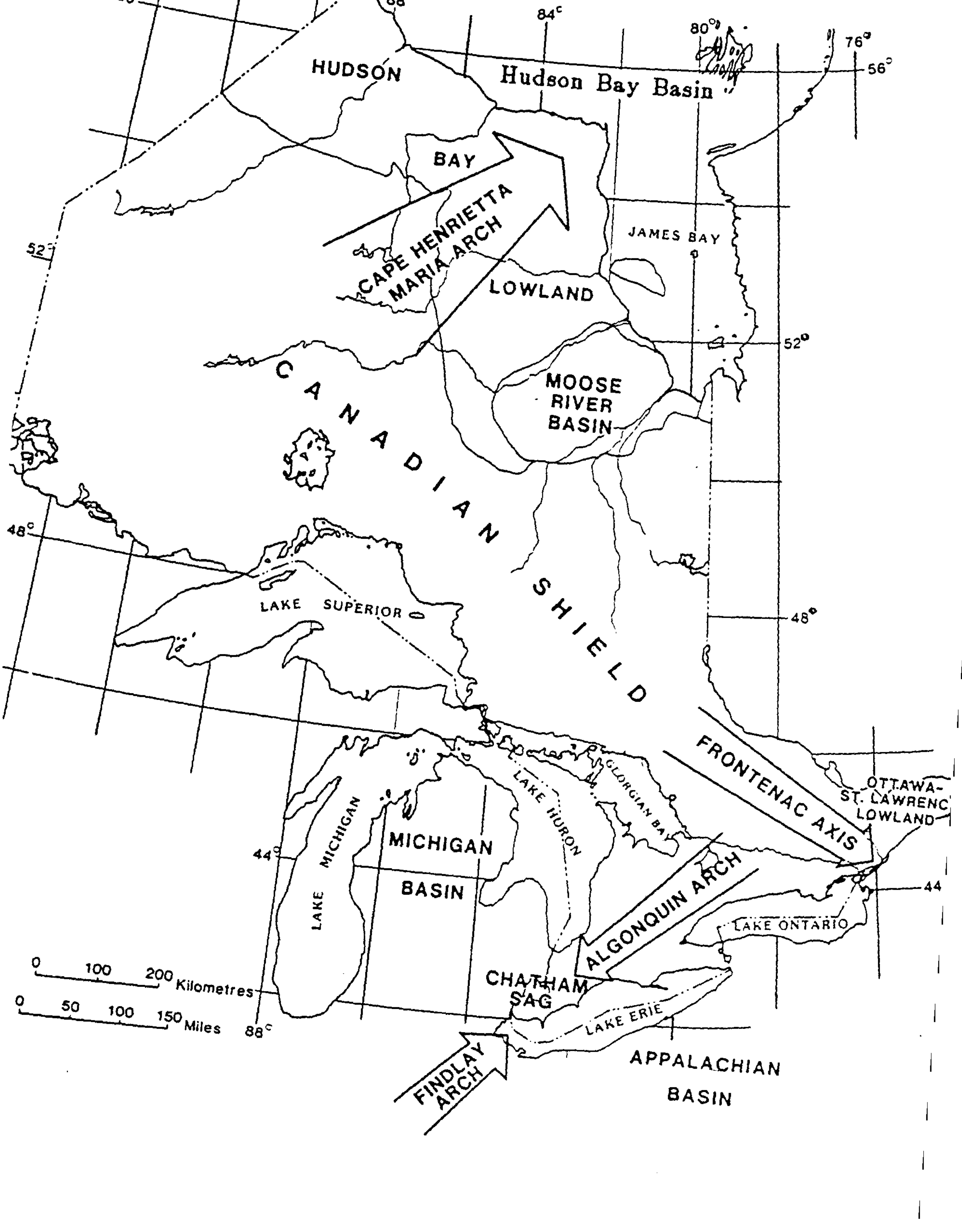
UPPER DEVONIAN BLACK SHALES AND THEIR RELATED DEPOSITS

1.1 Introduction

A black shale is defined as a dark mudrock exceptionally rich in organic matter (5% or more carbon content) and sulphide, and often contains unusual concentrations of certain trace elements (U, V, Cu, Ni). It is formed by the anaerobic decay of buried organic matter in a quiet-water, reducing environment (such as a stagnant marine basin) which is characterized by restricted circulation and a very slow deposition of clastic material (American Geological Institute, 1980). Black shales are of scientific interest because their deposits can make up a significant portion of the geologic record, and are possible sources of unconventional oil. Although modern deposits of black shales do exist (i.e. the Black and Baltic Seas), the ancient deposits are more enigmatic because of their unusual widespread occurrence during certain geologic periods (such as the Upper Devonian and Cretaceous). Upper Devonian black shale deposits on the North American continent include the Kettle Point Formation (southern Ontario-Michigan Basin), the Chattanooga Formation (Appalachian Basin) and the Long Rapids Formation (Moose River Basin) (Figure 1.1). Others include the Ohio Formation (Ohio) and the New Albany Formation (New York).

Devonian shales constitute one of the largest worldwide concentrations of organic carbon and thus are thought to have

Figure 1.1: Map of Ontario showing major structural and sedimentary features (courtesy of the Engineering and Terrain Geology Section, Ontario Geological Survey).



HUDSON
Hudson Bay Basin
BAY
CAPE HENRIETTA MARIA ARCH
LOWLAND
JAMES BAY
MOOSE RIVER BASIN
CANADIAN SHIELD
LAKE SUPERIOR
LAKE MICHIGAN
LAKE HURON
GEORGIAN BAY
MICHIGAN BASIN
FRONTENAC AXIS
OTTAWA-ST. LAWRENC LOWLAND
ALGONQUIN ARCH
LAKE ONTARIO
CHATHAM SAG
LAKE ERIE
FINDLAY ARCH
APPALACHIAN BASIN
84°
80°
76°
56°
52°
48°
44°
88°
0 100 200 Kilometres
0 50 100 150 Miles

potential to produce shale oil and gas. A number of major studies have been completed under the Eastern Gas Shales Project (EGSP) and under the sponsorship of the U.S. Department of Energy's Morgantown Energy Technology Center (DOE/METC) in the United States (Lewin and Associates, Inc., 1983; Rex and Lynch, 1984; Spiewak 1982). Other extensive black shale deposits occurred in the Lower Jurassic to mid-Cretaceous periods.

Mudrocks are difficult to work with because of their fine-grained nature and their lack of sedimentary features, and thus, depositional models are rare. Compared to other lithologies, such as sandstones or carbonates, parameters affecting mudrock deposition are much less known, even though mudrocks form more than 60% of the world's sediments. A problem arises when dealing with the question of black shale deposition, because the present is often used as the key to the past, and many black shale sequences were deposited under conditions which are rare or non-existent on the earth today.

Other sedimentary deposits are well enough known that it is possible to construct models which explain their depositional history. It is hoped that with perseverance, applicable models for mudrocks may develop that could eventually ease the pain of studying them.

1.2 Black Shales and their Depositional Environments

The deposition of black shales occurs under quiet-water conditions where the organic matter that comprises the shale remains relatively intact. In order to inhibit the destruction of the organic debris by oxidation, the water column (or the sediment-water interface) must be anoxic (=reducing) with a minimum amount of clastic input. The presence of bottom scavengers must also be excluded or be at a minimum to preclude excessive bacterial decay.

Three depositional environments where black shale deposition can occur are; 1) continental lacustrine (e.g. the Eocene Green River oil shales), 2) epeiric seas, interior (intracratonic) basins, or marginal basins, whose connections to the open ocean may have been restricted (e.g. the Devonian-Mississippian Ohio-Chattanooga-New Albany-Exshaw shale sequence), and 3) small lakes, bogs, or lagoons of limited geographic extent (Macauley, 1984; Byers, 1977; Potter *et al.*, 1980). Other examples of famous black shales are the Burgess Shale, a thick, dark grey to black, uniquely fossiliferous Middle Cambrian shale; the Cretaceous Cody-Pierre-Lewis shales in the western interior of the Western States; and the Permian Kupferschiefer of western Europe, a very thin, but widespread shale, famous for its syngenetic mineralization of Cu, Pb, and Zn.

1.3 Objectives of the Present Study

The deposition of black shale across the North American continent during Late Devonian and Early Mississippian time is enigmatic and numerous papers have been published dwelling entirely on this subject (Ettenshon and Barron, 1981; Heckel and Witzke, 1979; Woodrow, 1985; Ettenshon, 1985). It appears that as a continent-wide marine transgression occurred in the Appalachian Basin area, black shale was the dominant sedimentary deposit, almost to the exclusion of all other types of deposits. By studying the black shales from the Long Rapids Formation in the Moose River Basin, and by using sedimentary, stratigraphic, geochemical and paleontological parameters, it is hoped that some facies control can be established to set the stage for future attempts on predicting models for their deposition.

CHAPTER 2:

THE STRATIGRAPHY AND SETTING OF THE LONG RAPIDS FORMATION

2.1 Introduction

The Upper Devonian Long Rapids Formation in northern Ontario was studied to assess its sedimentology, stratigraphy, and paleontology. Initial interest in the Long Rapids Formation by the staff of the Ontario Geological Survey concerned its possible use as an unconventional source of oil. This interest was sparked by the worldwide shortage of petroleum in the last decade. Similar studies were conducted on other Paleozoic oil shales in southern Ontario which had potential to produce shale oil, such as the Upper Devonian Kettle Point Formation.

The Upper Devonian Long Rapids Formation ranges in age from mid-Frasnian at the base to early Famennian at the top. The boundary between the two ages occurs approximately 35 to 40 metres from the base of the Formation. This was based on conodont studies on the Formation, in which species representing at least six of the standard Upper Devonian conodont zones are represented. The zones range from the earliest Frasnian Lower *asymmetricus* zone to the middle Famennian lower *rhomboidea* zone (Telford, 1985).

2.2 Setting

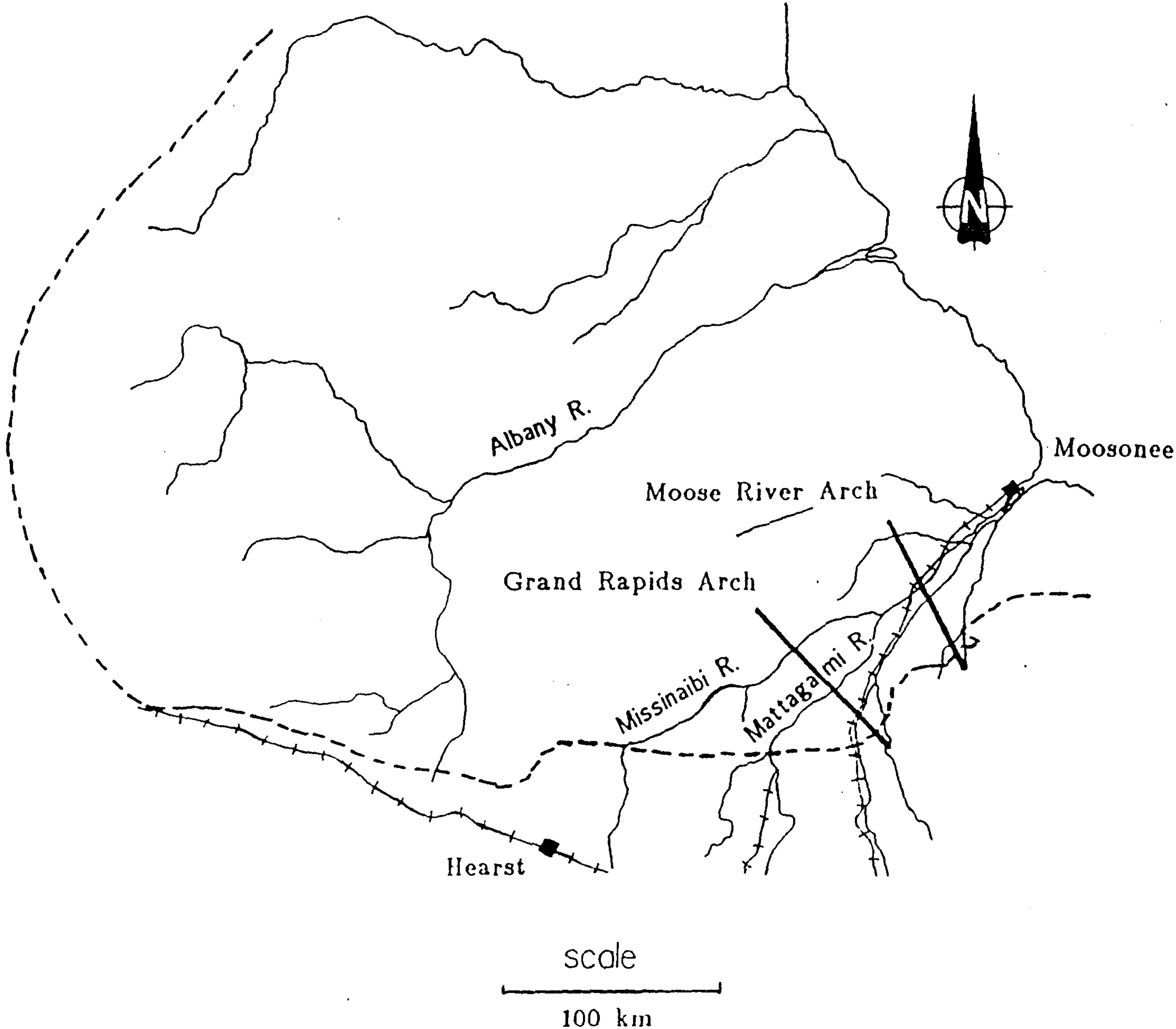
The Moose River Basin is located in the James Bay Lowland portion of the Hudson Bay Lowlands and encompasses an area of approximately 100,000 square kilometres. Two basement highs are located within the Moose River Basin, the Grand Rapids Arch and the Moose River Arch, both trending approximately northwest to southeast, parallel to each other, along the southeastern edge of the Basin (Figure 2.1).

2.2.1 <u>Structural Geology:</u>

The Moose River Basin (Figure 2.1) is one of a number of shallow sedimentary basins on the North American craton. It shows a history of relative tectonic stability with only local interruptions of the regional basinal dips. The Hudson Bay Basin (located to the north) and the Moose River Basin are erosional remnants of a more extensive cratonic cover, which probably had connections to the Appalachian, Michigan, and Williston Basins in the south and the Arctic Platform to the north. The Hudson Bay and Moose River Basins are separated from each other by the northeast-trending Cape Henrietta Maria Arch (Figure 1.1). This Arch is actually the northeast end of a much larger structural feature, the northeast-trending Transcontinental Arch located to the south in the States.

The Moose River Basin is truncated in the south by an east-west *en-echelon* fault escarpment system, the Kapuskasing-Moosonee trend. In this area, faulting and uplift of the Precambrian rocks has taken place relative to the rocks in the Basin. Definite evidence that this escarpment is fault-bounded is found along the Missinaibi and Mattagami Rivers, with probable episodes of reactivation (Stoakes, 1975; Watts, Griffis, and McOuat Ltd., 1983). Various lines of evidence

Figure 2.1: Setting of the Moose River Basin in northern Ontario (after Sanford and Norris, 1975, p.11; Bennett, 1967, p. 28).



Albany R.
Moosonee
Moose River Arch
Grand Rapids Arch
Missinaibi R.
Mattagami R.
Hearst
N
scale
100 km

have suggested the following three periods of epeirogeny have affected this area (Sanford and Norris, 1975);

1) Late Ordovician (Richmond)

2) Early Devonian (Siegenian to Emsian)

3) Early Cretaceous.

The major faults and lineaments in the general area occur along two main strike trends, north- to northwest and northeast. Southeast of the Basin, swarms of diabase dikes and occasional carbonatite complexes are associated with the faults. Although the Moose River Basin is usually viewed as a relatively shallow, simple gravity-sag feature, some data indicate it to be a more complex, block-faulted and gravity-sag basin, made up of essentially two major sub-basins. The major structural feature separating these two sub-basins is the northwest-trending Grand Rapids Arch and it is thought to have developed in Devonian times (Figure 2.1).

The Grand Rapids Arch probably influenced sedimentation patterns, as indicated in the thickness and distribution of the Upper Devonian Long Rapids Formation and the Cretaceous sediments. From drill core data, this structural high is overlain by a relatively thin veneer of Long Rapids Formation and Cretaceous sediments; in some holes, both units are absent (Watts, Griffis, and McOuat Ltd., 1983). The two marginal valleys flanking the Arch contain substantial thicknesses of Long Rapids Formation and Cretaceous sediments. Another arch, the Moose River Arch, trends approximately parallel to the

Grand Rapids Arch, although its influence on the sediments in the Moose River Basin is not fully understood. The Moose River Arch was probably a positive element for much of the Paleozoic. It may have been covered during Ordovician times, but as a result of subsequent uplift and erosion in the Lower Ordovician, the succeeding Middle Silurian Severn River Formation rested directly on the Precambrian.

The area of the Williams Island outcrop section for the Long Rapids Formation straddles the Williams Island anticline. It is a prominant northeast-trending (110°) anticlinal fold that plunges gently to the southwest; Williams Island itself owes its existence to this fold. Some minor fold structures are superimposed on the structure, and one was delineated by Ontario Hydro drilling (Haygarth, 1980). Resistant carbonate beds of the upper member of the Williams Island Formation form the core of the anticline, and shale from the Long Rapids Formation is exposed along its north and south flanks. Dips on either side of this structure are approximately 20° to the north and south, respectively, but some reversals of dip are evident which may have been caused by smaller scale folding (Sanford and Norris, 1968; Watts, Griffis, and McOuat Ltd., 1982).

Folding on a minor scale is also present and appears to be due to supratenuous folding over basement highs. An overall dip of approximately 3 to 5° is maintained toward the center of the basin (Bennett *et al.*, 1967). Local folding has occurred around the Otter Rapids - Coral Rapids area and is probably due to post-Middle Devonian lamprophyric and kimberlitic dikes and sills.

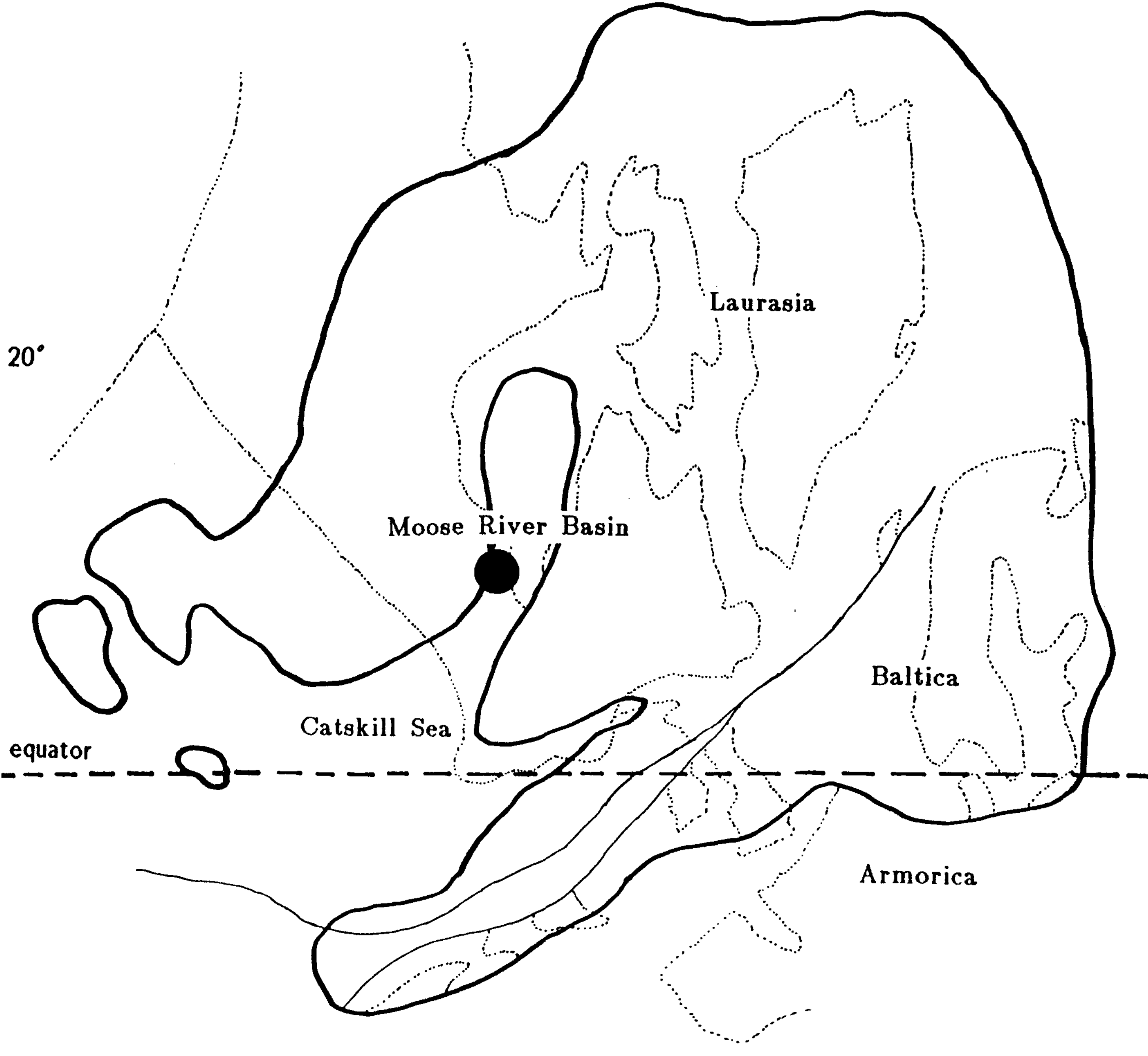
Most sediments in the Moose River Basin appear to be shallow-water in origin and are predominantly carbonates. Clastic units are rare and can be explained by terrigenous influx in marginal areas due to tectonically positive peripheral areas undergoing epeirogeny (Stoakes, 1975).

2.2.2 Stratigraphic Setting:

The Long Rapids Formation was deposited in an intracratonic basin and was connected to the Appalachian Basin by the large Devonian Catskill Sea (Figure 2.2). The Catskill Sea had developed on the Laurasian (Old Red Sandstone) Continent and extended from Canada's Hudson Bay to the southern portion of the United States. Its connection to the open ocean is thought to be to the south. The Long Rapids Formation is present in the small Moose River Basin, as well as in the much larger Hudson Bay Basin to the north. Black shale units predominate in the Moose River Basin and red, pink, and grey mudstone, shale, siltstone and sandstone units occur in the Hudson Bay Basin (Norris, 1986).

The Long Rapids Formation in the Moose River Basin probably represents the most northerly deposition of black shales that occurred in conjunction with the worldwide Upper Devonian marine transgression. After the Devonian, the entire

Figure 2.2: Configuration and placement of the Laurasian Continent in the Upper Devonian. The Catskill Sea and the Moose River Basin are indicated (after Woodrow, 1985, p.52 & 53).



20°
Laurasia
Moose River Basin
Baltica
Catskill Sea
equator
Armorica

Moose River Basin was uplifted and exposed to an intensive period of erosion, with the Paleozoic sedimentary cover on the Shield in whole or in part removed.

Only the portion of the Long Rapids Formation present in the Moose River Basin was incorporated in this study, because the Formation in the Hudson Bay Basin possesses no black shale units. The lithologies present in the Hudson Bay Basin for the Long Rapids Formation reflect restricted basin conditions with intermittent supratidal conditions, and thus the typical black shale facies of the Moose River Basin did not develop.

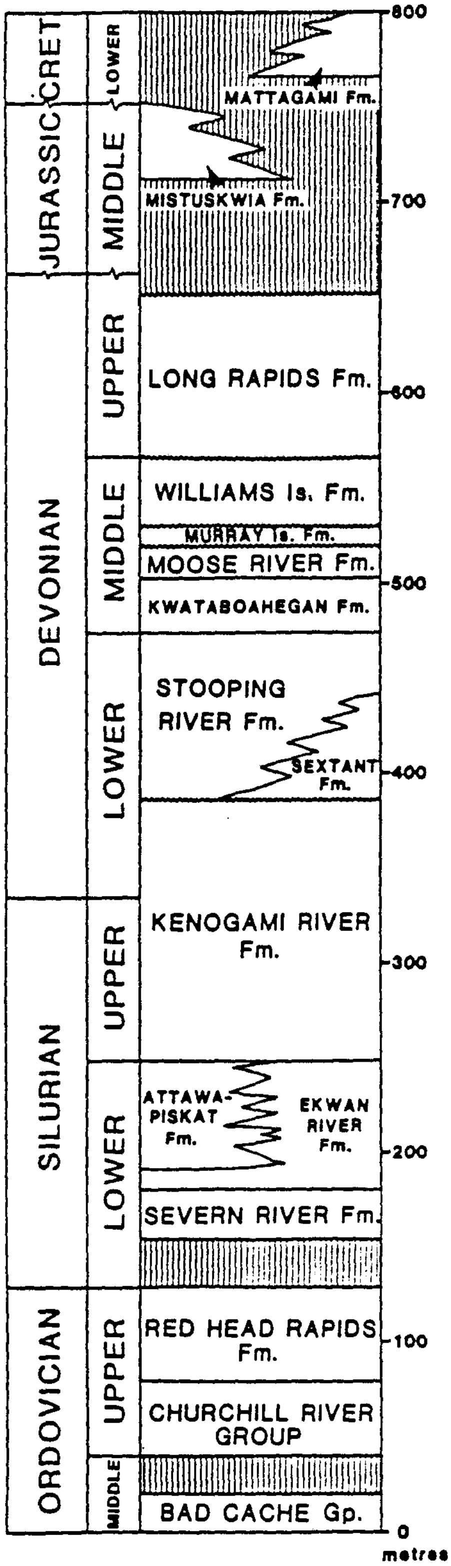
2.2.3 <u>Stratigraphy:</u>

Rocks in the Moose River Basin range in age from Middle Ordovician to Lower Cretaceous, with the Lower Silurian and Ordovician strata only present in the western margin (Sanford *et al.*, 1968). The section is approximately 760 metres thick (Figure 2.3).

In the Moose River Basin, the Long Rapids Formation attains a subsurface area of approximately 5000 km (see Figure 2.4) and averages 30 metres in thickness, reaching 87 metres in the Onakawana area. The Formation disconformably overlies the Middle Devonian Williams Island Formation (limestone and shale) and is in turn unconformably overlain by either Cretaceous sediments or Quaternary deposits.

The Long Rapids Formation consists predominantly of black shale, but other facies are also present in lesser amounts. In total, five facies have been identified: laminated black shales, laminated bioturbated black shales, massive green-grey

Figure 2.3: Stratigraphy of the Moose River Basin (modified after Norris, 1986, p. 23). Draft is courtsey of the Engineering and Terrain Geology Section, Ontario Geological Survey.



Modified after Norris(1986) p.23

mudstones, laminated green-grey shales, and dolomitic limestone beds and concretions. These are described in detail in Chapter 3.

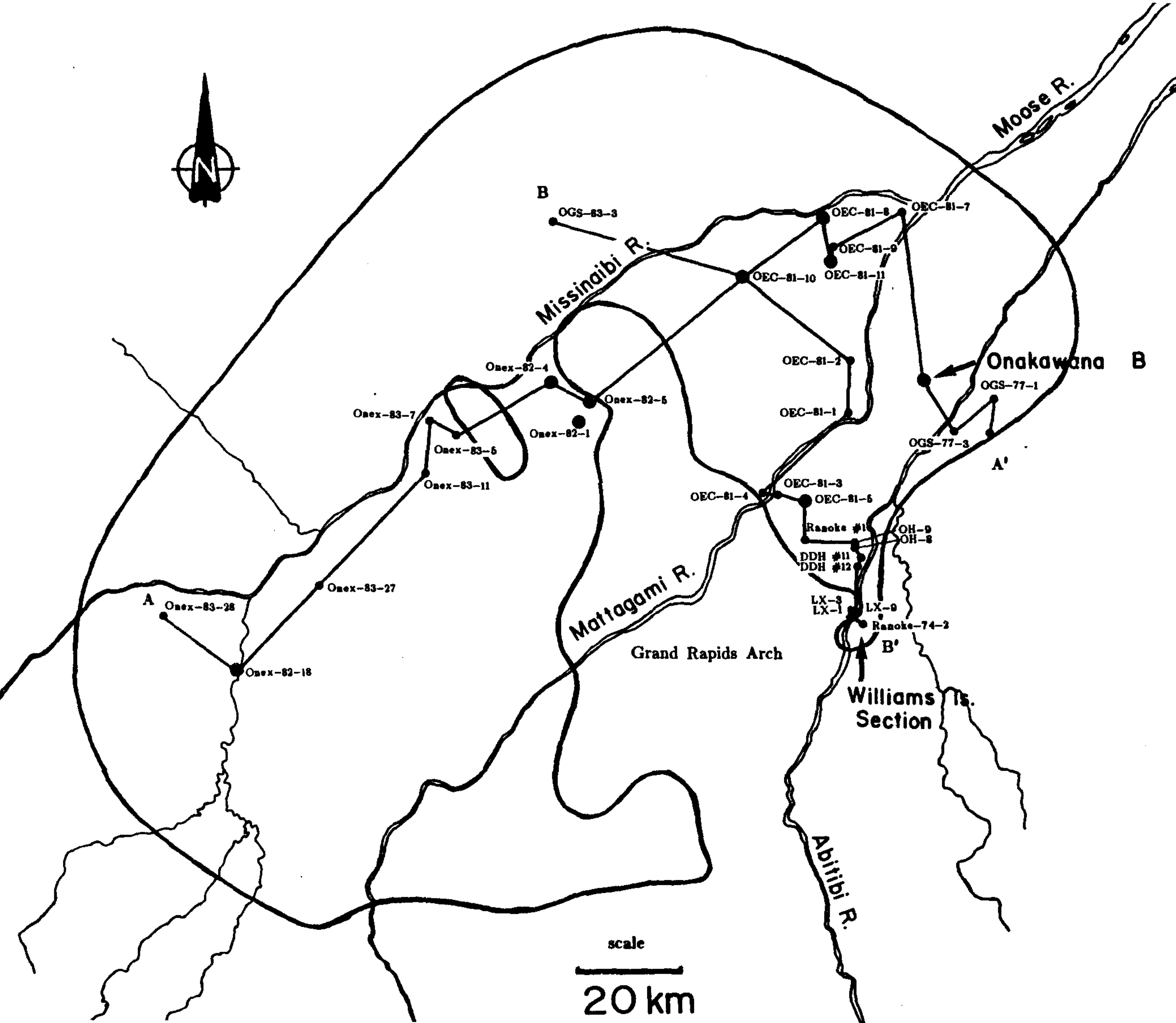
2.2.4 <u>Outcrop:</u>

Only one outcrop section of the Long Rapids Formation was measured, at Williams Island on the Abitibi River (Figure 2.4). It was measured in increments because of dips in the strata of 2-5 to the southeast. The base of the Formation is placed at the contact with the Williams Island Formation. The upper contact has been eroded, and the Formation grades into Quaternary deposits. A stratigraphic section of approximately 60 metres was measured in the Fall of 1984 and 1985 and a total of 135 samples taken. Other exposures of the Long Rapids Formation occur on the east bank of the Abitibi River and elsewhere in the Basin, but no attempt was made to map them because they were limited in vertical thickness and they possessed no marker horizons that could aid in correlations. The Williams Island outcrop section appears in Figure 2.5 and its geologic log in Appendix A.

2.2.5 <u>Subsurface:</u>

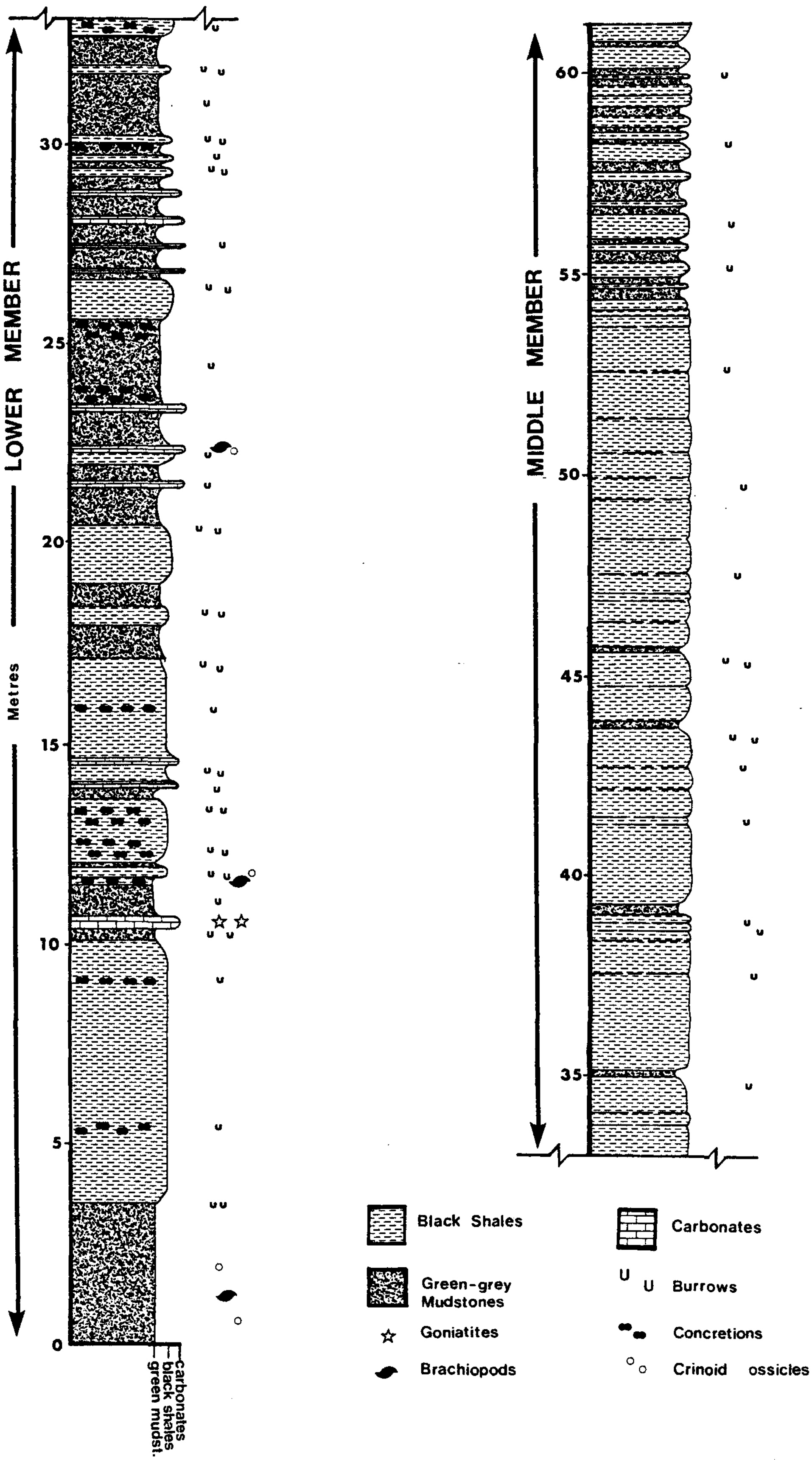
To complement the Williams Island section, eight boreholes which possessed accessable core material were also examined, sampled, and logged in detail (Figure 2.4). These eight holes (Appendix B and C) had been drilled by Onexco

Figure 2.4: Locations of drill holes, the Williams Island outcrop section, and the cross sections A-A' (Figure 2.7) and B-B' (Figure 2.8) in the Moose River Basin. Solid line is the subsurface delineation of the Long Rapids Formation (redrawn from maps compiled by Telford and Sanderson (1984-1985), Engineering and Terrain Geology Section, Ontario Geological Survey). Large solid dots represent boreholes logged for this study.



N
B
OGS-83-3
Missinaibi R.
Moose R.
OEC-81-8
OEC-81-7
OEC-81-9
OEC-81-11
OEC-81-10
OEC-81-2
OEC-81-1
Onakawana B
OGS-77-1
OGS-77-3
A'
Onex-82-4
Onex-82-5
Onex-83-7
Onex-82-1
Onex-83-5
Onex-83-11
OEC-81-3
OEC-81-4
OEC-81-5
Ranoke #1
OH-9
OH-8
DDH #11
DDH #12
A
Onex-83-28
Onex-83-27
Mattagami R.
LX-3
LX-1
LX-9
Ranoke-74-2
B'
Grand Rapids Arch
Onex-82-18
Williams Is. Section
Abitibi R.
scale
20 km

Figure 2.5: The Williams Island stratigraphic section. This section extends for about 1 km along the east bank of the Abitibi River from 50 21'54"N to 50 22'18". The Williams Island Formation underlies the section, and its upper contact is covered by Quaternary deposits. See also Appendix A.



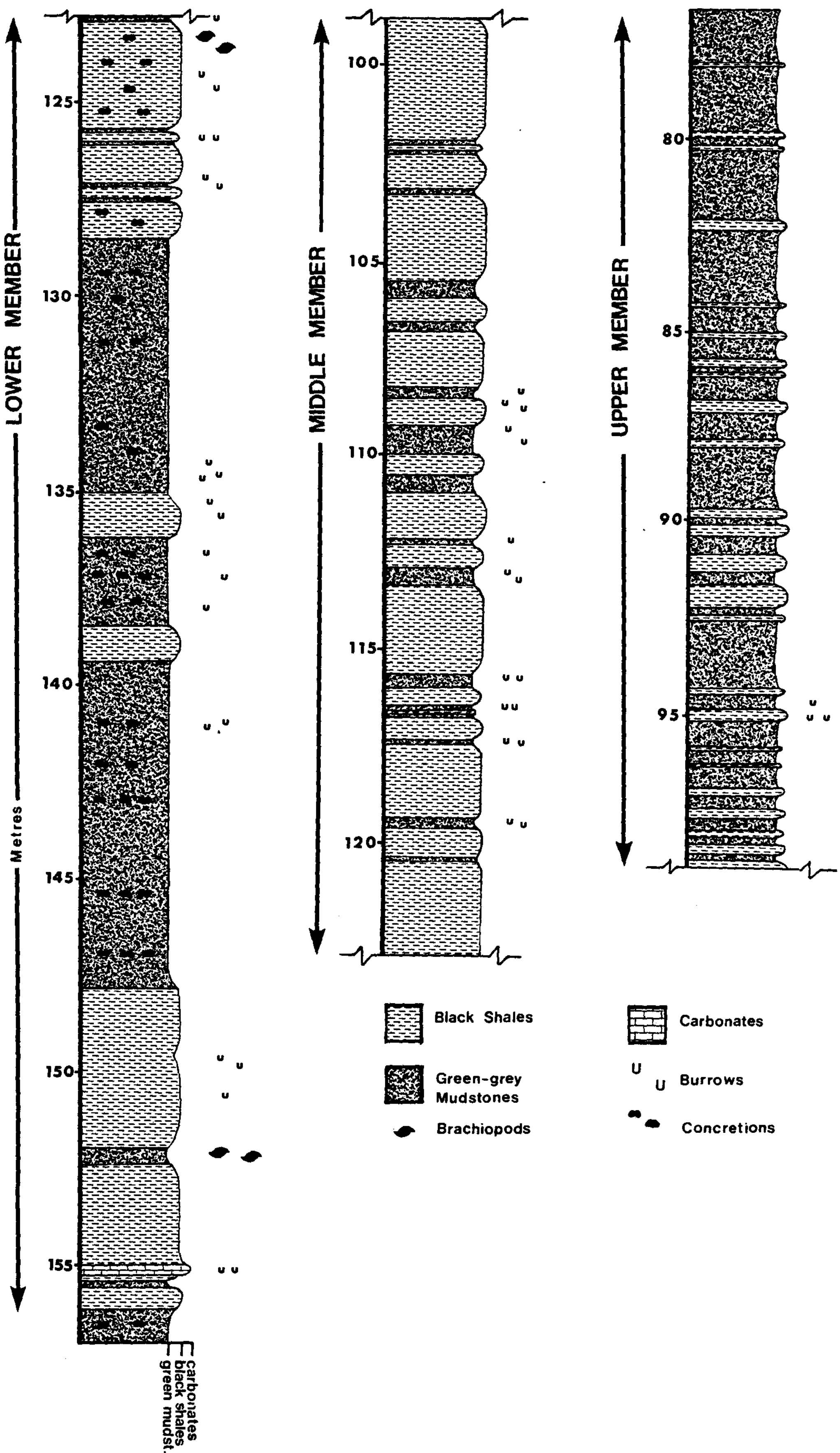
LOWER MEMBER
Metres
0
5
10
15
20
25
30
carbonates
black shales
green mudst.
MIDDLE MEMBER
35
40
45
50
55
60
Black Shales
Green-grey Mudstones
Goniatites
Brachiopods
Carbonates
Burrows
Concretions
Crinoid ossicles

Minerals Ltd. (ONEX), Ontario Energy Corporation (OEC), and the Ontario Geological Survey in the late seventies and early eighties for the purpose of defining the geographic extent of the Cretaceous Onakawana Lignite field. Thus, many boreholes did not penetrate the Long Rapids Formation or, if they did, they did so only partially, which hampered correlation of the Formation. In March of 1985, the Engineering and Terrain Section of the Ontario Geological Survey (OGS) (Ministry of Northern Development and Mines) drilled the Onakawana B Borehole at Onakawana to penetrate the entire Paleozoic and Mesozoic sequence to the Precambrian basement (see Sanderson and Telford, 1985). The Onakawana B hole was helpful for correlations with the Williams Island outcrop section, because it possessed a complete section of the Long Rapids Formation through all three members (Figure 2.6; see also Appendix B).

2.2.6 <u>Member Definition:</u>

The Onakawana B Borehole was a re-drill of the Ontario Department of Mines Onakawana A Borehole which had been originally drilled in 1929. The Onakawana A Borehole had been originally logged by Dyer and Crozier in 1930 (see Dyer and Crozier, 1933) and then re-logged in 1931 by Dyer and Gerrie (both logs are in Martison, 1953) and both reported a thickness for the Long Rapids Formation of 87 metres.

Figure 2.6: Long Rapids Formation: Onakawana B Borehole stratigraphic section. The Williams Island Formation is located at the base, and the section is overlain by the Mattagami Formation. See also Appendix B.



LOWER MEMBER
MIDDLE MEMBER
UPPER MEMBER
Metres
125
130
135
140
145
150
155
100
105
110
115
120
80
85
90
95
carbonates
black shales
green mudst.
Black Shales
Green-grey Mudstones
Brachiopods
Carbonates
Burrows
Concretions

Dyer and Crozier (1933) subdivided the Formation into three informal members;

> <u>upper member:</u> interbedded green-grey mudstones and brown-black shales (approximately 20 m thick)
> <u>middle member:</u> brown-black shale with thin beds of green-grey mudstones (approximately 30 m thick)
> <u>lower member:</u> green-grey mudstones with interbedded black shale beds and carbonate beds and nodules (approximately 37 m thick)

When the Long Rapids Formation interval in the Onakawana B Borehole was logged by the author in 1985, approximately 81 metres of the Formation and all three members were defined.

Upon re-examination of the Williams Island outcrop section in the Fall of 1985, it was found that the lower two members (the lower and middle) could be positively identified at the outcrop section. All three members, in both outcrop and in drill core, were solely defined on the basis of the relative abundance of the five facies described previously.

2.2.7 Subsurface - Outcrop Relationships:

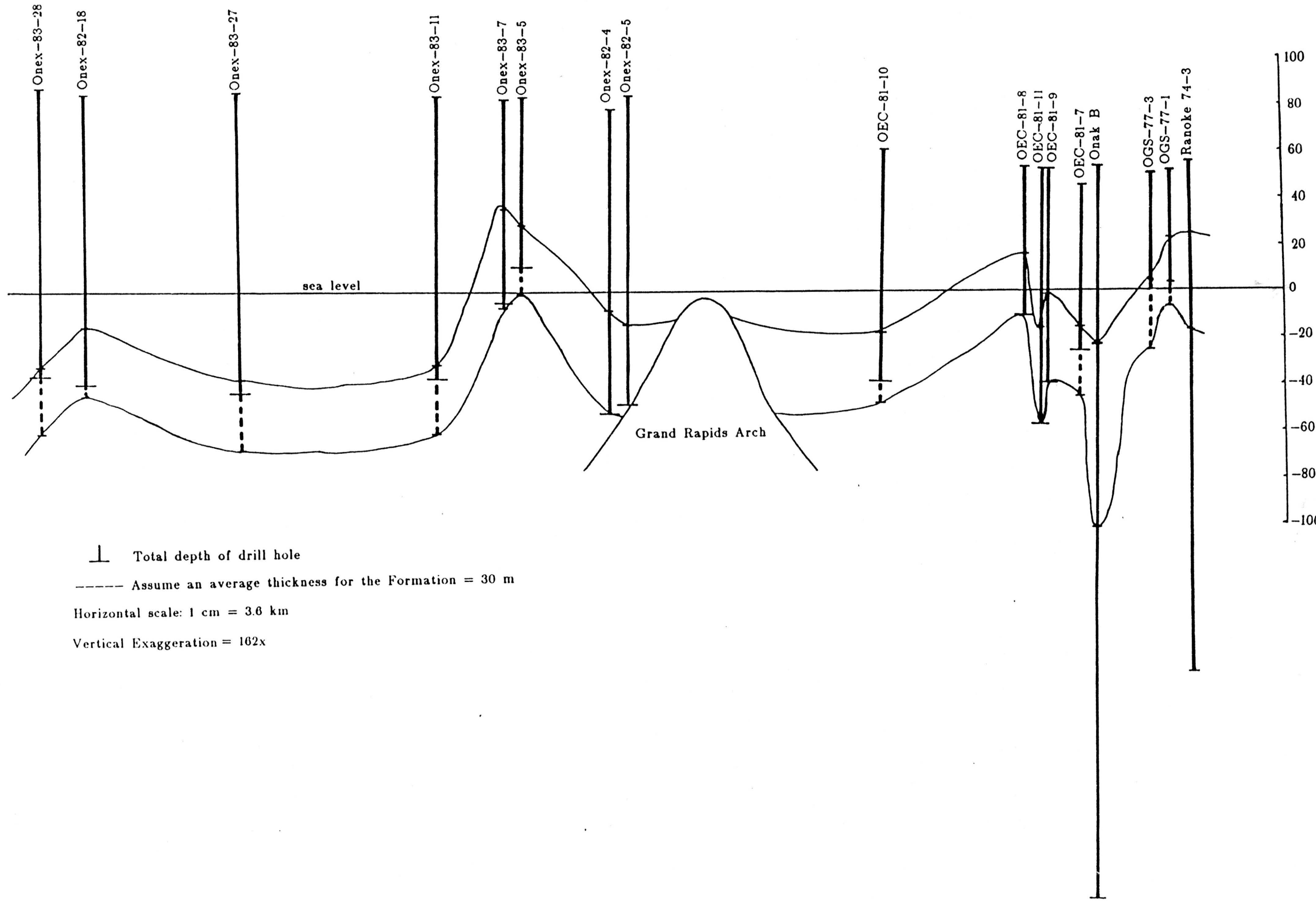
Correlation of the Long Rapids Formation between the Onakawana B Borehole, the other boreholes, and the measured section has proven difficult because of variation in the Formation's thickness throughout the Moose River Basin and lack of stratigraphic control. Borehole information is also lacking because of the limited penetration into the Long Rapids Formation by the various drilling agencies. Also, the fact that the Long Rapids Formation is the youngest Paleozoic unit in the Basin casts suspicions on using the upper contact as a marker. Attempts have been made, although speculative, to draw some cross-sections of the Long Rapids Formation in the Moose River Basin using as datum the boreholes' elevation above sea level (Figure 2.7 and 2.8). Highs and lows are quite pronounced on the cross-sections, and the Long Rapids Formation in the south-east corner of the Basin may be faulted due to its irregular thickness. It may also be affected by its proximity to the Williams Island anticlinal dome.

2.3 Previous Work

Early exploration in the Moose River Basin was done by workers of the Geological Survey of Canada and the Ontario Department of Mines. Between 1870 and 1915 most of the bedrock exposures along the rivers had been visited and described. The first stratigraphic sequence for the Moose River Basin was attempted by Savage and Van Tuyl (1919) who proposed formation nomenclature for the Paleozoic units. This was to become the foundation for later workers. In 1928, Dyer summarized the stratigraphy, paleontology, structural geology, and mineral resources of the Moose River Basin (Dyer and Crozier, 1933).

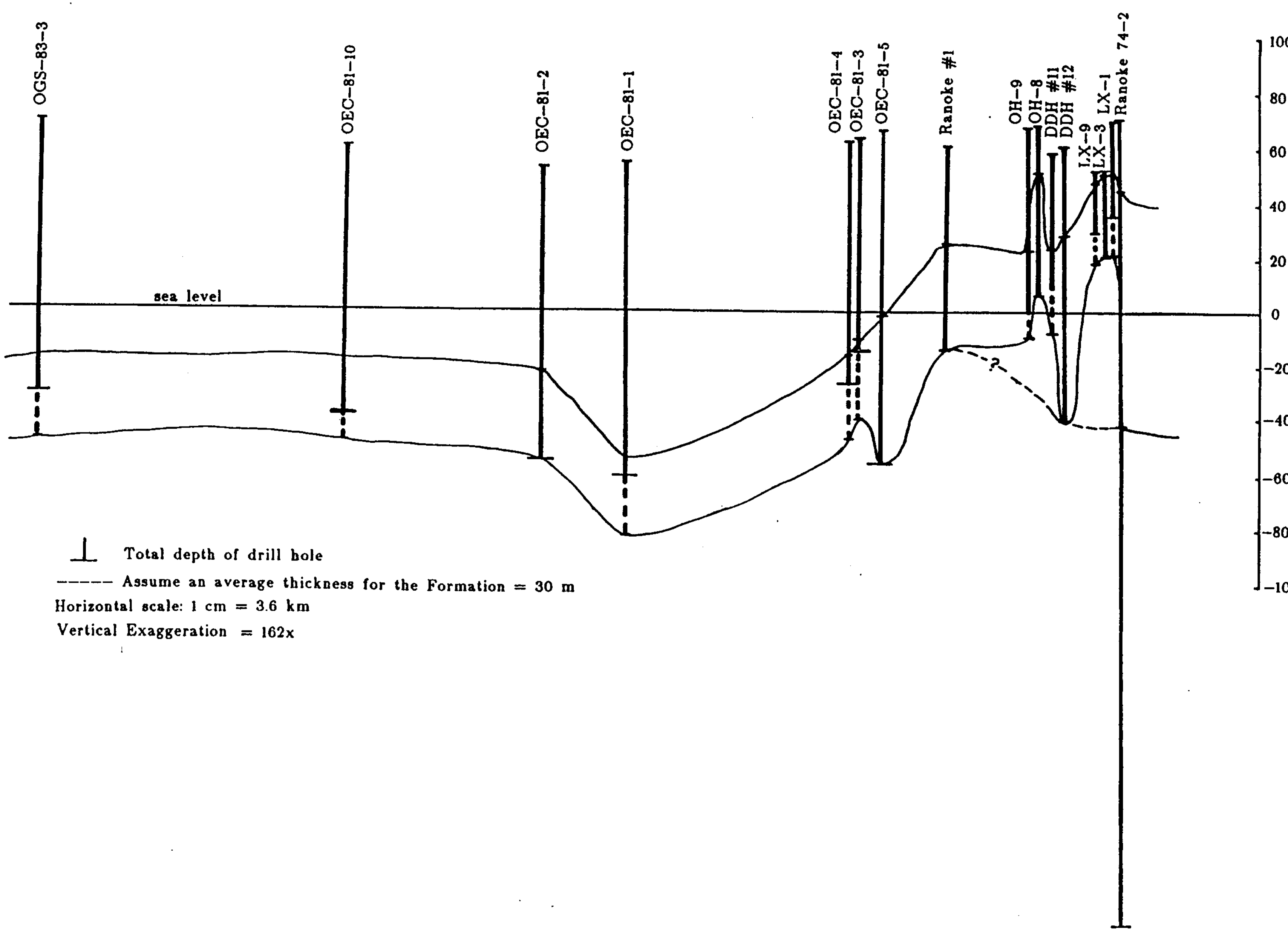
Martison (1953) reported on the stratigraphic, structural, and hydrocarbon potential of the Moose River Basin in an Ontario Department of Mines report. Later in 1967, Operation Kapuskasing (Bennett *et al.*, 1967) was published by the Ontario Department of Mines which was a mapping project for the southern part of the Moose River Basin, along with an

Figure 2.7: Cross-section A-A' of the Long Rapids Formation in the Moose River Basin. Sea level is used as datum. See Figure 2.4 for location of cross-sections. See Appendix C for drill hole information. The placement of the Grand Rapids Arch is only tentative.



Onex-83-28
Onex-82-18
Onex-83-27
Onex-83-11
Onex-83-7
Onex-83-5
Onex-82-4
Onex-82-5
OEC-81-10
OEC-81-8
OEC-81-11
OEC-81-9
OEC-81-7
Onak B
OGS-77-3
OGS-77-1
Ranoke 74-3
100
80
60
40
20
0
-20
-40
-60
-80
-100
sea level
Grand Rapids Arch
Total depth of drill hole
----- Assume an average thickness for the Formation = 30 m
Horizontal scale: 1 cm = 3.6 km
Vertical Exaggeration = 162x

Figure 2.8: Cross-section B-B' (see previous figure).


OGS-83-3
OEC-81-10
OEC-81-2
OEC-81-1
OEC-81-4
OEC-81-3
OEC-81-5
Ranoke #1
OH-9
OH-8
DDH #11
DDH #12
LX-9
LX-3
LX-1
Ranoke 74-2
sea level
100
80
60
40
20
0
-20
-40
-60
-80
-10
Total depth of drill hole
----- Assume an average thickness for the Formation = 30 m
Horizontal scale: 1 cm = 3.6 km
Vertical Exaggeration = 162x

inventory of drilling data provided by the Hydro-Electric Power Commission of Ontario. In that same year (1967), Operation Winisk (Sanford *et al.*, 1968) was implemented by the Geological Society of Canada, which was a mapping project for all of the Paleozoic rocks of the Hudson Bay Lowlands (see also Sanford and Norris, 1968; Norris and Sanford, 1968 & 1969).

Data for the stratigraphy in the Moose River Basin come from outcrops and drill holes. Between the years of 1930 and 1974, 35 boreholes were drilled in the basin by various agencies, 15 of which extended to basement. Also, between the years 1930 and 1942, 300 closely spaced shallow holes were drilled by the Ontario Department of Mines to delineate the Cretaceous lignite fields near Onakawana. Then between the years 1975 and 1985, another 37 holes were drilled by the Ontario Geological Survey (see Telford and Verma, 1982), the most recent hole being the Onakawana B Borehole which was mentioned earlier. See Sanford and Norris (1975) and Norris (1986) for more details.

CHAPTER 3:

SEDIMENTARY FACIES

3.1 Introduction and Methods

A discussion on terminology is necessary to introduce the study of mudrocks. Potter *et al.* (1980) use the term shale for all fine-grained argillaceous sediments, which includes mud, clay, and mudstone. The shales must have greater than 33% clay sized material and have laminae less than 10 millimetres thick. Moon and Hurst (1984) define a shale as an indurated clay rock which splits readily into thin laminae along the bedding planes. Consolidated clay rocks which do not fit this description are referred to as mudstones. The latter description was used for this study.

Mudrocks are difficult to work with because of their fine-grained nature and their lack of sedimentary features. Most studies of mudrocks have placed the emphasis on mineralogy and geochemistry. Perhaps for this reason, other lithologies, such as sandstones and carbonates, are much better known, despite the fact that mudrocks form more than 60% of the world's sediments. The study of mudrocks has lagged behind other lithologies because of their lesser economic potential and the difficulty in studying individual mudrock particles. Today, the study of single particles has greatly advanced because of the use of the scanning electron microscope (SEM), as well as the use of standard bulk geochemical analyses (i.e. X-ray fluorescence).

It is now possible to recognize environmental profiles in the vertical succession of mudrocks, similar to those found in sandstones and carbonates. For mudrocks, the parameters that could be used include bedding (types, thickness, and degree of perfection), bioturbation (kinds and abundance), fossil content (kinds and abundance), and the type and amount of organic matter present. This information, along with data such as adjacent lithologies, the mudrock's body geometry, bounding contacts, and its position in a basin, could help develop an environmental scenario for a mudrock unit. Parameters which were used to study the Long Rapids Formation included bedding, ichnology, paleontology, and geochemistry. A depositional setting for the Moose River Basin during the Upper Devonian is also attempted.

3.2 Facies and Facies Sequences

The facies divisions presented herein are based on information gained from examination of core and outcrop. The basis of facies division is discussed first, followed by a brief description of each facies and an overall sedimentological interpretation.

The mudrocks in the Long Rapids Formation are predominantly black shales, but other lithologies are also present in lesser amounts. Overall, five facies have been identified: laminated black shales (facies A), laminated bioturbated black shales (facies B), massive green-grey mudstones (facies C), laminated green-grey shales (facies D), and micritic dolomitic limestone beds and concretions (facies E). These facies have been identified based on Reading's (1978) facies definition, where a group of rocks can be subdivided based on lithology, sedimentary structures, and biological features.

3.3 Facies Descriptions

3.3.1 Facies A: Black shale (Figure 3.1 a,b)

Facies A occurs throughout the Long Rapids Formation, and is most common within the middle member. It is typically dark grey, dark brown, to black in colour, noncalcareous, and is very indurated (fissile) in both outcrop and core. Rare cream coloured silty laminae may also occur. Distinct burrow forms are absent. Facies E (micritic dolomitic limestone beds and nodules) may be present within facies A, and pyrite blebs and small nodules are also common.

Upper and lower contacts are usually sharp, although some are diffuse. Facies A is usually overlain by facies C or D and rarely E. Facies A may sometimes grade into facies B. It is usually underlain by facies C or E. Facies A is found in all members. Rare *Lingula* shells and conodonts can be found along bedding planes (Figure 4.3c). In thin section, the algae spore case *Tasmanites* is very abundant. (Figure 3.2). The average thickness of this facies is approximately 37 centimetres.

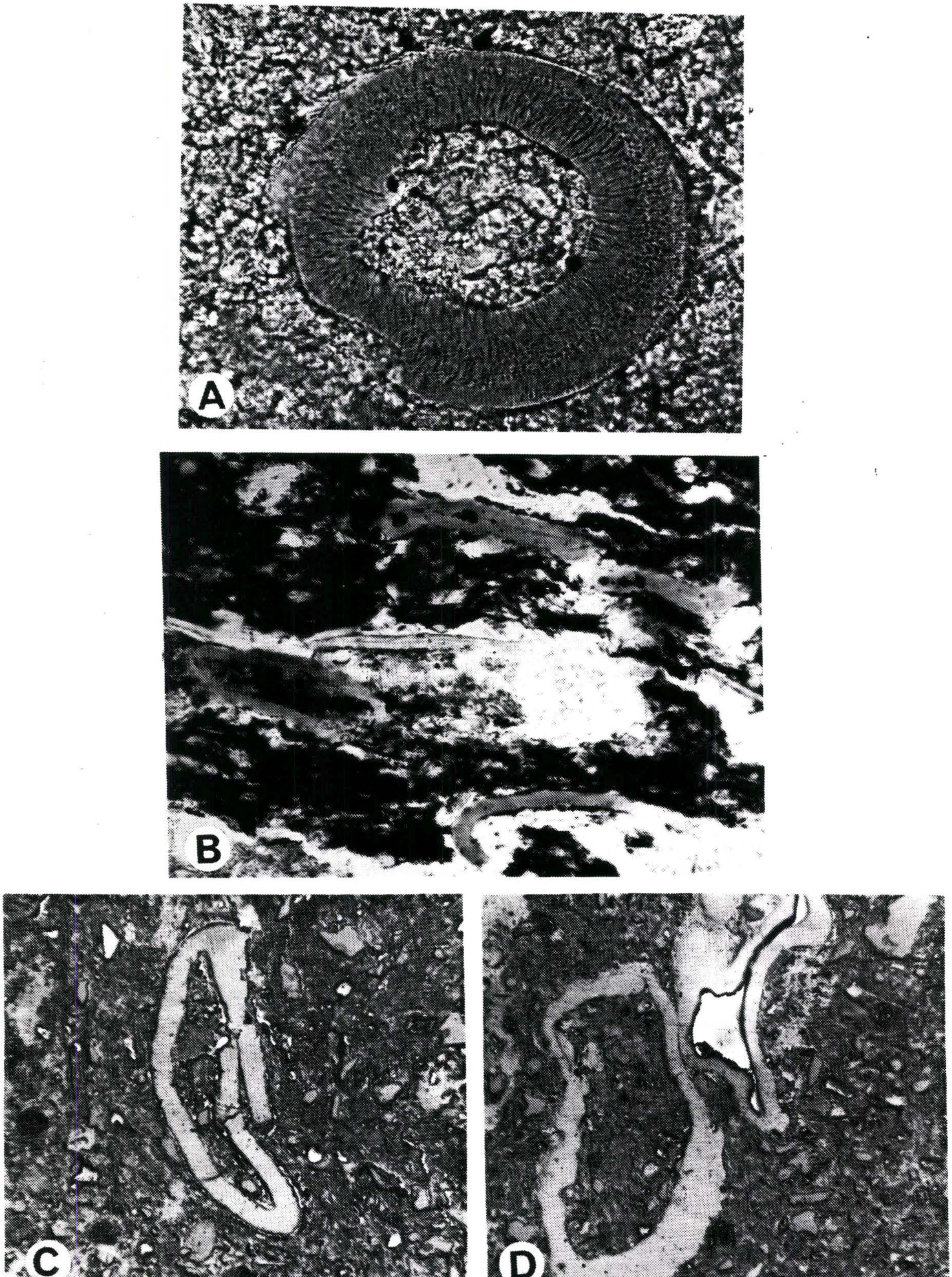
Figure 3.1: Facies A, B, C, and E; A) The fissile character of facies A in outcrop (lower member), B) Facies C-E-A in outcrop (E appears as concretionary green-grey nodules directly beneath A at arrow), C) Core specimen of facies C-B-C. Note small *?Chondrites* at the top of facies B.


3
CENTIMETRE
INCH
A


7
CENTIMETRE
INCH
B


C

Figure 3.2: *Tasmanites;* A) Photomicrograph of *Tasmanites* in facies E surrounded by calcite (field of veiw = 0.5 mm), B) Photmicrograph of deformed *Tasmanites* in facies A with amorphous organic matter and quartz grains (field of veiw = 1.5 mm), C & D) SEM photographs of *Tasmanites* in facies A (field of veiw = 33.3μ).


A
B
C
D

3.3.2 Facies B: Bioturbated black shale (Figure 3.1c)

This facies is identical to facies A, except that it contains mottled and distinct burrow forms. The burrows usually occur at the top of the facies and are infilled with a lighter coloured sediment (usually a green-grey mud). The burrows tend to occupy the top 2 to 5 centimetres of the facies with the rare case of *Alcyonidiopsis* being found 20 centimetres from the facies upper contact. Upper contacts are always gradational or diffuse, with the bottom contacts either sharp or gradational. Trace fossils present include (listed in decreasing abundance) *Chondrites, Planolites, Zoophycos, Teichichnus,* and *Alcyonidiopsis*. Two burrow forms, ?*Cylindrichnus* and Ichnogenus "A", occur rarely in outcrop and can be found along bedding contacts in core (Figure 4.8 & 4.13). The facies is found in all three members, but is rare in the upper member.

The average thickness of this facies is 48 centimetres and it is overlain and underlain by the same facies as facies A. Facies E can also occur within facies B and pyrite blebs and crystals are common.

3.3.3 Facies C: Massive green-grey mudstone (Figure 3.1 b,c)

This facies usually overlies facies A or B with either sharp or gradational boundaries. It possesses no distinct internal sedimentary structures such as laminations or bedding, except for the presence of burrows or mottling. This facies can be overlain by facies E (commonly in the lower member) or facies A or B. It sometimes grades into facies D. It usually overlies facies A or B. Mottling is common and is enhanced by colour variations within the mudstone (pale greens to dark greys). Occasional black mud laminae are also present. Colour variations also help to enhance discernable burrows.

Facies C is slightly to very calcareous. Occasionally, the facies can be quite clayey, especially outcrop exposures. Body fossils can be found at some horizons in high abundance, especially in the lower member in the outcrop section. Brachiopods and crinoid ossicles are the most common body fossils present. Rare chitinophosphatic or pyritized *Lingula* shells have also been found, as well as goniatites. The burrows present include (listed in decreasing abundance) *Chondrites, Planolites, Zoophycos, Teichichnus,* and other indiscernible burrows. Occasional limonitic and hematitic staining is also present. Scattered carbonate and siderite nodules can be present within the facies, as well as pyrite blebs and crystals. The average thickness for facies C is 29 centimetres. It is suspected that bioturbation is pervasive throughout the facies because mottling is so common.

Facies C is found throughout the entire Long Rapids Formation in all three members. In thin section, micro-crystalline to very fine-crystalline carbonate grains are abundant, and when comparing it to facies A, the most noteworthy distinction is the lack of organic matter.

3.3.4 <u>Facies D</u>: Laminated green-grey shale.

Facies D is similar in colour to facies C, but instead displays fissility. Rocks vary in colour from green-grey to brown, and can have a blocky or chippy character. Some portions of this facies can be clayey. Burrows and body fossils are rare to absent, except for the scattered traces *Planolites* and *Chondrites*. Scattered pyrite crystals are also common. Overall, facies D is a rare facies and its average thickness is approximately 48 centimetres.

3.3.5 <u>Facies E</u>: Micritic dolomitic limestone beds and concretions (Figure 3.1b, 3.3, and 3.4)

Facies E is found in two forms; as discrete, individual nodules or concretions and as beds. When it occurs as a bed, its contacts are very irregular and in some places it appears concretionary. It is usually green-grey, grey, to grey-brown in colour, microcrystalline to fine-crystalline, and can be classified as a micritic to biomicritic limestone (sometimes dolomitic) (Folk, 1962). Bed thicknesses vary from 1 to 50 centimetres and concretions range from 1 by 1 centimetres to 1 by 1 metres in diameter. The larger concretions are oblate in shape and slightly dolomitic. The smaller nodules are more spherical. Bed thicknesses vary laterally in outcrop (Figure 3.4c). The average thickness for the facies is 15 centimetres. In outcrop there are rare occurrences of coarse-grained calcarenites overlying facies E (Figure 3.3c).

Figure 3.3: Facies E; A & B) Concretionary nodules of facies E with vertical *?Skolithos* burrows in A) (scale bar = 1 cm), C) Concretionary bed of facies E displaying its typical mottled pattern. It is sharply overlain by a dark coloured, laminated calcarenite bed (arrow indicates up) (scale bar = 1 cm).

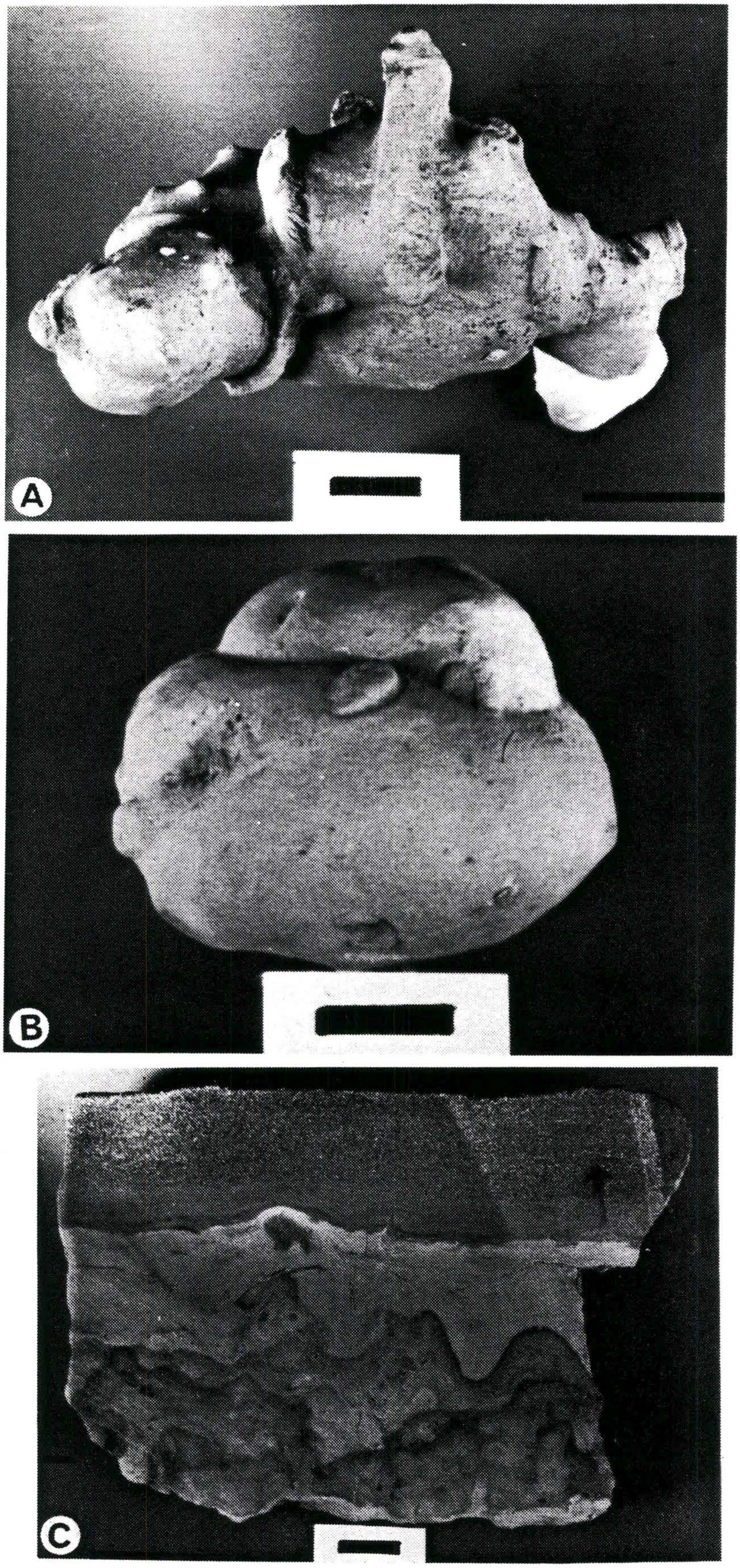
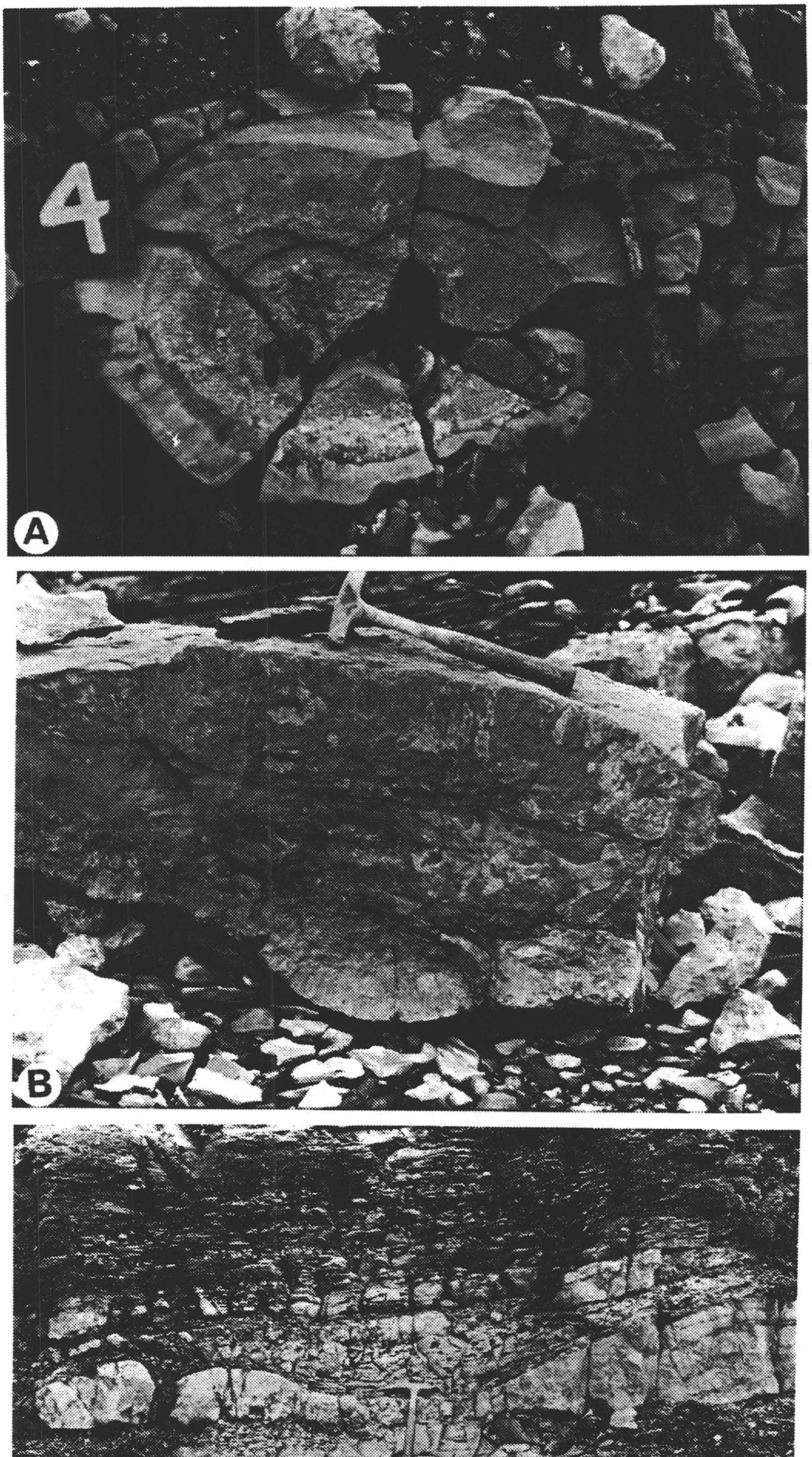

A
B
C

Figure 3.4: Facies E; A & B) Large concretions of facies E in outcrop (hammer for scale), C) Hummocky character of a bed of facies E in outcrop (hammer for scale).


4
A
B
C

Body fossils (especially fragments) are common and include brachiopods, goniatites, crinoids, bivalves, orthoconic nautiloids, and gastropods. Fossilized plant remains *(?Callixylon)* have also been found in some larger concretions (Figure 3.5). Facies E usually appears very mottled with rare occurrences of *Skolithos* and *Planolites*. In thin section, abundant microfossils are present and include pelletoid material [which may be cross-sections of brachiopod spines or tintinnes (Horowitz and Potter, 1971)], shelly material, orthoconic nautiloids, and gastropod sections.

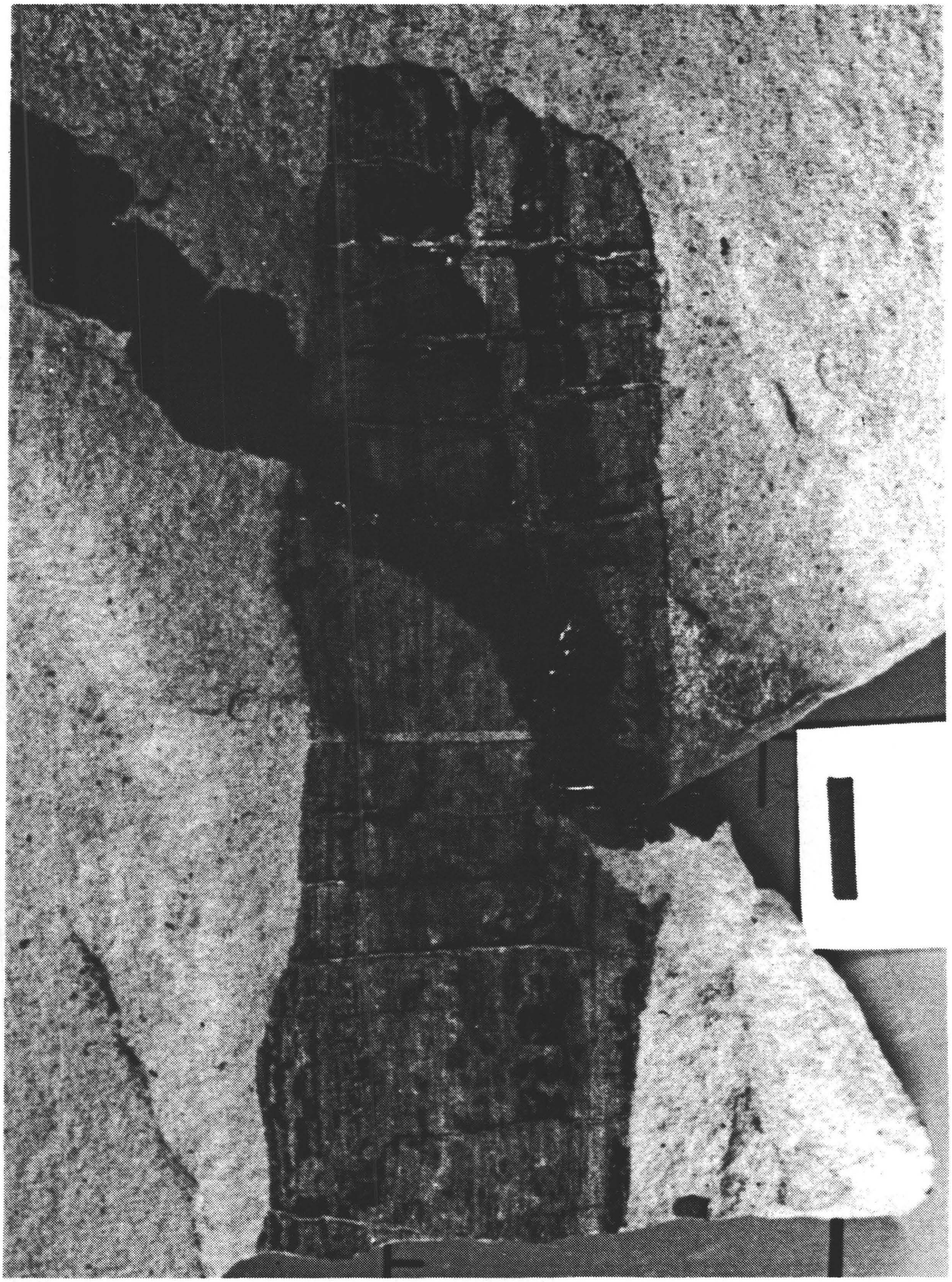
Facies E is abundant in the lower member and occurs only rarely in the middle and upper members. It usually caps the facies sequence A-C-E, or B-C-E, or A-D-E. Rare sulphide blebs and crystals have also been found in this facies, as well as vuggy calcite in fractures.

3.4 Discussion

Generalized facies sequences were attempted after the examination of the Long Rapids Formation drill core and outcrop data. The most common recurring sequence is the facies A/B-C couplet which is pervasive throughout the Formation. The next most common sequence or "rhythm" is the facies sequence A/B-C-E, which only occurs in the lower and middle members (Figure 3.1b and 3.6).

The sedimentary couplets begin with a dark shale facies (A or B) and are overlain by a massive, green-grey mudstone

Figure 3.5: ?*Callixylon* (scale bar = 1 cm).



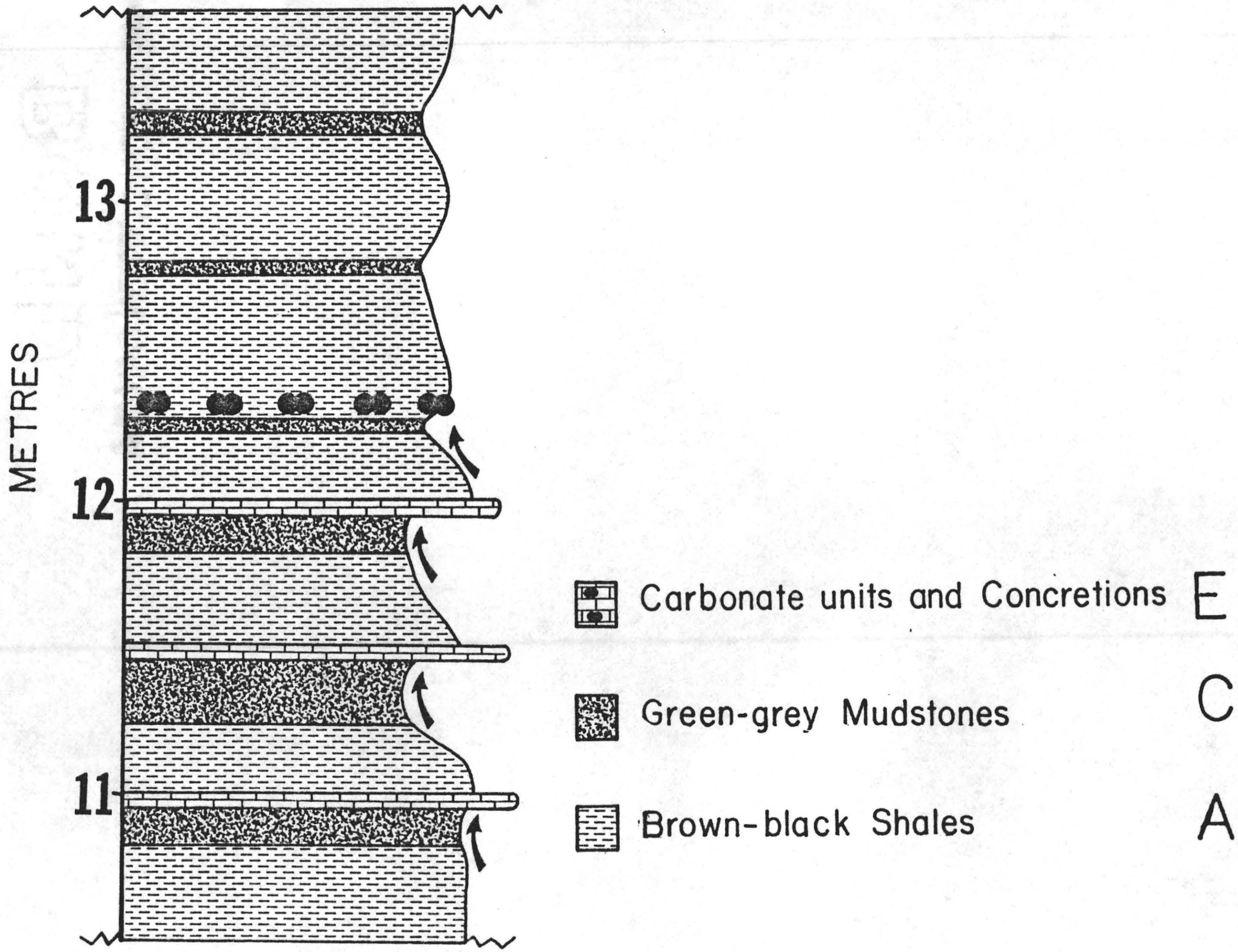
/shale unit (facies C or D). The contact is sharp with facies A and gradational with facies B due to the affects of bioturbation. The sedimentary triplets begin with facies A/B-C, and are overlain by facies E (as a distinct carbonate bed or small nodules) (Figure 3.6). These rhythms can range from approximately 5 to greater than 100 centimetres.

House (1983) also noted small-scale rhythms in the Upper Devonian Rhinestreet Shale in New York:

> "...each (small-scale rhythm) shows an initiating black shale and the change from anoxic to oxic conditions is marked by a burrowed horizon which is followed by a variable sequence of gray shales usually culminating near the top with a septarian concretion level rich in goniatites."

This same sequence is evident in the Long Rapids Formation where the dark shale facies represent deposition under relatively deep water and anoxic conditions (with quiet water conditions). The bioturbated black shales may represent dysaerobic conditions (which allowed introduction of organisms tolerant of low-oxygen conditions) or the organisms may have been introduced with the overlying facies when more oxygen was present and burrowed into the organic-rich sediments. The green-grey mudstones/shales (facies C and D) represent dysaerobic to oxic conditions, and rocks of facies E are the most oxic and shallow-water units. A dark shale facies usually sharply overlies a carbonate bed. Some very sharp contacts between facies A and C are interpreted as erosional, due to the presence of fragmented fossil debris along the bedding

Figure 3.6: Idealized outcrop diagram of sedimentary triplets (facies A-C-E).



METRES
13
12
11
Carbonate units and Concretions
E
Green-grey Mudstones
C
Brown-black Shales
A

planes.

The facies sequences in the Long Rapids Formation seem to represent small-scale cyclic shallowing and oxygenation events in the Basin. Large-scale rhythms or trends in the Formation are not obvious, although the middle member probably represents a time when anoxia was most prevalent because of the high number of black shale units.

The concretions of facies E are formed diagenetically and by using their shapes, a guess can be made when diagenesis occurred (i.e. early or late). The small, spherical nodules probably formed early, before compaction of the sediments and near to the sediment-water interface. The large, oblate concretions reflect later diagenesis when compaction of the shales was occurring. Similar shaped concretions were recorded by Dix and Mullins (1987) in the Middle Devonian Hamilton Group in New York.

The source of carbonate for these concretions is difficult to ascertain since most occur in host rocks which possess little carbonate. They can occur in both the dark shale facies and the green-grey mudstone, with the larger concretions found in black shales and the smaller nodules in the mudstones. The source of carbonate may be from the dissolution of calcareous organisms, with the nodule forming around a nucleus such as a burrow or a plant fragment.

The Long Rapids Formation represents a period of transgression during the Frasnian-Famennian. The small-scale sequences were probably eustatic in origin, although their ultimate interpretation is difficult. House (1983) suggests such factors as climatic oscillations, periodic ocean circulation changes resultant upon orbital perturbations, and land-based erosion cycles as possibly causes for the small-scale changes. These factors and others are discussed in more detail in Chapter 6.

CHAPTER 4:

PALEONTOLOGY

4.1 Introduction

The body fossils found to date in the Long Rapids Formation include goniatites, crinoids, brachiopods, solitary corals, orthoconic nautiloids, conodonts, and molluscs. Most fossils are well preserved, and although many are allochthonous, some *in situ* representatives are also present. Body fossils have been found in all facies.

Trace fossils are the best records for evidence of organisms that have lived in or passed through the sediments. In total, nine ichnogenera appear in the Long Rapids Formation; six are positive identifications, two are questionable, and one is unknown. The list includes *Alcyonidiopsis, Chondrites, ?Cylindrichnus, Planolites, ?Skolithos, Teichichnus, Terebellina, Zoophycos,* and Ichnogenus "A". Trace fossils have been found in all facies.

4.2 The Fossil Record

The following discussion will touch briefly on all the body fossils found in the Long Rapids Formation, with emphasis placed on trace fossils. Trace fossils were more abundant and more obvious than body fossils, and yielded greater information.

4.2.1 Body Fossils

i) Phylum Mollusca: Class Cephalopoda: Subclass Ammonoidea: Order Goniatitida: *Manticoceras sinuosum* sp.

(Figure 4.1 a,b and 4.2 a,b)

Goniatites are ammonoid cephalopods having a shell with angular sutures with eight undivided lobes. The goniatites in the Long Rapids Formation were found only in outcrop and reached diameters of approximately 8 centimetres. Fragments and whole specimens of *M. sinuosum* were found within the lower member, predominantly in facies C and E. When found in facies E, the goniatites were usually present with other body fossils such as brachiopods, orthoconic nautiloids, gastropods, etc. (Figures 4.1a and 4.7a). When found in massive green-grey mudstones (facies C), goniatites were present as whole or slightly fragmented specimens (Figure 4.2 a,b). One specimen (Figure 4.2b) had a small brachiopod attached to its inner coil, probably the result of postmortem attachment. The presence of goniatites may imply a pelagic habitat, but a bottom-feeding (nekto-benthic) habitat may also be possible.

M. sinuosum is worldwide in its distribution during the Frasnian, and does not usually extend into the Famennian (House 1973; 1985). The disappearance of *M. sinuosum* at the end of the Frasnian was possible a result of the Frasnian-Famennian extinction event. In the Long Rapids Formation, the goniatites are only found in the lower 10 metres.

Figure 4.1: *Manticoceras sinuosum* A) A cross-sectional view of a goniatite in facies E (bar scale = 1 cm), B) Goniatite located on a bed of facies E. Other fragments are located to the left, pen for scale.

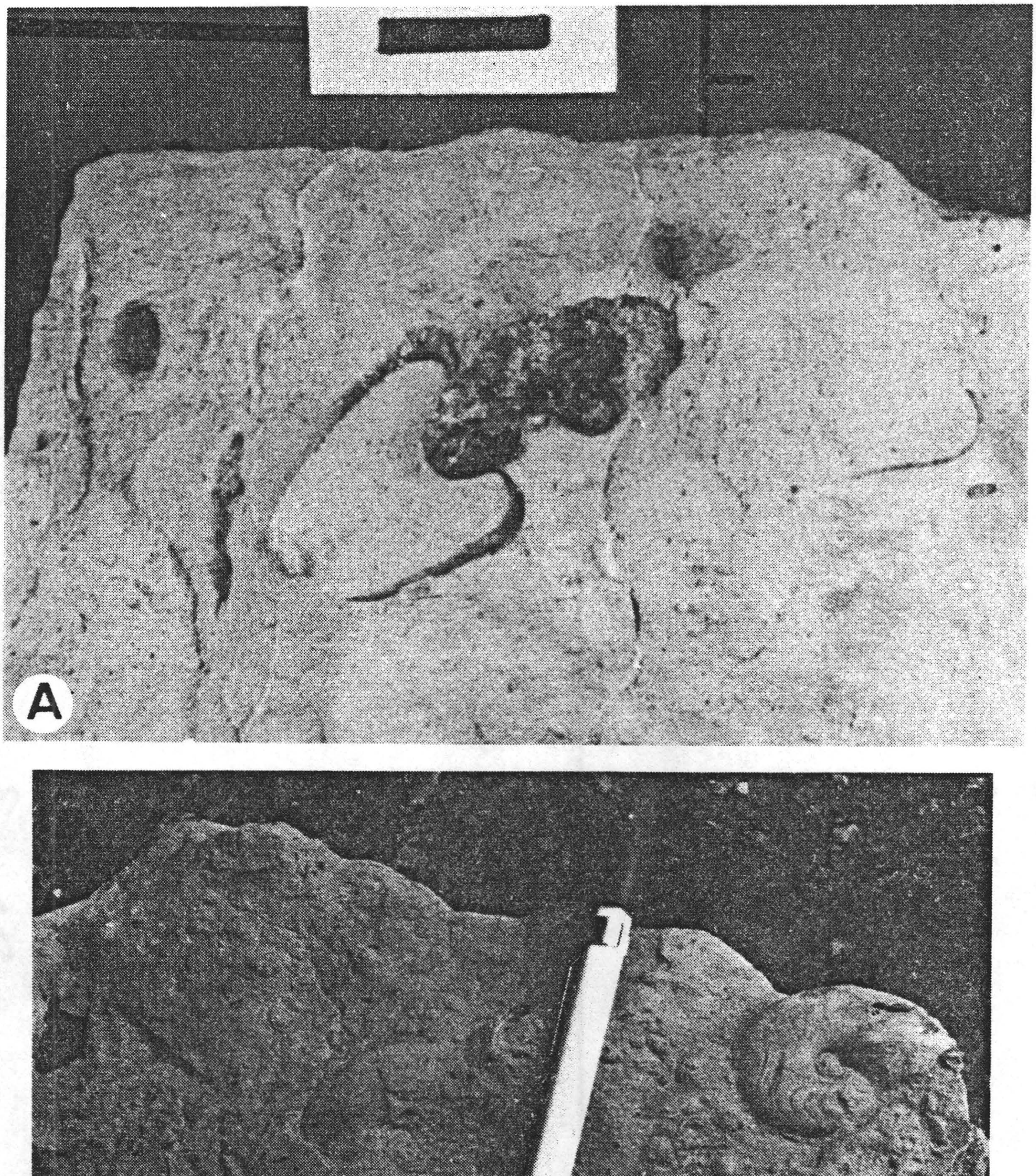
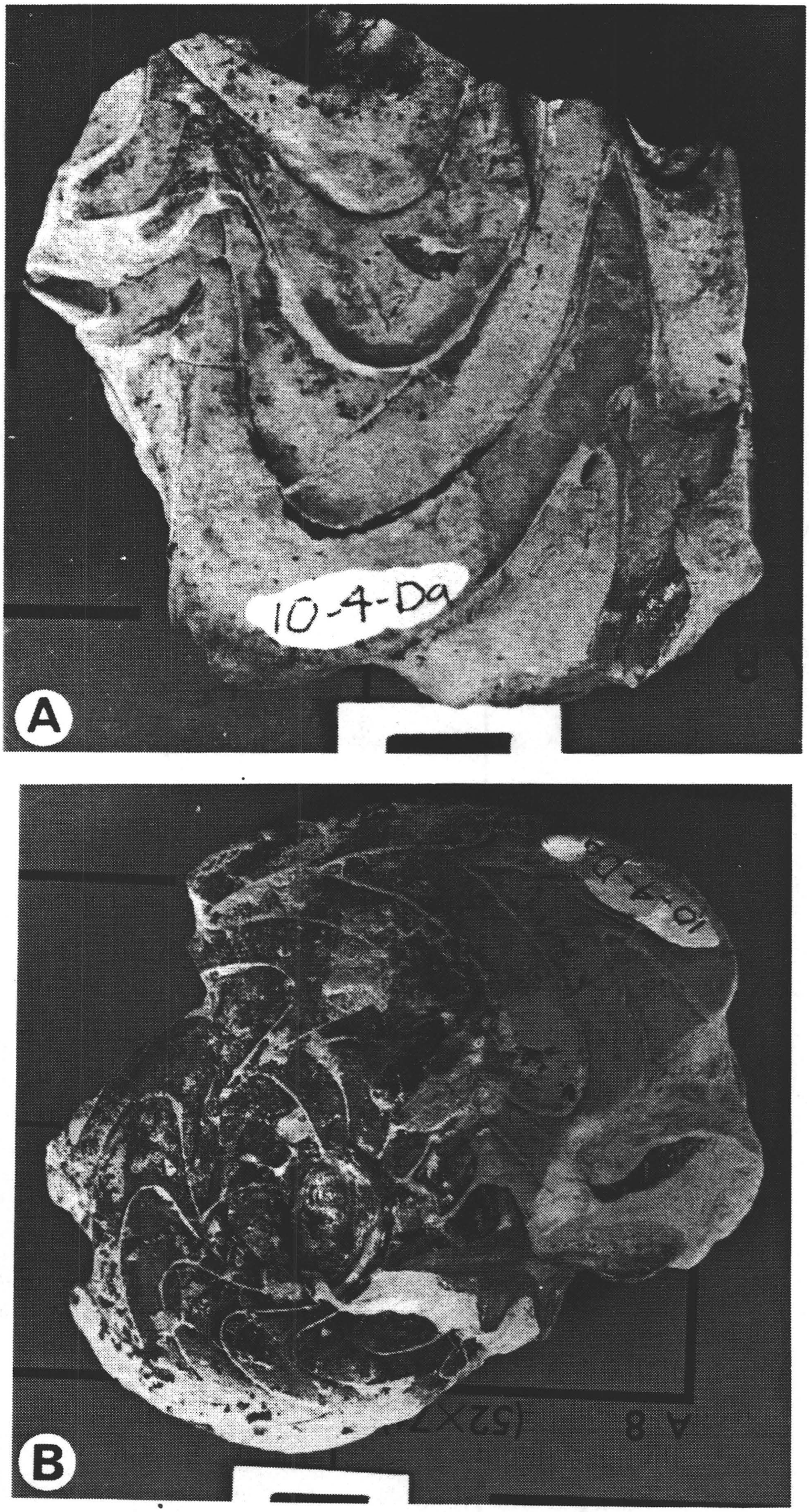

A
B

Figure 4.2: *Manticoceras sinuosum* A & B) Close-ups of shell morphology. Found at the base of a light brown shale bed (scale bar = 1 cm).


10-4-Da
A
B

ii) Phylum Mollusca: Class Cephalopoda: Subclass Nautiloidea

Orthoconic nautiloid undet. sp. (Figure 4.3a)

Small orthoconic nautiloids have been found in carbonate beds (facies E), usually associated with other body fossils.

iii) Phylum Mollusca: Class Bivalvia: Class Pectinidae

Pecten undet. sp. (Figure 4.4b)

One specimen of *Pecten* (5 by 5 cm) was found in a concretionary bed (Figure 4.4b).

iv) Phylum Mollusca: Class Gastropoda

Gastropods undet. sp. (Figures 4.4a, 4.5)

Gastropods have also been found in concretionary carbonate beds and are common in thin sections of facies E.

v) Phylum Brachiopoda: (Figures 4.6 a,b,c and 4.7 a,b)

Brachiopods are found in both outcrop and drill core and can occur within the various facies in the Long Rapids Formation. The most abundant occurrence is in the lower portion of the lower member (to the top of the Williams Island Formation) in facies C. Approximately 20 species have been identified (Table 1).

Sizes for the brachiopods, except for the large atrypids, are relatively dwarfed and more than half are well below the normal size. The majority of the specimens represent benthic fauna that are predominantly sedentary, except for

Figure 4.3: Various body fossils, A) Goniatite (x), orthoconic nautiloid (y), crinoid (z) (also present are brachiopods and gastropods), B) Rugose corals (scale bars = 1 cm).

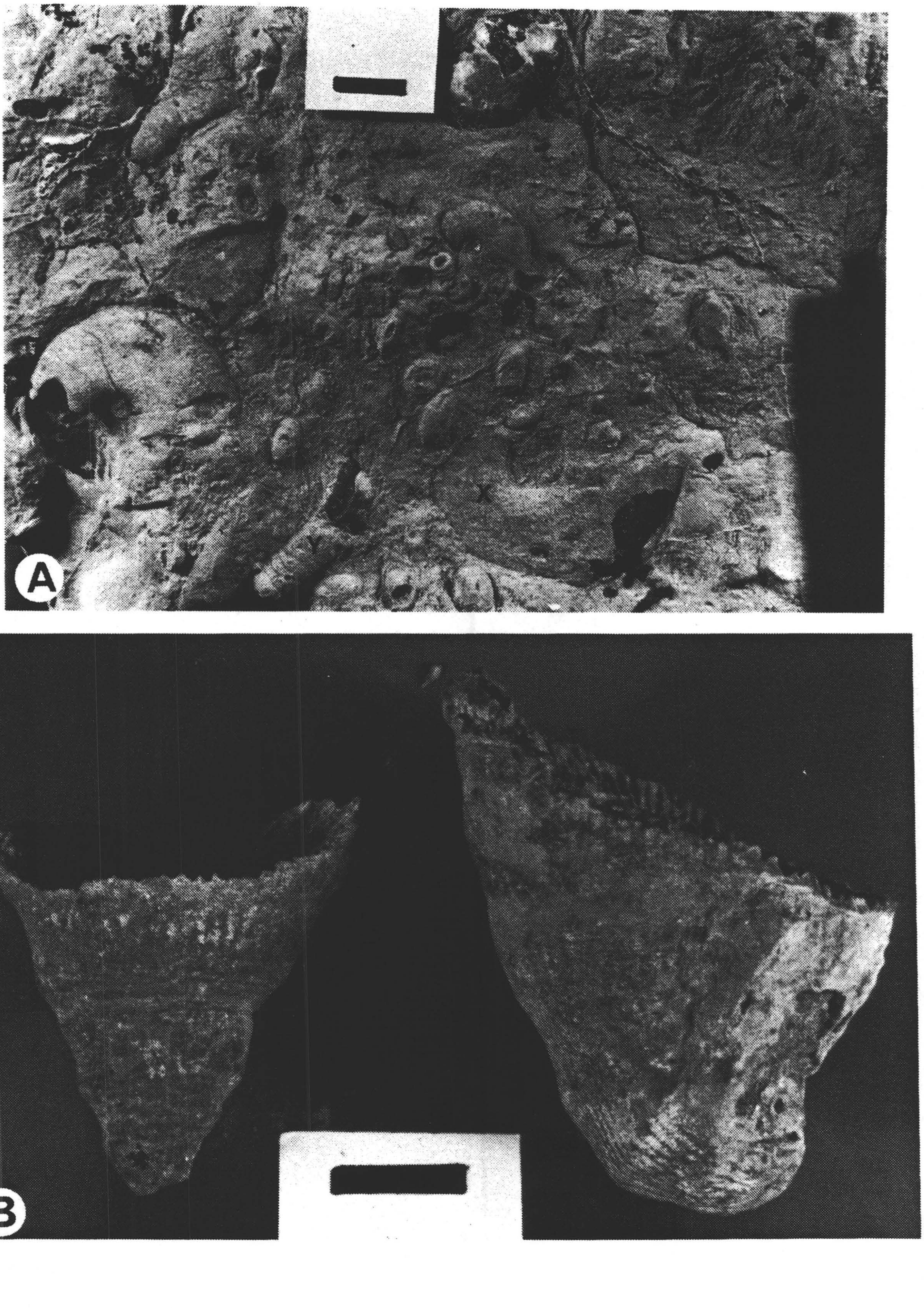

A
B

Figure 4.4: Molluscs A) Gastropod (undet. sp.) on a bed of facies E (arrow), B) *Pecten* shell on a bed of facies E (scale bars = 1 cm).

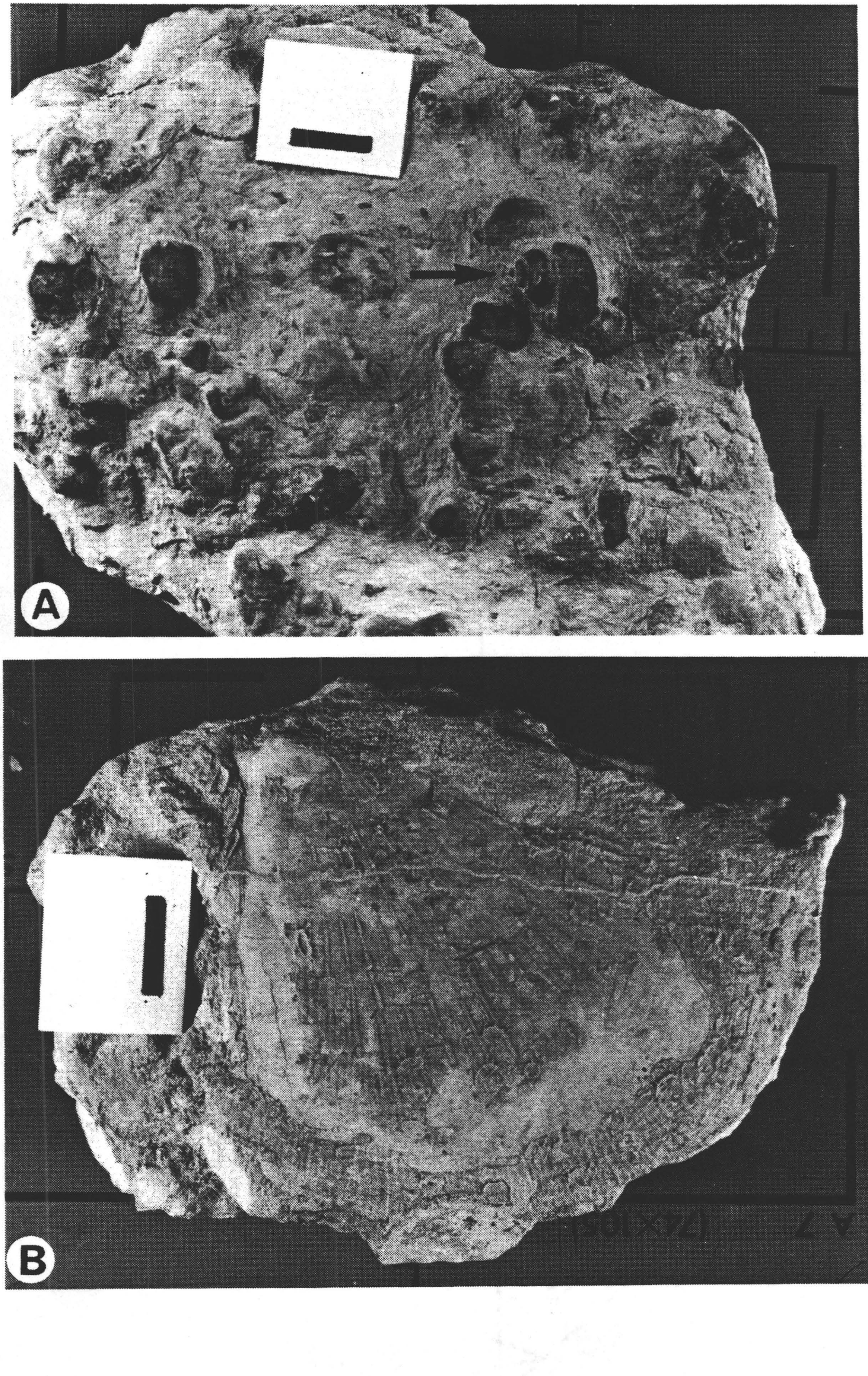
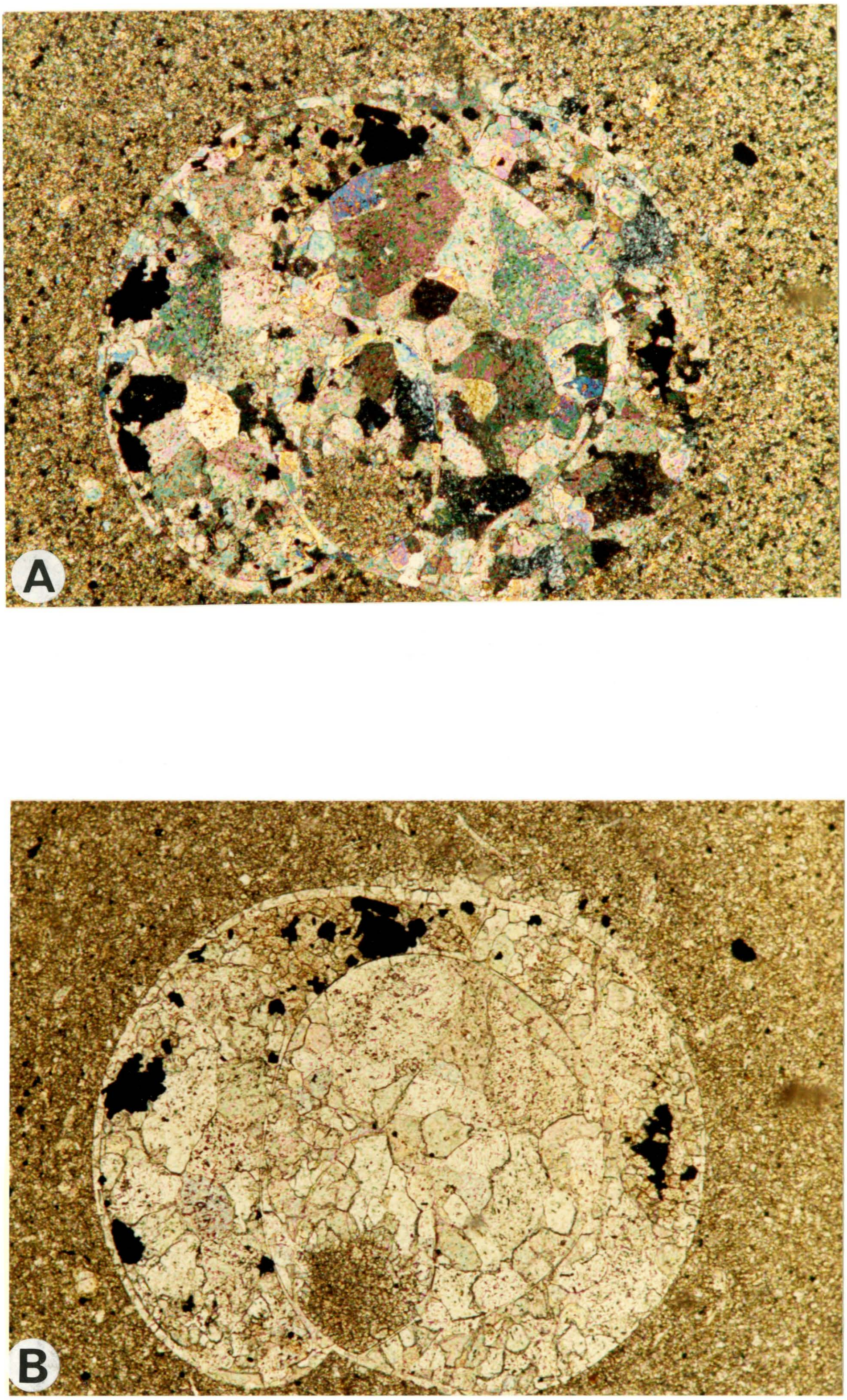

A
B

Figure 4.5: Gastropods A) Thin-section photomicrograph of a gastropod cross-section in facies E (1 mm across), B) Same photo as A) under plane light.


A
B

Schizophoria, Cyrtina, and *Tylothyris* (P. Copper, 1986, Laurentian University, personal communication). Copper suggests this indicates muddy substrates with few hold-fast opportunities, probably deeper or sheltered quiet waters. This, coupled with dwarfism, implies poor water circulation and oxygen deficient conditions.

Lingula, a chitinophosphatic, inarticulate brachiopod, is quite common along black shale bedding planes and is believed to have lived in restricted environments (Rudwick, 1965; 1970) (Figure 4.6c). They burrow into the substrate, and thus, specimens found in the Long Rapids Formation represent forms that had been washed in from elsewhere. One trace fossil (Figure 4.11b) may represent a burrow of a *Lingula* (=*?Lingulichnus*), but an *in situ Lingula* has yet to be found in the Long Rapids Formation.

Since most of the brachiopod families were found in the lowermost portion of the Long Rapids Formation, it may be possible that they were affected by the Frasnian-Famennian faunal crisis or were facies controlled.

vi) Phylum Echinodermata: Subphylum Crinozoa: Class Crinoidea

Figure 4.3a

Crinoid stems have been found in facies C and E and ossicles have been found in the lowermost bed of the Long Rapids Formation outcrop section. Crinoids are of an undeterminate species.

TABLE 1: LIST OF BRACHIOPODS FOUND IN THE LONG RAPIDS FORMATION

(The following were identified by Dr. P. Copper, Laurentian University (1986); staff at the Ontario Geological Survey; and E.M. Kindle and A.E. Wilson in Martison, 1953, p.46).

Productella sp.
Douvillina arcuata (Hall)
Chonetes cf. *lepida* (Hall)

Ambocoelia umbonata (Conrad)
Tylothyris sp.
Cyrtina sp.
?Tecnocyrtina cf. *missouriensis*
Desquamatia (Seratrypa) cf. *snyderensis* (Greger)
?Warrenella
Pseudoatrypa cf. *devoniana* (Webster)
Costatrypa americana (Stainbrook)

Schizophoria iowensis (Hall)
Rhipidomella sp.
Styliolina fissurella (Hall)

Leiorhynchus cf. *quadracostatum*
Leiorhynchus cf. *laura* (Billings)
Ladogioides pax
Calvinaria cf. *variabilis athabascensis*

Lingula ligea (Hall)

Figure 4.6: Brachiopods A) Miscellaneous brachiopods (bar scale = 1cm), B) Whole brachiopod specimens on a bedding plane in core (facies E) (the sprirferid ?*Warrenella*), C) *Lingula* on a drill core bedding plane (rulers in cm).

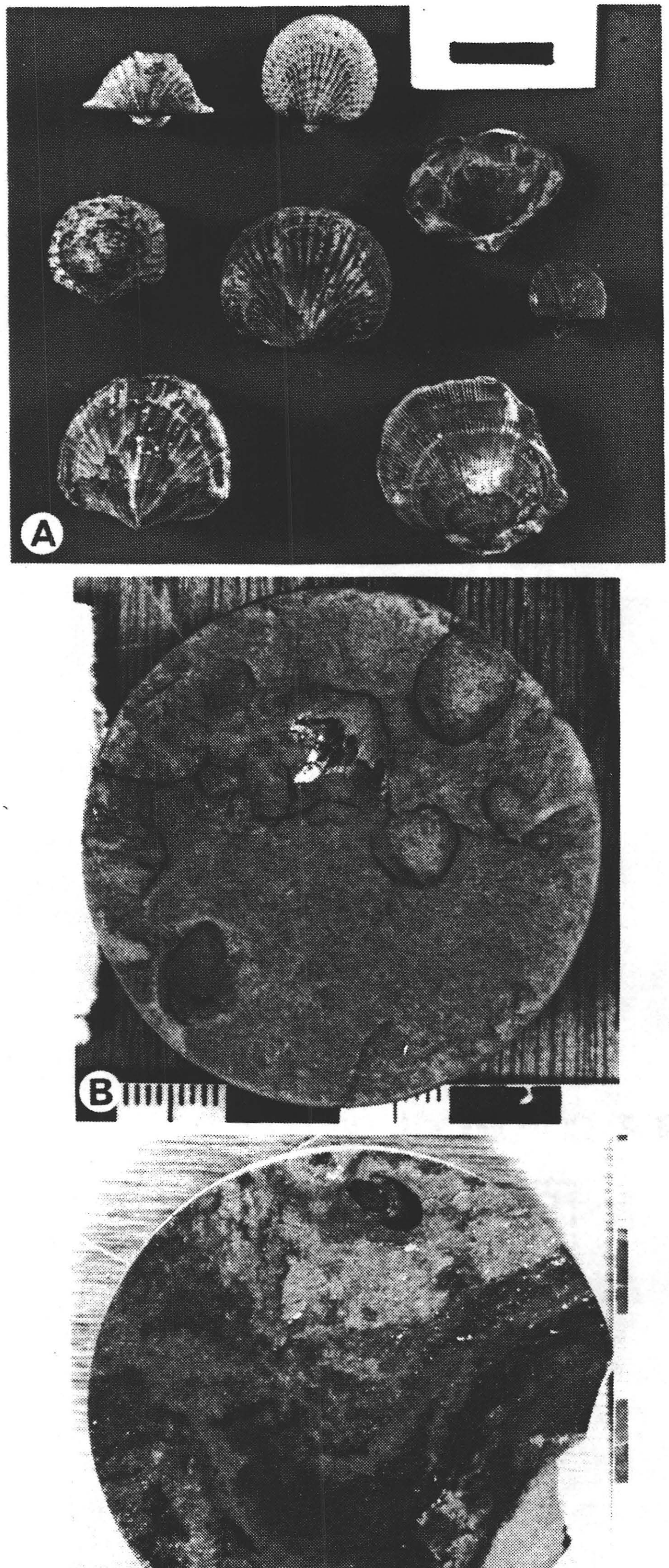
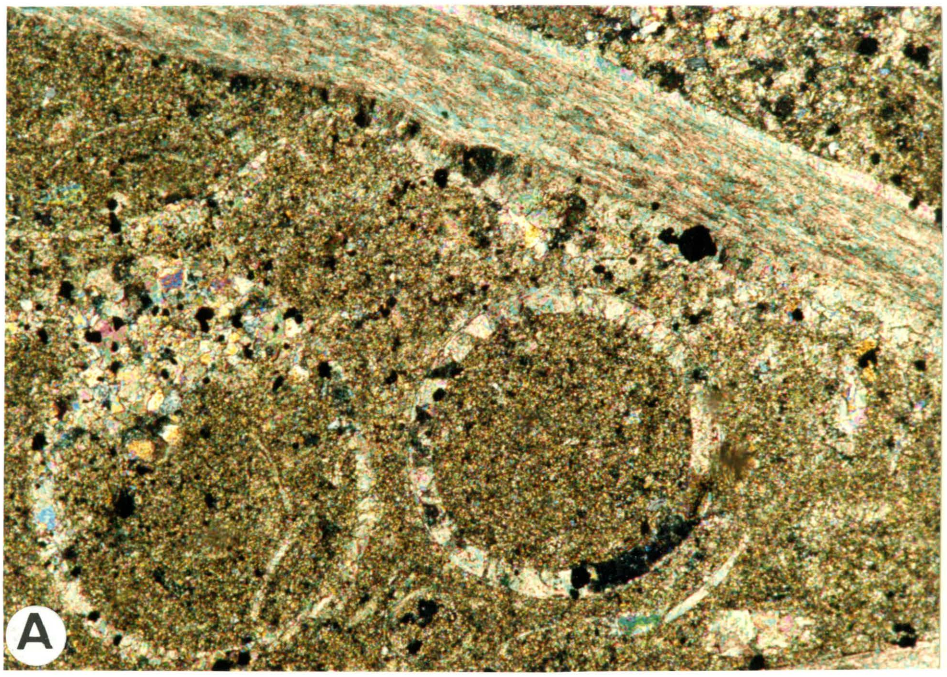
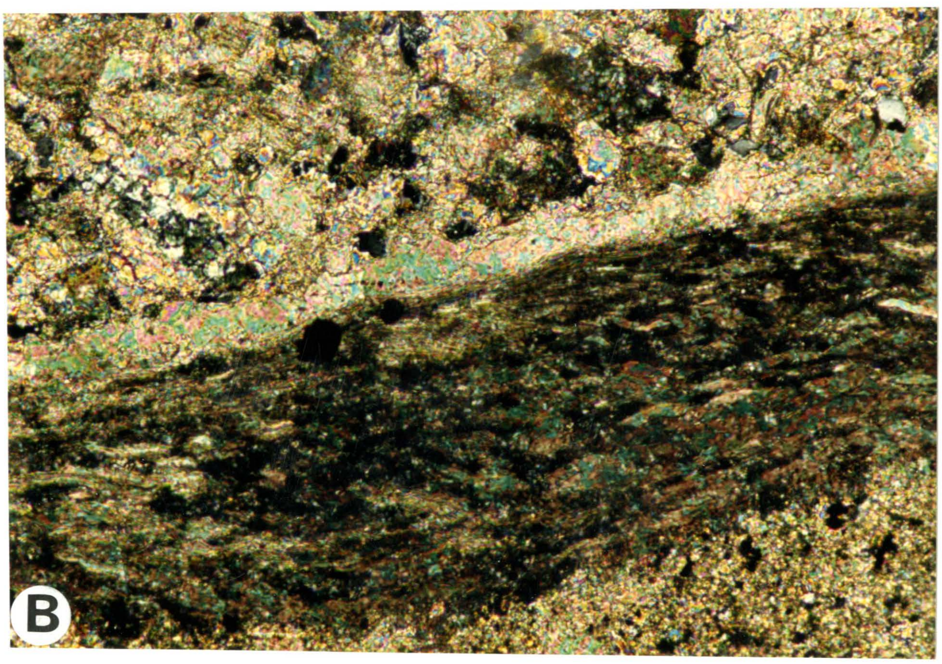

A
B
C

Figure 4.7: A) Thin-section photomicrograph of a brachiopod shell with growth lamellae (cross-section at top) with calcareous pelletoid material (field of veiw = 2mm), B) Close-up of A).



A



B

vii) Phylum Cnidaria: Class Anthozoa: Subclass Zoantharia

Order Rugosa (undet. sp.) (Figure 4.3b)

Solitary rugose corals have been found in the lowermost green-grey mudstone bed of the outcrop section (facies C).

viii) Conodonts: (Group Conodontophorida) (Table 2)

Abundant conodonts have been extracted from the carbonate beds by the staff at the Ontario Geological Survey, and can be observed on black shale bedding planes in both drill core and in outcrop. Telford (1985) reports that at least six of the standard Upper Devonian conodont zones are represented by the Long Rapids Formation conodont species. The zones range from the earliest Frasnian Lower *asymmetricus* zone to the middle Famennian Lower *rhomboidea* zone.

ix) Miscellaneous: (Figure 4.8 a,b,c,d)

Rare occurrences of plant remains have been found in outcrop. These specimens are tentatively assigned to ?*Callixylon* (Figure 3.5), and are common in Appalachian Basin shales (Conant and Swanson, 1961). Some specimens are present in concretionary units and coaly plant remains have been found as thin laminae in facies C. These specimens probably drifted from a nearby land source.

In thin section and SEM microphotographs, the marine algal spore case, *Tasmanites huronensis* (Dawson) (Figure 3.2), is quite abundant in facies A & B. It can also be found along black shale bedding planes in both outcrop and drill core.

TABLE 2: LIST OF CONODONTS IN THE LONG RAPIDS FORMATION

(The following condodonts were identified by Dr.T.T. Uyeno, Institute of Sedimentary and Petroleum Geology, Geological Survey of Canada, Calgary, and the staff at the Ontario Geological Survey, Toronto)

Palmatolepsis asymmetricus asymmetricus ?
P. crepida (Sannemann)
P. foliacea (Youngquist)
P. gigas (Miller & Youngquist)
P. glabra (Ulrich & Bassler)
P. glabra prima (Zeigler & Huddle)
P. glabra pectinata (Zeigler)
P. hassi (Muller and Muller)
P. linguiformis (Muller)
P. minuta minuta (Branson & Mehl)
P. perlobata perlobata (Ulrich & Bassler)
P. perlobata helmsi ?
P. quadrantinodosa quadrantinodosa (Branson & Mehl)
P. quadrantinodosa inflexa (Muller)
P. quadrantinodosa inflexoidea (Ziegler)
P. quadrantinodosalobata (Sannemann)
P. rhomboidea (Sannemann)
P. subperlobata (Branson & Mehl)
P. subrecta (Miller & Youngquist)
P. tenuipunctata (Sannemann)
P. triangularis (Sannemann)
P. unicornis (Miller & Youngquist)
P. cf. regularis (Bond)

Polygnathus asymmetricus asymmetricus (Bischoff & Zeigler)
P. dengleri (Bischoff & Zeigler)
P. dubius (Hinde)
P. webbi (Stauffer)
P. cf. P. normalis (Miller & Youngquist)

Icriodus symmetricus (Branson & Mehl)

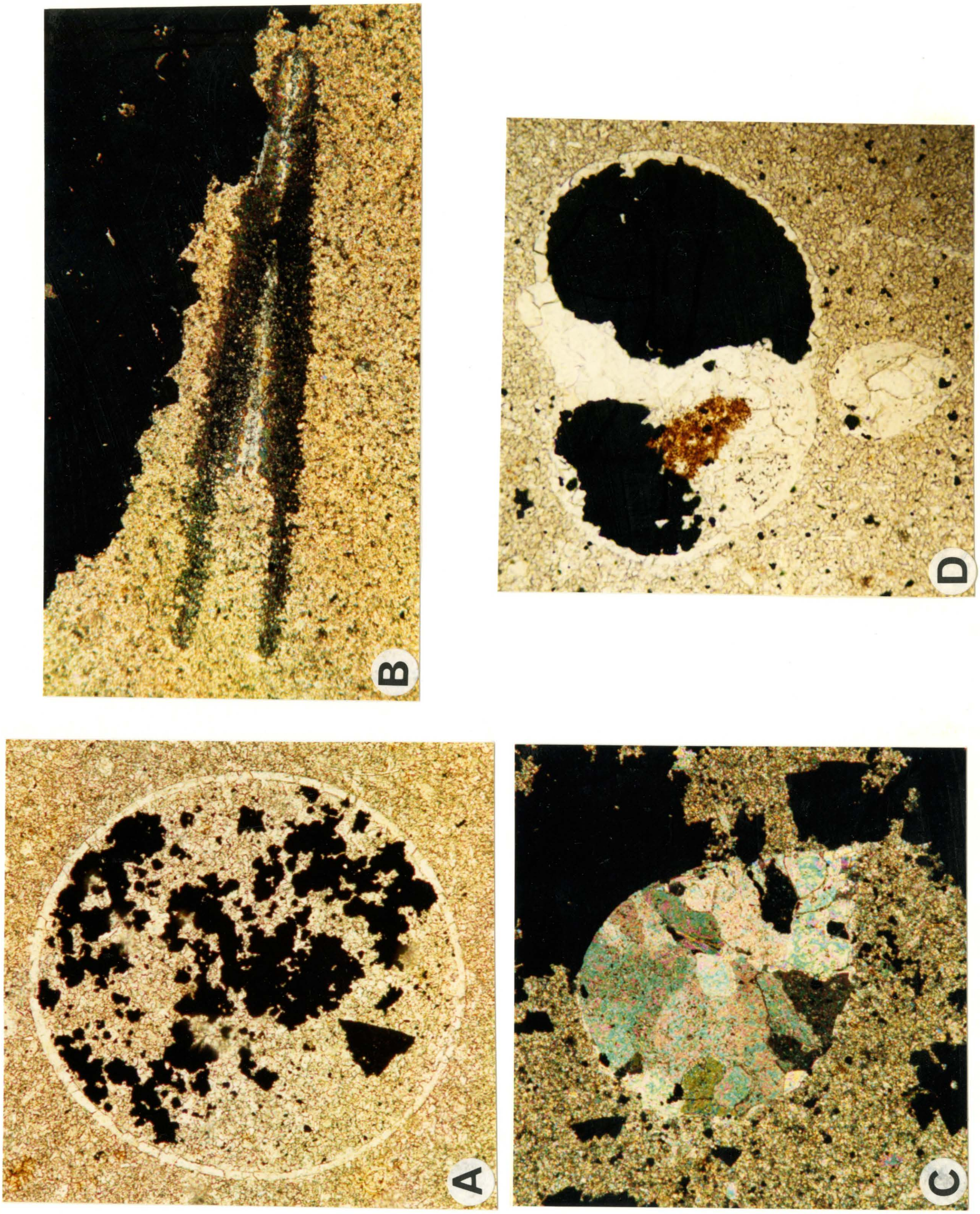
Ancyrodella rotundiloba rotundiloba (Bryant)

Ancyrognathus sp.

Mesotaxis sp.

Thin sections from carbonate facies reveal biomicrites with abundant pelletoid and fossiliferous material (commonly re-crystallized to sparry and blocky calcite) emplaced within a micritic matrix of microcrystalline calcite, minor dolomite, and undeterminate material (clays). The fossil fragments present include shelly material with well preserved growth lamellae, gastropod sections, pelletoid material, and ammonoid fragments. Spine-shaped objects may be brachiopod spines, while pelletoid material may be tintinnine shells or calcareous worm tubes (Horowitz and Potter, 1971).

Figure 4.8: Miscellaneous fossil objects in thin-section A) Thin-section photomicrograph of pellet-shaped object with a calcified outer rim and abundant pyrite in its center (= 0.6 mm), B) ?Brachiopod or ?enchinoderm spine (= 2mm), C) Spar calcite infilled brachiopod (= 0.4 mm), D) Gastropod cross-section (= 0.5 mm) (all are from facies E).


A
B
C
D

4.2.2 Trace Fossils:

Trace fossils in the Long Rapids Formation occur everywhere, except in facies A. No trends are obvious, except there appears to be a slight decrease in their abundance upwards in the Formation. Specimens are most abundant in the upper portions of facies B, and are common in C and E. Traces are found in facies B only when it is overlain by a green mudrock facies (C or D) and a carbonate (facies E). When traces were found in facies B, the burrows possessed a green-grey sediment infill (usually very similar to the overlying green unit) and can sometimes be found as far down as 20 centimetres from the upper boundary of the facies. When found in facies E, burrows were only identifiable in the outcrop section where the facies was weathered. Otherwise, no discernable burrows were present and the unit appears very mottled.

Most traces represent horizontal, deposit-feeding specimens, except for the rare traces ?*Skolithos*, ?*Cylindrichnus*, Ichnogenus "A", and possibly *Terebellina*. These latter, more vertical traces, may represent the activities of suspension-feeding organisms. Best representations of these traces are within concretionary units or small nodules (facies E). The small-sized, spherical concretions (average size, 3 by 6 cm) contain spaghetti-like burrows oriented at various angles, and it appears that these burrows are the nucleus around which the concretions grew.

Systematic Ichnology

i) Ichnogenus *Alcyonidiopsis* Massalongo, 1856

(Figure 4.9 a,b,c)

Diagnosis: Tubular burrows filled with circular to ovoid fecal pellets. No burrow margin is outlined, but the pellets themselves are packed in a tubular form.

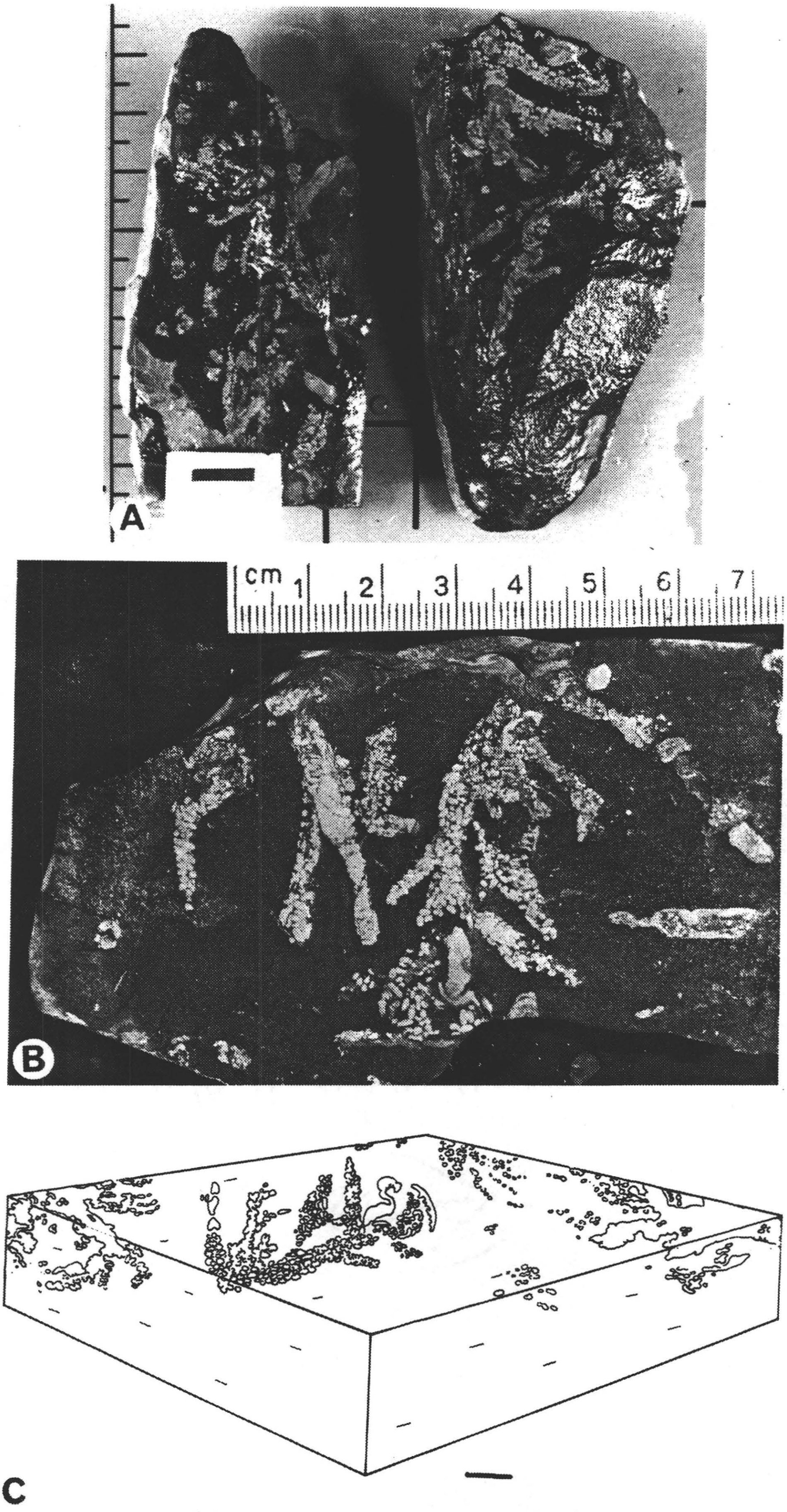
Remarks: This trace was recognized to be a junior synonym of *Tomaculum* Groom (1902) that represented only the pellets. Richter and Richter (1939; in Chamberlain, 1977) described the pellets as *Coprulus* and the burrow as *Syncoprulus pharmaceus* and placed it as a junior synonym of *Tomaculum.* For this study, *Alcyonidiopsis* is defined as tubular burrows filled with fecal pellets and *Syncoprulus* is a junior synonym. *Granularia* looks similar, but is a pellet-lined burrow. See Chamberlain (1977) for a more thorough discussion.

Alcyonidiopsis longbardiae sp. Massalongo, 1856

Description: Mainly linear, near-horizontal burrows, filled with small ovoid pellets. Branching is common and angles are steep in some transverse views (25 to 35). The pellets are packed in a tubular burrow which possesses no distinct burrow margin. The pellets have a green-grey mud infill and contrast because of the black shale matrix.

Remarks: Burrow lengths in the Long Rapids Formation can reach up to 4 cm and widths vary from 2 to 5 mm. Pellet sizes

Figure 4.9: *Alcyonidiopsis* A) Hand sample of *A. longbardiae* (scale bar = 1 cm), B) Hand sample of *A. longbardiae* (ruler in mm) (both samples in facies B), C) Pictorial view of *A. longbardiae* (scale bar = 1 cm).


A
cm 1 2 3 4 5 6 7
B
C

range from 0.2 to 2.0 mm in diameter and appear circular to elliptical. If the overall burrow size is small, the pellets also tend to be small. In transverse cross-section, the pellets tend to be elongated parallel to bedding. Many burrows grade into *Chondrites* burrows that contain the green-grey mud infill, but lack the pellets.

Occurrence: Found within facies B beneath green-grey mudstone units. Burrows usually extend to depths of about 3 to 5 cm, although one specimen was found 20 cm beneath a green-grey bed.

Association: Occurs with small and normal size *Chondrites* and occasionally *Planolites*.

Sediment: Pellets occur as green-grey mud infill, surrounded by a black shale matrix. The interstitial spaces between the pellets also contain black shale. Occasionally the spaces between the pellets are lighter in colour (grey-black) than the overall surrounding black shale host rock.

Origin: Chamberlain (1977) suggests *Alcyonidiopsis* is the feeding burrows of polychaetes based on the large pellet size versus the small burrow diameter. Two mechanisms are possible to explain its formation; a suspension-feeding organism used the burrow as a domicile and excreted fecal pellets into the burrow, or the organism may have been a deposit-feeder that passed through the sediment, consuming it, and then excreting fecal pellets.

ii) Ichnogenus *Chondrites* von Sternberg, 1833

(Figure 4.10)

Diagnosis: *Chondrites* consists of three-dimensional burrow systems branching in a plant-like, dendritic pattern, at approximately 25 to 45 from a main tube. The burrow systems tend to level off horizontally away from the main shaft and generally run parallel to bedding. Crossovers may also occur. One or more main axes may have been open to the surface. For further discussion, see Simpson (1957) and Chamberlain (1977).

Chondrites sp.

Description: *Chondrites* sp. burrows branch from one or more main tunnels and lengths range from 1.5 to 4.0 cm, although most are approximately 2.5 cm. Dendritic *Chondrites* is not common in the Long Rapids Formation. In transverse view, most burrow diameters are elliptical versus circular, which may be due to compaction. Burrow diameters range from 1 to 4 mm. Tunnels are usually straight to gently curved and do not show any radial pattern.

Remarks: In the Long Rapids Formation, assignment of an ichnospecies has not been attempted due to the need of a taxonomic revision of the ichnogenus. There seem to be two types of *Chondrites sp.* present in the Long Rapids Formation that have a similar morphology, but possess different sizes. These may represent juvenile and adult stages of a burrowing

Figure 4.10: *Chondrites* in facies B (in core) (width of core = 3.5 cm), with a *Zoophycos* in facies C at the top (arrow).

organism, or two different species.

Occurrence: Occurs within facies B, directly beneath green-grey mudstones (facies C) (commonly 3 to 5 cm from the top). It rarely occurs within green-grey mudstone beds.

Association: Occurs most commonly with *Alcyonidiopsis* and *Planolites*, and rarely with *Zoophycos* and ?*Cylindrichnus*.

Sediment: Most are preserved as green-grey mud infill enclosed in a black shale matrix. In core, some bedding planes of green-grey mudstones have *Chondrites* burrows outlined by a black, pyritic film.

Origin: A debate exists as to whether *Chondrites* is a dwelling burrow, feeding burrow, or both. Simpson (1957) interpreted the trace as being produced by a deposit-feeding sipunculan worm with a retractable proboscis, but he was unable to confirm his theory with Recent examples. The proboscis would have allowed the animal to mine the sediment from a fixed point (within the main vertical tunnel with its posterior down) and keep the burrow open to circulating waters. Tauber (1949; in Ksiazkiewicz, 1977) suggests they were the burrows of sessile filter-feeding Annelida.

Origin of the infill is also a problem. Many authors believe the infill was passively introduced from overlying sediments, whereas others believe the tunnels were filled actively by the burrowing organism. See Ksiazkiewicz (1977) for further discussion.

iii) Ichnogenus *Cylindrichnus* Howard, 1966

(Figure 4.11 a,b)

Diagnosis: Sub-conical to sub-cylindrical burrows, straight to slightly curved, circular to oval diameters with concentrically layered walls. Overall diameters range from 5 to 20 mm and inner core diameters from 2 to 4 mm (Hantzschel, 1975; Howard and Frey, 1984).

?Cylindrichnus sp.

Description: Long Rapids Formation specimens range in size from 7 to 12 mm. Most burrow diameters are elliptical and possess concentric layering along the walls. Burrows without concentric layering have irregular margins.

Remarks: The concentric layering consists of alternating light- and dark-coloured sediments. Burrow lengths are undeterminable and some appear to taper to a point. Concentric zoning does not occur deep into the burrow. In Figure 4.11b, a shadow is seen behind one of the specimens, and may represent a previous position of the burrowing organism or a dewatering halo. In planar views the burrows are similar to *Cylindricum* (see Hantzschel, 1975).

Occurrence: Found in facies B, usually beneath green-grey mudstones (facies C or D) (approximately 2 to 5 cm below the contact). It can be found in both outcrop and drill core.

Association: Occurs rarely with *Chondrites*, *Planolites* and Ichnogenus "A".

Sediment: Burrow consists of alternating light green and

Figure 4.11: *?Cylindrichnus* A) *?Cylindrichnus* with circular Ichnogenus "A" toward the top in facies B (scale bar = 1 cm), B) Close-up of the previous view, with shadow structures (arrow).


5
A
B

dark grey muds. All burrows occur in black shales (facies B).

Origin: Dwelling or feeding-dwelling burrows of vermiform animals. The organism may have temporarily lived in the burrow, filter-fed or deposit-fed, and then moved on.

iv) Ichnogenus *Planolites* Nicholson, 1973

(Figure 4.12 a,b,c)

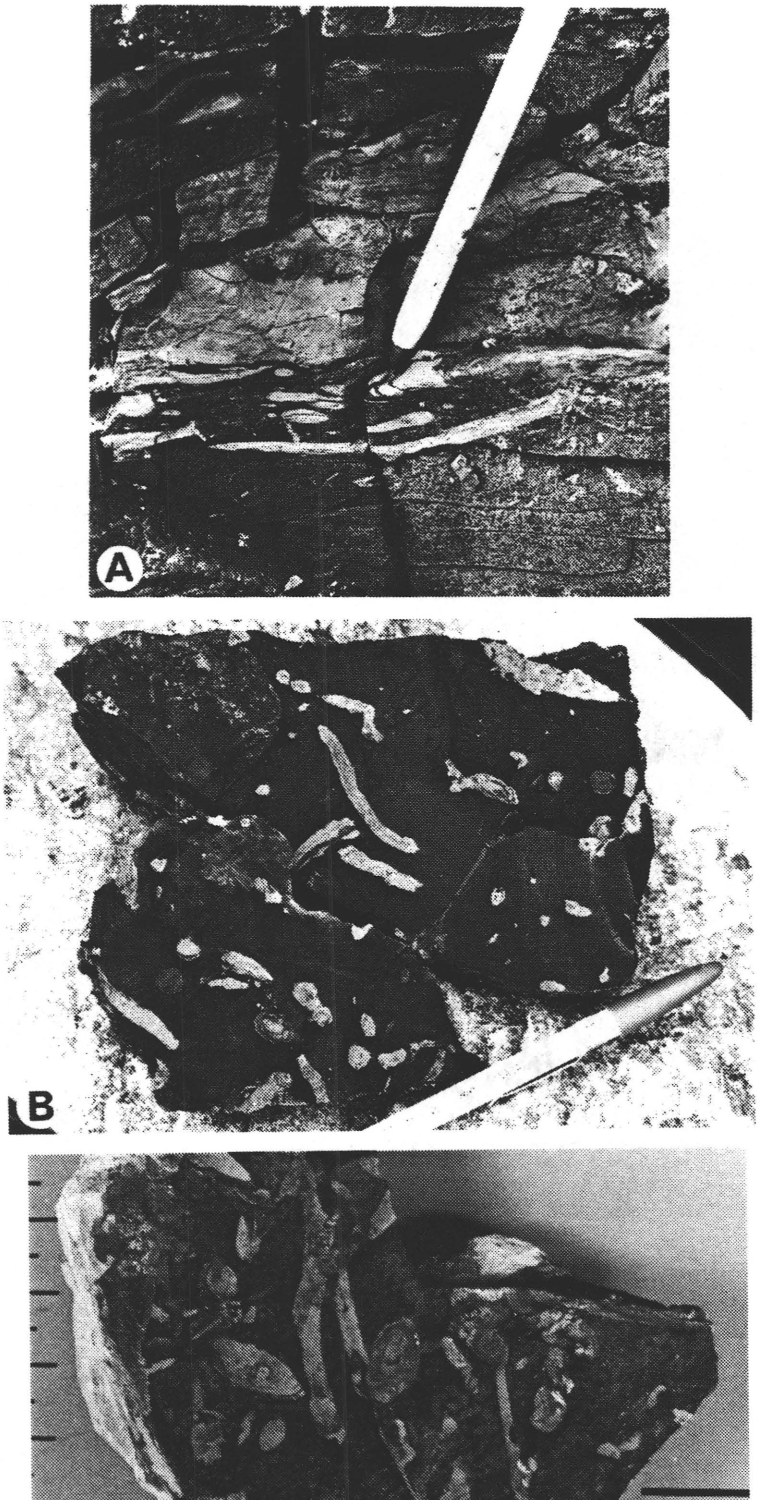
Diagnosis: Straight to contorted, rarely branching, horizontal to subhorizontal burrows. The tunnels are circular in transverse view where they are not compacted. Burrow walls may be smooth or irregular and sediment infill contrasts with the host rock. Lengths range from 1 to over 25 cm and diameters range from less than 1 to 1.5 cm.

Remarks: Three species of *Planolites* are currently recognized (Pemberton and Frey, 1982); *P. montanus* represents small, curved to tortuous burrows (average diameter: 3 mm); *P. beverleyensis* represents large, straight to gently curved burrows (average diameter: 10 mm); and *P. annularis* which are transversely annulated burrows. *Planolites* is believed to represent an actively infilled burrow where sediment has been ingested by the trace maker and passed through the alimentary canal. See Pemberton and Frey (1982) for a thorough discussion of this ichnogenus.

Planolites ?beverleyensis sp. Richter, 1937

Description: *Planolites* is abundant in the Long Rapids Formation. Most are straight to gently curved, and thus

Figure 4.12: *Planolites* A) Outcrop sample of *P. beverleyensis* and small *Chondrites* in facies B & C (pen for scale), B) *P. beverelyensis* on a hand sample (facies B) with *?Cylindrichnus* and Ichnogenus "A" (pen for scale), C) Hand sample of *P. beverelyensis, ?Cylindrichnus,* and *Alcyonidioposis* (near the scale bar) in facies B (scale bar = 1 cm).


A
B
C

closely resemble *P. beverleyensis.* The size range, however, is closer to that of *P. montanus.* The *Planolites* found in the Long Rapids Formation are assigned tentatively to *P. ?beverleyensis.*

Remarks: In the Long Rapids Formation, both longitudinal and transverse views are exposed. Burrow lengths can reach 10 cm and diameters range from 3 to 7 mm. No curved or tortuous forms of *Planolites* are represented in the Long Rapids Formation. Many burrows resemble a large-sized *Chondrites* and identification is difficult.

The light green sediment infill contrasts strikingly with the black shale host. Occasionally, longitudinal striations occur within the burrows parallel to the tunnel walls.

Occurrence: Found within facies B, directly beneath green-grey mudstone/shale beds (facies C or D) (usually 3 to 5 cm below the contact) and/or within carbonate nodules or beds.

Association: Occurs commonly with *Chondrites* and *Alcyonidiopsis*, and rarely with *?Cylindrichnus.*

Sediment: Preserved as green-grey mud infill within a black shale host. Many concretionary beds and nodules show distinct and well preserved burrows. The infill is similar to the host medium (green-grey micritic carbonates) and some have been pyritized. These forms resemble *Palaeophycus.* No branching has been observed. Some are nearly vertical, and in transverse cuttings and thin sections they resemble *?Skolithos*-type burrows.

Origin: Possible producers of *Planolites* include a variety of cylindrical, vermiform deposit-feeders, including polychaetes and enteropneusts. The common consensus is that these traces were formed by deposit-feeding organisms, but since the sediment infill is so contrasting, the burrows may have been passively infilled by sediments from the upper units.

v) Ichnogenus *Skolithos* Haldemann, 1843

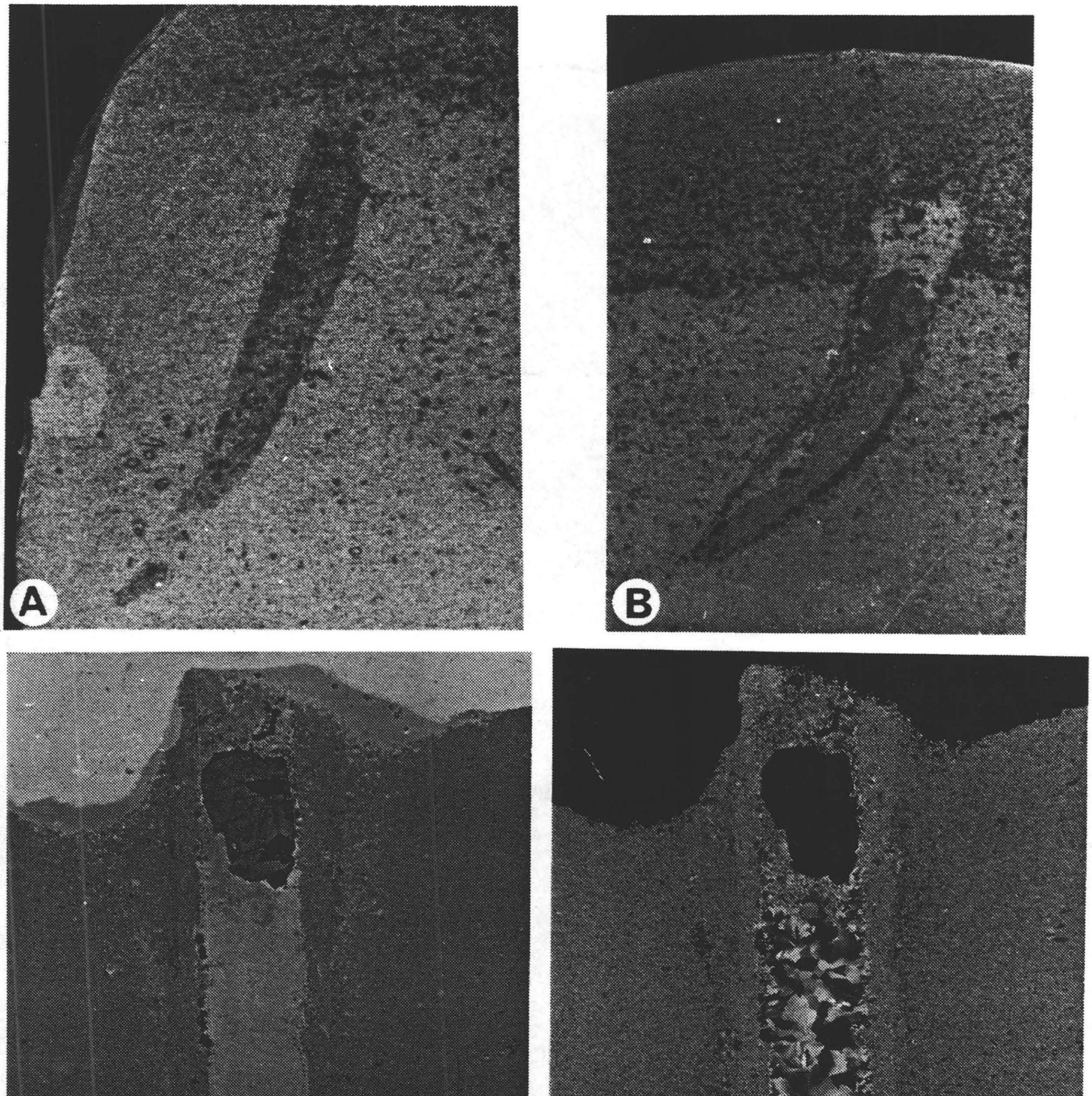
(Figure 3.3a and 4.13 a,b,c,d)

Diagnosis: Cylindrical tubes, either straight or gently curved, distinctly walled, rarely branched, vertical to steeply inclined to bedding. Diameters may range from 1 to 15 mm and lengths can reach 30 cm (maximum 100 cm) (Hantzschel, 1975).

?*Skolithos* sp.

Description: Long Rapids Formation specimens are all gently curved and tapered. Diameters range from 1 to 4 mm and lengths from 0.7 to 2.2 cm. All occur within facies E and are best observed on weathered carbonate bed and nodule specimens, or in cut slabs and thin sections. All are walled by a concentration of coarser-grained material (pyrite, quartz and calcite). Infilling can consist of either dark-coloured micritic carbonate, or sparry calcite. Many examples have burrow tops plugged by large grains of pyrite or collophane (Figure 4.13 c,d). Burrow wall thicknesses are usually only a few grains thick.

Figure 4.13: *Skolithos* A) *Skolithos* burrow in facies E (a small concretionary nodule) (ruler in mm), B) *Skolithos* burrow in facies E with what appears to be the remnant sediment-water interface, dark coloured grains are pyrite (burrow = 18 mm), C) Thin-section microphotograph of *Skolithos* in a concretionary nodule (burrow = 1 cm), D) The same burrow under polarized light; it is infilled with sparry calcite and a large collophane crystal plugs the hole. All specimens are oriented upwards.



Remarks: All specimens of ?*Skolithos* occur within facies E. Since most are somewhat curved, and burrow lengths are short (maximum 2.2 cm), assignment to ?*Skolithos* is tentative.

Association: Occurs with many indistinct and mottled burrows, with identifiable ones being *Planolites* and possibly some *Chondrites*. Some specimens occur with small ?gastropod or goniatite fossil fragments.

Sediment: Preserved in concretionary nodules (Figure 3.3a) in a micritic carbonate with occasional ?gastropod, goniatite, and brachiopod fossil fragments. Sediment infill is usually similar. Some burrows have pyrite and collophane grains infilling their openings, and some are completely infilled with sparry calcite.

Occurrence: Preserved in facies E which may occur as a bed above facies C or D or as discrete carbonate nodules within facies A or C.

Origin: Dwelling burrows of vermiform animals (suspension-feeding maldanid or sabellid polychaetes?). The burrows were probably a hollow tube until they were infilled by sediment from the overlying unit, or re-crystallized by diagenesis.

vi) Ichnogenus *Teichichnus* Seilacher, 1955

(Figure 4.14a)

Diagnosis: Long, horizontal burrows with spreiten structures stacked vertically to bedding. Represents the progressive vertical movement of a horizontal burrower that mined the sediment for food. Most are retrusive.

Teichichnus ?rectus Seilacher, 1955

Description: Only a few specimens of *Teichichnus* have been found in the Long Rapids Formation. Most are protrusive forms displaying excellent spreiten, and are approximately 2 cm long and 0.8 cm wide. They occur predominantly in facies B. They have tentatively been assigned to *T. ?rectus*. Figure 4.11a displays the structure of a protrusive *Teichichnus* burrow.

Occurrence: Found in drill core samples within facies B which are capped by facies C.

Association: Occurs with and cross-cuts small *Chondrites.*

Sediment: Occurs as green-grey mud infill within a black shale host.

Origin: The producer of the trace is unknown, but due to its long time range, it may have been produced by a variety of different animals (Hantzschel, 1975). The Recent polychaete, *Nereis diversicolor,* makes comparable traces (Seilacher, 1957, in Hantzschel, 1975), as do *Echiurus* and *Corophium* (Chisholm, 1970).

Figure 4.14: *Teichichnus* and *Terebellina* A) A protrusive *Teichichnus* in facies B (core sample), associated with *Chondrites*, B) *Terebellina* in facies B cross-cutting larger burrow (possibly a *Lingula* burrow) (rulers in cm).


A


B

vii) Ichnogenus *Terebellina* Bather, 1905.

(Figure 4.14b)

Diagnosis: Lined, straight and narrow tubes that never branch. See Bather (1905), Webby (1967), and Begg *et al.* (1983) for more detailed descriptions.

Terebellina sp.

Description: One specimen was found in a core sample, with a thickness of 2 by 17 mm. The burrow wall thickness was approximately 1 mm.

Remarks: The single specimen cross-cuts a larger unknown burrow (1.5 by 3.0 cm) (Figure 4.14b) in facies B and occurs 2.5 cm below a green-grey mudstone bed (facies C). No outcrop specimens were found.

Occurrence: Occurs within facies B and is overlain by a green-grey mudstone (facies C).

Association: Occurs with the large unknown burrow mentioned above and some mottled *Chondrites* that occur beneath it.

Sediment: The burrow wall is lined with green mud, and the burrow is infilled with black mud. It occurs in a matrix of black shale.

Origin: Burrow maker is problematic. It was a burrowing organism that structured its wall (i.e. lined it with sediment grains) and probably used the burrow as a domicile until the food supply was diminished or it was covered up by the overlying sediments.

viii) Ichnogenus *Zoophycos* Massalongo, 1855

(Figure 4.15 a,b,c and 4.16)

Diagnosis: Consists of near-horizontal to horizontal lobate spreiten structures which contain *en echelon* spreiten. They may or may not contain a marginal tube.

Remarks: Ksiazkiewicz (1977) describes two major morphological forms of *Zoophycos*: one with a circular outline, and another with a lobed, antler-like outline. In the Long Rapids Formation, only one outcrop specimen exhibits a well defined circular morphology, lacking a marginal rim (Figure 4.15c). In core, numerous cross-sections of *Zoophycos* have been found, but without planar views, it is difficult to assess the complete morphology.

Zoophycos ?briantus Massalongo, 1855

Remarks: Only two outcrop samples of *Zoophycos* have been encountered, one possessing a circular morphology. It can be tentatively assigned to *Z. briantus* based on the absence of the marginal rim. The majority of the *Zoophycos* specimens were seen in core sections, and thus their morphology is difficult to determine. See Ksiazkiewicz (1977) and Seilacher (1967) for a more thorough description on this genus.

Description: All specimens of *Zoophycos* in the Long Rapids Formation occur as a green-grey, mud-infilled burrow in a darker shale host (facies B). Only rarely do they occur within a green-grey mudstone bed (facies C) (see Figure 4.10).

Figure 4.15: *Zoophycos ?briantus* A & B) Cross-sections of *Z. ?briantus* in core with distinct spreiten (arrows) (located in facies B, the latter associated with *Chondrites*) (ruler in cm), C) Top veiw of *Z. ?briantus* in hand sample, associated with *Chondrites* (scale bar = 1 cm).

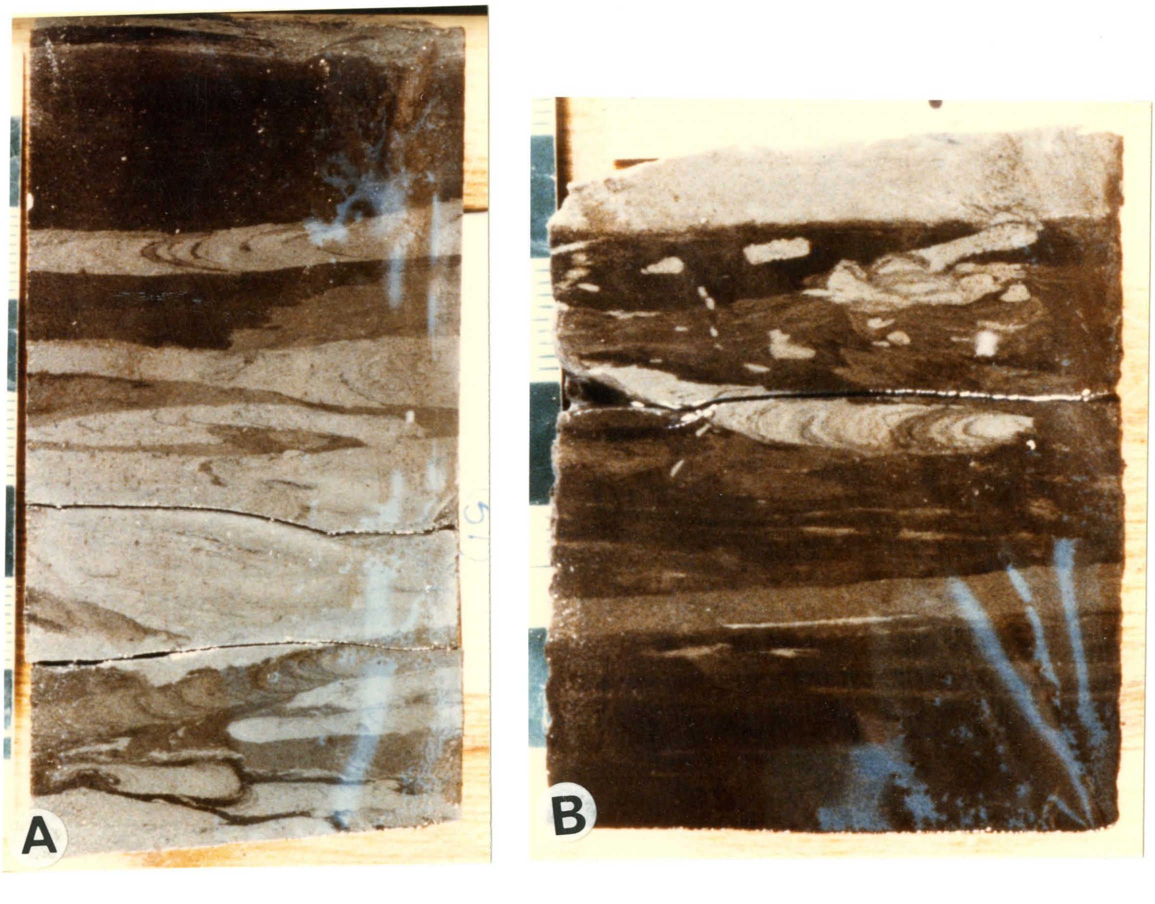
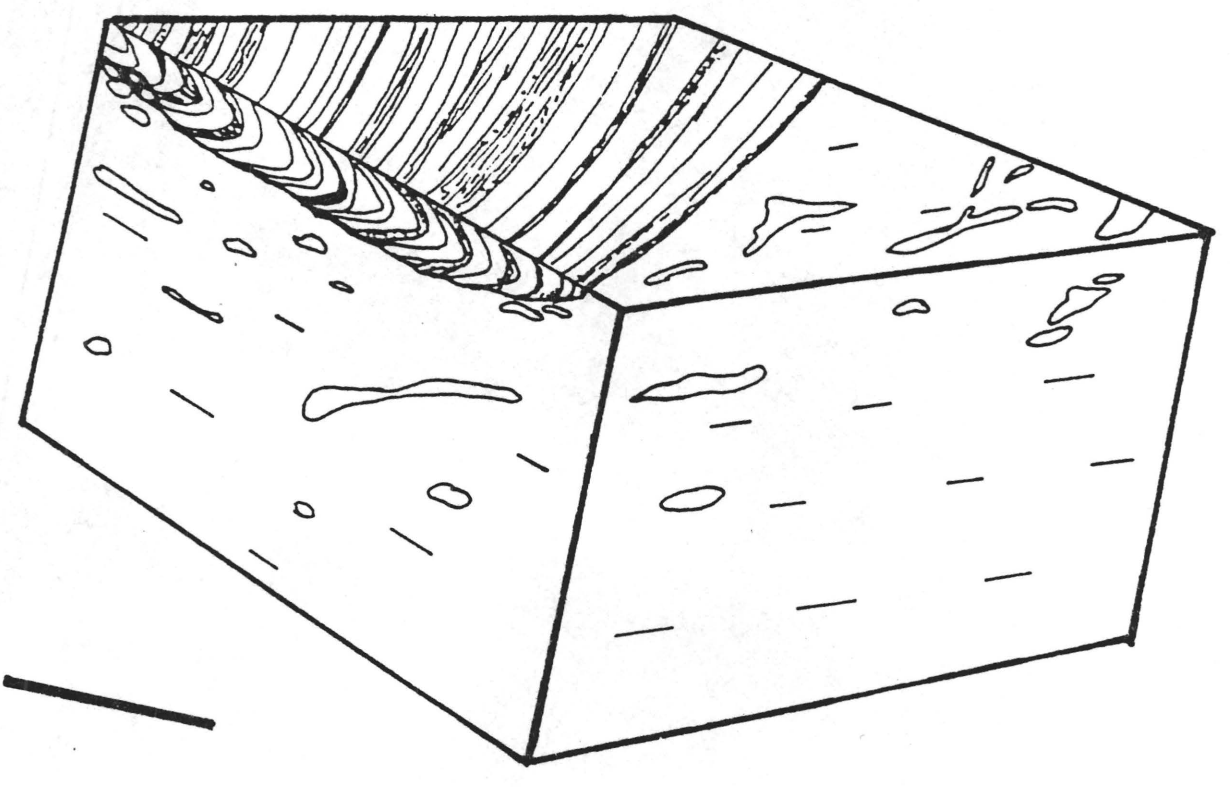

A
B
C

Figure 4.16: Diagramatic veiw of a perpendicular section through the *Zoophycos* sample in 4.15c (scale bar = 1 cm).



In vertical cross-section, they occur as near-horizontal tunnels with back-filled spreiten structures (Figure 4.16). When found within a black shale unit (facies B) *Z. ?briantus* can sometimes be found 5 cm from the top of the unit and the unit is usually overlain by facies C.

Sizes of outcrop examples vary from 11 by 18 cm in diameter for one complete specimen and about 20 cm (length) by 3 mm (width) for an incomplete specimen. Some specimenscontain excellent spreiten (Figure 4.15b).

In drill core samples, *Zoophycos* occurs as near-horizontal features. Specimens can encompass the entire width of the core (4.5 cm) and burrow thicknesses vary from 3 to 12 mm. Specimens are usually separated from each other by a distance of approximately 1 to 3 cm, and rare cross-overs do occur. Excellent spreiten are preserved in most examples, except one which was located entirely within a green-grey mudstone bed. In this case, the sediment seemed to be re-mined, which resulted in a mottled appearance with no discrete solitary tunnels. Some of the core specimens have a lobate appearance and diverge at approximately 20 to 25^{0} to bedding.

Occurrence: Found within facies B, directly beneath green-grey shale/mudstone beds (facies C or D). Rarely do they occur entirely within green mudstones (facies C).

Association: Occurs with small *Chondrites* (diameters of about 1 to 4 mm) and small horizontal *Planolites* (about 2.5 cm long and 3 mm in diameter).

Sediment: Preserved as green-grey mud infill with spreiten represented by alternating light and dark sediments. Host rock is usually a black, laminated shale (facies B).

Origin: Interpreted as a feeding structure or a grazing trace of a soft-bodied, worm-like organism (Seilacher, 1967). Ekdale (1977) suggests that the *Zoophycos*-creating organism may have belonged to the Sipunculida or Phoronida. He also suggests, however, that the origin of this trace fossil is a problem and the different forms of ichnogenus may have been produced in different ways by different kinds of animals. Many authors (see Bischoff, 1968; Plicka, 1970) have suggested that *Zoophycos* represents the feeding burrows of polychaete annelids. It is possible they were formed by echuiroids (Risk, 1973).

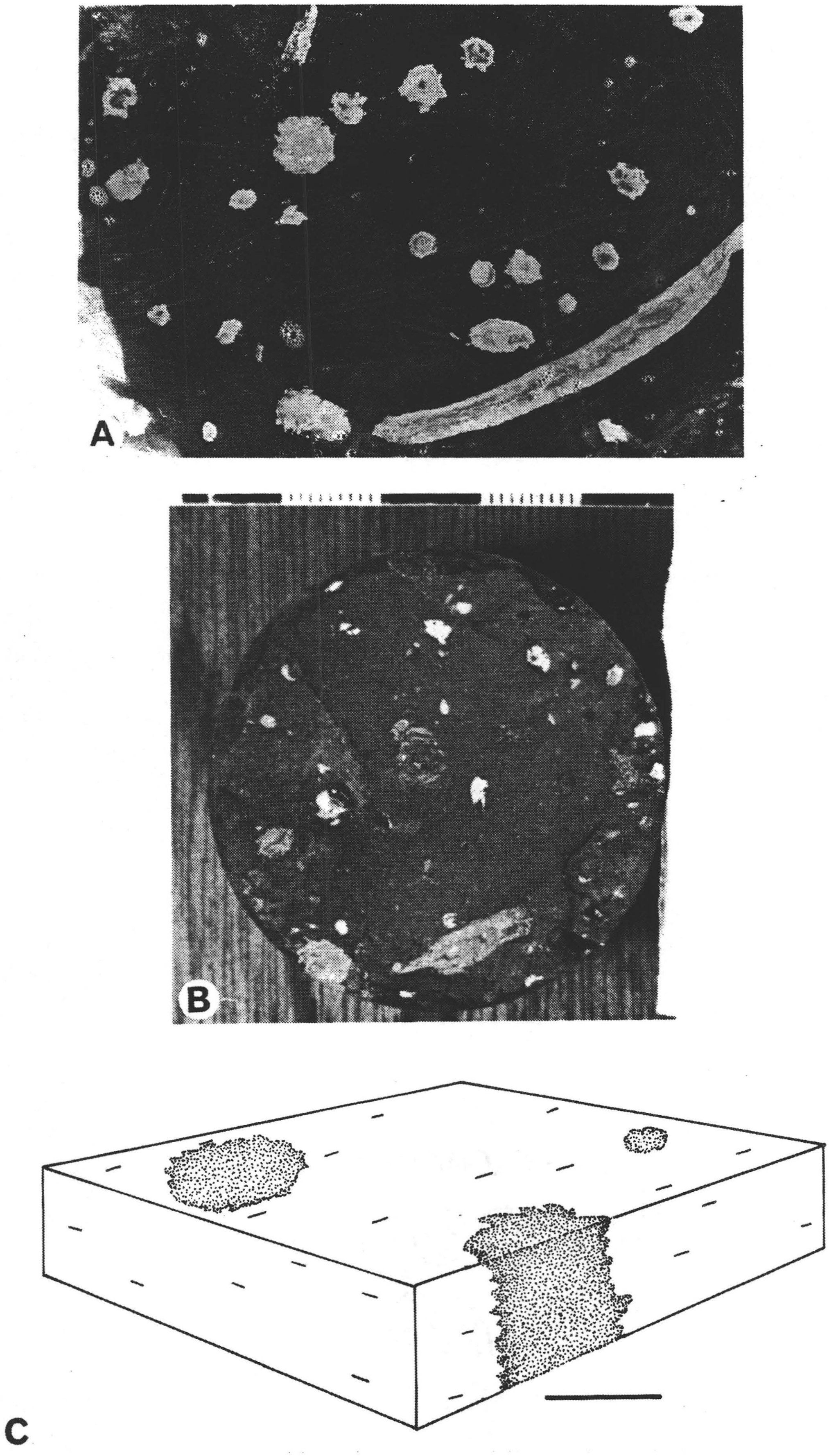
ix) Ichnogenus "A"

(Figure 4.17 a,b,c)

Description: Circular to sub-circular, vertical burrows with serrated or crenelated margins. Burrow diameters range from 2 to 8 mm. Burrows are infilled with light green-grey mud with no meniscate or backfill structures. Burrow lengths range from 2 to 10 mm and are incomplete measurements because entire burrows were not found.

Remarks: The distinguishing aspect of this burrow is its

Figure 4.17: Ichnogenus "A" A) Hand sample of Ichnogenus "A" with *Planolites*, note serrated edges around some burrows (feild of veiw = 6 cm), B) perpendicular veiw of a core sample, C) Diagramtic veiw with cross section (scale bar = 1 cm).


A
B
C

serrated edge. Serrations occur around the diameter of the burrow and along its walls in transverse section. Most burrows possess a solid light green-grey mud infill, although light grey mud infill has been found. Burrows usually occur in clusters with specimens of various sizes. They are best found on black shale bedding planes (facies B).

Occurrence: This genus is found within black shale beds (facies B) overlain by green-grey mudstone beds (facies C or D).

Association: Occurs with *Chondrites, Planolites,* and ?*Cylindrichnus.*

Sediment: Infilled with green-grey muds, rarely light grey in colour, within facies B.

Origin: Origin of this burrow is unknown. The presence of the crenelated margins suggest a similarity to *Ophiomorpha nodusa* burrows, made by arthropods.

4.3 Trace Fossil Discussion:

The most abundant traces in the Long Rapids Formation are *Chondrites* and *Planolites.* An assignment of an ichnofacies to the suite is difficult since *Chondrites, Planolites, Teichichnus,* and *Zoophycos* represent facies-breaking traces. Since *Alcyonidiopsis* is similar to *Chondrites,* the same reasoning probably applies to it. If Seilacher's (1964; 1967) paleoenvironmental classification of trace fossils were used, which is based on water depth, we could interpret the above traces as representing the *Zoophycos* Ichnofacies. This facies occupies bathyal or intermediate water depths below storm wave base, usually with a low trace fossil diversity, although the numbers may be high. The other traces present in the Long Rapids Formation (*Skolithos, ?Cylindrichnus, Terebellina,* and Ichnogenus "A") can generally be assigned to either a *Cruziana* or *Skolithos* Ichnofacies.

A classification scheme based on oxygen content versus water depth for trace fossils may be more reasonable. In the Long Rapids Formation, with its distinct facies types and trace fossils, an oxygen-minimum ichnofacies is proposed for the majority of the traces. The dark-coloured shale units (facies B) possess the most identifiable traces, whereas a scarcity of traces in facies A may be due to a complete absence of oxygen in the sediments. With an introduction of some oxygen (0.1-1.0 millimetres per litre of dissolved oxygen; Rhoads and Morse, 1971) (see also Figure 6.2) colonizing of the sediments by opportunists will occur in the black shale facies. These exploiting generalists are dominantly infaunal and epifaunal deposit feeders, occur in great abundance, and are of low diversity.

Fodinichnia (feeding) and pascichnia (grazing) traces are formed by the following Long Rapids Formation traces: *Chondrites-Planolites-Zoophycos-Alcyonidiopsis-(?Teichichnus)* which I propose to be an oxygen-minimum ichnofacies. Most of these traces are found in the upper 5 centimetres of the dark shale units (facies B), with some penetrating as far down as 20 centimetres from the sediment-water interface. Jordan (1985) observed a similar suite of ichnofauna in Upper Devonian (*Planolites, Chondrites,* and *Zoophycos*) black shales (Ohio or New Albany Shale) in Kentucky. He noted that interbedded grey and black shales had a greater diversity of traces, and he suggested oxygen was the restricting factor.

The organisms that produced the majority of the traces in the Long Rapids Formation were probably deposit-feeding, soft-bodied, vermiform-type organisms. They had a high tolerance for low oxygen levels, and probably had semipermanent shafts to the sediment-water interface to allow for oxygen circulation, as they fed on the organic-rich sediments. The burrows may eventually have been passively or actively infilled. For such traces as *Chondrites, Planolites,* and *Alcyonidiopsis,* is the green-grey mud infilling the burrows passively or actively introduced? Bromley and Ekdale (1984) suggest that *Chondrites* had its burrow open to the sediment-water interface, and the burrow was later passively infilled with sediment from the overlying units. This is probably somewhat correct for the semipermanent shaft, but for the rest of the burrow, the organism probably actively infilled its own burrows with feces or pseudofeces as it mined out a specific area. Since some of these traces have been found some distance from the sediment-water interface, it seems unlikely and a waste of precious energy to excrete at the surface. The same principle can be applied to *Alcyonidiopsis*, which is infilled with green-grey mud pellets in a matrix of black mud. As the organism mined the sediment, it back-filled its burrow with pellets, and the burrow walls where it had just passed were allowed to collapse behind it. This is diagrammatically portrayed in Figure 4.18 where the sediment grains are allowed to collapse due to a stress regime (Harding, 1982).

It is difficult to determine if the burrow walls were structured by the burrow-maker (i.e. parallel grain alignment, concentration of sediment grains, etc.). Upon close inspection in thin section and under the SEM, margins of *Chondrites* burrows are not sharp and do not contain aligned sediment grains (Figure 4.19). Photomicrographs of *Chondrites* burrows show that the grain size of sediments inside the burrow are the same size as those outside it. The major differences are the lack of organic matter and non-parallel alignment of grains in the green-grey mud infill. No meniscate or geopetal structures can be detected and there are no de-watering halos outside the burrow, indicating thixothrophic muds.

Planolites represents the active back-filling of sediment in a burrow constructed by a mobile deposit-feeder (Pemberton and Frey, 1982). Thus, if *Planolites* can be produced in this manner, so could *Chondrites* and *Alcyonidiopsis* in the same sediment type. *The Zoophycos* trace fossil is not a problem since it displays excellent spreiten structures within its

Figure 4.18: A hypothetical diagram portraying the movement of an organism through the sediment and its affect on the sediment (Harding, 1982, p.41).

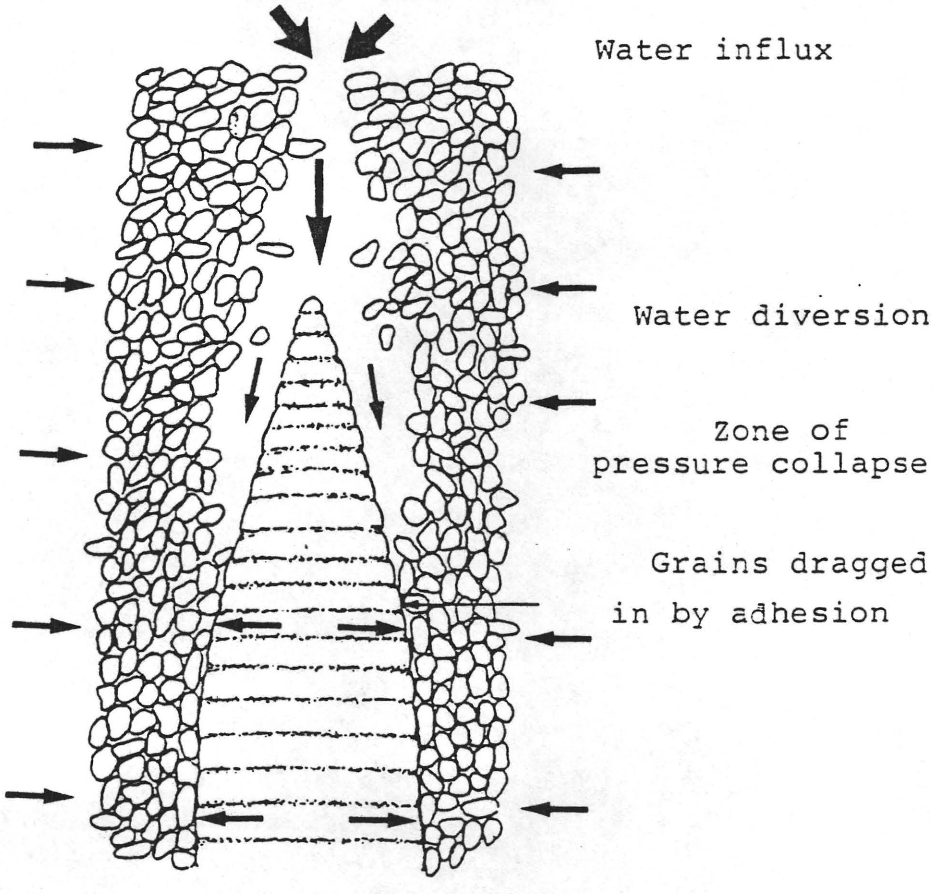
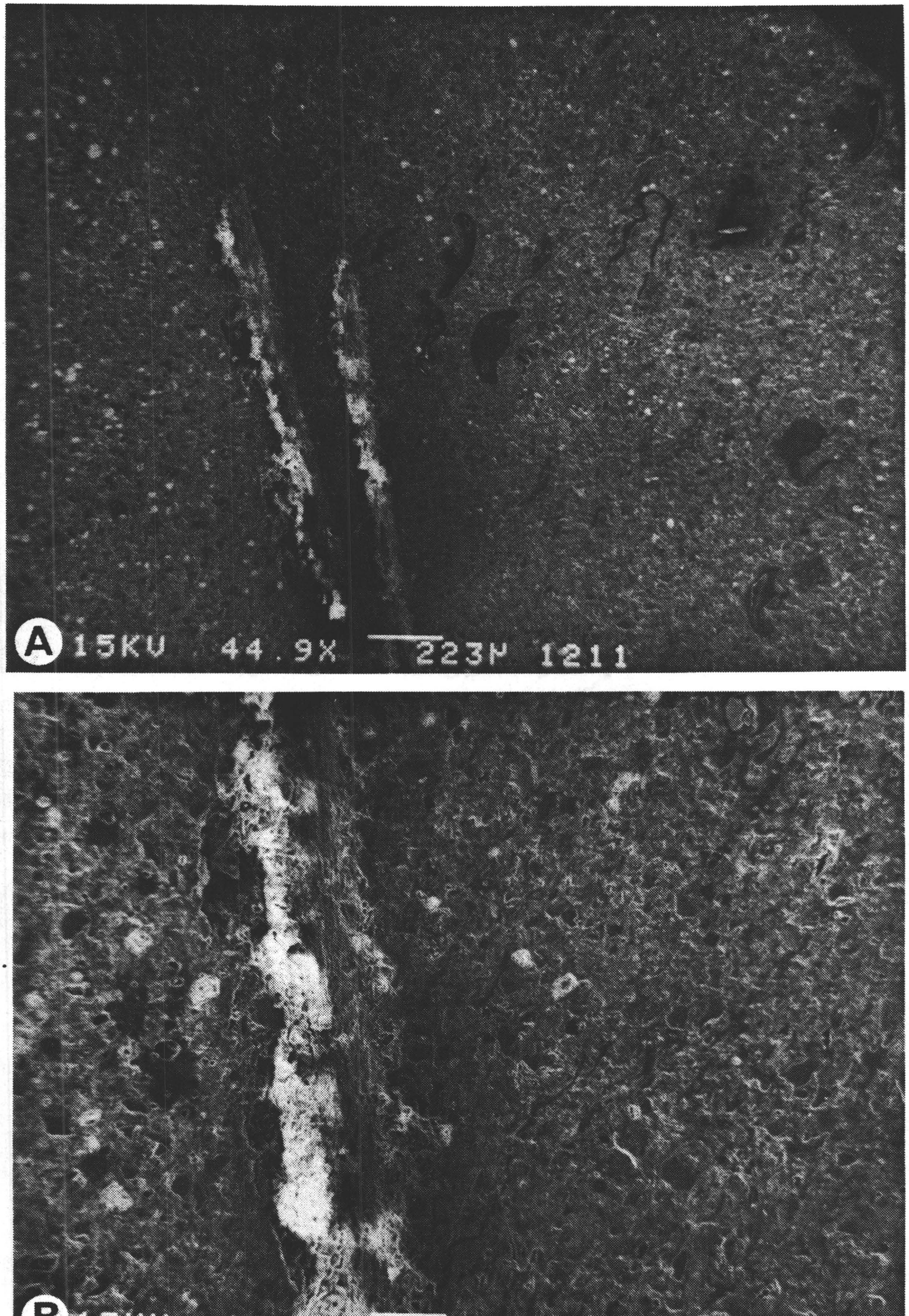

Water influx
Water diversion
Zone of
pressure collapse
Grains dragged
in by adhesion

Figure 4.19: A) SEM photomicrographs of a *Chondrites* burrow margin, burrow is to the left of the scratch mark. The right side appears darker in colour and has an abundance of *Tasmanites* (field of veiw = 223μ), B) close-up of A) (scale = 66.2μ).


A 15KV 44.9X 223µ 1211
B 15KV 151X 66.2µ 1228

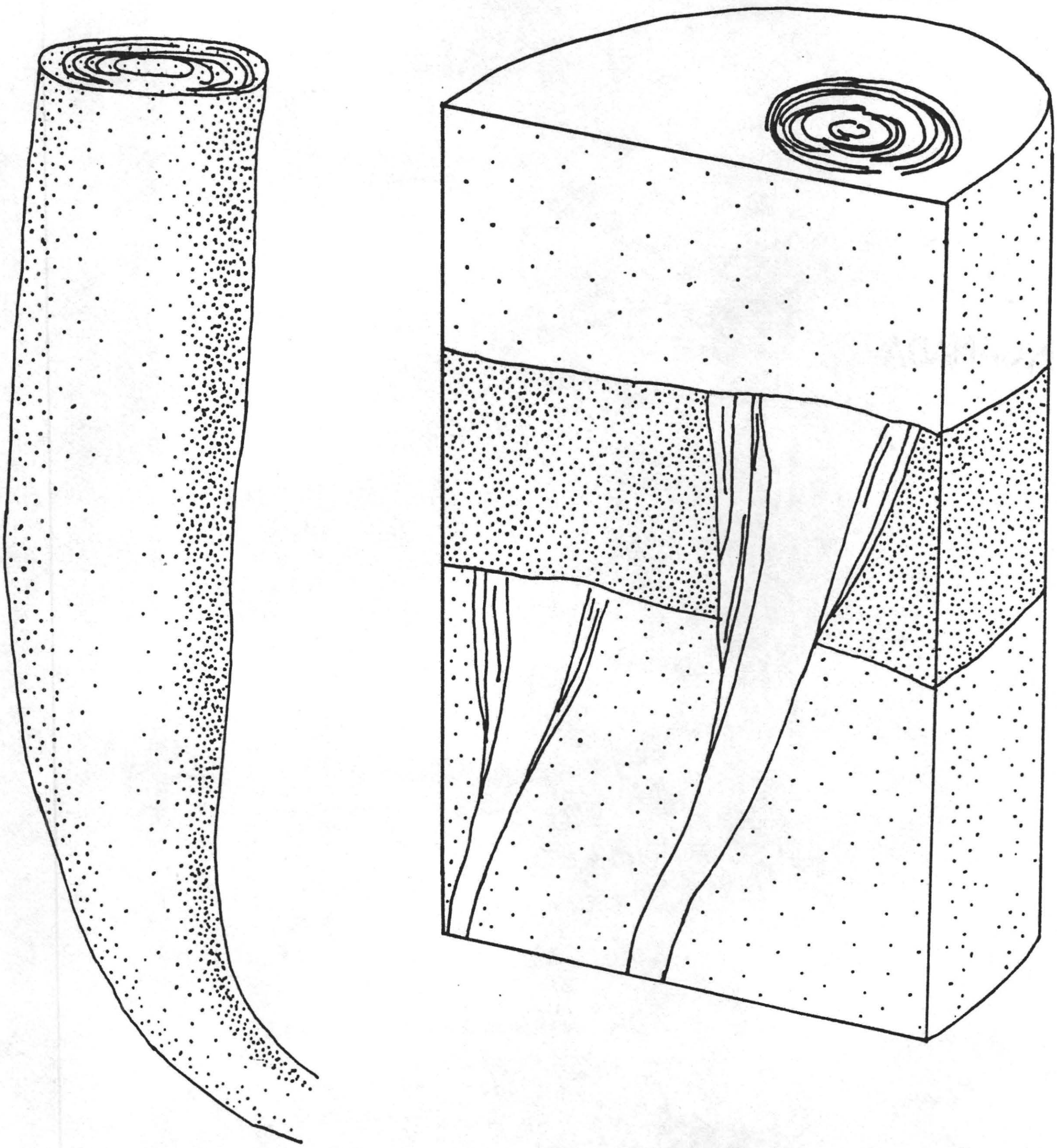
burrows, which indicate active backfilling.

As oxygen levels increased, other burrowing organisms were able to venture into the dark, organic-rich sediments for food. These are represented by *Teichichnus, Terebellina, ?Cylindrichnus, and* Ichnogenus "A", which have domichnia-related characteristics. Of the four traces, *Teichichnus* can probably tolerate the lowest level of oxygen. It can also become an oxygen-minimum trace when sedimentation rates are low because in some cases it crosses *Chondrites* burrows. *Terebellina* is noted for its characteristic burrow lining, and may have been a suspension feeder. Long Rapids Formation *?Cylindrichnus* and Ichnogenus "A" specimens are probably also suspension feeders which constructed semi-permanent domichnia in conditions which were optimum for them, and then fled when conditions deteriorated. Figure 4.20 is a typical example of *Cylindrichnus* in cross-section and in planar view, and it portrays some resemblance to a Long Rapids Formation *?Cylindrichnus*.

As even more oxygen was introduced (with a corresponding change in sediment type) more permanent dwelling structures were constructed, such as *Skolithos*. In thin sections (Figure 4.13 c,d), *Skolithos* specimens display excellent burrow margins, and some possess pyritized margins. With increasing oxygen content, calcified body shells were introduced.

Thus, the trace fossil suite present in the Long Rapids Formation represents a transition from fodinichnia and

Figure 4.20: A typical example of *?Cylindrichnus* (modified from Chamberlain, 1978, p. 130).



pascichnia-dominated traces to domichnia-dominated trace fossils, which parallel an increase in oxygen content.

4.4 Summary

The paleontological evidence in the Long Rapids Formation suggests an environment of deposition which experienced periodic changes in oxygen content. It seems that oxygen was the controlling factor in determining the type of fine-grained sediments deposited and the type of organisms that were able to live there. The *Chondrites-Planolites-Zoophycos-Alcyonidiopsis* ichnosuite contained the original pioneers, which was followed by the *Teichichnus-Terebellina-?Cylindrichnus*-Ichnogenus "A" ichnosuite, and then finally by *Skolithos*. This pattern followed a corresponding increase in oxygen levels in the water column. The coinciding facies change was from a dark, organic matter-rich shale to green-grey mudstone, to carbonates. Hard shelled organisms (such as brachiopods) were able to survive when enough oxygen was introduced to support their existence with calcified body shells.

Thayer (1981 in Ettenshon, 1985) indicates that some articulate brachiopods may survive quite well in poorly oxygenated or temporarily anoxic environments. Thus, Ettenshon (1985) suggests that a *Leiorhynchus* fauna (present in the Long Rapids Formation) present in dark shales probably represents a sparse epifauna living in those conditions in a basinal or open-shelf environment.

Many of the other body fossils were probably introduced from elsewhere in the basin and drifted in, or they may have actually existed on the Grand Rapids Arch which was a positive structure during the Upper Devonian. The Arch may have been completely oxygenated throughout the deposition of the Long Rapids Formation, and thus supported a greater abundance of shelly fauna. It is highly probable that their death assemblages eventually ended up in the valleys off the flank of the Arch and became incorporated into the Long Rapids Formation.

The cause of the sedimentary couplets and triplets (rhythms) is probably closely related to the repetitive change in the oxygen levels present in the water column, as was observed in the stratigraphic record discussed in Chapter 3.

CHAPTER 5:

GEOCHEMISTRY

5.1 Introduction

To help understand further the depositional environment of the shales from the Long Rapids Formation, three types of geochemical tests were performed. Two hundred and three samples were analyzed for total organic carbon (TOC) content to possibly predict target areas for shale oil extraction. $\delta^{13}C$ isotope analyses were carried out on a few of the samples to evaluate the relative importance of terrestrial versus marine sources for the organic matter. Lastly, major elements were analyzed to attempt to determine provenance of the shales.

5.2 Total Organic Carbon Content (TOC)

A measure of a shale's potential for production of shale oil is the percentage of organic matter, preferably aliphatic, that is present. The best method for analysis of TOC of sediments is combustion of a sample at high temperatures (~1200 °C) in an atmosphere of dry, CO_2 - free oxygen. A LECO CR-12 carbon analyzer can be used. The Long Rapids Formation samples were first treated with hydrochloric acid (HCl) to eliminate carbonate carbon using the procedure outlined in Appendix D.

In total, 203 samples were analyzed for TOCs, 125 of these from outcrop and 78 from drill core samples. Appendix E lists the TOC values obtained from these samples. Table 3 lists the mean TOC values for the individual facies from each sample group.

As expected, black shale facies (A & B) had higher TOC values compared to the other facies.

Pyrolysis is a method used to simulate the process of petroleum generation by heating rock samples in the absence of oxygen. Temperatures considerably higher than those normally found in the subsurface are used so that an appreciable reaction can occur in a reasonable amount of time (Barker, 1974). This method is used for shale retorting and temperatures are never greater than 500-600°C. If the energy required to raise the temperature of a sample to 500°C is approximately 250 calories per gram of rock, and if the heat value of organic matter is approximately 10,000 calories per gram of rock, the minimum organic content of the sample would be 2.5 % (Macauley, 1984). The lower limit of organic matter required for economic recovery (i.e. including transportation and mining costs) is generally set at 5 %. This would make the Long Rapids Formation undesirable for oil shale extraction based on the data from this study, but the sample group is a bit a speculative when based on only one drill hole and one outcrop location.

5.3 Stable Carbon Isotope Composition

Carbon possesses two stable isotopes, ^{12}C and ^{13}C, with a ratio ($^{12}C/^{13}C$) of about 99:1 (Fuex, 1977). Differences in this ratio are used to elucidate chemical processes that have

TABLE 3: MEAN TOC VALUES FOR THE FACIES IN THE LONG RAPIDS FORMATION

LEGEND:

o/c=outcrop	n=number of samples
dh=drill hole	s=standard deviation
x=mean	s^2=variance

Facies A: o/c: n=20 x=4.60 % s=1.61 s^2=2.59
dh: n=50 x=4.09 % s=1.40 s^2=1.96

Facies B: o/c: n=35 x=3.28 % s=1.62 s^2=2.62
dh: n=26 x=4.47 % s=1.47 s^2=2.17

Facies C: o/c: n=43 x=0.98 % s=1.17 s^2=1.37
dh: n=1 x=0.26 %

Facies D: o/c: n=13 x=0.64 % s=0.26 s^2=0.07
dh: n=2 x=2.70 %

Facies E: o/c: n=16 x=0.21 % s=0.45 s^2=.20

occurred in the geologic record. Terrestrial organic matter is enriched in the lighter isotope (^{12}C) relative to marine organic matter, and thus, it is possible to measure the proportion of these two types of organic matter in $\delta^{13}C$ isotope analyses. The isotopic composition of C is expressed in terms of the delta notation (δ) using the following relationship:

$$\delta^{13}C = \frac{(^{13}C/^{12}C)_{samp} - (^{13}C/^{12}C)_{std}}{(^{13}C/^{12}C)_{std}} \times 10^3$$

The reference standard is CO_2 gas which is acquired by reacting belemnites of the Peedee Formation with 100 % phosphoric acid [PDB standard of the University of Chicago (*Belemnitella Americana,* Peedee Formation, Cretaceous, South Carolina)] (Faure, 1986).

Shale samples from the Long Rapids Formation were analyzed to determine the type of organic matter present (either terrestrial or marine). Marine (sapropelic) organic matter contains hydrogen-rich aliphatic compounds that are a likely source of petroleum, or will yield greater volumes of shale oil upon pyrolysis than terrestrial (aromatic) organic matter.

A total of 18 shale samples were analyzed for $\delta^{13}C$ values. All samples were first treated with warm 20 % HCl to remove all carbonate carbon. Powdered samples were placed in quartz glass tubes with some cupric oxide, evacuated and sealed, and then baked at 900 °C for two hours. The samples were run on a mass spectrometer in Dr. H.P. Schwarcz's isotope laboratory at McMaster University.

The sample values range from -25.59 to -30.53 ‰ with a mean of -29.52 ‰ (Table 4). Two vitrinite samples (woody plant material) had isotope values of -22.90 and -22.67 ‰ (x = -22.79 ‰).

Table 5 contrasts the isotopic composition of organic carbon in the Long Rapids Formation and that of other representative materials. Long Rapids Formation values indicate a terrestrial source for the organic matter, although paleontological evidence suggests a marine depositional setting. An average value of -21.0 ‰ was recorded for modern marine sediments in the Atlantic Ocean with surface water temperatures at approximately 25°C (Sackett *et al.*, 1965). Cold water temperatures (around 2°C) will produce marine plankton with signatures of about -30 ‰ in modern oceans.

The Long Rapids Formation shales may actually represent depleted marine values of $\delta^{13}C$ that were produced in cold water, or the signatures may represent terrestrial values (possibly with some mixing of marine organic material). Evidence suggests that it is unlikely that the epicontinental sea in the area of the Moose River Basin possessed cold water temperatures (see Chapter 6).

Maynard (1981) analyzed 200 samples from the Devonian-Mississippian shale sequence of the Appalachian Basin and obtained $\delta^{13}C$ isotope values ranging from -25.0 ‰ in the eastern portion of the Basin (closer to the source area) to

TABLE 4: COMPARISON OF $\delta^{13}C$ ISOTOPE AND TOC VALUES BETWEEN OUTCROP AND DRILL HOLE SAMPLES

sample #	dh #	$\delta^{13}C$(‰)	TOC %	depth(m)	facies
OX-3	82-4	-29.99	4.84	100.30	A + B
OX-14	82-5	-30.29	5.08	117.00	A
OX-23	82-18	-27.95	5.06	114.47	A
OX-37	81-5	-29.45	8.21	111.35	B
OX-50	81-8	-30.09	3.82	48.75	A
OX-52	81-10	-30.15	3.09	90.96	B
OX-59	81-11	-29.76	2.40	97.39	A
OX-64	Onak B	-30.46	5.69	150.37	A
OX-73	Onak B	-29.49	5.25	119.75	A
OX-74	Onak B	-29.15	5.50	118.74	B

dh total: n=10 x=-29.68 range:-27.95 to -30.46 ‰

o/c #	$\delta^{13}C$(‰)	TOC(%)	depth(m)	facies
9c	-29.78	6.27	5.26	A
10-2-bx	-29.93	2.08	6.94	C
11-5-ax	-29.61	0.78	8.86	D
11-8-c	-30.32	1.99	9.13	B
12-2-a	-29.73	0.89	9.74	D
12-5-a	-30.53	4.10	9.95	B
12-9-a	-29.33	0.55	10.56	D
19-1-a	-25.29	0.75	24.29	C

o/c total:n=8 x=-29.32 range:-25.29 to -30.53 ‰
Total: n=19 x=-29.52

Facies A: n=8 x=-29.73
Facies B: n=6 x=-29.93
Facies C: n=2 x=-27.61
Facies D: n=3 x=-29.56

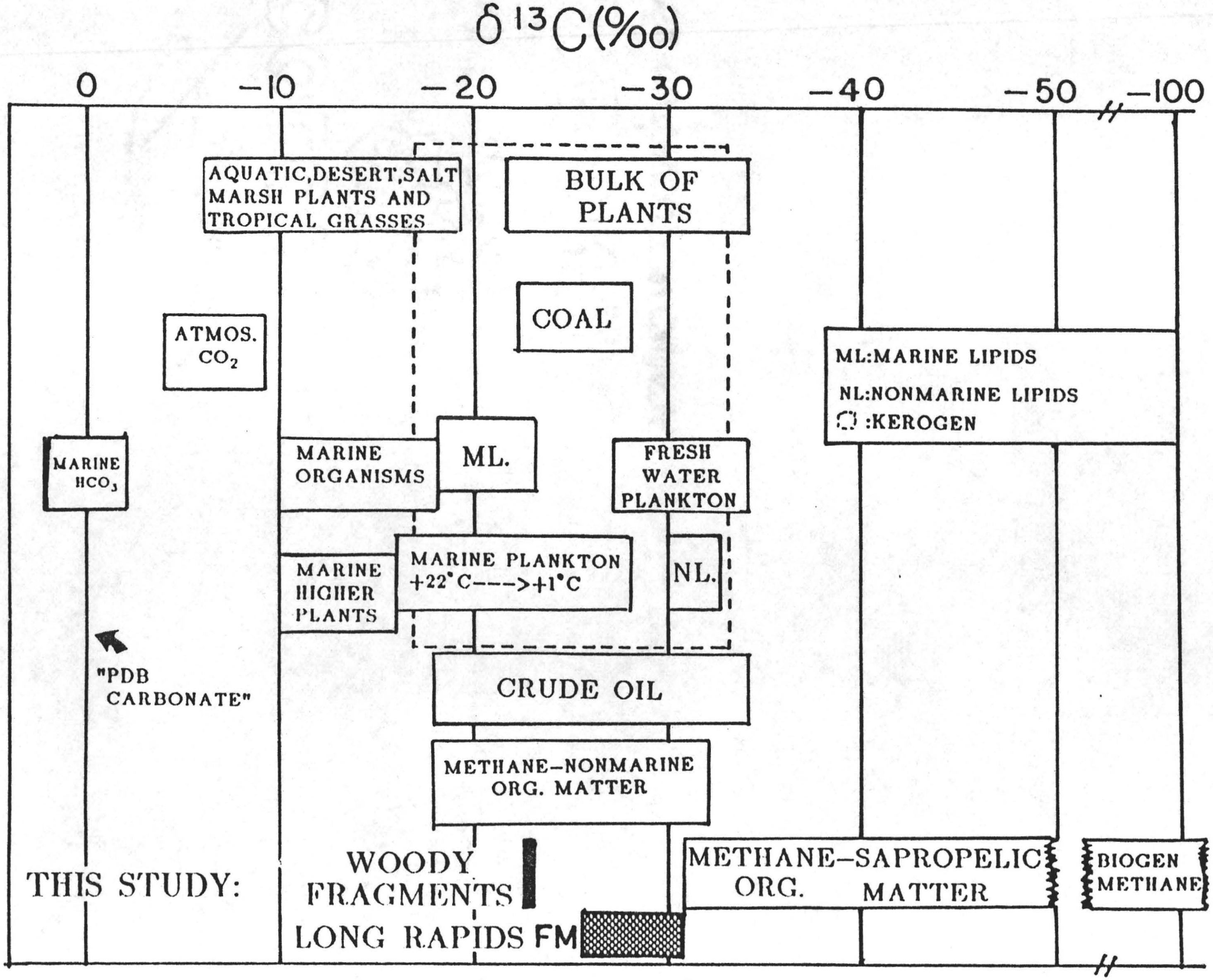


TABLE 5: $\delta^{13}C$ COMPARISONS WITH LONG RAPIDS FORMATION DATA AND OTHER MATERIALS (modified from Stahl, 1979)

-30.5 ‰ in the west. The expected trend would be nonmarine values (-30.5) close to the source area, whereas marine (basinal) values (-25) would be further away from the source area. Maynard's values show a reverse trend (i.e. more nonmarine values in the basin, versus close to source areas). His data is also backed by paleocurrent evidence from sole markings on turbidite siltstone beds which indicate a sedimentary source from the east. Maynard suggests that this anomaly was caused by the ^{12}C enrichment of the basinal samples by an enrichment of a lipid fraction during diagenesis compared to near shore samples. He suggests another alternative where marine plankton in the Devonian period were more enriched in ^{12}C than modern plankton.

Hailer *et al.*, (1983) also obtained similar $\delta^{13}C$ isotope results on the Upper Devonian New Albany Shale (Illinois Basin). The unit consists of black shale horizons (=Long Rapids Formation facies A and B) with interbedded green mudstone beds (=facies C). Carbon isotope values for 137 samples ranged from -24.5 to -31.0 ‰, with a median of -29.35‰. These shales are also interpreted to be marine through paleoecologically evidence, but also possess depleted isotope values. Quiescent, warm and productive conditions are thought to have existed in the Illinois Basin when the shales were deposited, and such conditions would not have caused extreme photosynthetic fractionations that would result in large $\delta^{13}C$ depletions.

Hailer *et al.* (1983) suggest that $\delta^{13}C$ depletions may have been caused by diagenetic alterations of the carbon isotope abundances. Non-biological alteration could arise from thermal degradation of heavier ^{13}C compounds, such as proteins and carbohydrates. The remaining residues would then be enriched with refractory ^{12}C-rich lipids. Biologically, anaerobic bacteria may alter the isotopic values by consuming proteins and carbohydrates (rich in ^{13}C) in the sediments and leaving behind the lipids (rich in ^{12}C) that are relatively resistant to biological destruction. Also, recycling of any sediment already depleted in ^{13}C could produce these similar results.

It appears that the isotopic composition of carbon in the organic matter of the sedimentary rocks cannot be used confidently to identify the type of organic matter present or the depositional environment. The $\delta^{13}C$ value of organic matter in sedimentary rocks changes as a function of time due to the preferential destruction of carbohydrates and proteins and the resulting enrichment of the remaining organic matter in lipids, lignin, and cellulose (Faure, 1986). Welte *et al.* (1975) had mean $\delta^{13}C$ values of -27.5 and -27.7 ‰ for 22 samples from Upper Devonian marine sediments in Germany and they interpreted the depletion to be caused either by the massive emergence of land plants during Devonian time and/or increasing water temperatures of the Devonian oceans.

Table 4 compares $\delta^{13}C$ isotope values with their corresponding TOC values and no trends could be determined between the two and the facies. Also, no basinal trends were observed when the data were plotted on a map of the Moose River Basin.

5.4 Chemical Index of Maturity

A test was conducted on the shales from the Long Rapids Formation to determine provenance for the sediments. This method was obtained from S. Zymela (personal communication, McMaster University, 1985) and the technique was devised by Nesbitt (see Nesbitt and Young, 1982; 1984). The chemical index of maturity is a measure of weathering. By comparing weathering profiles of shales, information can be obtained on provenance, mechanical mixing of components and diagenetic processes. Weathering profiles are produced when compositional changes occur in a rock, and by determining the extent to which weathering has proceeded, this can be illustrated on ternary diagrams. The end members include K_2O (felsic end member), $CaO + Na_2O$ (basic end member), and Al_2O_3 (aluminum end member).

The weathering trends for various igneous rocks can thus be illustrated on a ternary diagram. Felsic rocks have weathering trends towards the K_2O end member, mafic towards the $CaO + Na_2O$ end member and intermediate rocks trend between mafic and felsic trends (Nesbitt in Hoy, 1980).

The major clay minerals in shale include kaolinite, illite, montmorillonite, and chlorite (Shaw and Weaver, 1965). With increasing maturity, mineralogical and chemical changes occur within shales that are similar to weathering profiles and information may be gained on: a) possible source area or provenance and b) processes which occurred during diagenesis (Hoy, 1980). This study concentrated on determining the provenance of the Long Rapids Formation.

Sediments within the Moose River Basin are principally thought to have a source off the Precambrian Shield and would be subsequently reworked within the basin to form younger units. Since the southern boundary of the Moose River Basin abuts sharply onto the Shield, a prediction of the probable source rock can be made. An Ontario Geological Survey map (Map 2393) indicates the Precambrian Shield at the basin's southern end to be granodiorites and granites. By using Nesbitt's method (in Hoy, 1980) for determining the chemical index of maturity (CI), a probable provenance rock can be determined. The CI can be determined as follows:

$$CI = 1 - \frac{(\%Al_2O_3)}{100} \quad \text{or} \qquad (1)$$

$$= \frac{CaO_{sil} + Na_2O + K_2O}{CaO_{sil} + Na_2O + K_2O + Al_2O_3} \qquad (2)$$

Values for CI lie within the range 0.0 to 0.5 and represent the following maturities:

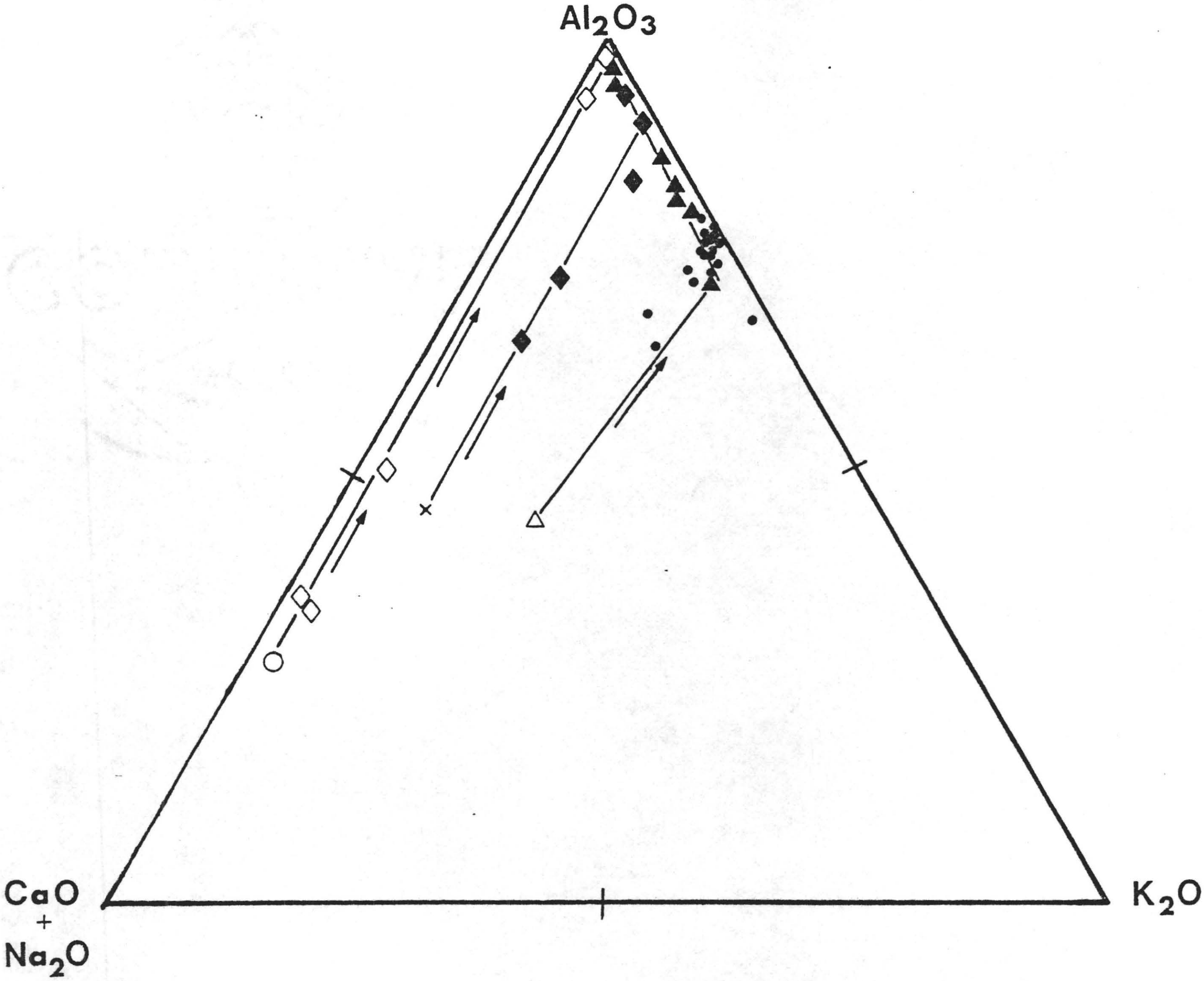
0.5	0.35	0.15	0.0
immature	mature	supermature	

Once plotted on a ternary diagram, a weathering trend can be determined (Figure 5.1). Any shifts of the points above or below the weathering trend represents a diagenetic trend and/or mixing of the two trends. This can be represented better pictorially in Figure 5.2a. If diagenetic trends were present, an indication of continental or marine environmental diagenesis could be attempted (Figure 5.2b).

A total of 18 drill core samples were analysed for major element composition (methodology is outlined in Appendix F). The CI values range from 0.21 to 0.35 with a mean of 0.26 (Table 6). The Long Rapids Formation samples lie in the mature zone.

The average values for selected igneous rocks and the Long Rapids Formation are plotted on Figure 5.1. From the ternary diagram, the shales exhibit a weathering trend indicative of a granitic gneiss as the source rock. This correlates well with the predicted source rocks of granites and granodiorites and thus verifies the probable provenance area as the Precambrian Shield to the south. The Long Rapids Formation data show no diagenetic trends indicating either marine or continental diagenesis.

Figure 5.1: Chemical index of maturity (CI): Ternary diagram with the average weathering trends of selected igneous rocks and CI values for Long Rapids Formation data (after Nesbitt in Hoy, 1980).



◇ Weathered basalts Koloa Volcanic Series

△ Fresh Morton granite gneiss

▲ Weathered Morton granite gneiss

◆ Weathered Toorongo granodiorite

○ Fresh basalt Koloa Volcanic Series

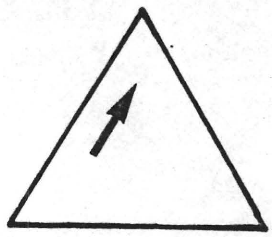
× Average continental crust

• Long Rapids shale values

Figure 5.2: Chemical index of maturity: A) Weathering trend (as was depicted in Figure 5.1), B) Diagenetic trends [1) continental or 2) marine] (after Nesbitt in Hoy, 1980).

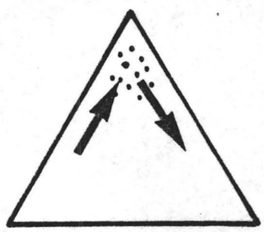
A

1) Weathering trend



B

1) Continental environmental diagenesis since clays take up K_2O during diagenesis



2) Marine environmental diagenesis since clays take up K_2O and Na_2O during diagenesis

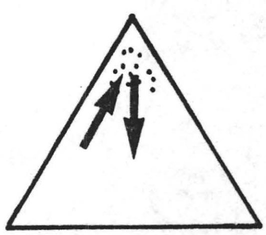


TABLE 6: CHEMICAL INDEX OF MATURITY VALUES
FOR THE LONG RAPIDS FORMATION

sample number	drillhole number	depth (metres)	chemical index of maturity
4	Onex 82-4	112.75	0.28
7	Onex 82-4	128.70	0.24
10	Onex 82-5	108.00	0.22
14	Onex 82-5	117.00	0.24
22	Onex 82-18	113.07	0.24
24	Onex 82-18	114.87	0.22
29	Onex 82-18	103.00	0.21
37	OEC 81-5	111.35	0.27
39	OEC 81-5	105.92	0.24
45	OEC 81-8	63.05	0.35
49	OEC 81-8	52.78	0.32
58	OEC 81-11	99.41	0.25
62	OEC 81-11	85.94	0.33
65	Onak B	139.45	0.25
67	Onak B	128.76	0.28
72	Onak B	122.74	0.27
75	Onak B	114.83	0.24
81	Onak B	101.39	0.21

CHAPTER 6:

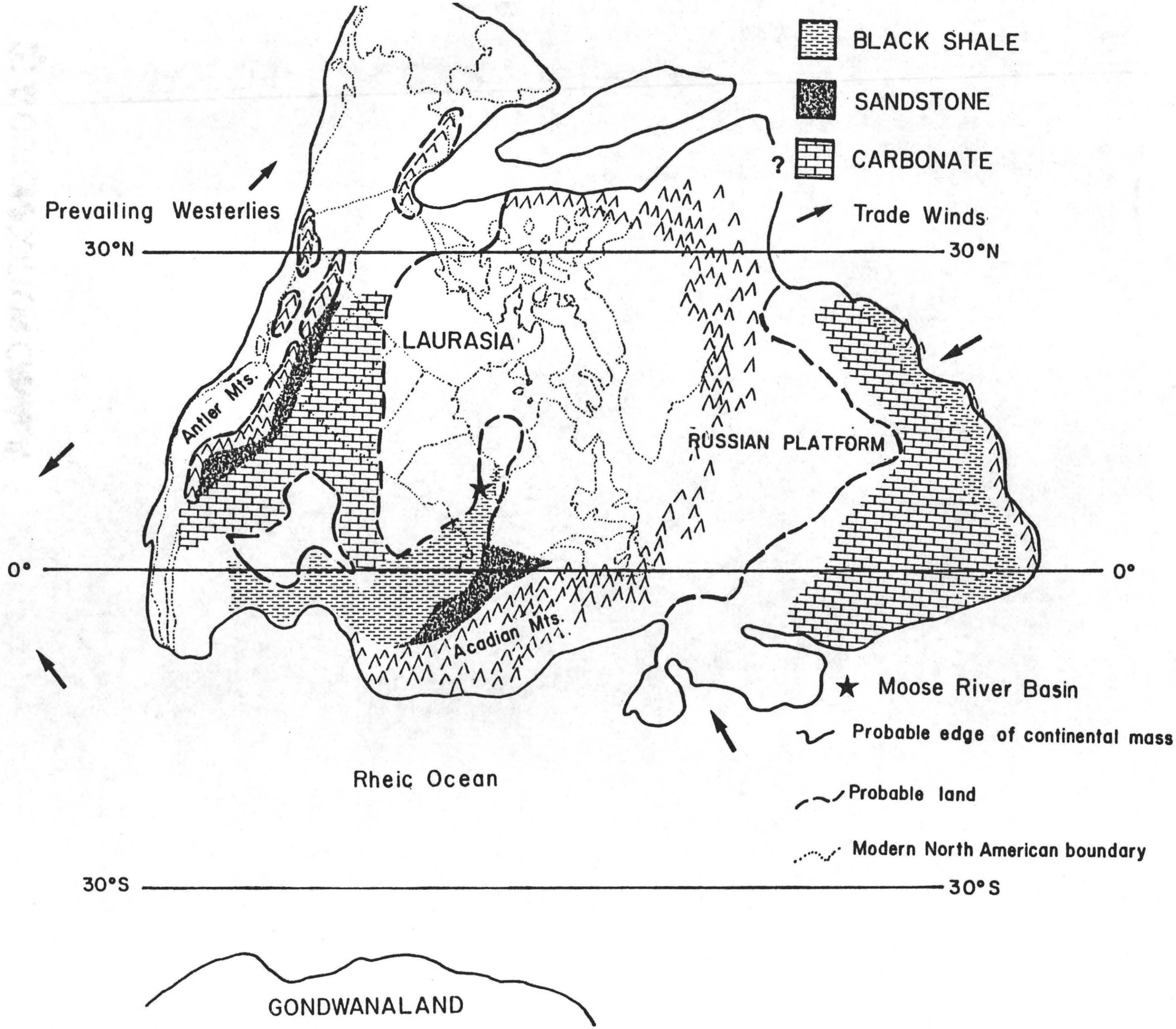
DEVONIAN PALEOGEOGRAPHY

6.1 Setting

As was mentioned earlier, the Long Rapids Formation was part of a large scale deposition of black shales that occurred on the North American continent in Late Devonian times. A synthesis of interpretations on paleoclimatology, paleogeography, and sedimentary processes in the Appalachian Basin is presented here to help illustrate the probable depositional setting for the black shales in the Moose River Basin.

In the Silurian, the collision of the North American and northwestern European landmasses produced a large, equatorial continent called Laurasia (=Laurussia), although the terrestrial portions of the continent have been called the Old Red Sandstone landmass. A nearly north-south range of mountains (the Appalachians) was created by this collision. The Acadian Orogeny in the Early Devonian continued the southwest extension of the mountain belt and produced the Acadian Mountains (Figure 6.1). The buildup of these highlands nearly enclosed the Appalachian Basin area where the epicontinental sea (the Catskill) was confined (Figure 2.2). The Sea was bounded to the north by the Old Red Sandstone Continent, and to the west by the Transcontinental Arch. The interior surface of the craton was low lying and covered predominantly by epicontinental seas (Ettenshon, 1985).

Figure 6.1: Paleo-reconstruction of the Laurasian landmass during the Upper Devonian (Ettenshon and Barron, 1981, p.348; Ettenshon, 1985, p.67).


BLACK SHALE
SANDSTONE
CARBONATE
Trade Winds
Prevailing Westerlies
30°N
30°N
LAURASIA
Antler Mts.
RUSSIAN PLATFORM
0°
0°
Acadian Mts.
Moose River Basin
Probable edge of continental mass
Probable land
Modern North American boundary
Rheic Ocean
30°S
30°S
GONDWANALAND

The Appalachian Basin was separated from the world ocean by the Appalachian Peninsula, but was probably joined to it in the southwest. To the north, the rock record is incomplete, and thus the extent of this epicontinental sea is not exactly known. It is known that the Devonian rocks in the Hudson Bay Basin (north of the Moose River Basin) are evaporites and carbonates, probably deposited in a highly saline bay which connected to the Catskill Sea to the south. Adjacent to the shoreline (and next to the Appalachian Mountains), the Catskill Delta was debouching sediments into the Catskill Sea (Woodrow, 1985).

6.2 Paleoclimate

The depositional environment for the Appalachian Basin area had warm to hot temperatures, geographically variable rainfall patterns, relatively high evaporation rates and generally easterly winds (Woodrow *et al.*, 1973). Over the Catskill Delta, the climate was either tropical wet and dry, or desert, due to the rainshadow effect caused by the mountains to the east. Although most authors believe Laurasia was an equatorial continent, different placements of the equator do exist (i.e. Heckel and Witzke, 1979; Ettenshon and Barron, 1981; Ettenshon, 1985). The entire Appalachian Basin area developed during a global transgression.

Streams probably displayed variations in sediment discharge and drought conditions were a common event. Fine sand and mud were transported across the shoreline by distributaries of larger streams to the floor of the Catskill Sea, either by turbidity currents or slow deposition by suspension. Wave-related processes, deltaic processes and tides shaped a predominantly muddy shoreline.

Ettenshon (1985) postulates that the Catskill Delta occurred within five degrees of the paleoequator because at the equator, convectional precipitation will occur regardless of an orographic barrier. An equatorial belt is typically warm, humid, and characterized by heavy rainfall. The precipitation is of the convectional type, formed by the convectional rising of moisture-laden trade winds due to equatorial heating and condensation in the rising air leading to extensive precipitation. If a high mountain range were to block the moisture-laden trade winds before converging on the equator, the mountains will act as an orographic barrier and will cause the trade winds to rise on the windward side of the mountains and precipitate.

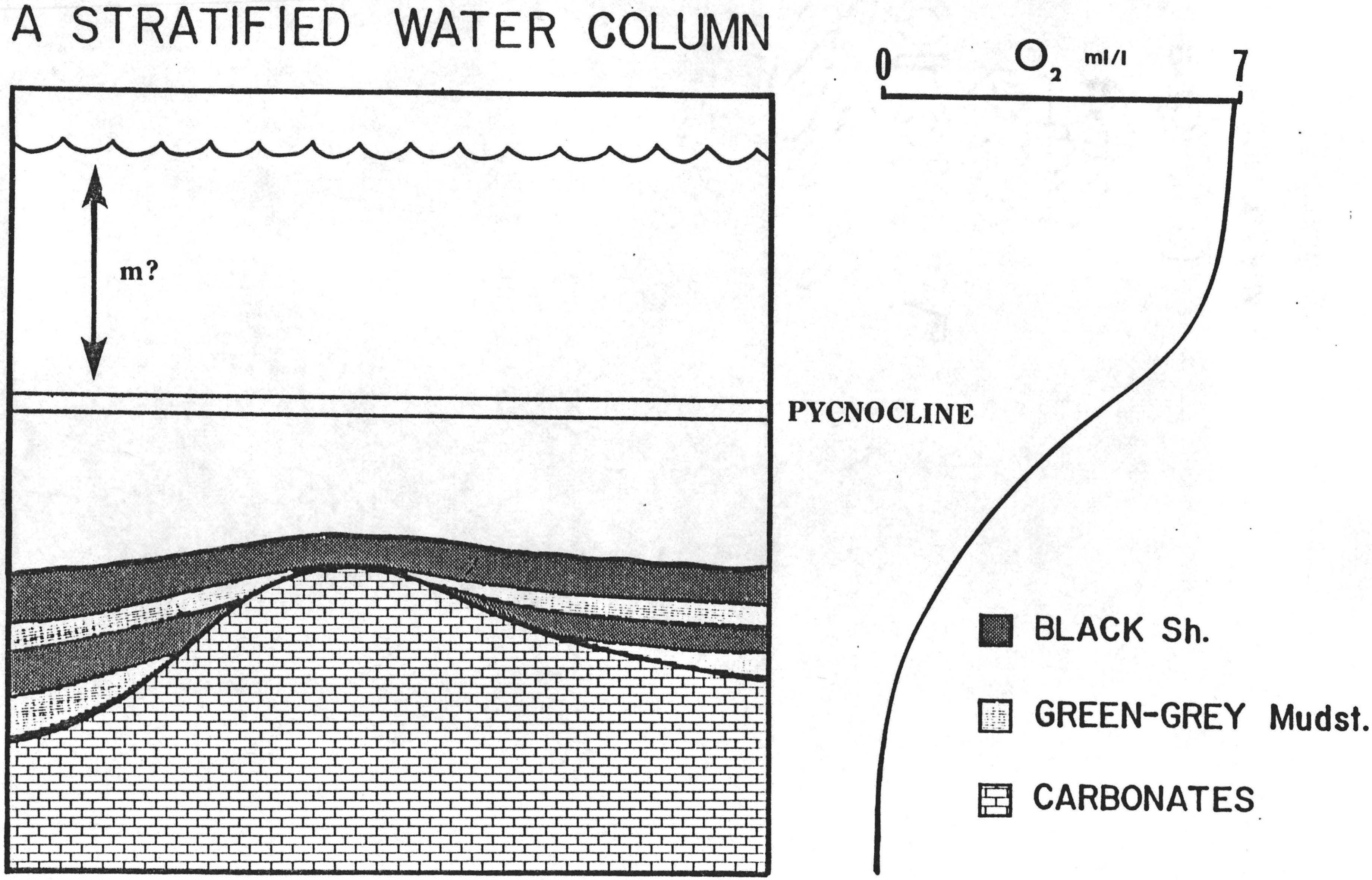
If orographic precipitation was occurring during Devonian times in the Appalachian Basin, most of the area west of the mountain ranges would be in the rainshadow. Thick sequences of non-marine clastics occur on the eastern side of the mountains in Europe and the Russian platform, but the only clastic sequence west of the mountains is the Catskill Delta. Ettenshon (1985) explains the Delta's presence due to the ability of moisture-laden air to rise regardless of a barrier because of convection at the equator. This process would only occur in the area bounded by five degrees of the equator. Although the mountains may have formed an effective barrier most of the time, periods of aridity and low rainfall are evidenced in some facies of the Catskill Delta sequence.

6.3 Origin of Black Shales:

Sediments from the deeper portion of the Appalachian Basin are fine grained, thinner bedded, and persistent as individual laminae and beds of strata. This is due to a limited range of sedimentary processes active on these surfaces. The development of a pycnocline [a zone of changing salinity and temperature (halocline and thermocline)] would impede the transfer of physical energy to deeper depths (Byers, 1977). The pycnocline also corresponds to an area of rapid decrease in oxygen between the surface and bottom waters. A stratified water column can be represented using oxygen content (Rhoads and Morse, 1971) (Figure 6.2).

The warm, humid conditions present in the Appalachian Basin area were conducive for the production of organic matter in the Catskill Sea. Along with a terrestrial input from the nearby coastal areas, the Sea was probably overloaded with organic debris. Although this is not a crucial factor for the development of organic-rich basinal sediments, the preservation of the organic material from physical destruction and oxidization are. If the oxygen demand produced by the rain of

Figure 6.2: A stratified water column with a pycnocline (modified after Russell, 1985, p.250; Rhoads and Morse, 1971, p.420).


A STRATIFIED WATER COLUMN
m?
PYCNOCLINE
0
O2 ml/l
7
BLACK Sh.
GREEN-GREY Mudst.
CARBONATES

organic matter overwhelms the oxygen produced by the biological system, and there is no replenishment of oxygen from outside sources, free oxygen will be depleted at depth. This will lead to anaerobic, reducing conditions in bottom waters and stratification of the water column. A pycnocline will help restrict the vertical transfer of mechanical energy, and thus, only turbidity currents will carry sandy sediments to deeper depths.

The presence or absence of a pycnocline will be reflected in the type of sediment deposited. If a pycnocline were depressed, or disappeared completely, oxygenated waters would reach the substrate and green-grey mudstones or shales would be deposited. Russell (1985) used the movement of a pycnocline in a stratified water column to explain the green-grey mudstones and black shales in the Upper Devonian Kettle Point Formation in southern Ontario (Figure 6.2). Russell postulates that the absolute depth of the water column was not important, but the relative depth of the pycnocline to the sediment-water interface was. The pycnocline's position would control the distribution and proportion of organic-rich and poor sediments.

In the Long Rapids Formation, the black shale and green-grey mudstone/shale facies can be explained by the presence of a stratified water column with a pycnocline. The carbonate facies (E) may have been deposited when the pycnocline had completely disappeared and the water column became more oxygenated and clastic free.

Hallam and Bradshaw (1979) observed a link between marine transgressions and the deposition of black shales, because organic productivity will increase on shelf areas due to increased surface areas. Possibly the reverse of this trend, a period of shallowing (i.e. a regression), will allow for the production of carbonate in the water column.

The Moose River Basin in northern Ontario was definitely covered by the Catskill Sea during Upper Devonian times, but its stratigraphic correlation with similar processes in the Appalachian Basin can only be assumed due to a lack of control in the Moose River Basin. When one looks at a map such as Figure 6.1, the Moose River Basin is quite removed from the Appalachian Basin located further south. With the Moose River Basin's proximity to the Hudson Bay Basin in the north, which contains Devonian evaporites and carbonates, one might expect the Devonian sediments in the Moose River Basin to be quite similar. This is not the case, but faulting along the Moose River Basin's southern edge may have deepened the Basin enough to allow for water stratification and black shale deposition to occur.

The location of the paleoshore is also difficult to determine since no paleocurrent indicators are present in the Long Rapids Formation. Chemical index of maturity tests have predicted a source for the shales to have come off a granitic terrain, probably somewhere in the south-southeast. The rare occurrence of plant debris is also indicative of the presence of a shoreline, but woody material can travel long distances before being deposited, and thus is not an accurate indicator. The crucial evidence needed to solve these puzzles probably lies in rock units that once covered the Precambrian Shield, but now have been eroded away.

CHAPTER 7:

CONCLUSIONS

1. The Upper Devonian shales of the Long Rapids Formation, Moose River Basin were part of a continent-wide deposition of shale that also included the Kettle Point, Chattanooga, New Albany and Ohio Formations.

2. The Long Rapids Formation is the youngest Paleozoic unit in the Moose River Basin. The Formation disconformably overlies Middle Devonian carbonates and shales (Williams Island Formation) and is turn unconformably overlain by the Cretaceous Mattagami Formation or Quaternary deposits. It has a subsurface area of approximately 5000 square kilometres and averages 30 metres in thickness. It can be subdivided into three informal members based on facies abundances (lower, middle, and upper members).

3. The Moose River Basin is an intracratonic basin which was connected to the Appalachian Basin to the south by the large, epicontinental Catskill Sea. The Moose River Basin is approximately 100,000 square kilometres in area, and its southern boundary is fault-bounded.

4. Five facies were distinguished in the Long Rapids Formation based on lithological and biological characteristics. The five facies include:

Facies A: Black shale

Facies B: Bioturbated black shale

Facies C: Massive green-grey mudstone

Facies D: Laminated green-grey shale

Facies E: Micritic dolomitic limestone beds and concretions.

5. The facies sequence A/B-C was the most common in the Long Rapids Formation, whereas facies sequence A/B-C-E was most prevalent in the lower and middle members. These facies cycles probably represent a shallowing-upward sequence from relatively deep water, anoxic black shales, to dysaerobic green-grey mudstones/shales, to eventually oxic carbonate deposition. Concretionary facies E were formed diagenetically, probably early.

6. The Frasnian-Famennian sequence represents a period of transgression in the Upper Devonian which followed the Acadian Orogeny. The small-scale facies sequences in the Long Rapids Formation may represent eustatic perturbations relative to the overall transgression.

7. Body fossils present include goniatites, crinoids, brachiopods, solitary corals, orthoconic nautiloids, conodonts, and molluscs. Some represent *in situ* forms, although most are allochthonous. The *Leiorhynchus* brachiopod fauna present in the dark-coloured shales probably represent a sparse epifauna living in poorly oxygenated or temporarily anoxic conditions in a basinal or open-shelf environment.

8. Trace fossils present include *Alcyonidiopsis*, *Chondrites*, *?Cylindrichnus*, *Planolites*, *?Skolithos*, *Teichichnus*, *Terebellina*, *Zoophycos*, and Ichnogenus "A".

a) The ichnosuite *Chondrites-Planolites-Zoophycos-Alcyonidiopsis-(?Teichichnus)* represents an oxygen-minimum ichnofacies which is predominantly found in dark shale facies. These traces represent deposit-feeding, soft-bodied, vermiform-type organisms which had a high tolerance for low oxygen levels and were found in dark, organic-rich shales. Most ichnofauna probably had semipermanent shafts to the sediment-water interface to allow for oxygen circulation as they burrowed through the sediment.

b) With increasing oxygen content to the sediment-water interface, more permanent burrow structures were constructed and these are represented by *Teichichnus-Terebellina-?Cylindrichnus-Skolithos*-Ichnogenus "A". The appearance of these traces correspond to a facies change from dark shales to green-grey mudstones to carbonates.

9. Total organic carbon values from Long Rapids Formation samples indicate facies A and B have the highest values, but mean values are below the minimum 5 % needed to make economic shale oil extraction feasible.

10. $\delta^{13}C$ isotope analyses indicate an average value of -29.52 ‰ for organic matter in the shales and -22.79 ‰ for woody plant material. The shale values are depleted in $\delta^{13}C$ compared to expected trends and indicate a terrestrial source for the organic matter, although other evidence predicts a marine source. It appears that the carbon isotopic composition of organic matter from sedimentary rocks of Devonian age cannot be confidently used to distinguish terrestrial versus marine carbon. Factors which may cause a depletion in $\delta^{13}C$ isotopic values include:

a) Non-biological alteration, dependant on time, which causes preferential destruction of carbohydrates and proteins and the resulting enrichment of the remaining organic matter in lipids, lignin, and cellulose.

b) Biologically, anaerobic bacteria may alter the isotopic values by consuming proteins and carbohydrates of the organic matter.

c) The massive emergence of land plants during Devonian time may have been a factor in affecting the original isotopic signature.

d) The water temperatures of the Devonian oceans may have been higher which affected the original isotopic values.

11. Chemical index of maturity values indicate a provenance for the shales as granitic gneiss, which complements the composition of Precambrian Shield rocks seen to the south of the Moose River Basin.

12. The Moose River Basin was probably a stratified water basin which contained a pycnocline to separate oxygenated surface waters and anoxic bottom waters. Anoxia helped to preserve organic matter by inhibiting its destruction and excluding most organisms. The relative depth of the pycnocline to the sediment-water interface, not the absolute depth of the water column, was the important factor in determining black shale deposition.

13. The Laurasian Continent, which included the Moose River Basin, was an area that straddled the equator and experienced warm to hot temperatures, geographically variable rainfall patterns, relatively high evaporation rates and generally easterly winds. Precipitation was inhibited on the leeward side of the mountains (located on the eastern edge of the Continent) because of the rain shadow effect. Thus, clastic rocks are not found on the western side of the mountains, except for the Catskill Delta (located at the equator) where

moisture-laden air would rise regardless of an orographic barrier.

14. Although no concrete depositional models can be postulated for the Long Rapids Formation shales, it is known that the three conditions needed for black shale deposition a) high organic productivity, b) no clastic dilution, and c) no oxygenation of the organic matter, were present most of the time when the Formation was deposited.

It is hoped that a better understanding of the Long Rapids Formation's position in the Moose River Basin has been demonstrated.

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APPENDIX A
WILLIAMS ISLAND OUTCROP SECTION
LONG RAPIDS FORMATION

METRES:	UNIT DESCRIPTION:
56.89-57.29	Black shale; top is covered with overburden (facies A).
56.83-56.89	Green mudstone; very clayey; very limonitic stained (facies C).
56.81-56.83	Black shale (facies A).
56.79-56.81	Green mudstone; very clayey (facies C).
56.72-56.79	Black shale (facies A).
56.70-56.72	Green-blue mudstone; burrowed (facies C).
56.25-56.70	Black shale; poor exposure (facies A).
56.19-56.25	Green mudstone (facies C).
56.00-56.19	Black shale (facies A).
55.85-56.00	Green-blue mudstone; top is very covered with slump features (facies C).
55.75-55.85	Black shale (facies A).
55.59-55.75	Green mudstone with a slight bluish tinge; very clayey (facies C).
55.34-55.59	Black shale; very limonite stained (facies A).
55.29-55.34	Interbedded green and black mudstones; burrowed with *Chondrites* (facies C & B).
55.09-55.29	Black shale (facies A).
55.06-55.09	Green mudstone; base is very burrowed with *Chondrites* (facies C).

55.01-55.06	Black shale (facies A).
54.91-55.01	Green mudstone (facies C).
54.66-54.91	Black shale (facies A).
54.56-54.66	Green mudstone (facies C).
54.42-54.56	Black shale (facies A).
54.30-54.42	Green mudstone; blocky appearance; very burrowed at the base with black mud laminae (facies C).
53.80-54.30	Black shale; 20 cm from the top, 1-2 cm thick green mudstone bed (facies A).
53.58-53.80	Green-blue mudstone; burrowed with *Planolites* and *Chondrites* (facies C).
53.38-53.58	Black shale (facies A).
52.98-53.38	Green mudstone (facies C).
52.92-52.98	Green mudstone (facies C).
52.77-52.92	Black shale (facies A).
52.61-52.77	Green mudstone; very clayey; no burrows (facies C).
52.16-52.61	Black shale; 10 cm from top, 3 mm green clay layer (facies A).
52.13-52.16	Green mudstone (facies C).
52.01-52.13	Black shale (facies A).
51.91-52.01	Green mudstone; very clayey (facies C).
51.77-51.91	Black shale (facies A).
51.67-51.77	Green mudstone; very clayey (facies C).
51.60-51.67	Black shale (facies A).

51.48-51.60	Green mudstone (facies C).
51.29-51.48	Black shale; very rare burrows at the top (facies B).
51.27-51.29	Green mudstone; clayey; limonitic (facies C).
51.13-51.27	Black shale (facies A).
50.96-51.13	Green mudstone; very clayey; burrowed with *Chondrites* (1 x 1 mm) (facies C).
50.86-50.96	Black shale; sharp lower contact (facies A).
50.64-50.86	Green mudstone (facies C).
50.48-50.64	Black shale (facies A).
50.41-50.48	Green mudstone (facies C).
49.95-50.41	Black shale; 10 cm from the base, very thin limonite laminae (1-2 mm thick), very oxidized, and contains thin calcite veining (facies A);
49.94-49.95	Green mudstone; with very small *Chondrites* (1 x 1 mm) (facies C).
49.80-49.94	Black shale (facies A).
49.78-49.80	Green mudstone (facies C).
49.31-49.78	Black shale; massive; fissile; very weathered (facies A);
49.28-49.31	Green mudstone; very sharp contacts (facies C).
48.41-49.28	Black shale; very weathered (facies A).
48.38-48.41	Green mudstone; very clayey and weathered; no burrows (facies C).

48.33-48.38	Black shale (facies A).
48.27-48.33	Green mudstone (facies C).
47.79-48.27	Black shale (facies A).
47.70-47.79	Green mudstone; no burrows; sharp contacts (facies C).
47.59-47.70	Black shale (facies A).
47.51-47.59	Green mudstone; clayey (facies C).
47.42-47.51	Black shale (facies A).
47.41-47.42	Green mudstone (facies C).
46.91-47.41	Black shale (facies A).
46.87-46.91	Green mudstone; sharp contacts (facies C).
46.42-46.87	Black shale (facies A).
46.40-46.42	Green mudstone (facies C).
45.68-46.40	Black shale; 45 cm from the top, 2-3 mm green mud layer (facies A).
45.56-45.68	Black shale; green mud layer at the top (facies A).
44.66-45.56	Black shale; massive and fissile; overlain by 0.5 cm green mud lamination with burrows (facies A).
44.59-44.66	Green mudstone; very clayey (facies C).
44.51-44.59	Black shale (facies A).
44.48-44.51	Green mudstone (facies C).
44.38-44.48	Black shale (facies A).
44.33-44.38	Green mudstone; sharp contacts; burrowed (facies C).

43.83-44.33	Black shale (facies A).
43.79-43.83	Green mudstone (facies C).
43.69-43.79	Black shale; burrowed top with *Planolites* and *Chondrites* (facies B).
43.67-43.69	Green mudstone; very clayey with interbedded black mud wisps (facies C).
43.65-43.67	Black shale (facies A).
43.63-43.65	Green mudstone (facies C).
43.23-43.63	Black shale (facies A).
43.09-43.23	Black shale; overlain by 4-5 mm green mudstone layer (facies A).
42.59-43.09	Black shale; with a very thin green clay layer (~4-5 mm thick) at the base - burrowed (facies A).
42.53-42.59	Green-grey mudstone; weathers yellow-orange (facies C).
41.63-42.53	Black shale; sharp top; fissile; very oxidized; 5 cm from the base, 1 cm thick green mudstone with sharp contacts (facies A).
41.53-41.63	Green mudstone (facies C).
41.03-41.53	Black shale; burrowed top (*Chondrites*) (facies B).
41.00-41.03	Green mudstone; clayey (facies C).
40.36-41.00	Black-brown shale (facies A).
40.24-40.36	Green mudstone; rare burrows (facies C).
40.14-40.24	Black shale (facies A).
40.09-40.14	Green mudstone; burrowed (facies C).

40.06-40.09	Grey-brown shale; burrowed (facies B).
39.26-40.06	Black-brown shale (facies A).
39.24-39.26	Green mudstone; burrowed base (*Chondrites* and *Planolites*); gradational contacts (facies C).
38.74-39.24	Black shale (facies A).
38.71-38.74	Green mudstone (facies C).
38.01-38.71	Black shale (facies A).
37.98-38.01	Green mudstone; burrowed base (*Chondrites*) (facies C).
37.88-37.98	Black shale (facies A).
37.84-37.88	Green mudstone; burrowed base (facies C).
37.64-37.84	Black shale (facies A).
35.64-37.84	Black shale; semi-fissile (facies A).
35.41-35.64	Grey-green mudstone; scattered burrows - *Chondrites* and ?*Zoophycos* (facies C).
35.28-35.41	Black shale (facies A).
35.24-35.28	Green-grey mudstone (facies C).
35.20-35.24	Black shale (facies A).
35.15-35.20	Green-grey mudstone (facies C).
35.00-35.15	Brown-black shale (facies A).
34.95-35.00	Green-grey mudstone (facies C).
34.70-34.95	Black shale; fissile; very oxidized; gradational top (facies A).
34.65-34.70	Green mudstone (facies C).
33.85-34.65	Black shale (facies A).

33.81-33.85	Green mudstone (facies C).
33.56-33.81	Black shale (facies A).
31.56-33.56	Black shale; fissile; very weathered with scattered burrows throughout (*Chondrites*) (facies B).
31.41-31.56	Green-grey mudstone (facies C).
30.51-31.41	Black shale (facies A).
30.41-30.51	Green-grey mudstone; clayey; sharp upper contact (facies C).
30.26-30.41	Black-brown shale; fissile (facies A).
30.19-30.26	Green-grey mudstone; gradational contacts (facies C).
29.49-30.19	Black-brown shale; covered by river water and sand (facies A).
29.14-29.49	Black shale; contains very large carbonate concretions (1 x 1 m in diameter), one of which contained a plant fragment, found in 1984 (facies A & E).
28.44-29.14	Green-grey mudstone; sharp upper contact (facies C).
28.24-28.44	Brown shale (facies A).
27.84-28.24	Green-grey shale (facies D).
27.14-27.84	Grey-brown mudstone (facies C).
26.37-27.14	Green-grey mudstone; massive; very blocky and chippy with subtle colour changes; upper contact is gradational (facies C).
26.15-26.37	Brown shale; fissile (facies A).
26.13-26.15	Grey micritic dolomitic limestone bed (facies E).
25.80-26.13	Green-grey mudstone (facies C).

25.65-25.80	Brown shale with scattered burrows (facies B).
25.45-25.65	Green-grey mudstone (facies C).
25.25-25.45	Brown shale; with *Chondrites* and *Planolites* (facies B).
24.95-25.25	Green-grey mudstone (facies C).
24.75-24.95	Grey limestone concretions, spherical and small (facies E).
24.20-24.75	Green-grey mudstone (facies C).
24.00-24.20	Grey dolomitic limestone bed; mottled appearance; thickness varies laterally (facies E).
23.46-24.00	Green-grey mudstone; very weathered and chippy (facies C).
23.33-23.46	Grey dolomitic limestone bed (facies E).
22.87-23.33	Brown to green mudstone (facies C).
22.77-22.87	Grey dolomitic limestone bed (facies E).
22.63-22.77	Green-grey mudstone (facies C).
21.63-22.63	Black shale; very fissile (facies A).
21.61-21.63	Green-grey limestone nodular bed; sharp upper contact (facies E).
19.81-21.61	Green-grey mudstone; subtle colour variations; very chippy and clayey; 25 cm from the top, 1-2 cm thick calcareous nodular bed (facies C).
19.77-19.81	Green-grey dolomitic limestone bed (facies E).
19.62-19.77	Green-grey mudstone; mottled and blocky (facies C).

19.60-19.62	Grey dolomitic limestone bed (facies E).
19.30-19.60	Green-grey mudstone; very clayey; gets greener at the top; browner at the base (facies C).
19.14-19.30	Grey dolomitic limestone bed; mottled; thickness varies laterally (facies E).
18.24-19.14	Brown and green mudstones; subtle colour changes from brown at the base, to greens and olive greens at the top (facies C).
18.09-18.24	Grey dolomitic limestone bed (facies E).
18.06-18.09	Green mudstone (facies C).
17.81-18.06	Brown-black shale; calcareous (facies A).
17.41-17.81	Green-brown mudstone; gradational upper contact (facies C).
17.24-17.41	Grey dolomitic limestone bed; mottled; thickness varies laterally (facies E).
16.45-17.24	Light brown-green shale; very clayey; top becomes a green mudstone (facies C & D).
15.90-16.45	Light brown-green shales and mudstones; subtle colour changes; green mudstone at the top; gradational top (facies C & D).
14.90-15.90	Black-brown shale; fissile; greener in colour at the base (facies A).
13.90-14.90	Green-grey shale; with darker green-brown shale at the top and base (facies D).

12.90-13.90	Green-grey shale; very weathered and clayey; grades into olive-green coloured shale at the base, gets darker towards the top (facies D).
12.40-12.90	Black shale (facies A).
12.37-12.40	Green mudstone; sharp upper contact (facies C).
11.72-12.37	Brown-black shale; fissile; very olive-green towards the top; burrowed (facies B).
10.82-11.72	Black-brown shale; with 2 cm green mudstone at the base; upper 50 cm are burrowed with *Planolites, Chondrites, Teichichnus,* and *Alcyonidiopsis;* at top, 3 cm thick nodular limestone bed (facies B).
10.45-10.82	Black shale (facies A).
10.35-10.45	Grey dolomitic limestone bed (facies E).
10.30-10.35	Green mudstone (facies C).
9.85-10.30	Black-brown shale; fissile; becomes blocky at the top (facies A).
9.77-9.85	Grey limestone bed; variable thickness (facies E).
9.54-9.77	Green-grey shale; fissile; very blocky and chippy; sharp upper contact (facies D).
9.31-9.54	Black-brown shale; gradational upper contact (facies A).
9.26-9.31	Grey, coarse-grained calcarenite; slightly laminated (facies E).
9.06-9.26	Black shale (facies A).

9.03-9.06	Laminated dolomitic limestone bed; laterally discontinuous (facies E).
8.48-9.03	Black-brown shale (facies A).
8.44-8.48	Grey dolomitic limestone bed (facies E).
8.14-8.44	Brown-black shale; gradational to green-grey mudstone with *Planolites* (facies B).
8.10-8.14	Grey dolomitic limestone bed (facies E).
7.95-8.10	Brown-grey shale; grades to an 8 cm thick green mudstone bed; sharp upper contact (facies A).
7.88-7.95	Green mudstone; clayey with dark green limestone nodules (facies C & E).
7.68-7.88	Brown-grey shale; fissile; with *Planolites* (1 x 4 mm) and *Chondrites* (facies B).
7.63-7.68	Black shale; fissile; rare sulphide blebs (1 x 2 cm in diameter); unit is sharply overlain by 7-10 cm thick fine-grained calcarenite bed, dark brown, with faint laminae (facies A & E).
7.58-7.63	Grey-brown limestone bed; thickness is laterally variable; scattered *Planolites* (facies E).
6.78-7.58	Grey-olive brown shale; becomes blacker 3/4 the way up, but becomes a clayey green mudstone at the very top (facies C & D).

6.48-6.78	Grey limestone bed; thickness varies laterally; contains small crinoid fragments (5 x 10 mm), along with brachiopod and goniatite fragments; mottled throughout with rare sulphide blebs; upper contact is sharp (facies E).
6.00-6.48	Black shale, which grades into a green-grey mudstone at the top; very clayey and less fissile at the top; sharp upper contact; unit contains large calcareous concretions (35 x 45 cm); contains fragments of the goniatite *Manticoceras sinuosum*, along with orthoconic nautiloids; 50 cm from the top, 1 cm thick silt bed (facies A & C).
4.00-6.00	Black shale; fissile (facies A).
3.00-4.00	Black shale; massive and fissile; rare sulphide blebs (1 x 1, and 3 x 4 cm) (facies A).
2.00-3.00	Black shale; massive and fissile; rare sulphide blebs (facies A).
1.00-2.00	Black shale; chippy and fissile (facies A).
0.00-1.00	Black shale; fissile (facies A).

3.0-4.0 metres of covered section (debris and river sediments), consisting of green-grey mudstones. This unit contains abundant brachiopods (both entire and fragmented shells), as well as scattered crinoid ossicles. These shales are sharply underlain by very weathered, brecciated, medium-crystalline limestone which represents the Middle Devonian Williams Island Formation. Therefore, approximately 60-61 metres of section of the Long Rapids Formation is present.

APPENDIX B
MOOSE RIVER BASIN BOREHOLES
OGS ONAKAWANA B BOREHOLE
lat.: 50°35'24" long.: 81°29'10"

Cretaceous sediments (Mattagami Formation):

METRES:	UNIT DESCRIPTIONS:
75.33-76.64	Brown to rust coloured siltstones; abundant coaly and woody material towards the top.
Long Rapids Formation (Upper Devonian):	
76.64-79.55	Green mudstone with interbeds of black shales (~1-2 cm thick) (facies A & C).
79.55-82.32	Green-grey mudstone with interbedded black shales (~1-2 cm thick) (facies A & C).
82.32-82.47	Black shale; sharp upper and lower contacts (facies A).
82.47-83.62	Green mudstone with interbedded black shale intervals, varying from < 1 cm to ~2 cm thick (facies A & C).
83.62-83.66	Black shale (facies A).
83.66-83.68	Green-grey mudstone (facies C).
83.68-83.70	Black shale (facies A).
83.70-84.06	Green-grey mudstone (facies C).
84.06-84.08	Black shale (facies A).
84.08-84.38	Green-grey mudstone (facies C).
84.38-84.50	Black shale (facies A).
84.50-84.55	Green-grey mudstone (facies C).
84.55-84.59	Black shale (facies A).
84.59-85.22	Green-grey mudstone (facies C).
85.22-85.42	Brown-black mudstone (facies A).

85.42-85.61	Green-grey mudstone (facies C).
85.61-85.67	Black shale (facies A).
85.67-85.78	Green-grey mudstone (facies C).
85.78-85.83	Black shale (facies A).
85.83-85.96	Green-grey mudstone (facies C).
85.96-86.25	Black shale (facies A).
86.25-86.36	Green-grey mudstone (facies C).
86.36-86.47	Black shale (facies A).
86.47-87.06	Green-grey mudstone (facies C).
87.06-87.43	Black shale (facies A).
87.43-87.51	Green-grey mudstone (facies C).
87.51-87.58	Brown-black shale (facies A).
87.58-87.78	Green-grey mudstone (facies C).
87.78-87.86	Black-brown shale (facies A).
87.86-88.09	Green-grey mudstone (facies C).
88.09-88.25	Black shale (facies A).
88.25-88.45	Green-grey mudstone (facies C).
88.45-88.49	Black shale (facies A).
88.49-89.14	Green-grey mudstone (facies C).
89.14-89.19	Black shale (facies A).
89.19-89.34	Green-grey mudstone (facies C).
89.34-89.59	Black shale (facies A).
89.59-89.73	Green-grey mudstone (facies C).
89.73-89.90	Black shale (facies A).
89.90-89.99	Green-grey mudstone (facies C).
89.99-90.20	Black shale (facies A).

90.20-90.66	Green-grey mudstone (facies C).
90.66-91.04	Black shale (facies A).
91.04-91.19	Green-grey mudstone (facies C).
91.19-91.30	Black shale (facies A).
91.30-91.47	Green-grey mudstone (facies C).
91.47-91.98	Black shale (facies A).
91.98-92.08	Green-grey mudstone (facies C).
92.08-92.10	Black shale (facies A).
92.10-92.12	Green-grey mudstone (facies C).
92.12-92.18	Black shale (facies A).
92.18-92.20	Green-grey mudstone (facies C).
92.20-92.23	Black shale (facies A); Sample OX-82, @92.15 m, TOC=0.42 %.
92.23-93.28	Green-grey mudstone (facies C).
93.28-93.30	Black shale (facies A).
93.30-93.64	Green-grey mudstone (facies C).
93.64-94.00	Black shale (facies A).
94.00-94.23	Green-grey mudstone (facies C).
94.23-94.33	Interbedded green-grey and black mudstones (75/25 %) (facies A & C).
94.33-94.36	Green-grey mudstone (facies C).
94.36-94.48	Black shale (facies A).
94.48-95.00	Green-grey mudstone (facies C).
95.00-95.05	Black shale (facies A).
95.05-95.32	Micritic dolomitic limestone; sharp upper and lower contacts (facies E).

95.32-95.66	Green-grey mudstone (facies C).
95.66-95.73	Black shale (facies A).
95.73-96.24	Green-grey mudstone with calcite concretion halfway down, 2 x 3 cm in diameter (facies C & E).
96.24-96.36	Black shale (facies A).
96.36-96.73	Green-grey mudstone (facies C).
96.73-96.88	Black shale (facies A).
96.88-97.22	Green-grey mudstone (facies C).
97.22-97.99	No core.
97.99-98.19	Green-grey mudstone; clayey; chippy appearance in places (facies C).
98.19-98.41	Black shale (facies A).
98.41-98.55	Green-grey mudstone (facies C).
98.55-98.79	Black shale (facies A).
98.79-98.89	Green-grey mudstone; chippy appearance (facies C).
98.89-99.39	Black shale; at 99.14 m, 1 cm thick green mudstone bed, very clayey and chippy (facies A).
99.39-99.44	Interbedded black and green-grey shales and mudstones (50/50 %) (facies A, C, & D).
99.44-99.91	Black shale (facies A).
99.91-99.94	Green-grey mudstone (facies C).
99.94-100.34	Black shale (facies A).
100.34-100.41	Green-grey mudstone (facies C).
100.41-100.55	Black shale (facies A).
100.55-100.62	Green-grey mudstone (facies C).

100.62-101.49	Black shale (facies A).
101.49-101.61	Green-grey mudstone; chippy appearance (facies C).
101.61-101.82	Black shale (facies A); Sample OX-81, @ 101.39 m, TOC=4.72 %.
101.82-102.00	Green-grey mudstone; chippy and clayey appearance (facies C).
102.00-102.91	Black shale; very fissile (facies A); Sample OX-80, @ 102.84 m, TOC=4.99 %; Sample OX-79, @ 102.90 m, TOC=4.48 %.
102.91-103.05	Interbedded green-grey and black mudstones and shales (50/50 %) (facies A, C, & D).
103.05-103.58	Black shale; 0.5 cm thick green mud lamination halfway down (facies A).
103.58-103.62	Interbedded green and black-brown mudstones and shales (75/25 %); ~1 to 1.5 cm thick (facies A,C, &, D).
103.62-105.87	Black shale; very fissile; at 104.68 m, 2 cm thick green mudstone bed with mottled burrows (facies A); Sample OX-78, @ 105.46 m, TOC=1.89 %.
105.87-106.12	Green-grey mudstone (facies C).
106.12-106.27	Black shale (facies A).
106.27-106.43	Green-grey mudstone (facies C).
106.43-106.55	Black shale (facies A).
106.55-106.70	Green-grey mudstone; chippy appearance (facies C).

106.70-107.27	Black shale; rare burrows (facies B).
107.27-107.52	Green-grey mudstone (facies C).
107.52-107.65	Black shale (facies A); Sample OX-77, @ 107.61 m, TOC=4.80 %.
107.65-107.69	Green-grey mudstone (facies C).
107.69-107.83	Black shale (facies A).
107.83-107.86	Green-grey mudstone; burrowed with *Chondrites* and ?*Zoophycos* (facies C).
107.86-108.41	Black shale; very fissile (facies A).
108.41-108.46	Brown-green shale (facies C).
108.46-108.89	Black shale (facies A).
108.89-109.10	Green-grey mudstone; sharp upper contact (facies C).
109.10-109.30	Black shale; at 109.27 m, 2 cm thick green mudstone bed (facies A).
109.30-109.37	Green-grey mudstone with interbeds of black mud laminae (~80/20 %) (facies C & A).
109.37-109.84	Black shale; burrowed towards the middle, possibly ?*Zoophycos* and *Chondrites* (facies B).
109.84-109.94	Green-grey mudstone; scattered black mud laminae with rare burrows (facies C).
109.94-110.07	Black shale (facies A).
110.07-110.30	Green-grey mudstone (facies C).
110.30-110.39	Black shale (facies A).
110.39-110.58	Green-grey mudstone (facies C).
110.58-111.17	Black shale (facies A).

111.17-111.39	Green-grey mudstone; very poor core (facies C).
111.39-111.48	Black shale; burrowed top (facies B).
111.48-111.58	Green-grey mudstone (facies C).
111.58-112.95	Black shale; at 112.31 m, 3 cm thick green mudstone bed with burrows (?*Teichichnus*) (facies A); Sample OX-76, @ 112.83 m, TOC=2.83 %.
112.95-113.03	Green-grey mudstone (facies C).
113.03-113.56	Black shale; burrows at top (~6 cm down) (facies B); Photo OX-78, @ 113.03 m of burrowed top with *Teichichnus* and *Alcyonidiopsis*.
113.56-113.62	Green-grey mudstone with some black mud laminae and burrows (facies C & B).
113.62-113.75	Black shale; bioturbated top (facies B).
113.75-113.88	Green-grey mudstone (facies C).
113.88-113.97	Black shale (facies A).
113.97-114.07	Green-grey mudstone (facies C); gradational top.
114.07-114.51	Black shale; very fissile; *Zoophycos* burrow present at top (facies B); Photo OX-77, @ 114.08 m of *Zoophycos*.
114.51-115.50	Black shale; same as above (facies B); Sample OX-75, @ 114.83 m, TOC=3.39 %.
115.50-115.54	Green-grey mudstone (facies C).
115.54-115.96	Black shale (facies A).

115.96-116.01	Green-grey mudstone (facies C).
116.01-116.08	Black shale (facies A).
116.08-116.17	Green-grey mudstone (facies C).
116.17-116.22	Black shale (facies A).
116.22-116.30	Green-grey mudstone (facies C).
116.30-116.37	Black shale (facies A).
116.37-116.44	Green-grey mudstone (facies C).
116.44-116.88	Black shale with green-grey mudstone laminae at 116.66 and 116.80 m, 2 cm thick (facies A & C).
116.88-117.00	Green-grey mudstone (facies C).
117.00-117.13	Black shale; bioturbated top (facies B).
117.13-117.25	Green-grey mudstone (facies C).
117.25-117.88	Black shale; burrowed top (facies B).
117.88-118.04	Green-grey mudstone; clayey (facies C); Photo OX-75, @ 117.88 m.
118.04-118.99	Black shale; fissile with a burrowed top; green-grey claystone at base (facies B); Sample OX-74, @ 118.74 m, TOC=5.50 %.

118.99-123.56	Black shale; very fissile; at 122.26 m, 7 cm thick interbedded black and green-grey mudstone interval occurs (burrows at the base, core is very fractured); at 120.96 m, 4 cm thick green mudstone bed, burrowed; at 120.15 m, 9 cm thick green mudstone bed, base is burrowed into the black shale ~2 cm; at 119.99 m, 6 cm thick green-grey mudstone bed (facies A & C); Photo OX-76, @ 123.19 m Sample OX-72, @ 122.74 m, TOC=5.28 %; Sample OX-73, @ 119.75 m, TOC=5.25 %.
123.56-125.95	Black shale; massive and indurated; contains one green mudstone bed (1 cm thick) at 120.65 m (facies A); Photo OX-74, @ 124.94 m (of "hockey puck" fissility); Sample OX-70, @ 124.94 m, TOC=5.72 %; Sample OX-71, @ 125.38 m, TOC=5.28 %.
125.95-126.02	Green-grey micritic dolomitic limestone bed (facies E).
126.02-126.35	Black shale; burrowed top (facies B).
126.35-126.42	Green-grey micritic dolomitic limestone bed; upper and lower contacts are very irregular (facies E).
126.42-127.42	Black shale; massive with a burrowed top (very small *Chondrites*); sharp base (facies B); Sample OX-69, @ 126.68 m, TOC=4.81 %.
127.42-127.48	Green-grey micritic limestone (facies E).

127.48-127.80	Black shale; massive and fissile; top is burrowed (facies B); Photo OX-73, @ 127.66 m, of burrowed contact; Sample OX-68, @ 127.66 m, TOC=4.33 %.
127.80-127.89	Green-grey micritic dolomitic limestone; *lingula* fragments present throughout (facies E).
127.89-128.10	Black shale; very fissile; core breaks into a "hockey puck" fissility; scattered small calcite nodules (odd shapes); top is bioturbated with *Chondrites*, rare *lingula* is present; one calcite concretion at the top (2 x 3 cm) (facies B).
128.10-129.03	Black shale; same as above (facies B); Sample OX-67, @ 128.76 m, TOC=3.96 %.
129.03-132.77	Green mudstone; scattered limestone concretionary beds and nodules; clayey in places; vague grey mud laminations (facies C & E); Photo OX-72 @ 129.03 m, of sharp contact to black shale, erosional base with tiny (< 1 mm x 3 mm long shell debris) and burrows; possible crinoid ossicle; chalcopyritized burrow.
132.77-135.56	Green mudstone; scattered black interbeds at the base (~ 1 cm thick); becomes very clayey at the base; scattered micritic limestone beds with pyritized burrows; some calcite nodules; base is burrowed with *Chondrites* (facies C, A, & E).

135.56-136.47	Brown-black shale; becomes blacker towards the top; top is sharp; rare scattered burrows (*Chondrites*) in brown shales; rare green mudstone beds at the base (facies B); Sample OX-66, @ 135.60 m, TOC=3.45 %.
136.47-136.51	Green-grey mudstone; sharp top (facies C).
136.51-136.66	Black shale; sharp top (facies-A).
136.66-137.14	Green-grey micritic dolomitic limestone bed; clayey and muddy at the base; sharp top (facies-E).
137.14-137.30	Green-grey mudstone; with brown shaly interbeds (facies C & A).
137.30-137.94	Green-grey mudstone; rare brown mud laminations (~1-2 mm thick); scattered mottled burrows present (facies C).
137.94-138.42	Brown-black shale; rare green-grey mudstone interbeds (~ 1 cm thick) (facies A).
138.42-139.14	Green mudstone with some interlaminated black shale laminae (facies C & A).
139.14-139.99	Black shale; top and bottom are bioturbated (facies B); Sample OX-65, @ 139.45, TOC=3.51 %.
139.99-141.01	Green-grey mudstone; calcite concretion at top (2 x 3 cm); scattered nodules throughout (~2 x 4 cm) (facies C & E).
141.01-141.28	Interlaminated green and black-brown mudstones (25/75 %); rare burrows; laminae are mainly ~ 1 mm thick; scattered pyrite nodules (~1 x 1 cm) (facies A & C).

141.28-141.63	Green-grey mudstone (facies C).
141.63-141.78	Green-grey mudstone; massive; halfway down, vague green mud laminae (1 - 10 mm thick); scattered calcite nodules throughout (1 x 3 cm max.) (facies C & E).
141.78-141.95	Brown-black shale; massive (facies A).
141.95-144.89	Green-grey mudstone; very clayey with rare black laminae; scattered calcite concretions throughout (1 x 2 cm) (facies C & E).
144.89-145.07	Interlaminated green and brown/black mudstone (60/40 %) (~1 mm thick) (facies A & C).
145.07-145.15	Black shale; sharp base; scattered burrows, *Chondrites* (facies B).
145.15-146.35	Green-grey mudstone; shaly in places; massive and well indurated; vary calcareous; scattered calcite nodules (1 x 1 cm); micritic limestone bed at top (~1 to 2 cm thick) (facies C).
146.35-149.59	Green shale; becomes clayey upwards and loses its fissility; calcite nodules throughout (~2 x 3 cm and less in diameter); gradational base (facies D).
149.59-150.58	Black shale; massive and fissile; @ 149.79 m, 1 cm thick micritic limestone bed with some internal pyritization; some faint silt laminae present at 149.40 m, (~ 0.5 cm thick); scattered green mud laminae also present (facies A); Sample OX-64, @ 150.37 m, TOC=5.69 %.

150.58-151.02	Brown mudstone; clayey (facies C).
151.02-153.99	Black shale; rare interbeds of brown and green mudstones; sharp base and gradational top; calcite concretion at top (4 x 6 cm); burrows abundant where brown-green beds are present; at 151.91 m, carbonized piece of plant material (~1 mm thick); three distinct burrow horizons are present, up to 1.5 cm thick (*Chondrites* and *Planolites*), various sizes and lengths (up to 4 x 6 mm), some have burrowed down ~20 cm from the top (facies B); Sample OX-63, @ 153.24 m, TOC=4.39 %; Photo OX-71, @ 151.91 m of woody material.
153.99-155.07	Green calcareous mudstone; abundant shell debris; top is erosional with fragments of *lingula* (~1 mm in diameter, some are pyritized as blebs, some chitinophosphatic), scattered brachiopod shells (half shells) are located within the mudstone; shells are replaced with sparry calcite; shell positions are random (facies C); Photo OX-70, @ 153.99 m of sharp erosional contact with *lingula* hash.
155.07-157.66	Brown shale; becomes very calcareous at the top; abundant shelly debris also at the top (facies A); Photo OX-69, @ 156.34 m of shell debris.
157.66-157.75	Green-grey micritic dolomitic limestone bed; very mottled and burrowed (facies E).

157.75-157.80	Brown-black shale; very burrowed (facies B); Photo OX-68, @ 157.77 m of *Chondrites* cross-cutting a larger burrow.
156.93-157.91	Green-grey micritic dolomitic limestone bed; mottled appearance; appears concretionary in places (facies E).
157.91-158.01	Brown-black shale; with scattered indistinct burrows (facies B).
158.01-158.16	Green mudstone; scattered calcite nodules containing abundant shell debris; pyrite blebs also present; gradational top (facies C); Photo OX-67, @ 158.01 m of burrow.
158.16-157.68	Black shale; sharp base; burrowed top, mainly *Chondrites* and *Teichichnus* (facies B); Photo OX-66, @ 157.22 m of lower contact.

Williams Island Formation
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157.68-159.72	Green mudstone; with interbedded brown-black mudstones; scattered burrows.
159.72-164.14	Green-grey mudstone and limestone beds; some pyrite and fracturing is present; very irregular appearance; mudstone is very calcareous.

End of Log

OEC 81-05
lat.: 50°29'30" N, long.: 81°38'30" W
Contact between middle and upper members at 91.03 m.

METRES:	UNIT DESCRIPTIONS:
Contact of Cretaceous sediments to the Upper Devonian Long Rapids Formation at 60.70 m.	
70.70-73.47	No core.
73.47-75.34	Green mudstone; with minor interbeds (up to 1 cm thick); no burrows (facies C).
75.34-75.38	Black shale (facies A).
75.38-75.53	Green-grey mudstone (facies C).
75.53-75.64	Black shale (facies A).
75.64-75.75	Green-grey mudstone (facies C).
75.75-75.88	Black shale (facies A).
75.88-75.95	Green-grey mudstone (facies C).
75.95-76.14	Black shale; slump features present (facies A).
76.14-77.53	Green-grey mudstone (facies C).
77.53-77.59	Black shale (facies A).
77.59-77.76	Green-grey mudstone (facies C).
77.76-77.79	Black shale (facies A).
77.79-77.92	Green-grey mudstone (facies C).
77.92-78.00	Brown-black shale (facies A).
78.00-79.34	Green-grey mudstone (facies C).
79.34-82.58	Green-grey mudstone; with scattered interbeds of black shale laminae (facies C).
82.58-82.71	Black shale (facies A).

82.71-83.48	Green-grey mudstone with interbedded black shale laminae (facies C & A).
83.48-84.16	Black shale (facies A).
84.16-84.36	Green-grey mudstone; sharp base (facies C).
84.36-84.70	Black shale (facies A).
84.70-84.88	Green-grey mudstone (facies C).
84.88-84.93	Black shale (facies A).
84.93-85.00	Green-grey mudstone; burrowed base (facies C).
85.00-85.06	Black shale (facies A).
85.06-85.36	Green-grey mudstone (facies C).
85.36-85.48	Black shale (facies A).
85.48-85.88	Green-grey mudstone (facies C).
85.88-86.17	Black shale (facies A).
86.17-86.43	Green mudstone (facies C).
86.43-87.65	No core.
87.65-87.78	Green-grey mudstone (facies C).
87.78-87.91	Black shale (facies A).
87.91-88.35	Green-grey mudstone; slightly bioturbated top and base (facies C).
88.35-88.76	Black shale (facies A).
88.76-89.10	Interbedded green and black mudstones (40/60 %); occasional burrows (facies C & A).
89.10-89.30	Green-grey mudstone (facies C).
89.30-89.37	Black shale; rare bioturbation (facies A & B).

89.37-89.80	Green-grey mudstone; with a micritic limestone bed at the base, 23 cm thick (facies C & E).
89.80-90.07	Black shale (facies A).
90.07-90.34	Green-grey mudstone (facies C).
90.34-90.37	Black shale (facies A).
90.37-90.47	Green-grey mudstone (facies C).
90.47-90.57	Black shale (facies A).
90.57-91.03	Green-grey mudstone; burrowed base (facies C).
91.03-91.17	Black shale (facies A).
91.17-91.23	Green-grey mudstone (facies C).
91.23-92.34	Black shale (facies A).
92.34-92.42	Green-grey mudstone; burrowed top (facies C).
92.42-92.80	Black shale (facies A); Sample OX-41 @ 92.41 m, TOC=5.92 %.
92.80-93.59	Black shale (facies A).
93.59-93.91	Green-grey mudstone; burrowed top with *Chondrites* and black shale interbeds (facies C).
93.91-93.97	Black shale (facies A).
93.97-94.09	Green-grey mudstone; burrowed with black shale interbeds (facies C).
94.09-94.79	Black shale; Sample OX-43, @ 94.73, TOC=4.71 % (facies A).
94.79-94.86	Green-grey mudstone; clayey with green-black mud laminae at the top (facies C).

94.86-95.03	Black shale (facies A).
95.03-95.12	Green-grey mudstone; with some black shale interbeds; sharp top; *Chondrites* present (facies C).
95.12-97.24	Black shale; burrowed with *Zoophycos* (facies B).
97.24-97.27	Green-grey mudstone; Photo OX-47 @ 97.25 m (facies C).
97.27-98.33	Black shale; Sample OX-42, @ 97.47 m, TOC=3.63 % (facies A).
98.33-98.45	Green shale; burrowed base; (facies D).
98.45-98.58	Black shale (facies A).
98.58-98.65	Green shale; burrowed base, sharp top (facies D).
98.65-98.73	Black shale (facies A).
98.73-98.83	Green shale; with black shale interbeds (~1 cm thick) (facies D).
98.83-99.34	Black shale (facies A).
99.34-99.41	Green mudstone; burrowed base, down approx. 4 cm-*Chondrites* and wispy burrows at top-*Planolites* (facies C).
99.41-99.53	Black shale (facies A).
99.53-100.55	Black shale; with scattered green-grey mud laminae; Photo OX-46, @ 99.61 m of *Zoophycos* in green beds (facies B).
100.55-100.62	Green-grey mudstone (facies C).

100.62-101.37	Black shale; with rare green mud laminae (< 1 cm thick); Sample OX-41 @ 100.9 m, TOC=5.92 % (facies A).
101.37-101.47	Green-grey mudstone; burrowed base; sharp top (facies C).
101.47-101.56	Black shale; massive (facies A).
101.56-101.85	Green-grey micritic limestone; concretionary; with vuggy calcite veining (facies E).
101.85-102.39	Black shale (facies A).
102.39-102.48	Green shale; burrowed base; diffuse top (facies D).
102.48-104.61	Black shale; Sample OX-40, @ 104 m, TOC=7.51%; Photo OX-44 + 45, @ 104.32 + 103.2 m of *Zoophycos* (facies B).
104.61-104.67	Green mudstone; sharp top; burrowed base, with ?*Zoophycos*; Photo OX-43, @ 104.65 m of boundary (facies C).
104.67-105.15	Black shale; sharp top; Photo OX-42 @ 105.2 m (facies A).
105.15-105.27	Green-grey mudstone; extremely bioturbated with *Alcyonidiopsis* which burrows down approx. 10 cm (facies C).
105.27-105.64	Black shale (facies A).

105.64-109.86	Black shale; with scattered green-grey mudstone beds; slightly calcareous in places; very fissile; some places are light brown in colour; chippy; @ 107.52 m, 8 cm thick green mudstone bed with rare *Zoophycos;* Photo OX-41, @ 106.8 m of green and black mudstone/shale; Sample OX-39, @ 105.92 m, TOC=5.44% Sample OX-38, @ 108.65 m, TOC=5.6% (facies A).
109.86-109.99	Green-grey mudstone; very clayey; chippy; burrowed top; top and bottom are diffuse (facies C).
109.99-111.59	Black shale; fissile; rare green-grey mudstone beds; burrowed in places Photo OX-41 @ 110.82 m of pyrite nodule Sample OX-37 @ 111.35 m, TOC=8.21% (facies B).
111.59-114.82	Black shale; occasional green-grey mud layers (1-2 cm); bioturbated base; sharp top; scattered pyrite blebs and nodules (1 x 1 cm); *Teichichnus, Chondrites, Zoophycos* present, with brachiopods at the top; Photo OX-39, @ 114.21 m Photo OX-40, @ 112.62 m of *Zoophycos* Sample OX-35, @ 113.82 m, TOC=7.35 %, Sample OX-36, @ 112.42 m, TOC=4.05 % (facies B).
114.82-114.90	Green-grey micritic limestone; concretionary; mottled; with shelly fragments; semi-sharp base and top (facies E).

114.90-115.50	Black shale; very fractured at base with horizontal calcite veins; sharp base; Photo OX-38, @ 115.42 m of fractures Sample OX-34, @ 115.12 m, TOC=6.17 %.
115.50-115.77	Green-brown mudstone; chippy (facies C).
115.77-117.46	Black shale; burrowed top; diffuse base; faint laminations throughout; occasional silty blebs; rare scattered burrows- *Teichichnus + Chondrites* Sample OX-33, @ 117.22, TOC=3.76 % Photo OX-36, @ 116.92 m of *Teichichnus* Photo OX-37, @ 115.72 m of burrows (facies B).
117.46-120.10	Black shale; scattered silty laminae (facies A).
120.10-120.28	Green-grey mudstone; abundant burrows at the base; mottled and chippy at top; slightly calcareous; with *Chondrites, Teichichnus,* rare *Planolites* (facies C).
120.28-120.73	Black shale; sharp base, fuzzy top; abundant silty blebs and laminae towards the top; scattered pyrite blebs (facies A).
120.73-120.85	Brown-green mudstone; very mottled; diffuse base, sharp top; very green at the top; slightly calcareous; small scattered *Chondrites* burrows (facies B).
120.85-121.33	Black shale; with 1 mm thick silt laminae at top; becomes lighter brown at top; mottled (facies A).

121.33-121.44	Green-grey concretionary limestone bed; mottled; sharp top (facies E).
121.44-122.44	Black shale; fissile; 15 cm from the base, green mud unit with burrows (1 x 2 cm), mainly *Chondrites* + *Teichichnus*; some small (1 x 1 mm) burrows scattered within black shales; gradational top; faint silt laminae; Photo OX-34, @ 121.97 m of *Teichichnus* Photo OX-35, @ 122.02 m of gradational top (facies B).
122.44-122.54	Green-brown mudstone; slightly calcareous; gradational base; sharp top; very mottled Photo OX-33, @ 122.54 m of sharp top (facies C).
122.54-123.04	Black shale; very indurated; rare silt laminae; bioturbated to ~ 16 cm from the top; Photo OX-32, @ 123 m of burrowed top.

End of drill hole.

OEC 81-08

lat.: 50°43'42" N, long.: 81°36'54" W.

Contact between middle and upper members at 57.54 m.

METRES:	DESCRIPTIONS:
Long Rapids Formation:	
47.41-47.61	Green-grey mudstone (facies C).
47.61-47.66	Black shale (facies A).
47.66-48.01	Green-grey mudstone (facies C).
48.01-48.09	Black shale (facies A).
48.09-48.23	Green-grey mudstone; massive; fractured core (facies C).
48.23-48.31	Black shale (facies A).
48.31-48.69	Green-grey mudstone; interbedded base with two black mud beds, 1 cm thick (facies C).
48.69-49.30	Black shale (facies A). Sample OX-50 @ 48.75, TOC=3.82%.
49.30-49.83	Green-grey mudstone; 2 cm thick black shale bed at 49.58 m; sharp top (facies C).
49.83-51.16	Brown-black shale; fissile and massive (facies A).
51.16-51.30	Interbedded green and black mudstones; (75/25 %); burrowed with *Planolites* (facies B & C).
51.30-51.62	Black shale (facies A).
51.62-52.27	Green-grey mudstone; massive; fuzzy top and bottom; top is burrowed (5 cm) (facies C). Photo OX-52 @ 51.60 m, of *Teichichnus*, 2.5cm x 2mm, good protrusive spreiten, scattered *Chondrites*.

52.27-52.91	Black shale; one green mud bed (1 cm) at 52.56 m (facies A); Sample OX-49, @ 52.78 m, TOC=4.51 %.
52.91-53.15	Green-grey mudstone; sharp top and base; scattered burrows (very small *Chondrites*); at top, 10 cm of interbeds (25/75 black/green), burrowed with *Chondrites* (facies C).
53.15-53.45	Black shale (facies A).
53.45-53.93	Green-grey mudstone; sharp top and base; very clayey and chippy (facies C).
53.93-54.07	Black shale (facies A). Photo OX-52 @ 54.47 Sample OX-48 @ 54.54, TOC=3.31 %.
54.07-54.47	Green-grey mudstone; burrowed base (3cm down into black); top is fuzzy (facies C).
54.47-54.64	Black shale (facies A).
54.64-54.73	Interbedded green/black mudstone (80/20 %); more green and massive at top; small burrows (< 1 mm) at base (facies B & C).
54.73-55.58	Black shale (facies A).
55.58-55.71	Green-grey mudstone; clayey; sharp top and base (facies C).
55.71-55.98	Black shale (facies A).
55.98-56.11	Interbedded green/black mudstones (50/50 %); fuzzy top; abundant *Zoophycos* burrows; becomes 75/25 % (green/black) at the base; gets blacker upwards (facies B & C). Photo OX-51 @ 56.0 m
56.11-56.31	Black shale (facies A).

56.31-56.89	Green-grey mudstone; brown-black interbeds in the middle; calcareous; sharp top and base (facies C).
56.89-57.74	Black shale; @ 57.07 m, 2 cm thick green mudstone bed; top is burrowed with *Chondrites* (facies B).
57.74-58.01	Green micritic dolomitic limestone; green-grey claystone at top; massive and indurated; (facies C & E).
58.01-58.98	Black shale (facies A). Sample OX-47 @ 58.34, TOC=3.32 %.
58.98-59.32	Interbedded green and black mudstones (50/50); burrowed with *Zoophycos*, rare small *Chondrites* (2 x 10 mm) (facies B & C); Sample OX-46, @ 59.16 m, TOC=4.70 %.
59.32-59.36	Black shale (facies A).
59.36-59.46	Green-grey mudstone; sharp top; burrowed base (facies C). Photo OX-50 @ 59.4 m, of burrows below green mudstone
59.46-59.68	Black shale (facies A). Photo OX-49, @ 59.68 m of green mudstone contact with silt laminae at top
59.68-59.80	Green-grey mudstone; burrowed base; fuzzy top; 2.5 cm from the top, silt laminae (~1-2 mm) (facies C).

59.80-63.78	Black shale; massive; fissile; @ 59.98 m, green mud laminae (~2 mm to 4 cm thick) @ 60.98 m, green mudstone, 12 cm thick with rare burrows @ 61.26 m, 2-3 mm thick green mud laminae, small burrows, *Chondrites* @ 61.0 m, two silt laminae, ~1-2 mm thick @ 62.5 m, interbeds of green and black muds, burrowed Photo OX-48, @ 62.49 m of *Zoophycos* (facies B); Sample OX-45, @ 63.05 m, TOC=2.11 %.
63.78-64.08	Interbedded green and black shale/mudstone (60/40 %); rare burrows; very mottled (facies B, C, & D).
64.08-64.22	Black shale (facies A).
64.22-64.30	Green-grey mudstone; with scattered bioturbation at the base; sharp top (facies C).

End of drill hole.

OEC 81-10
lat.: 50°40'36" N, long.: 81°43'06" W.

METRES: Long Rapids Formation: (middle member)	UNIT DESCRIPTIONS:
77.63-79.13	Green-grey mudstone; with red and purple shades; grey micritic dolomitic limestone bed (concretionary) at the top (6 cm thick) (facies C & E).
79.13-79.20	Black shale; grades to green mudstone with a purple tint, interbedded (~1 mm thick laminae) (facies A).
79.20-79.63	Green-grey mudstone; at 79.48 m, 0.5 cm thick black mud lamina; at 79.38 m, 2 cm thick black mud bed (facies C).
79.63-79.70	Black shale (facies A).
79.70-81.86	Green-grey mudstone; with scattered black mud laminae; @ 81.70, 81.62, and 81.54 m, 1 cm thick black mud beds; @ 81.43 m, 2 cm thick black mud bed; @ 81.38 m, 1 cm thick black mud bed; @ 81.29 m, 2 cm thick black mud bed; @ 81.15, 80.99, and 80.46 m, 1 cm thick black shale beds; top becomes a green-grey micritic dolomitic limestone, hard and concretionary; @ 79.83 m, 5 cm thick interbedded black and green shale/mudstone (~ 1 mm thick laminae) (facies C, A, & E).
81.86-81.94	Black shale (facies A).
81.94-81.98	Green-grey mudstone (facies C).
81.98-82.01	Black shale (facies A).
82.01-82.09	Green-grey mudstone (facies C).

82.09-82.19	Black shale (facies A).
82.19-82.34	Green-grey mudstone; sharp upper contact (facies C).
82.34-82.36	Black shale; sharp upper and lower contacts (facies A).
82.36-82.46	Green-grey mudstone (facies C).
82.46-82.51	Black shale; burrowed with *Zoophycos* and *Chondrites;* gradational base; sharp upper contact (facies B).
82.51-82.54	Green-grey mudstone (facies C).
82.54-82.56	Black shale; burrowed with 1 x 1 mm diameter *Chondrites,* and *?Zoophycos;* upper and bottom contacts are burrowed (facies B).
82.56-82.60	Green-grey mudstone (facies C).
82.60-82.68	Black shale (facies A).
82.68-82.72	Green-grey mudstone (facies C).
82.72-82.73	Black shale (facies A).
82.73-82.99	Green-grey mudstone (facies C).
82.99-83.05	Black shale; with interbedded green and black mud laminae in the middle (< 1 mm in diameter) (facies A).
83.05-83.19	Green-grey mudstone (facies C).
83.19-83.21	Black shale (facies A).
83.21-83.27	Green-grey mudstone (facies C).
83.27-83.28	Black shale (facies A).
83.28-83.36	Green-grey mudstone (facies C).
83.36-83.41	Black shale; sharp top and base (facies A).

83.41-83.48	Green-grey mudstone (facies C).
83.48-83.50	Black shale (facies A).
83.50-83.91	Green-grey mudstone; scattered laminae of black mud (facies C).
83.91-84.25	No core.
84.25-84.53	Green-grey micritic dolomitic limestone (facies E).
84.53-84.67	Black shale (facies A).
84.67-84.75	Green-grey mudstone (facies C).
84.75-84.79	Black shale (facies A).
84.79-85.09	Green-grey mudstone (facies C).
85.09-85.11	Black shale (facies A).
85.11-85.17	Green-grey mudstone; massive (facies C).
85.17-85.19	Black shale (facies A).
85.19-85.39	Green-grey mudstone; massive (facies C).
85.39-85.54	Black shale (facies A).
85.54-85.69	Green-grey mudstone; sharp top and base (facies C).
85.69-85.79	Black shale; sharp base (facies A).
85.79-86.05	Green-grey mudstone; two black mud laminae at 9 and 18 cm from the base, 1 and 2 cm thick (facies C & A).
86.05-86.10	Black shale (facies A).
86.10-86.23	Green-grey mudstone (facies C).
86.23-86.43	Black shale; fissile and massive (facies A).

86.43-86.50	Green-grey mudstone; clayey (facies C).
86.50-86.55	Black shale; sharp top and bottom contacts (facies A).
86.55-86.85	Green-grey mudstone; sharp base; clayey; crumbly appearance (facies C).
86.85-86.96	Black shale (facies A).
86.96-87.11	Green-grey mudstone; sharp top and base (facies C).
87.11-87.14	Black shale; sharp base (facies A).
87.14-87.23	Green-grey mudstone (facies C).
87.23-87.35	Black shale (facies A).
87.35-87.58	Green-grey mudstone; sharp top (facies C).
87.58-87.73	Interbedded black and green mudstone (50/50 %) (< 1 mm thick); greener at base; blacker at top; sharp top; gradational base (facies A & C).
87.73-87.91	Black shale (facies A).
87.91-88.38	Green-grey mudstone; sharp top (facies C).
88.38-88.44	Black shale; burrowed top; *Chondrites* (facies B).
88.44-88.48	Green-grey mudstone (facies C).
88.48-88.58	Black shale; top is burrowed, 5 cm thick, mainly *Zoophycos* and *Chondrites* (facies B); Photo OX-57 @ 88.53 m.
88.58-88.64	Green-grey mudstone (facies C).
88.64-88.66	Black shale; massive; sharp top and base (facies A).

88.66-88.76	Green shale; sharp base (facies D).
88.76-88.92	Black shale; massive; sharp base (facies A).
88.92-89.07	Green-grey mudstone; small (~0.75 cm) black mud laminae (facies C).
89.07-89.09	Black shale; burrowed with *Zoophycos* and *Chondrites* (facies B); Photo OX-56 @ 89.08 m.
89.09-89.16	Green-grey mudstone; sharp top (facies C).
89.16-89.20	Black shale; sharp top and base (facies A).
89.20-89.24	Green-grey mudstone (facies C).
89.24-89.82	Black shale; with a bioturbated top; ~ 4 cm down from the top, *Chondrites* and *Planolites* (facies B).
89.82-90.07	Green-grey mudstone; massive; sharp top (facies C).
90.07-90.10	Black shale; sharp top and bottom; green clayey base (facies A).
90.10-90.25	No core.
90.25-90.36	Green-grey mudstone (facies C).
90.36-91.58	Black shale; @ 90.94 m, burrows (~ 1 cm thick, *Chondrites*) (facies B); Sample OX-52, @ 90.96 m, TOC=3.09 %.
91.58-91.67	Green-grey mudstone; burrowed base; fuzzy top (facies C).
91.67-91.80	Black shale; with obscure *Zoophycos* burrows at top (burrows go down 5 cm from contact) (facies B).

91.80-92.82	Green-grey mudstone; massive; @ 92.52 m, 1 cm thick black shale unit with burrows (facies C); Photo OX-56 @ 92.5 m of burrows (*Chondrites*).
92.82-92.88	Black shale; green interbeds at top (~ 2 mm) (facies A & C).
92.88-93.15	Green-grey mudstone; massive (facies C).
93.15-93.37	Black shale; faint laminations; sharp top; obscure base (facies A).
93.37-93.61	Green-grey mudstone; clayey; crumbly appearance (facies C).
93.61-93.84	Black shale; *Zoophycos* burrow, 8 cm from the top (facies B).
93.84-93.91	Green-grey shale; sharp top; very indurated (facies D).
93.91-94.06	Black shale; small burrows at top, *Chondrites* (facies B).
94.06-94.09	Green-grey shale; small burrows at base (*Chondrites*) (facies D).
94.09-94.12	Black shale; burrowed with (2 x 10 mm) *Planolites* (facies B).
94.12-94.71	Green-grey mudstone; at 2 cm from the base, 1 cm thick black mud bed; base is bioturbated; fuzzy top (facies C).
94.71-94.79	Black shale; massive (facies A).
94.79-95.26	Green-grey mudstone; very indurated; appears concretionary at top, calcareous; very clayey at base (facies C & E).
95.26-95.39	Black shale (facies A).

95.39-95.79	Green-grey mudstone; becomes concretionary towards the top; massive with rare mottled areas; fuzzy top and base (facies C & E).
95.79-95.87	Black shale (facies A).
95.87-95.95	Purple-yellow and green claystone; wispy colours; sharp top (facies C); Photo OX-55 @ 95.9 m of interbedded black shale bed.
95.95-96.45	Black shale (facies A).
96.45-96.72	Green-grey mudstone; very clayey and chippy; very indurated; concretionary micritic limestone bed at top (facies C & E).
96.72-96.88	Black shale (facies A).
96.88-97.34	Green-grey mudstone; massive and calcareous; sharp base; fuzzy top; green micritic limestone bed at top (facies C & E).
97.34-97.50	Black shale (facies A); Sample OX-51 @ 97.41 m, TOC=2.79%.
97.50-97.53	Green-grey mudstone; massive; base is bioturbated (facies C).
97.53-97.59	Black shale (facies A).
97.59-97.67	Green-grey mudstone; burrowed base (facies C); Photo OX-54 @ 97.67 m of burrows beneath green mud bed, *Zoophycos*.
97.67-97.93	Black shale (facies A).
97.93-98.13	Green-grey mudstone; massive; sharp top and base (facies C).

98.13-98.33	Black shale; massive; faintly laminated; sharp top (facies A).

End of drill hole.

OEC 81-11
lat.: 50°42'06" N, long.: 81°36'48" W.
Contact between middle and upper members at 92.2 m.

METRES:	UNIT DESCRIPTIONS:
Long Rapids Formation:	
72.09-72.52	Interbedded green and black mudstones, very deformed and mottled (facies A + C.)
72.52-73.24	Green-grey mudstone (facies C).
73.24-73.36	Black shale (facies A).
73.36-74.98	Green-grey mudstone; clayey in places; rare black mud laminae (facies C).
74.98-76.36	no core
76.36-76.43	Green-grey mudstone (facies C).
76.43-76.45	Black shale; sharp top and base (facies A).
76.45-77.89	Green-grey mudstone; abundant black mud laminae; very deformed core (facies C).
77.89-77.91	Black shale (facies A).
77.91-78.02	Green-grey mudstone (facies C).
78.02-78.06	Black shale (facies A).
78.06-78.60	Green-grey mudstone (facies C).
78.60-78.68	Black shale; fissile and chippy appearance (facies A).
78.68-78.76	Green-grey mudstone/shale; chippy appearance (facies C + D).
78.76-79.01	Black shale; very fissile and chippy appearance (facies A).
79.01-79.09	Green-grey mudstone (facies C).
79.09-79.14	Black shale (facies A).

79.14-79.38	Green-grey mudstone (facies C).
79.38-79.40	Black shale (facies A).
79.40-79.64	Green mudstone (facies C).
79.64-79.71	Black shale (facies A).
79.71-79.76	Green-grey mudstone (facies C).
79.76-79.83	Black shale (facies A).
79.83-79.94	Green-grey mudstone (facies C).
79.94-79.96	Black shale (facies A).
79.96-80.22	Green-grey mudstone (facies C).
80.22-80.36	Black shale (facies A).
80.36-80.51	Green-grey mudstone (facies C).
80.51-80.52	Black shale (facies A).
80.52-80.53	Green-grey mudstone (facies C).
80.53-80.55	Black shale; with few green mud laminae (facies A).
80.55-80.69	Green-grey mudstone (facies C).
80.69-80.73	Black shale (facies A).
80.73-80.96	Green-grey mudstone (facies C).
80.96-80.97	Black shale (facies A).
80.97-80.98	Green-grey mudstone (facies C).
80.98-80.99	Black shale (facies A).
80.99-81.03	Green-grey mudstone (facies C).
81.03-81.11	Black shale (facies A).
81.11-81.52	Green-grey mudstone; with scattered black mud laminae (facies C).
81.52-81.60	Black shale; sharp top and base (facies A).

81.60-81.69	Green-grey mudstone (facies C).
81.69-81.74	Black shale (facies A).
81.74-81.95	Green-grey mudstone (facies C).
81.95-82.06	Black shale (facies A).
82.06-82.12	Green-grey mudstone (facies C).
82.12-82.28	Black shale (facies A).
82.28-82.30	Green-grey mudstone (facies C).
82.30-82.40	no core
82.40-83.00	Interbedded green and black shales and mudstones; very crumbly (facies A + C).
83.00-83.15	Green-grey mudstone (facies C).
83.15-83.29	Black shale (facies A).
83.29-83.33	Green-grey mudstone (facies C).
83.33-83.42	Black shale; sharp top and base (facies A).
83.42-83.72	Green-grey mudstone (facies C).
83.72-84.38	Black shale; massive and fissile (facies A).
84.38-84.66	Green-grey mudstone; massive (facies C).
84.66-84.69	Black shale; sharp top and base (facies A).
84.69-84.76	Green-grey mudstone (facies C).
84.76-84.79	Black shale (facies A).
84.79-84.95	Green-grey mudstone (facies C).
84.95-85.53	Black shale; one small *Teichichnus* burrow at 85.4 m (facies B).
85.53-85.63	Green-grey mudstone (facies C).

85.63-86.28	Black shale; massive and fissile (facies A); Sample OX-62 @ 85.94, TOC=2.91%
86.28-86.42	Green-grey mudstone; @ 2 cm from the base, 3 cm thick black shale bed (facies C).
86.42-86.62	Black shale; fissile (facies A).
86.62-87.68	Green-grey mudstone; with black mudstone beds at top; bioturbated with *Zoophycos* and *Teichichnus* (facies C).
87.68-88.07	Black shale; 19 cm from base, 1 cm thick green mudstone (facies A).
88.07-88.18	Interbedded green and black mudstones; abundant burrows (*Zoophycos* and *Chondrites)* Photo OX-65 @ 88.12 m (facies A + C).
88.18-88.39	Green-grey mudstone; massive (facies C).
88.39-88.70	no core
88.70-88.78	Green-grey mudstone; massive Photo OX-64 @ 88.76 m (facies C).
88.78-88.99	Black shale; burrowed top (facies B).
88.99-89.08	Green-grey mudstone; massive; sharp top (facies C).
89.08-89.22	Black shale; burrowed top, *Zoophycos* (facies B); Photo OX-63 @ 89.10 m.
89.22-89.68	Green-grey mudstone; with some black mud laminae at the base; deformed at 3 cm from the top (facies C).

89.68-89.78	Black shale; fissile; fractured throughout; top 2 cm is burrowed (*Chondrites*, < 1 x 1 mm) (facies B).
89.78-90.24	Green-grey mudstone; with a micritic limestone bed at top; scattered pyrite blebs (facies C).
90.24-90.62	Black shale; with less than 1 cm thick green mud laminae @ 13 cm from the base; burrowed with *Chondrites* (facies B).
90.62-90.97	Green-grey mudstone; clayey at base with small black interbedded mud laminae; micritic limestone bed at top; borrowed ?*Zoophycos*; occasional pyrite blebs (facies C).
90.97-91.23	Black shale; massive and faintly laminated; crumbly top; Sample OX-61, @ 91.14 m, TOC=4.64 %, (facies A).
91.23-91.25	Green-grey mudstone (facies C).
91.25-91.31	Black shale (facies A).
91.31-91.53	Green-grey mudstone; massive; sharp top (facies C).
91.53-91.60	Black shale; small burrows, *Chondrites* at base; sharp top (facies B).
91.60-91.99	Green-grey shale; burrowed top (facies C).
91.99-92.20	Black shale; fuzzy base; burrowed top (facies B).
92.20-92.44	Black shale; with bioturbated top, *Zoophycos* (facies B). Photo OX-62 @ 92.25 m.
92.44-92.47	Green-grey mudstone (facies C).
92.47-92.61	Black shale (facies A).

92.61-92.72	Green-grey mudstone; crumbly and massive (facies C).
92.72-94.38	Black shale; fissile and massive; with scattered occurrences of green mud laminae @ 94.27 m, 4 cm thick interbedded unit (green/black muds, 50/50 %), well preserved *Zoophycos* @ 93.93 m, 2 cm thick crumbly green bed @ 93.36 m, 4 cm thick green unit @ 93.20 m, 3 cm thick green mud bed; Sample OX-60, @ 93.54 m, TOC=4.61 % (facies B).
94.38-94.42	Green-grey mudstone; with scattered black mud laminae (facies C).
94.42-94.52	Black shale (facies A).
94.52-94.62	Green and black mudstone beds; ?*Zoophycos* (facies C).
94.62-95.21	Black shale (facies A).
95.21-95.28	Green-grey mudstone; crumbly appearance (facies C).
95.28-95.45	Black shale; massive; sharp top (facies A).
95.45-95.63	Green-grey mudstone; micritic limestone bed at top; scattered burrows at base into black (facies C + E).
95.63-96.78	Black shale; fissile (facies A).
96.78-96.95	Interbedded green and black mudstones (75/25 %); mottled; rare burrows (facies A + C).

96.95-97.46	Black shale; massive and fissile; rare green laminae Sample OX-59 @ 97.39 m, TOC=2.40%, (facies A).
97.46-97.52	Interbedded green and black mudstones (50/50 %); burrowed, ?*Zoophycos* (facies A + B).
97.52-98.46	Black shale; massive and fissile (facies A).
98.46-98.50	Interbedded green and black mud laminae; burrowed with *Zoophycos;* small scale faulting present Photo OX-61 @ 98.47 m (facies A + B).
98.50-99.73	Black shale; scattered green mud laminae (facies A); Sample OX-58 @ 99.41 m, TOC=3.04%
99.73-99.89	Green-grey mudstone (facies C).
99.89-100.03	Black shale; with green mud laminae; small *Chondrites* present (facies B).
100.03-100.12	Green-grey mudstone; crumbly appearance (facies C).
100.12-100.27	Black shale; fissile and massive (facies A).
100.27-100.36	Green-grey mudstone (facies C).
100.36-100.60	Black shale (facies A); Sample OX-57 @ 100.26, TOC=3.44%
100.60-100.65	Green-grey mudstone; mottled and burrowed (facies C).
100.65-101.33	Black shale; massive with rare burrows (facies B).
101.33-101.47	Green-grey mudstone; crumbly and massive; sharp top (facies C).

101.47-102.98	Black shale; fissile and massive @ 102.45 m, green mud wisps @ 102.25 m, 2 cm thick black and green muds @ 101.73 m, 5 cm thick interbedded green and black (50/50 %), some rare *Zoophycos*; (facies B).
102.98-103.15	Green-grey mudstone; crumbly and blocky (facies C).
103.15-103.31	Black shale; fissile and laminated (facies A).
103.31-103.41	Interbedded green and black mud laminae (50/50 %); burrowed, *Zoophycos* (facies B + C); Photo OX-60 @ 103.35 m of *Zoophycos* burrows
103.41-103.98	Black shale; massive; rare burrows at top (very small *Chondrites*) (facies B).
103.98-104.14	Green-grey mudstone; massive (facies C).
104.14-104.25	Black shale; sharp top (facies A).
104.25-104.59	Green-grey micritic dolomitic limestone bed; green muddy base; calcareous; with sparry calcite in small vugs and fractures (facies E).
104.59-104.65	Black shale; massive; burrowed top with *Chondrites* (facies B).
104.65-104.68	Green-grey mudstone; sharp top and base (facies C).
104.68-105.37	Black shale; fissile and massive (facies A); Sample OX-56 @ 105.03 m, TOC=5.40%

105.37–105.41	Green-grey mudstone; black mud laminae in middle; burrowed, with ?*Zoophycos* and *Chondrites* (pyritized) (facies C).
105.41-105.44	Black shale (facies A).
105.44–105.49	Green-grey mudstone (facies C).
105.49–105.56	Black shale (facies A).
105.56–105.62	Green-grey mudstone; laminated (facies C).
105.62–106.30	Black shale (facies A); Sample OX-55 @ 105.82, TOC=3.47%
106.30-106.34	Interbedded green and black mudstones and shales; burrowed with *Planolites* and *Zoophycos* (facies B + C).
106.34–106.68	Black shale; burrowed at top with *Chondrites* (facies B).
106.68–107.20	Black shale; with burrows at top; some pyrite nodules (~0.5 cm) (facies B); Sample OX-54 @ 106.85, TOC=4.43%
107.20–107.25	Green-grey mudstone; with wisps of black laminae (facies C).
107.25–107.38	Black shale; burrowed at top with *Zoophycos* (facies B).
107.38–107.48	Green-grey mudstone (facies C).
107.48–107.59	Black shale (facies A).
107.59–107.66	Green-grey mudstone (facies C).
107.66–108.37	Black shale; burrowed top, *Chondrites* (facies B); Photo OX-58 @ 107.65 m.
108.37–108.44	Green mudstone (facies C).

108.44-109.77	Black shale; near base, green mud wisps @ 109.28 m, 2 cm thick (facies A).
109.77-109.93	Green-grey mudstone; massive (facies C).
109.93-110.04	Black shale; massive (facies A).
110.04-110.58	Green-grey mudstone; clayey in places; rare black mud laminae in middle (facies C).
110.58-110.78	Black shale; massive; with a small calcite vein at the base (facies A).
110.78-110.89	Green-grey mudstone; clayey; pore core (facies C).
110.89-111.01	Black shale; massive; with silt laminae at the base (facies A).
111.01-111.11	Green and black mudstone, (50/50 %) (facies A + C).
111.11-111.21	Green-grey mudstone (facies C).
111.21-111.27	Black shale; massive (facies A).
111.27-111.39	Green-grey mudstone; calcareous in places (facies C).
111.39-111.45	Black-brown shale/mudstone (facies A).
111.45-111.65	Green-grey mudstone; massive and slightly mottled in places; micritic limestone bed at base; at top, black mud wisps with green mudstone; burrows present, *Zoophycos* and *Chondrites* (facies C + E).
111.65-111.71	Black shale; small burrows at the base, *Chondrites* (facies B).
111.71-111.73	Green-grey mudstone (facies C).

End of drill hole.

ONEX 82-04
lat.: 50°35'16" N, long.: 81°58'18" W.
Contact of lower and middle members at 111.89 m.

METRES:	DESCRIPTIONS:
Long Rapids Formation:	
94.50-100.58	Green-grey shale; massive; fissile with interbeds of green-grey mudstones (laminae 1-10 mm); scattered pyrite crystals (< 0.5 mm); rare limonite staining (facies C); Photos OX-1, 2, 3, & 4 @ 97.3 m of burrows.
100.58-103.43	Grey shale; faint green-grey mud laminae; very blocky in middle; @ 102.46 m, some burrows - small *Planolites*; tiny pyrite crystals; abundant bioturbation at top (~45 %); with *Planolites* (3 x 10 mm) (facies D); Sample OX-1 (at base), TOC=2.30%; Sample OX-2 (at top), TOC=3.09%.
103.43-104.05	Green mudstone; massive; grey shaly mud laminae scattered about; very bioturbated with *Chondrites* and *Planolites* (facies C).
104.05-104.63	Interbedded grey and black shale; lighter at base; darker at top; rare to no burrows; one near vertical joint halfway down; rare *Chondrites* (facies A & B); Photo OX-5 of black green muds; Sample OX-3, @ 104.3m, TOC=4.84%.
104.63-106.15	Green-grey mudstone; massive; very blocky; clayey (facies C).

106.15-106.64	Grey micritic limestone; appears ?concretionary; with vuggy calcite in fractures (facies E).
106.64-106.76	Green-grey mudstone (facies C).
106.76-108.84	Chocolate brown shale; darker at base; gradational top; @ 107.26 m, 12 cm thick pale green mudstone (gradational top and base); scattered burrows (facies B).
108.84-109.44	Brown shale; light green at top; dark brown to black at base; sharp base (facies A).
109.44-109.59	Green micritic limestone; mottled; sharp top and base; pyrite blebs (facies E).
109.59-110.64	Black shale; sharp base - burrowed; very dark at base; some scattered green mudstone beds, very burrowed (facies B); Photo OX-29 @ 109.6 - one burrow (2 x 4 mm), green sediment infill.
110.64-110.75	Grey micritic dolomitic limestone; scattered shell fragments (facies E).
110.75-111.36	Black shale; massive; fissile; indistinct burrows at top; sharp base (facies B).
111.36-111.50	Green-grey mudstone; with 1 cm concretionary limestone bed at top; mudstone is very chippy (facies C).
111.50-111.89	Chocolate brown shale; massive; slightly calcareous in places (facies A).
111.89-112.08	Green-grey micritic dolomitic limestone; ?concretionary; calcitic veining; mottled (facies E).

112.08-112.94	Chocolate brown shale; same as above; slightly calcareous; faintly laminated (facies A); Sample OX-4, @ 112.75 m, TOC=1.44%.
112.94-112.97	Green-grey mudstone (facies C).
112.97-113.40	No core.
113.40-113.75	Black shale; rare calcareous concretions (facies A & E).
113.75-113.78	Grey micritic dolomitic limestone (facies E).
113.78-113.86	Black shale; bioturbated at base (facies B). Photo OX-5 at 113.80 m.
113.86-114.01	Grey micritic dolomitic limestone (facies E).
114.01-114.11	Black shale (facies A).
114.11-114.16	Grey micritic dolomitic limestone (facies E).
114.16-114.27	Black shale (facies A).
114.27-114.31	Grey micritic dolomitic limestone (facies E).
114.31-114.62	Black shale (facies A).
114.62-114.66	Grey micritic dolomitic limestone (facies E); Photo OX-6 at 114.64 m.
114.66-114.82	Black shale (facies A); Sample OX-5, @ 114.67 m, TOC=3.88 %.
114.82-124.70	No core.

124.70-125.80	Light brown shale; with green-brown shale interbeds; semi-fissile; calcareous in places; scattered burrows - *Chondrites*; scattered pyritized burrows (black); scattered shell fragments (prob. *Lingula*) at base (< 1 mm); becomes darker upwards (facies B).
125.80-126.04	Grey micritic dolomitic limestone; pale green; massive; scattered whole shell fragments (*Lingula*), up to 2 cm in diameter (facies E).
126.04-127.74	Brown shale; fissile; massive in places; more pale green at base; becomes darker upwards; very dark and black at top; Sample OX-6, @ 127.63 m, TOC=4.31%; scattered silt intervals @ 127.38 m, 2.5 cm interbedded black and white silt laminae; shell hash fragments scattered about; Photo OX-9 at 126.3 m; @ 126.31 m, 1 cm thick green-grey mudstone - sharp base and burrowed top (facies A); Photo OX-7 & 8 at 127.5 m.
127.74-128.43	Green-grey mudstone; with interbedded brown and black muds; very bioturbated; deformed laminae; calcareous; burrowed at top - *Chondrites* and *Planolites* (2 x 13 mm), found along bedding planes (facies C).

128.43-129.10	Brown-black shale; darker at base; lighter at top; mainly massive; fissile within black portions; blocky at top; abundant shell fragments (1 x 1 mm) (facies A); Sample OX-7, @ 128.7 m, TOC=2.93 % Sample OX-8, @ 129 m, TOC=1.56%.

End of drill hole.

ONEX 82-05
lat.: 50°34'12" N, long.: 81°55'39" W.
Contact between lower and middle members at 111.43 m.

METRES:	UNIT DESCRIPTIONS:
Long Rapids Formation:	
100.60-101.63	Pale grey mudstone; with wisps of darker laminae; completely burrowed (sp. indet.) Photo OX-15 @ 101.6m of deformed laminae (facies C).
101.63-101.84	Chocolate brown shale; base is fuzzy; top is semi-sharp (facies A).
101.84-103.61	Grey-green mudstone; massive; with pale brown laminae scattered about; scattered pyrite blebs, some are black; scattered burrows - *Chondrites;* soft sediment deformation at top (facies C).
102.61-103.83	Grey-brown shale; chippy; scattered interbedded light and dark mud laminae; mottled; some small burrows (*Chondrites,* 2 x 12 mm and less); more green laminae at top (facies B).
103.83-104.15	Green mudstone; massive and chippy (facies C).
104.15-104.30	Grey-brown shale; with interlaminations of grey/black muds (~ 1 mm thick); scattered bioturbation (~25 %) - *Chondrites* (1 x 1 mm) (facies B).
104.30-104.63	Green mudstone; with grey mud interbeds; bioturbation at top (~30 %) (facies C).
104.63-104.78	Black-brown shale; faint brown laminae within black beds; scattered *Chondrites* (facies B).

104.78-104.95	Green mudstone; small calcareous concretions (1 x 2 cm); gradational base (facies C + E).
104.95-106.34	Pale brown shale; with burrows at top, faint *Chondrites;* base is gradational with silt laminae (~1 mm thick) (facies B).
106.34-106.55	Green mudstone; massive; no burrows (facies C).
106.55-106.63	Chocolate brown shale; with small burrows (*Chondrites*); sharp top (facies B).
106.63-106.70	no core
106.70-106.93	Chocolate brown shale; (same as above); sharp base; burrowed throughout, *Planolites* and *Chondrites* (facies B); Sample OX-9 @ 106.9m, TOC=4.46% Photo OX-16 @ 106.9m, of burrows.
106.93-107.37	Pale green mudstone; massive (facies C).
107.37-107.48	Black shale; with burrows - *Chondrites* and *Planolites* (facies B).
107.48-107.57	Green-grey mudstone; massive; fractured; no burrows (facies C).
107.57-108.13	Black shale; massive; with burrows at top - *Chondrites,* some go down as far as 6 cm; very fissile; mottled base; sharp base (facies B); Sample OX-10 @ 108m, TOC=4.65%.
108.13-108.76	Interbedded grey and pale yellow mudstone; bioturbated (~30 %) (facies C).

108.76-109.02	Grey-green mudstone; massive; semi-sharp top; gradational base (facies C).
109.02-109.51	Pale brown mudstone; burrowed top and base; faint laminations at base; some long vertical burrows (2 x 30 mm), various morphologies; no burrows after 15 cm from the top (except for a few scattered small ones) Photo OX-17 @ 109.08 m of burrowed top, (facies B).
109.51-109.63	Pale green mudstone; massive; no sharp contacts; small *Chondrites* (facies C).
109.63-111.43	Light to dark brown shale; becomes lighter upwards; very dark at the base; faintly interbedded throughout (light and dark brown, 50/50 %); abundant bioturbation - mainly *Chondrites;* very massive (facies B).
111.43-111.53	Grey-green micritic dolomitic limestone; appears concretionary; very mottled; (facies E); Photo OX-18 @ 111.5 m of unit with some shell fragments within pyrite blebs
111.53-113.14	Light to dark brown shale; burrowed top; some burrows go down ~25 cm; concretionary limestone unit @ 111.8m (2 cm thick), along with a 1 cm thick one @ 112.37m; unit becomes darker towards the base; sharp base (facies B); Photo OX-19 @ 111.6m of *Planolites* (3 x 20mm) and *Chondrites;* Photo OX-20 @ 111.9m of burrows; Sample OX-11 @ 112.7m, TOC=2.90%.

113.14-113.27	Calcareous grey micritic dolomitic limestone; scattered pyrite nodules; burrowed base - *Planolites* (2 x 30 mm) and *Chondrites;* sharp top; gradational base (facies E).
113.27-113.84	Light and dark brown shale; fissile; darker at the base; massive; no burrows; one near vertical fracture present, ~15 cm long (facies A).
113.84-114.09	Green-grey mudstone; clayey; pale green at top; gets darker at base; gradational base (facies C).
114.09-114.36	Chocolate brown shale; fissile at top; no burrows; sharp base (facies C).
114.36-114.54	Grey micritic dolomitic limestone unit; concretionary?; mottled; pyritized shell fragments at top (facies E).
114.54-115.63	Brown shale; rare burrows; scattered fractures; massive; sharp base and top; @ 114.7 & 114.93 m, 1 cm thick concretionary limestone unit (grey-green) @ 115.25 & 115.57 m, 4 & 3 cm, respectively, concretionary limestone unit some have burrowed bases, with *Planolites* and *Chondrites;* Photo OX-21 @ 114.8 m of limestone unit (facies A + B).
115.63-115.79	Grey micritic dolomitic limestone unit; sharp top; gets shaly towards the middle; small *Chondrites* (2 x 2 mm) present towards the base; scattered shell fragments (facies E).

115.79-118.83	Brown-black shale; at top, 2 cm thick micritic limestone unit; massive; fissile; slightly lighter in colour at base (light brown); fractured throughout (facies A + E); Sample OX-12, TOC=1.45% Sample OX-13, TOC=4.87% Sample OX-14, TOC=5.08% Sample OX-15, TOC=4.02% Sample OX-16, TOC=4.62% (above samples are evenly spaced at approx. every 50 cm).
118.83-122.60	Black shale; massive; no burrows (facies A).
122.60-124.50	no core
124.50-125.10	Grey-green mudstone; slight bioturbation (10 %) @ 124.9 m, 2-3 mm thick coaly wood lamina which rests sharply on a green mudstone bed, and is overlain by a yellow clayey bed; @ 125 m, cream-coloured silt wisps, < 1 mm thick Photo OX-22 @ 124.9 m of coaly wood fragment with quartz stringers Sample OX-17 @ 124.9 m, TOC=0.26% (facies C).
125.10-130.50	no core
130.50-130.92	Black-brown shale; 1.5 cm thick silt laminated unit at 130.74 m; rare burrows around silt laminae, *Chondrites;* rare fractures; becomes lighter coloured at the base; Sample OX-18 @ 130.6 m, TOC=2.34% (facies B).
130.92-131.30	Grey micritic dolomitic limestone; appears concretionary?; large near vertical fractures, 10 cm long; vuggy calcite (~1 cm) (facies E).

131.30-131.40	Grey-green mudstone; burrowed base (very small burrows, ?*Chondrites*); massive (facies C).
131.40-131.46	Black shale; sharp top and base; blocky and massive; shell hash, *Lingula*, at the base (2 x 4 mm) (facies A).
131.46-131.75	Grey-green mudstone; massive with occasional light and dark laminae (brown to black); rare cream-coloured silt bands; gradational base (facies C).
131.75-131.86	Black shale; light brown at base; gradational top and base; burrowed throughout, *Planolites*, (3 x 13 mm) (facies B).
131.86-132.02	Grey micritic dolomitic limestone; concretionary?; green mudstone at top; very indurated at the base; scattered pyrite blebs (?originally burrows) (2 x 10mm) (facies E).
132.02-132.41	Green-grey mudstone; sharp base; becomes lighter in colour towards the base (facies C).
132.41-132.94	Black shale; @ 132.69 m, two silt laminae (5 mm), and 5 mm apart; no burrows; Photo OX-23 @ 132.7 m of silt laminae; Sample OX-19 @ 132.8 m, TOC=7.46% (of very dark shale) (facies A).

132.94-134.53	Green-brown mudstone; light brown at top; abundant silty wisps; rare fractures @ 133.3 m, shell hash; scattered bioturbation, *Chondrites;* @ 134.36 m, black shale with rare burrows - *Chondrites;* Sample OX-20 @ 134.36 m, TOC=3.45%; Photo OX-24 @ 133.2 m; Sample OX-21 @ 133.6 m, TOC=5.75% (facies C + B).

End of drill hole.

ONEX 82-18
lat.: $50^{\circ}20'41''$ N, long.: $82^{\circ}23'15''$ W.

METRES:	DESCRIPTIONS:
Long Rapids Formation: (middle member)	
100.60-102.03	Black shale (facies A).
102.03-102.10	Green-grey mudstone; sharp base; semi-sharp top (facies C).
102.10-103.13	Black shale (facies A); Sample OX-29 @ 103.0 m, TOC=5.10%.
103.13-103.24	Grey mudstone; sharp top; gradational base (facies C).
103.24-103.87	Black shale (facies A).
103.87-103.88	Green-grey mudstone; sharp top and base (facies C).
103.88-104.36	Black shale (facies A).
104.36-104.37	Green-grey mudstone; rare burrows; semi-sharp top and bottom (facies C).
104.37-105.60	Black shale (facies A); Sample OX-28 @ 105.5 m, TOC=3.83%.
105.60-106.40	No core.
106.40-111.87	Black shale; @ 110.8.m, 7 cm thick interbedded unit - repetitive laminae of green-grey and black muds; no burrows; scattered laminae of green shale throughout with very rare small burrows (< 1 x 1 mm) (facies A); Sample OX-27 @ 109.9 m, TOC=3.91%; Sample OX-26 @ 110.9 m, TOC=3.73%;

111.87-117.02	Black shale; very indurated; massive; fissile; occasional green mudstone laminae @ 116.63 m; @ 115.17 m, 5 cm micritic limestone unit with a burrowed base; @ 114.97 m, 7 cm micritic limestone with no burrows - tops for both are sharp (facies A & E); Sample OX-22 @ 113.07 m, TOC=4.19%; Sample OX-23 @ 114.47 m, TOC=5.06%; Sample OX-24 @ 114.87 m, TOC=2.21%; Sample OX-25 @ 116.67 m, TOC=3.98%; Photo OX-26 @ 114.27 m; Photo OX-27 @ 114.87 m of green and black mud laminae; Photo OX-28 @ 115.87 m of green mud wispy laminae; at 113.29 m, 7 cm thick green shale - noncalcareous and laminated.
117.02-117.72	Green-grey mudstone; clayey in places; scattered pyrite blebs; scattered wisps of iron-rich laminae; sharp top to black shale (facies C); Photo OX-25 of upper contact with fine wisps of silt interbedded into black (~ 2mm).
117.72-123.27	Pale green mudstone; scattered mottles of grey laminae and bioturbation (~15 %); small burrows (1 x 1 mm)-*Chondrites*; clayey in middle; scattered pyrite crystals and siderite nodules (~4 x 15 mm); scattered wisps of hematitic laminae (facies C).
123.27-123.39	Grey micritic dolomitic limestone nodules (2 x 3 mm) (facies E).

123.39-125.28	Green-grey mudstone; very indurated; massive; scattered pyrite blebs; rare burrows (facies C).

End of drill hole.

APPENDIX C
DRILL HOLE DATA FOR CROSS-SECTIONS A-A' AND B-B'

drill hole	lat.	long.	x	y	refs.
Ranoke #1	50°27'23"	81°38'33"	61	39	ERF 83.1-118
Ranoke 74-2	50°23'12"	81°33'50"	71	?88	"
Ranoke 74-3	50°33'04"	81°24'00"	55	42	"
DDH #11	50°26'24"	81°34'30"	59	14	Satterly, 1953 Sanford & Norris, 1975
DDH #12	50°26'12"	81°34'30"	61	69	"
LX-1	50°23'46"	81°35'51"	65	31	Haygarth, 1980
LX-3	50°23'46"	81°34'27"	52	15	"
LX-9	50°23'42"	81°34'27"	53	18	"
OH-8	50°26'55"	81°34'35"	69	48	Dykes, 1943
OH-9	50°27'07"	81°34'30"	68	22	"
OGS-77-1	50°34'45"	81°23'48"	51	19	Verma et al., 1978
OGS-77-3	50°33'10"	81°26'15"	50	4	"
OGS-83-3	50°43'30"	81°59'00"	70	13	WGM, 1984
OGS-OnakB	50°35'24"	81°29'10"	54	81	Sanderson & Telford, 1985
OEC-81-1	50°33'42"	81°35'06"	55	4	ERF LO14886
OEC-81-2	50°36'30"	81°34'48"	52	33	"
OEC-81-3	50°29'48"	81°40'36"	65	8	"
OEC-81-4	50°29'42"	81°42'00"	64	14	"
OEC-81-5	50°29'30"	81°38'67"	67	55	"
OEC-81-7	50°44'06"	81°30'36"	46	10	"
OEC-81-8	50°43'42"	81°36'54"	54	27	"
OEC-81-9	50°42'06"	81°36'48"	53	38	"

OEC-81-10	50°40'36"	81°43'06"	61	21	"
OEC-81-11	50°42'06"	81°36'48"	53	42	"
Onex-82-4	50°35'16"	81°58'18"	80	47	ERF 63.4180
Onex-82-5	50°34'12"	81°55'39"	84	35	"
Onex-82-18	50°20'41"	82°23'15"	85	25	"
Onex-83-5	50°32'36"	82°06'03"	83	17	ERF 63.4219
Onex-83-7	50°33'25"	82°07'58"	82	39	"
Onex-83-11	50°30'42"	82°08'18"	85	?5	"
Onex-83-27	50°23'54"	82°27'00"	87	6	"
Onex-83-28	50°23'24"	82°29'07"	88	2	"

x = elevation above sea level
y = Long Rapids Formation thickness

APPENDIX D: SAMPLE PREPARATION FOR TOTAL ORGANIC CARBON ANALYSES

Need:

concentrated HCl diluted to ~20 % strength
4.25 cm glass fibre filters
distilled water (with wash bottle)
several small (~150 ml) beakers
hot plate
stir rod
millipore filtration equipment (500 ml flask, filtration frit, glass funnel, clamp)
vacuum pump

Method:

1) Crush shale samples in a Shatterbox (Spex Industries) with a tungsten carbide ball mill to a fine powder.

2) Weigh out approximately 500 mg of sample and dispense this into a dry beaker (weight must be accurately known).

3) Add ~20-30 mls of warm 20 % HCl to the beaker and stir to facilitate mixing of the sample in the acid.

4) Allow the mixture to stand and repeat stirring occasionally until no more fizzing occurs upon agitation.

5) Place a filter in the millipore apparatus and turn on vacuum suction.

6) Pour sample onto filter and completely wash any residual sample remaining in the beaker using distilled water.

7) Wash the sample again with a few mls of distilled water.

8) Allow all water to filter through sample, unclamp apparatus and remove the filter carefully.

9) Roll-up the moist filter immediately and place the filter and sample into a LECO crucible.

10) Dry the sample for 24 hrs at 140 °C.

11) Use a LECO Carbon Determinator for TC or TOC.

Calculation of organic carbon:

1) Mass before - mass of filter = mass of sample

2) (1/sample mass) x (LECO # - blank) = TOC %

APPENDIX E

TOTAL ORGANIC CARBON VALUES (OUTCROP VALUES)

sample number	elevation from base of section (metres)	total organic carbon (%)
9a	4.26	6.77
9b	4.76	4.74
9c	5.26	6.27
9d	5.76	6.12
9e	6.26	6.23
10-1-a	6.41	5.61
10-2-a	6.90	1.80
10-2-bx	6.94	2.08
10-2-c	6.98	2.15
10-4-b	7.71	0.85
10-4-c	8.12	1.04
11-1-a	8.27	3.77
11-3-a	8.50	2.83
11-3-b	8.61	2.27
11-4-a	8.70	0.53
11-5-ax	8.86	0.78
11-6-a	8.91	0.17
11-8-a	8.99	3.76
11-8-b	9.15	1.46
11-8-cx	9.13	1.99 20
11-8-d	9.20	1.86
11-9-a	9.29	0.39
12-1-a	9.54	3.76
12-2-a	9.74	0.89
12-3-a	9.81	0.44
12-5-a	9.95	4.10
12-5-b	10.01	4.43
12-6-a	10.12	0.46
12-8-a	10.29	1.28
12-8-b	10.38	3.01 30
12-9-a	10.56	0.55
13-1-a	10.89	2.38
13-1-b	10.97	3.29
13-2-b	11.13	0.21
14-1-a	11.25	3.74
14-1-b	11.40	2.29
14-1-c	11.51	4.39
14-3-a	11.86	3.58
14-3-b	12.11	2.38
14-4-a	12.19	0.46 40
14-5-a	12.34	5.27
14-6-a	12.49	1.78
15-1-a	12.81	1.41
15-2-a	13.04	0.55
15-3-a	13.56	1.93
16-3-a	15.45	3.01
16-4-a	16.35	0.47
17-1-a	16.59	0.05
17-2-a	16.65	0.16

17-3-a	16.72	0.02
17-4-a	16.81	0.16
17-5-a	17.00	0.05
17-6-a	17.38	0.86
17-7-a	17.81	0.30
17-8-a	18.05	0.59
17-9-a	18.16	0.13
17-10-a	18.22	0.04
17-11/12-a	18.32	0.04
17-13-a	18.42	0.06
17-14-a	18.48	0.03
17-15-a	19.00	0.04
17-16-a	19.55	0.48
17-17-a	19.80	0.06
17-17-b	19.89	0.20
17-18-a	19.98	0.50
17-19-a	20.06	0.05
17-20-a	20.13	0.81
17-21-a	20.19	0.06
17-22-a	20.35	0.41
17-23-a	20.44	0.04
17-24-a	20.47	0.37
17-25-a	20.55	0.08
17-26-a	20.76	0.81
17-26-b	21.19	0.79
17-27-a	21.30	0.09
17-28-a	21.42	0.21
17-29-a	21.54	0.64
18-1-a	22.05	6.12
18-1-b	22.54	5.16
18-2-a	22.75	0.58
18-4-a	23.06	0.91
18-5-a	23.14	2.07
18-6-a	23.32	0.36
18-8-a	23.84	0.23
19-1-a	24.29	0.75
19-2-a	24.42	1.08
19-3-a	24.72	0.66
19-4-a	25.00	1.66
19-5-a	25.18	1.33
25-1-a	25.46	0.62
25-1-b	26.66	0.35
25-1-c	27.19	0.06
25-2-a	27.32	0.06
25-3-a	27.48	0.55
25-4-a	27.63	4.82
25-5-a	27.71	0.69
25-6-a	27.78	5.11
25-7-a	27.86	0.62
25-8-a	27.98	4.72
25-9-a	28.09	4.94
25-10-a	28.30	5.16
25-10-b	29.00	3.82
25-10-c	29.30	6.57
25-11-a	29.62	0.19
25-13-a	30.15	4.70

25-14-b	30.65	3.43
25-14-c	30.77	1.49
25-14-d	30.95	3.33 120
25-16-a	31.48	3.82
25-17-a	31.90	0.08
25-18-a	31.96	5.61
25-20-a	32.29	3.23
25-20-b	32.64	4.19
25-21-a	32.76	0.94
25-22-a	33.16	6.22
25-23-a	33.51	1.10
25-24-a	33.55	4.99 130
25-25-a	33.59	0.94
25-27-a	34.06	0.33
25-28-a	34.10	4.69
25-29-a	34.14	1.79
25-30-a	34.16	4.36
25-31-a	34.34	6.56
25-32-a	34.43	2.84
25-34-a	34.52	5.14
25-36-a	35.06	8.04 139

TOTAL ORGANIC CARBON VALUES (DRILLHOLE SAMPLES)

sample number	drillhole number	depth (metres)	TOC (%)
OX 1	Onex 82-4	100.40	2.30
OX 2	"	100.55	3.09
OX 3	"	100.30	4.84
OX 4	"	112.75	1.44
OX 5	"	114.67	3.88
OX 6	"	127.63	4.31
OX 7	"	128.70	2.93
OX 8	"	129.00	1.56
OX 9	Onex 82-5	106.90	4.46
OX 10	"	108.00	4.65
OX 11	"	112.70	2.90
OX 12	"	116.00	1.45
OX 13	"	116.50	4.87
OX 14	"	117.00	5.08
OX 15	"	117.50	4.02
OX 16	"	118.00	4.62
OX 17	"	124.90	0.26
OX 18	"	130.60	2.34
OX 19	"	132.80	7.46
OX 20	"	134.36	3.45
OX 21	"	133.61	5.75
OX 22	Onex 82-18	113.07	4.19
OX 23	"	114.47	5.06
OX 24	"	114.87	2.21
OX 25	"	116.67	3.98
OX 26	"	110.90	3.73
OX 27	"	109.90	3.91
OX 28	"	103.50	3.83
OX 29	"	103.00	5.10

OX 33	Oec 81-5	117.22	3.76
OX 34	"	115.12	6.17
OX 35	"	113.82	7.35
OX 36	"	112.42	4.05
OX 37	"	111.35	8.21
OX 38	"	108.65	5.60
OX 39	"	105.92	5.44
OX 40	"	104.00	7.51
OX 41	"	100.90	5.92
OX 42	"	97.47	3.63
OX 43	"	94.73	4.71
OX 44	"	92.42	4.77
OX 45	Oec 81-8	63.05	2.11
OX 46	"	59.16	4.70
OX 47	"	58.34	3.32
OX 48	"	54.54	3.31
OX 49	"	52.78	4.51
OX 50	"	48.75	3.82
OX 51	Oec 81-10	97.41	2.79
OX 52	"	90.96	3.09
OX 54	Oec 81-11	106.85	4.43
OX 55	"	105.82	3.47
OX 56	"	105.03	5.40
OX 57	"	100.26	3.44
OX 58	"	99.41	3.04
OX 59	"	97.39	2.40
OX 60	"	93.54	4.61
OX 61	"	91.14	4.64
OX 62	"	85.94	2.91
OX 63	Onak B	153.24	4.39
OX 64	"	150.37	5.69
OX 65	"	139.45	3.51
OX 66	"	135.60	3.45
OX 67	"	128.76	3.96
OX 68	"	127.66	4.33
OX 69	"	126.68	4.81
OX 70	"	124.94	5.72
OX 71	"	125.38	5.28
OX 72	"	122.74	5.28
OX 73	"	119.75	5.25
OX 74	"	118.74	5.50
OX 75	"	114.83	3.39
OX 76	"	112.83	2.83
OX 77	"	107.61	4.80
OX 78	"	105.46	1.89
OX 79	"	102.90	4.48
OX 80	"	102.84	4.99
OX 81	"	101.39	4.72
OX 82	"	92.15	0.42

APPENDIX F: CHEMICAL INDEX OF MATURITY CALCULATION

1) Calculate CO_2.

2) Do loss on ignition (LOI) at ~1040°C for 1/2 hour (use ~1-2 gm of sample.

$$LOI\ \% = \frac{\text{wt. before} - \text{wt. after}}{\text{wt. before} - \text{wt. crucible}} \times 100$$

3) Take samples that were heated at 1040°C and make fusion pellets.

4) Run XRF

5) Recalculate major elements to take into account CO_2 calculated in 1):

eg. corrected SiO_2 % = SiO_2/(total + CO_2) x 100

6) Recalculate Al_2O_3, CaO, Na_2O, K_2O, P_2O_5 and CO_2 to mole fraction:

$$\text{eg. } Al_2O_3 = [\%\ Al_2O_3/(\underset{\substack{\uparrow \\ Al}}{27} \times 2 + \underset{\substack{\uparrow \\ O}}{16} \times 3)] \times \underset{\substack{\uparrow \\ \text{since there are} \\ \text{2 Al's}}}{2}$$

7) Calculate CaO_{sil} (sil = silicate):

$CaO_{sil} = CaO - CO_2 - 5/3P_2O_5$

8) Calculate total mole fraction:

Total = $Al_2O_3 + Na_2O + K_2O + CaO_{sil}$

9) Calculte % K_2O

% K_2O = (moles K_2O/total) x 100

10) Calculate % CaO_{sil} + Na_2O

% CaO_{sil} + Na_2O = [(moles of CaO_{sil} + Na_2O)/total] x 100

11) Calculate % Al_2O_3

% Al_2O_3 = (moles Al_2O_3/total) x 100

12) CI = chemical index of sediment maturity

= 1 - (% Al_2O_3/100)

or = $CaO_{sil} + Na_2O + K_2O/CaO_{sil} + Na_2O + K_2O + Al_2O_3$