LITHOFACIES OF THE LOWER PALEOZOIC CARBONATE SHELF TO BASIN FACIES TRANSITION, WEST-CENTRAL ELLESMERE ISLAND, CANADIAN ARCTIC

BY

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ABSTRACT

The Upper Ordovician (Ashgillian) to Middle Silurian (Wenlockian) graptolitic carbonates and cherts of the Cape Phillips Formation accumulated in the deep water basinal environment of the Hazen Trough. The coeval platform carbonates of the Allen Bay Formation developed to the east in a shelf environment. Nineteen stratigraphic sections were measured in order to obtain data on the lithological variation within this facies transition, specifically within the Cape Phillips Formation. Integrated petrological and x-ray diffraction analyses of the samples collected indicates the presence of seven distinct lithofacies, six in the Cape Phillips and one in the Allen Bay Formation. These lithofacies are; 1) laminated limestone, 2) calcareous mudstone, 3) laminated argillaceous limestone, 4) massive limestone and rudaceous graded limestone, 5) chert, 6) laminated dolomite, and 7) massive dolomite.

The distribution of these lithofacies is strongly related to the paleogeography and water depth. The shallow water carbonate buildup of the Allen Bay Formation is composed of massive dolomite. The slope carbonates of the Cape Phillips Formation consist of laminated dolomite and laminated limestone with minor massive limestone and rudaceous graded limestone. The basin is dominated by calcareous mudstone and displays a significant development of chert.

To explain the distribution and origin of the lithofacies, a model is proposed whereby the carbonate grains and mud were produced on a shelf platform and carried basinward by wave - and tide - generated

currents. Massive limestone and rudaceous graded limestone are the proximal deposits of gravity flows. Laminated limestone and laminated argillaceous limestone are the distal deposits of gravity flows. Calcareous mudstone and radiolarian chert were deposited from hemipelagic and pelagic suspensions and turbid layers. Replacement chert resulted from the silicification of carbonate. Dolomitization of the platform carbonate buildup and the adjacent upper slope succession created the massive dolomite and laminated dolomite lithofacies respectively. Dolomitization may have occurred in a schizohaline environment.

The dominance of calcareous mudstone in the upper Cape Phillips compared to laminated limestone, which is dominant in the lower Cape Phillips, suggests a deepening of the basin and a general transgression during the accumulation of the Cape Phillips Formation. It appears to have been deposited in relatively deep water, at least below wave base and generally above the carbonate compensation depth, between about 100m and 5400m deep.

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CHAPTER 1

INTRODUCTION

Lower Paleozoic strata are well exposed in the west-central part of Ellesmere Island in the Canadian Arctic (Fig. 1-1). The region is notable for an interesting facies transition from shelf carbonates in the east to deep-water carbonates and cherts in the west. The purpose of this study is to: 1) examine the lithofacies of the lateral transition of the Allen Bay - Cape Phillips Formations; 2) describe the origin of the lithofacies; and 3) propose a depositional model for the Cape Phillips Formation.

STUDY AREA AND FIELD METHODS

The study area lies in the west-central part of Ellesmere Island between approximately 79°01' and 78°11' north latitude, and 82°09' and 85°18' west longitude (Fig. 1-2). The center of the study area is about 190km southeast of Eureka.

The nearest airline terminal is located 510km to the southwest at Resolute, Cornwallis Island. Resolute receives regular passenger flights from both Calgary and Montreal. Aircraft can be chartered there for further transportation to Ellesmere Island. Small STOL airplanes such as the de Havilland Twin Otter can land near some sections but most require a helicopter for access. The field season runs from mid-June to the end of August.

The topography of the area is characterized by low mountains up to about 900m. Most of these are underlain by Lower Paleozoic carbonate rocks. Some of the low mountains have small glaciers however, the main ice cap of central Ellesmere Island is situated to the east of

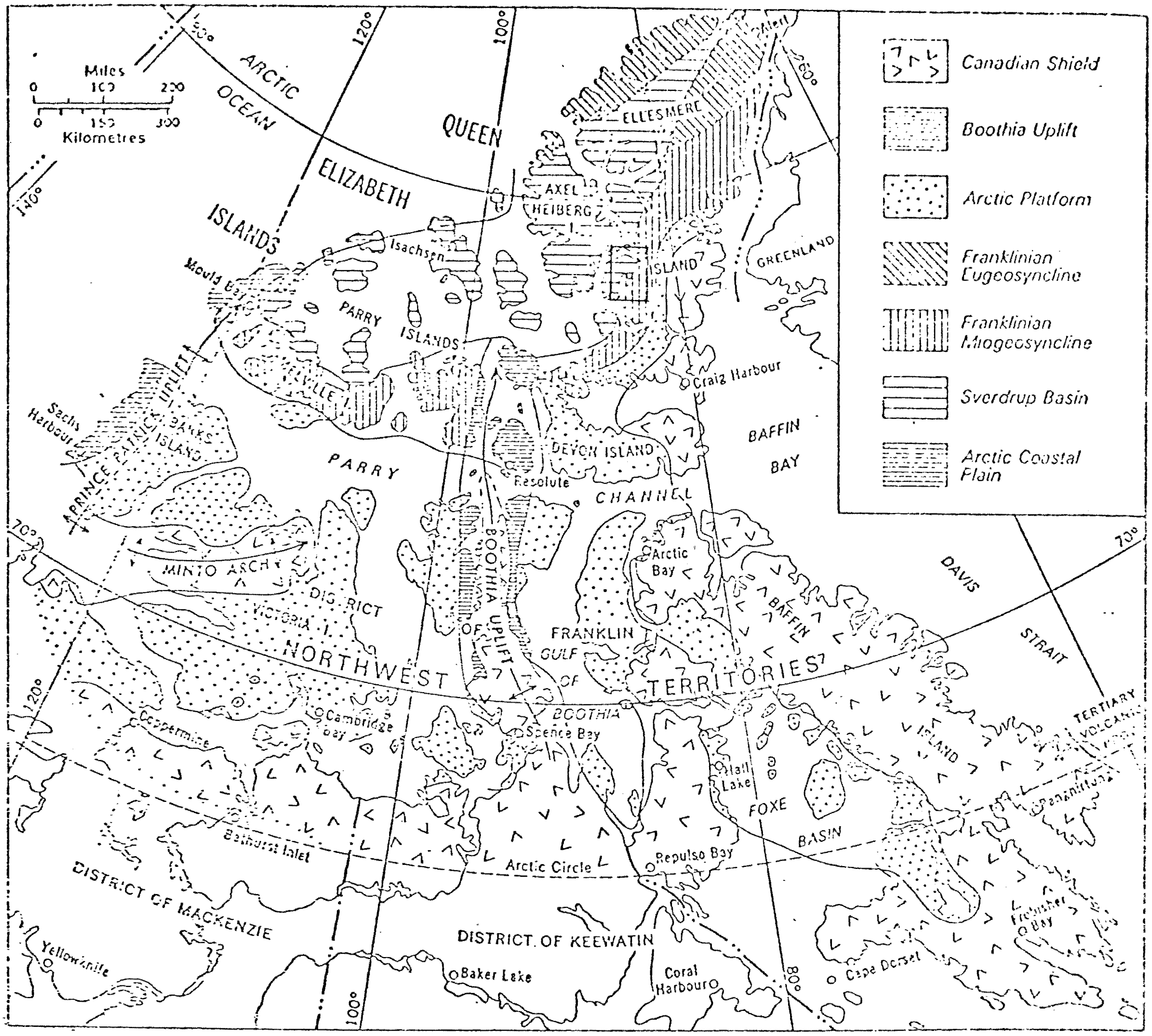


Figure 1-1: Geological provinces of Arctic Canada (Thonsteinsson and Tozer, 1970). Study area enclosed in box.

the study area. The coast is incised with bays and fiords. These and the low mountains are generally aligned parallel to the major southwest to northeast structural trend.

This report is based on a total of nineteen days field work during the summer of 1982 while the author was an employee of Petro-Canada Exploration Inc. Nineteen stratigraphic sections were measured in an area of approximately $4500km^2$ (Fig. 1-2). The sections were measured with a 30m chain. Surface mapping at a scale of 1:59322, was used to delineate stratigraphic, structural and spatial relationships within the study area. Representative samples of the lithologies and fauna were collected for laboratory analysis and identification.

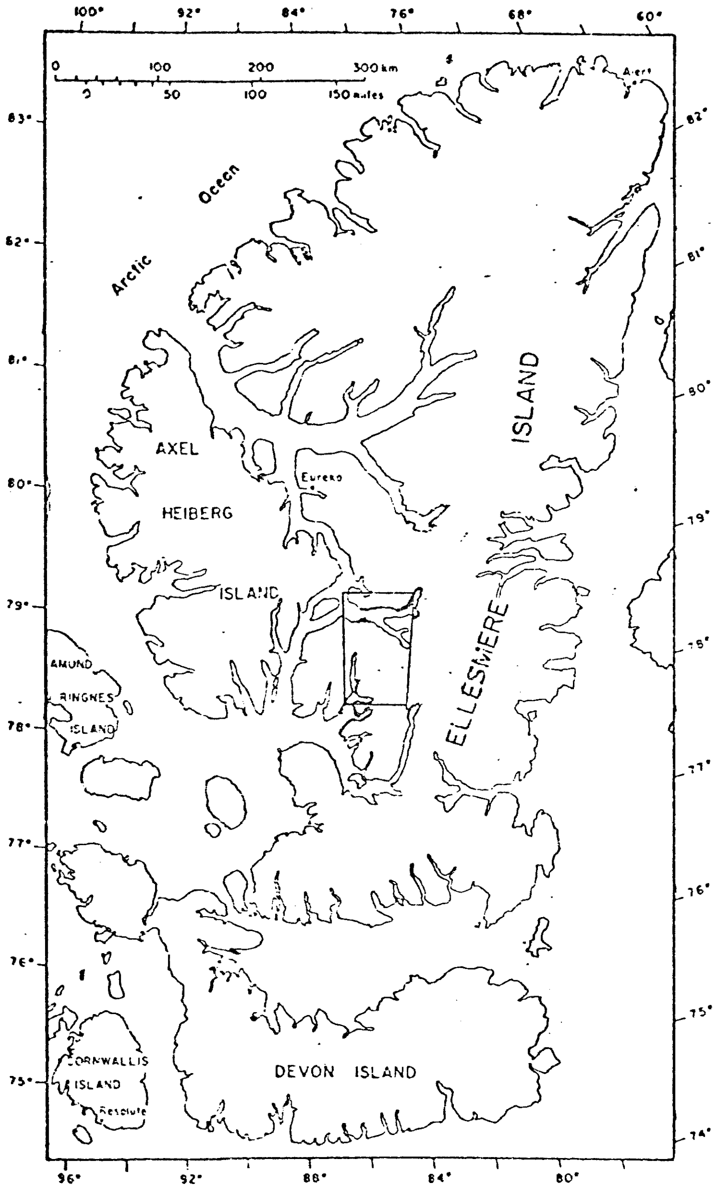


Figure 1-2: Ellesmere Island (Trettin, 1978). Location of study area is shown by the box.

CHAPTER 2

REGIONAL GEOLOGICAL SETTING

From late early Cambrian to earliest Devonian time, Ellesmere Island formed part of three tectonic provinces (Fig. 2-1): the Arctic Platform in the southwest, the Franklinian Geosyncline in the center, and the Pearya Geanticline in the northwest (Thorsteinsson and Tozer, 1960, 1970; Trettin et al., 1972; and Trettin, 1973).

The Arctic Platform on Ellesmere Island is the northernmost extent of the Canadian Shield. It is characterized by a high-grade metamorphic basement overlain by a relatively thin succession of shelf carbonates and smaller amounts of terrigenous clastics and evaporites. The boundary with the Franklinian Geosyncline is defined in a structural sense as the limit of folding (Thorsteinsson and Tozer, 1960) and in a stratigraphic sense as a hinge from which time-rock units thicken progressively to the northwest (Kerr, 1967d). Trettin (1978) suggested that the latter is more difficult to locate and therefore the limit of folding is generally used.

The Pearya Geanticline was a major source of clastic sediments for the Hazen Trough (Trettin, 1978, 1979). It was the site of intermittent metamorphism, uplift, plutonism and volcanism. It has been interpreted as a continental margin-type magmatic arc (Trettin et al., 1972). The core of the geanticline consists of Proterozoic gneisses which are presently exposed along the north coast of Ellesmere Island (Frisch, 1974, 1976).

From Cambrian to Late Devonian time, the Franklinian Geosyncline underwent subsidence and continual sedimentation. On Ellesmere Island, the geosyncline can be partitioned into three major belts (Fig. 2-1):

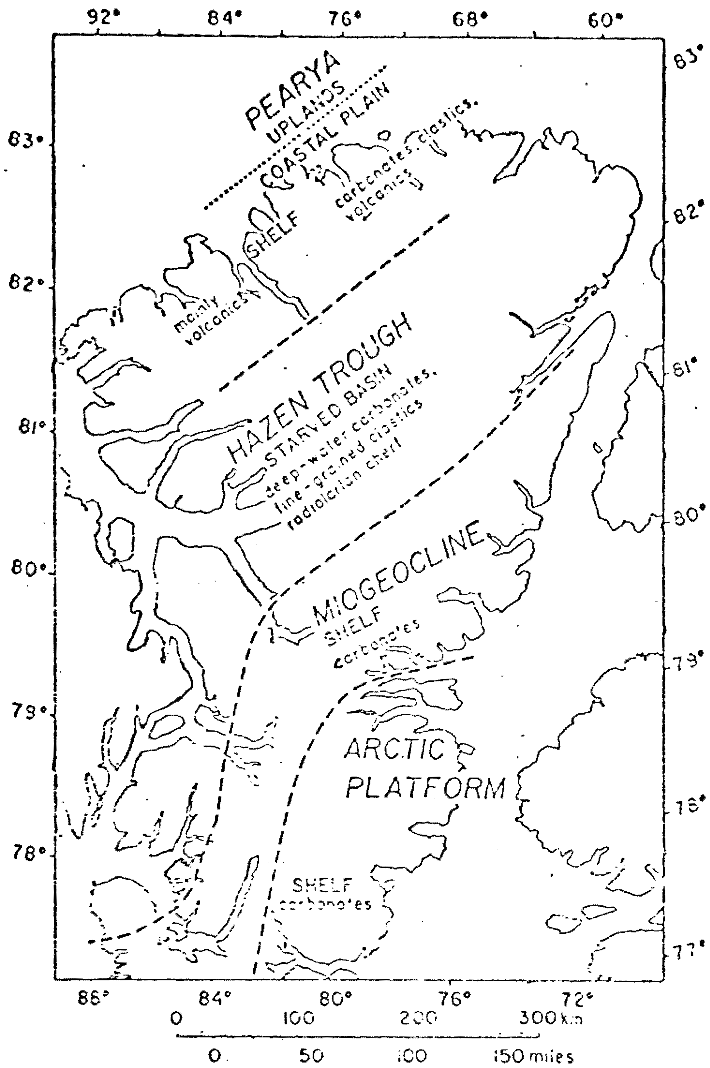


Figure 2-1: Tectonic provinces of northern and central Ellesmere Island (Trettin, 1978).

a southeastern shelf; the Hazen Trough; and in the northwest a complex belt of shelf and coastal plain deposits with volcanic arcs (Trettin, 1978, 1979). The southeastern shelf received mainly carbonates with minor evaporitic and clastic sediments. The study area consists of adjacent parts of the southeastern shelf and the Hazen Trough.

The Middle Ordovician to Lower Devonian Hazen Trough was a submarine furrow which may have extended from northeastern Greenland to Melville or Banks Islands (Trettin et al., 1972; Dawes, 1976). Trettin (1979) has divided the depositional history of the Hazen Trough into three diachronous depositional phases: pre-flysch; flysch and post-flysch. The pre-flysch phase is characterized by the occurrence of redeposited carbonate sediments, chert and graptolitic mudstone. The pre-flysch phase includes the Cape Phillips Formation. The flysch phase consists of alternating dolomitic and calcareous siltstones and sandstones with Bouma sequences and massive bedding (Imina Formation). The post-flysch phase (lower part of the Eids Formation) consists of laminated dolomitic and calcareous siltstones with minor flysch deposits (Trettin, 1979).

The Hazen Trough probably originated by subsidence rather than by seafloor spreading because the base of the succession comformably overlies carbonates and siliclastic sediments of shallow water origin instead of submarine volcanic rocks.

Thorsteinsson (1958) assigned the name Cape Phillips Formation to a Late Ordovician to Early Devonian succession of limestone, argillaceous limestone, chert, calcareous shale and dolomite on Cornwallis Island. The names Allen Bay Formation and Read Bay

Formation were given to a succession of carbonates on Cornwallis Island which are stratigraphically adjacent to the Cape Phillips Formation (Thorsteinsson, 1958). These units have since been extended into central Ellesmere Island by many workers (Tozer, in Fortier et al., 1963; Thorsteinsson and Kerr, 1963; Kerr, 1967b, 1976, Kerr and Thorsteinsson, 1972b, c). Kerr (1967a, b, 1968, 1976) investigated the upper Proterozoic to Upper Devonian succession of central Ellesmere Island in order to erect a coherent stratigraphic framework for the area. This stratigraphic framework serves as the basis for this report with the following revisions. The Upper Ordovician to Lower Devonian Cape Phillips Formation in the study area has since been subdivided into two units: Upper Ordovician to Middle Silurian Cape Phillips Formation and Middle Silurian to Lower Devonian Devon Island Formation (Thorsteinsson, pers. comm., 1982). The name Devon Island Formation was given to a succession on Devon Island consisting of dark graptolitic calcareous shale and shale with minor interbeds of argillaceous limestone (Thorsteinsson, in Fortier et al., 1963). In addition, the Allen Bay and Read Bay Formations cannot be distinguished in the study area and so are referred to as Undivided Allen Bay-Read Bay Formations by Thorsteinsson (1972a, b). Hereafter the Undivided Allen Bay-Read Bay Formations will be referred to as the Carbonate Buildup.

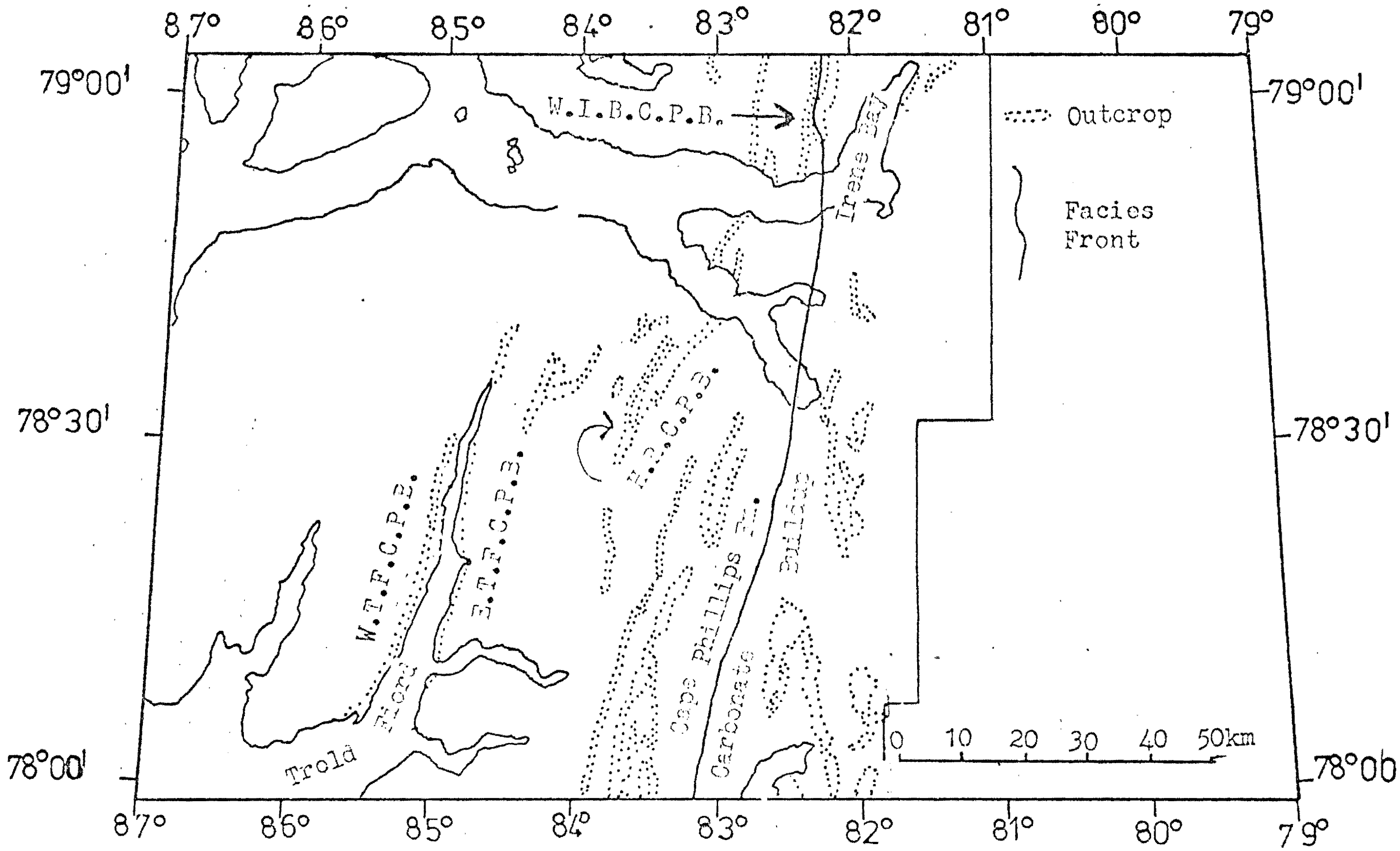
The geology of southwestern Ellesmere Island, adjacent to the study area has been investigated by McGill (1974) and Mayr (1974). In contrast to these studies the emphasis of the present work is on the Cape Phillips Formation. Trettin (1979) investigated the Middle Ordovician to Lower Devonian succession in the Cañon Fiord area, to the north of the present study area. Based on the lithological and paleontological characteristics of the Cape Phillips Formation in the Cañon Fiord area, he concluded that the unit was deposited on the southeastern slope and marginal bottom environments of the Hazen Trough, and in a back-reef basinal setting. Some of his ideas have been adopted in the present study.

The paleogeography of the Carbonate Buildup and the Cape Phillips-Devon Island Formations during the Lower Devonian are shown in Figure 2-2. Locations of measured sections and lines of section are also shown. The carbonate buildup is dolomitized, resistant, light colored and forms bluffs to low mountains. It grades vertically and laterally into beds of breccia which in turn grade laterally into the recessive, dark-colored and graptolitic carbonates, cherts and shales of the Cape Phillips and Devon Island Formations. The actual location of the facies transition of the Carbonate Buildup into the Cape Phillips Formation is not exposed. However, intercalation of the upper part of the Carbonate Buildup and the Devon Island Formation can be seen in the field. The Carbonate Buildup and Cape Phillips Formation conformably overlie the Irene Bay Formation in the study area. Figure 2-3 illustrates these stratigraphic relationships. The study uses the shelf to slope model shown in Figure 2-4 as a framework to interpret origin and distribution of the lithofacies of the Carbonate Buildup-Cape Phillips Formation facies transition.

STRUCTURE

The principal structure of the Franklinian Geosyncline in the west-central Ellesmere Island area is the Central Ellesmere Fold Belt.

Figure 2-2A: Paleogeographic map showing the distribution of the Carbonate Buildup and the Cape Phillips - Devon Island Formations during the early Lockkovian (Modified from Trettin, 1978).



Legend

W.I.B.C.P.B. - West Irene Bay Cape Phillips Belt

H.R.C.P.B. - Huff Ridge Cape Phillips Belt

E.T.F.C.P.B. - East Trold Fiord Cape Phillips Belt

W.T.F.C.P.B. - West Trold Fiord Cape Phillips Belt

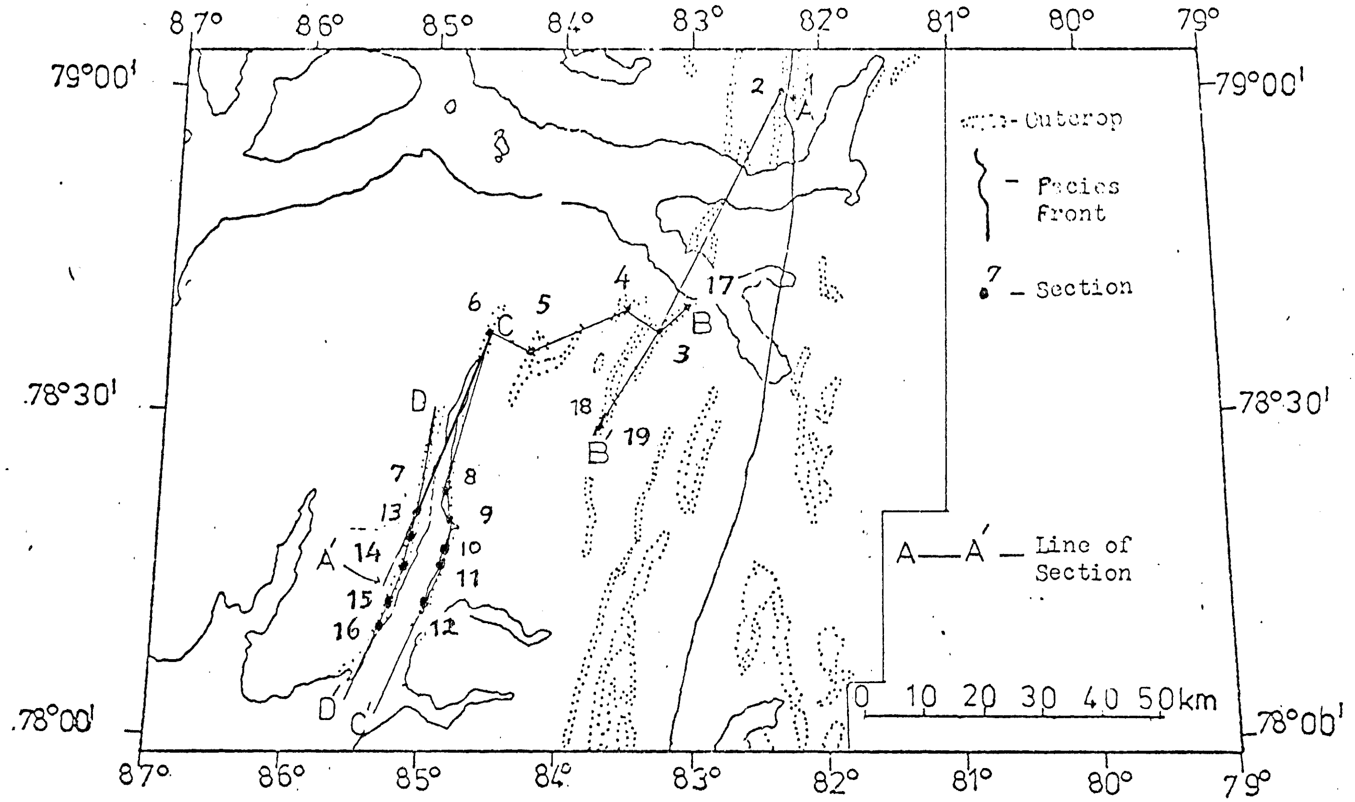


Figure 2-2B: Location of stratigraphic sections and lines of section (Modified from Trettin, 1978).

Figure 2-3: Table of Formations

System	Series	Stage	Formation or Group	Lithology	Thickness
Devonian	Lower	Lochkovian	Eids, Vendom Fiord, Imina and unnamed formations.	Clastic units including calcareous mudstone, sandy and silty turbidites and red and green siltstone; minor carbonates and anhydrite	[illegible]
Silurian	Upper	Pridolian	Devon Island Formation; Allen Bay-Read Bay Undivided	DEVON ISLAND - calcareous shale, shale, siltstone, minor argillaceous limestone and silty dolomite	0-350
		Ludlovian	Devon Island Formation; Allen Bay-Read Bay Undivided		
	Middle	Wenlockian	Cape Phillips Formation; Allen Bay-Read Bay Undivided	CAPE PHILLIPS - limestone, argillaceous limestone, calcareous mudstone, chert and dolomite. Minor calcareous turbidites and debris flows.	[illegible]
	Lower	Llandoverian	Cape Phillips Formation; Allen Bay-Read Bay Undivided	ALLEN BAY-READ BAY UNDIVIDED - an undivided succession; lower part mainly dolomite; upper part mainly limestone, commonly with dolomite; shaly limestone, sandstone and in places reef breccia	[illegible]
Ordovician	Upper	Ashgillian	Irene Bay	IRENE BAY limestone, argillaceous limestone, medium grey, weathers greenish, commonly fossiliferous.	37-325

Within this fold belt northeasterly-striking normal faults, folds and thrust faults are present. The folds may be recumbent in the direction of the craton. The thrust faults generally dip towards the northwest at moderate to steep angles, are commonly in echelon, and extend for more than 160 km. These rocks have been faulted and folded by two deformational events: the Upper Devonian Ellesmerian Orogeny and the Cenozoic Eurekan Orogeny (Thorsteinsson and Tozer, 1970). However, the relative effects of each orogeny are difficult to determine. Thorsteinsson and Tozer (1970) suggested that the major episode of recumbent folding and normal faulting resulted from the Ellesmerian Orogeny, whereas the thrust faulting was associated with the Eurekan Orogeny.

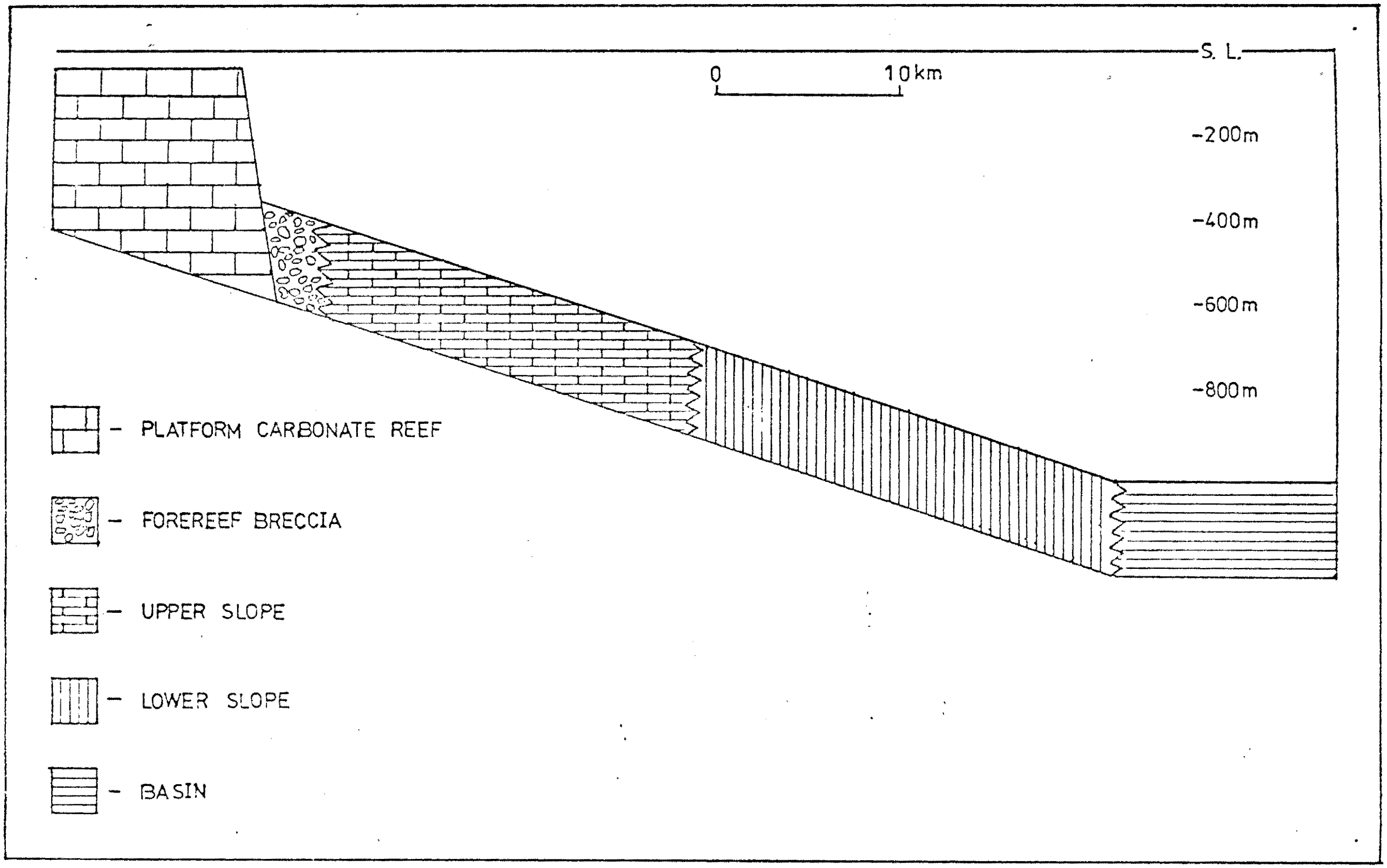


Figure 2-4: Shelf-slope model framework of the study (adapted from Mullins and Neumann, 1979).

CHAPTER 3

LITHOFACIES

METHODS OF IDENTIFICATION

Methods of mineral identification and rock description employed included whole rock X-ray diffraction, thin section petrology and hand sample observation. Thin sections were obtained from seventy-one samples. However, the fine-grained and fissile nature of fourteen samples precluded thin sectioning. These and nineteen fine-grained thin-sectioned samples were crushed to 63μ or less and analysed by X-ray diffraction. The diffractograms were analysed by methods adopted from Griffin (1971) and Cook _et al_. (1975). This work was done at Dalhousie University and the radiation used was CuKα, λ=1.54050Å. The minerals or mineral groups were identified by the presence of a single diagnostic peak and two secondary peaks (Appendix 1). Semiquantitative determination of mineral abundances were obtained by multiplying the principal peak height of each mineral by its intensity factor (Table Al-1).

Distinction between dolomite and calcite in thin section was enhanced by the Alizarin Red S staining technique (Dickson, 1965). Valuable information was also derived from megascopic examination of hand specimens, particularly the cut surfaces.

CLASSIFICATION

The general carbonate rock classification proposed by Dunham (1962) and modified by Embry and Kloxan (1971) has been adopted for this study.

Pore terminology has been taken from Choquette and Pray (1970). Compositional and textural modifiers are used to more accurately

Fig. 3-1a. BEDDING THICKNESS SCALE

Thin Laminated	< 2 mm
Thick Laminated	2 - 10 mm
Thin Bedded	1 - 10 cm
Medium Bedded	10 - 50 cm
Thick Bedded	< 50 cm

b. PARTING THICKNESS SCALE

Papery	< 1 mm
Fissile	1 - 5 mm
Platy	5 - 10 mm
Flaggy	1 - 10 cm
Slabby	10 - 30 cm
Blocky	30 - 100 cm
Massive	< 1 m

(From Petro-Canada Field Guide to Southeastern British Columbia, unpublished).

Fig. 3-2. CRYSTAL GRAIN SIZE CLASSIFICATION

2 - 1 mm	very coarsely crystalline
1 - 0.5 mm	coarsely crystalline
0.5 - 0.25 mm	medium crystalline
0.25 - 0.12 mm	finely crystalline
0.12 - 0.06 mm	very finely crystalline
0.06 - 0.004 mm	microcrystalline
0.004 mm or less	cryptocrystalline

(From Leighton and Pendexter, 1962 and Drummond, 1963).

represent the lithofacies types. For example, a laminated argillaceous wackestone is a fine-grained, laminated limestone with significant argillaceous content. Bedding and parting thickness scales used here are shown in Figures 3-1A and-1B. Crystal grain size is classified according to Figure 3-2.

LITHOFACIES TYPES

A combination of field observation, X-ray diffraction and petrological examination of the samples collected suggests that the lateral transition of the Carbonate Buildup-Cape Phillips Formation consists of seven lithofacies. Six of these are present in the Cape Phillips Formation: 1) laminated limestone; 2) laminated argillaceous limestone; 3) massive limestone and rudaceous graded limestone; 4) mudstone; 5) chert; and 6) laminated dolomite. The Carbonate Buildup contains the seventh lithofacies, massive dolomite, and minor amounts of massive limestone and mudstone. The characteristic features of each lithofacies are summarized in Table 3-1.

1) LAMINATED LIMESTONE

Laminated limestone is characterized by the predominance of calcite mm-scale planar lamination and wackestone to packstone textures. In outcrop the lithofacies consists of resistant, thin to very thick bedded, laminated, buff brown to medium grey weathering limestone (Fig. 3-3A, B). It also occurs locally as spherical oval nodules up to 30 cm in diameter.

The lithofacies consists of 49-100% calcite, 0-24% dolomite, 0-24% quartz, 0-10% mica, 0-20% pyrite and trace to relatively low amounts of organic matter. Microcrystalline calcite composes the matrix.

Table 3-1: Characteristics of the lithofacies.

LITHOFACIES	COLOR	LAMINATION	BEDDING	MINERALOGY	GRAIN TYPES	TEXTURES	FOSSILS	OUTCROP
LAMINATED LIMESTONE	W=BUFF BROWN TO MEDIUM GREY F=PALE TO MEDIUM GREY	MM-SCALE PLANAR. CONVOLUTE AND CROSS LAMINATION RARE. DEFINED BY VARIATIONS IN ORGANIC CONTENT.	THIN TO VERY THICK BEDDED AND LATERALLY CONTINUOUS. DISCONTINUOUS BEDS PRESENT BUT RELATIVELY RARE. GRADED BEDDING RARE	49-100% CALCITE 0-24% DOLOMITE 0-24% QUARTZ 0-20% PYRITE 0-15% MICA/ILLITE	PELOIDS/BIOCLASTS/ LITHOCLASTS	WACKESTONE AND PACKSTONE. LOW POROSITY.	MOSTLY OSTRACODS AND ECHINODERMS WITH MINOR MOLLUSC, BRYOZOAN AND BRACHIOPOD FRAGMENTS. SPONGE SPICULES, GRAPTOLITES AND TRILOBITES PRESENT LOCALLY.	RESISTANT. LOCALLY CROPS OUT AS OVAL AND SPHERICAL NODULES.
LAMINATED ARGILLACEOUS LIMESTONE	W=ORANGE-BROWN TO GREY-GREEN F=MEDIUM GREY	MM-SCALE PLANAR. DEFINED BY VARIATIONS IN ORGANIC AND CALCITE CONTENT.	THIN TO MEDIUM BEDDED AND LATERALLY CONTINUOUS.	56-60% CALCITE 25-30% QUARTZ 15-1[illegible]% MICA/ILLITE	PELOIDS/BIOCLASTS/ LITHOCLASTS	WACKESTONE AND PACKSTONE. LOW POROSITY.	MOSTLY ECHINODERMS AND SPONGE SPICULES WITH MINOR MOLLUSC, OSTRACOD AND BRACHIOPOD FRAGMENTS.	RESISTANT
MASSIVE LIMESTONE AND RUDACEOUS GRADED LIMESTONE	W=PALE GREY F=PALE TO MEDIUM GREY	CM-SCALE PLANAR LAMINATION PRESENT ONLY RARELY IN CLASTS OF MASSIVE LIMESTONE. CONVOLUTE AND CROSS LAMINATION MAY BE PRESENT IN RUDACEOUS GRADED LIMESTONE.	MEDIUM TO VERY THICK BEDDED. BEDS USUALLY PLANAR AND CONTINUOUS, RARELY LENSOIDA	85-100% CALCITE 0-15% QUARTZ TRACE ORGANICS	LITHOCLASTS/BIOCLASTS /PELOIDS	GRAINSTONE, FLOATSTONE AND RUDSTONE. LOW POROSITY.	MOSTLY ECHINODERMS WITH MINOR MOLLUSC, BRYOZOAN, BRACHIOPOD AND TRILOBITE FRAGMENTS. MINOR CORALS	RESISTANT
MUDSTONE	W=GREY-GREEN TO BLACK F=DARK GREY	MM-SCALE PLANAR WHEN PRESENT, USUALLY DISRUPTED BY PARTING	THIN TO VERY THICK BEDDED AND LATERALLY CONTINUOUS.	66-8[illegible]% CALCITE 2-18% DOLOMITE 10-26% QUARTZ 5-7% K-FELDSPAR HIGH ORGANICS	—	MUDSTONE. VERY LOW POROSITY.	VERY ABUNDANT AND DIVERSE GRAPTOLITE FAUNA	RECESSIVE
CHERT	W=DARK GREY TO BLACK F=BLACK	MM-SCALE PLANAR. IN RADIOLARIAN CHERT LAMINAE MAY BE SEVERELY DEFORMED AND DISRUPTED. LAMINATION DEFINED BY VARIATIONS IN ORGANIC AND CARBONATE CONTENTS	THIN TO MEDIUM BEDDED AND LATERALLY CONTINUOUS.	RADIOLARIAN CHERT 4-44% CALCITE 0-15% DOLOMITE 56-96% QUARTZ HIGH ORGANICS REPLACEMENT CHERT 5-44% CALCITE 0-5% DOLOMITE 54-[illegible]0% QUARTZ	RADIOLARIAN CHERT BIOCLASTS REPLACEMENT CHERT PELOIDS/BIOCLASTS/ LITHOCLASTS	RADIOLARIAN MUDSTONE AND WACKESTONE. VERY LOW POROSITY. REPLACEMENT WACKESTONE AND PACKSTONE.	RADIOLARIAN CHERT- RADIOLARIANS AND RARE SPONGE SPICULES. REPLACEMENT CHERT- ECHINODERMS, OSTRACODS AND MOLLUSCS WITH MINOR RADIOLARIAN, SPONGE SPICULE, BRYOZOAN AND BRACHIOPOD FRAGMENTS.	RESISTANT
LAMINATED DOLOMITE	W=BUFF BROWN TO MEDIUM GREY F=MEDIUM BROWN TO MEDIUM GREY	MM-SCALE PLANAR. SOMETIMES POORLY DEVELOPED. CONVOLUTE AND CROSS LAMINATION PRESENT LOCALLY. LAMINATION DEFINED BY VARIATIONS IN ORGANIC AND SILICA CONTENTS.	THIN TO VERY THICK BEDDED AND LATERALLY CONTINUOUS	0-14% CALCITE 77-9[illegible]% DOLOMITE 0-9% QUARTZ LOW ORGANICS	BIOCLASTS	VOID-INFILLING ANHEDRAL TO SUBHEDRAL INTERLOCKING DOLOMITE RHOMBOHEDRA	OSTRACOD AND ECHINODERM FRAGMENTS	RESISTANT
MASSIVE DOLOMITE	W=PALE GREY TO PALE BROWN F=MILKY WHITE TO PALE BROWN	PRESENT ONLY IN THE MATRIX OF INTRACLASTIC DOLOMITE	VERY THICK BEDDED. MOSTLY MASSIVE	VUGGY MASSIVE DOLOMITE 100% DOLOMITE INTRACLASTIC DOLOMITE 20-44% CALCITE 55-75% DOLOMITE 1-5% QUARTZ BIOCLASTIC DOLOMITE 10% CALCITE 90% DOLOMITE	VUGGY MASSIVE DOLOMITE → RARE GHOSTS OF BIOCLASTS INTRACLASTIC DOLOMITE → INTRACLASTS/ BIOCLASTS/PELOIDS BIOCLASTIC DOLOMITE → BIOCLASTS	VUGGY AND MOLDIC POROSITY LARGE SOLUTION CAVITIES. FLOATSTONE AND RUDSTONE. MATRIX AND CLAST SUPPORTED. VUGGY POROSITY FLOATSTONE AND RUDSTONE	VUGGY MASSIVE DOLOMITE- RARE GHOSTS OF UNIDENTIFIED FOSSILS INTRACLASTIC DOLOMITE- ECHINODERM, MOLLUSC AND BRACHIOPOD FRAGMENTS BIOCLASTIC DOLOMITE- ECHINODERMS AND CORALS	RESISTANT. CHARACTERIZED BY ITS LOW MOUNTAIN-FORMING TOPOGRAPHY

Fig. 3-3. Laminated limestone in outcrop.

A. Section 3, Huff Ridge Cape Phillips Belt. Foreground is about 50m thick.

B. Section 6, north of Trold Fiord. Hammer for scale (30cm).

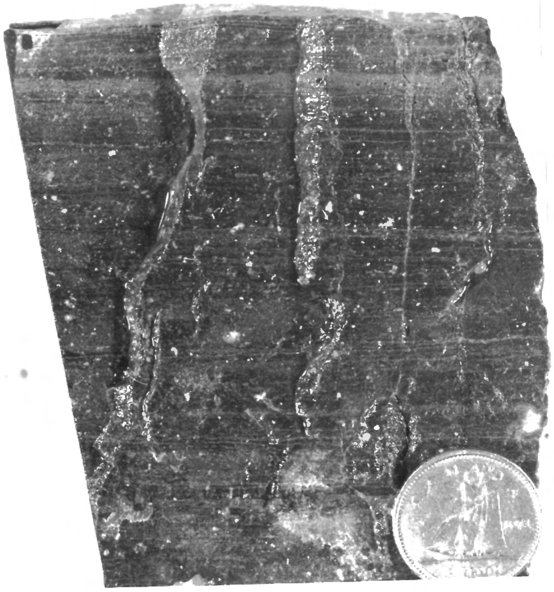


Fig. 3-4A. Hand specimen of laminated limestone showing mm-scale planar lamination (dime for scale, about 17mm in diameter).

Fig. 3-4B. Photograph of a thin section of laminated limestone showing mm-scale planar and cross lamination (bar is about 1cm)

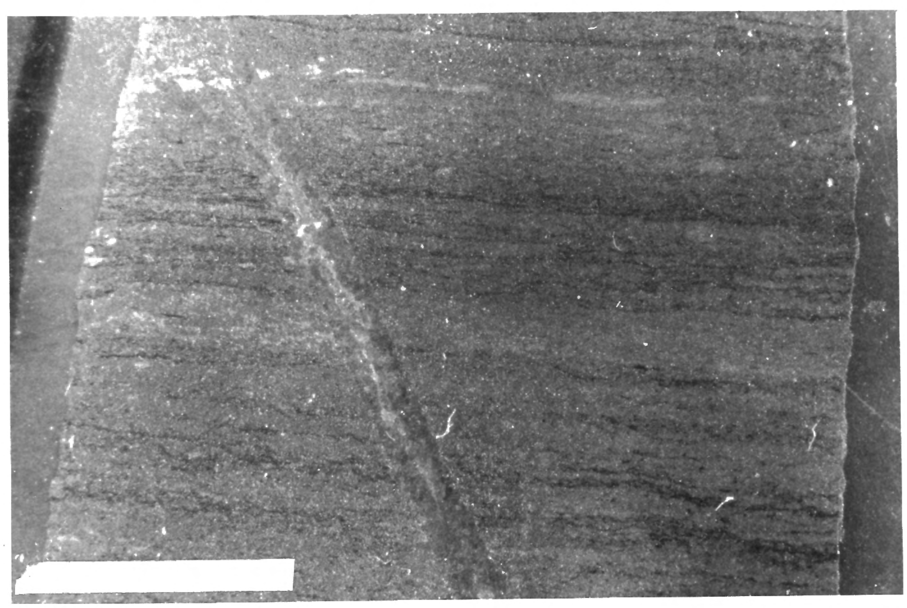


Fig. 3-4C. Photograph of a thin section of laminated limestone showing mm-scale wispy lamination (bar is about 0.5mm long).

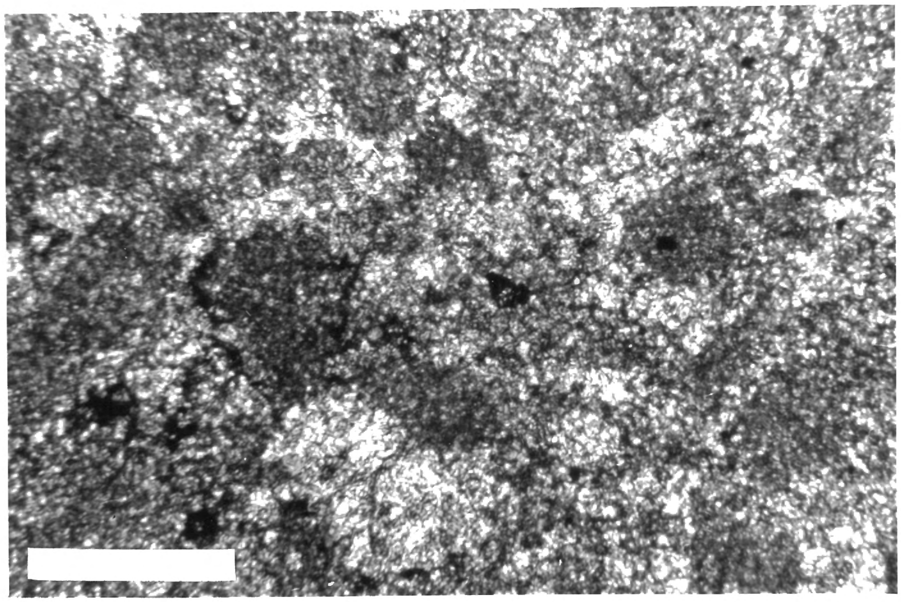


Fig. 3-5. Photomicrograph of peloids in laminated limestone (bar is about 0.1mm long).

Calcitic cement accounts for approximately 10%, and consists of medium crystalline and anhedral crystals. Dolomite rhombohedra are very finely crystalline and float in the calcitic matrix. Quartz is present in two forms: angular microcrystalline to very finely crystalline grains, and as a replacement of calcite.

The predominant structure of the lithofacies is mm-scale planar lamination defined by vertical variation in organic matter, calcite and quartz (Fig. 3-4A, B, C). Other structures present include stylolites and calcite veins.

Clast types include peloids and bioclasts with minor lithoclasts. Peloids are predominant and compose up to 60% of the rocks (Fig. 3-5). Bioclasts are mostly fragments of ostracods and echinoderms with minor molluscs, bryozoa, brachiopods, sponges and trilobites. Lithoclasts, when present, are 0.5 mm to 1.0 mm fragments of poorly sorted peloidal packstone.

2) LAMINATED ARGILLACEOUS LIMESTONE

Laminated argillaceous limestone differs from laminated limestone in containing quartz, clay and mica in significant quantities. In outcrop (Fig. 3-6), the lithofacies occurs as resistant, thin to medium bedded, orange-brown to grey-green weathering and distinctly laminated limestone.

It consists of 50-60% calcite, 25-30% quartz, 15-16% mica-illite. Organic matter is present in trace to relatively low amounts. Microcrystalline calcite composes the matrix. Cement consists of medium to coarsely crystalline and anhedral grains of calcite. Quartz is present as microcrystalline to very finely crystalline angular,

Fig. 3-6. Photograph of laminated argillaceous limestone in outcrop (left side of picture), section 3, Huff Ridge Cape Phillips Belt. Section is about 50m thick.

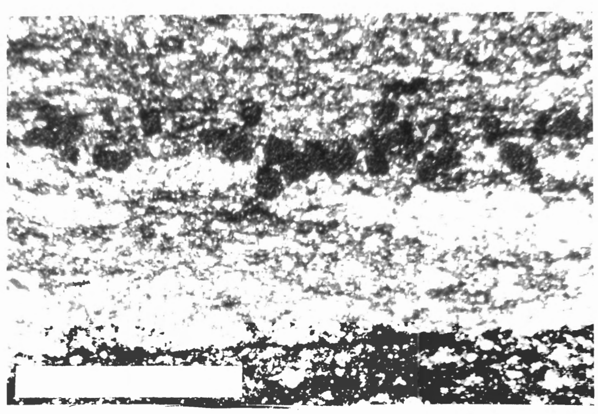


Fig. 3-7. Photomicrograph of mm-scale lamination in laminated argillaceous limestone (bar is about 0.6mm long).

detrital grains. When present, dolomite consists of finely crystalline rhombohedra. Microcrystalline to very finely crystalline elongate mica flakes are oriented parallel to bedding.

Mm-scale planar lamination is the predominant structure. It results from vertical variations in calcite, quartz, chlorite, mica, pyrite and organic matter contents (Fig. 3-7).

Wackestone and packstone textures are present. Peloids and bioclasts are the primary clasts with minor lithoclasts. Bioclasts are mostly fragments of echinoderms and sponge spicules with minor molluscs, brachiopods and ostracods.

3) MASSIVE LIMESTONE AND RUDACEOUS GRADED LIMESTONE

Massive limestone beds are unstratified (Fig. 3-8) while those of rudaceous graded limestone are coarsely graded (Fig. 3-9, -10). Massive limestone and rudaceous graded limestone are combined as one lithofacies because of their coarse-grained nature, spatial association (see Chapter 4) and relative rarity within the Cape Phillips Formation. In outcrop, the lithofacies is resistant, medium to thick bedded and weathers a pale grey.

The lithofacies consists of 85-100% calcite, and 0-15% quartz. Organic matter is present in trace amounts. The matrix is composed of microcrystalline to very finely crystalline calcite crystals. Dolomite may occur as very finely crystalline subhedral to euhedral rhombohedra. Quartz is present both as very finely crystalline angular grains and as a replacement of calcite.

Grainstone, floatstone and rudstone textures are present. Clast types include lithoclasts (up to 30mm) and bioclasts (up to 15mm)

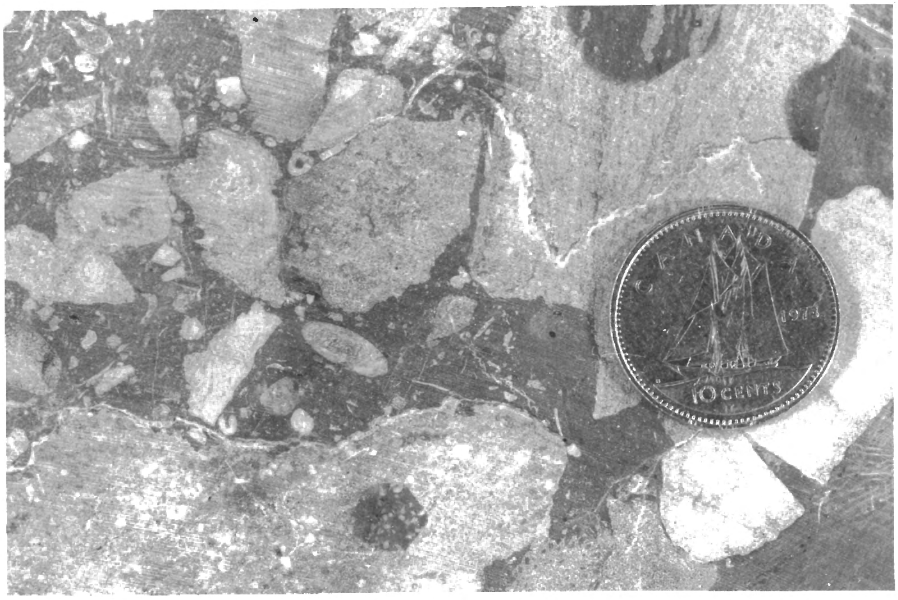


Fig. 3-8. Photograph of a hand specimen of massive limestone. Dime for scale (diameter = 17mm).

Fig. 3-9. Hand specimen of rudaceous graded limestone (dime for scale).

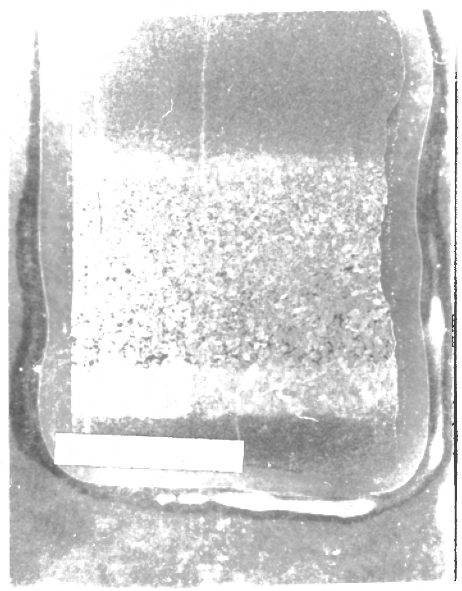


Fig. 3-10. Photograph of a thin section of rudaceous graded limestone (bar is about 1cm long).

with minor peloids, up to 1mm in diameter. The lithoclasts are fragments of peloidal and bioclastic packstone. Bioclasts are echinoderms with minor mollusc, brachiopod, bryozoan and trilobite fragments.

4) MUDSTONE

The diagnostic features of this lithofacies include its fine-grained nature, graptolitic fauna, recessiveness, dark color and fissile to platy parting (Fig. 3-1B). Mm-scale planar lamination, where present, is usually disrupted by the parting or cleavage.

Petrological examination of this lithofacies is not possible because of its fissility. However, compositions and semiquantitative estimates of mineral abundance were obtained using X-ray diffraction.

Calcareous and quartzose mudstone are present. Calcareous mudstone comprises a major proportion of the Cape Phillips Formation and is described below. Quartzose mudstone is present in the Devon Island Formation and in the extreme upper part of the Carbonate Build-up.

Calcareous mudstone consists of 66-87% calcite, 10-26% quartz, 2-18% dolomite and 5-7% K-feldspar. The proportion of organic matter could not be estimated using X-ray diffraction. However, the dark color and ubiquitous carbonaceous graptolites suggest that organic matter is a relatively important constituent.

5) CHERT

Extreme hardness and predominant siliceous composition characterize this lithofacies. In outcrop, chert is resistant, dark grey to black and thin to medium bedded (Fig. 3-12). Planar mm-scale lamination is generally disrupted by brecciation. Two sub-lithofacies are recognized:

Fig. 3-11. Photograph of calcareous mudstone in outcrop, section 6, north of Trold Fiord. Foreground is about 25m thick.

radiolarian chert and replacement chert. These are indistinguishable in outcrop. However, hand specimen and thin section study indicate that the two types occur in separate beds within interbedded successions.

Radiolarian chert consists of 56-96% silica, 4-44% calcite and 0-15% dolomite. In thin section, cryptocrystalline to microcrystalline silica is masked by a relatively high concentration of black and brown structureless organic matter. Calcite crystals are microcrystalline. Dolomite occurs as subhedral to euhedral microcrystalline to medium crystalline rhombohedra. The larger dolomite crystals are extensively corroded.

Mm-scale planar laminae are mostly bent, broken and disrupted as a result of brittle deformation. The lamination is defined by vertical variation in the concentrations of calcite, silica and organic matter. Other structures present include calcite and quartz veins.

Mudstone and wackestone textures are exhibited. Clasts consist mostly of microscopic spheres, spherical rings and irregular-shaped walls which surround organic matter (Fig. 3-13). These bodies have diameters of 0.02mm to 0.1mm and compose up to 20% of the rocks. The small size and spherical shape of these bodies suggests that they are poorly preserved radiolaria. Silicified ostracod fragments and sponge spicules are present locally.

Replacement chert is characterized by replacement and void in-filling fabrics (terminology from Orme, 1974). These rocks consist of 54-90% silica, 5-46% calcite and 0-5% dolomite. Organic matter is present in trace to low amounts. Microcrystalline silica is a replacement after a microcrystalline calcitic matrix (Fig. 3-14, 16) and bioclasts may also show partial or complete replacement (Fig. 3-15).

Fig. 3-12. Photograph of chert in outcrop, section 6, north of Trold Fiord. Laminated limestone bed in center of picture is about 2m thick.

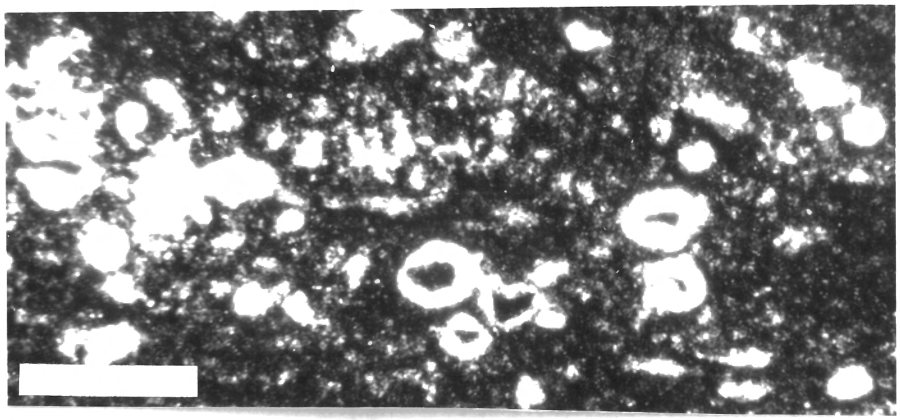


Fig. 3-13A. Photomicrographs of spherical rings and irregular shaped walls enclosing organic matter (bar is about 0.05mm long) in radiolarian chert.

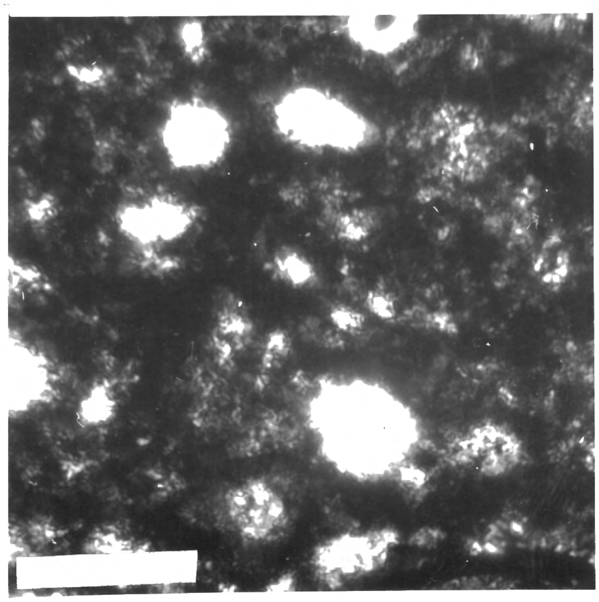


Fig. 3-13B. Photomicrograph of poorly preserved radiolaria (bar is about 0.04mm long) in radiolarian chert.

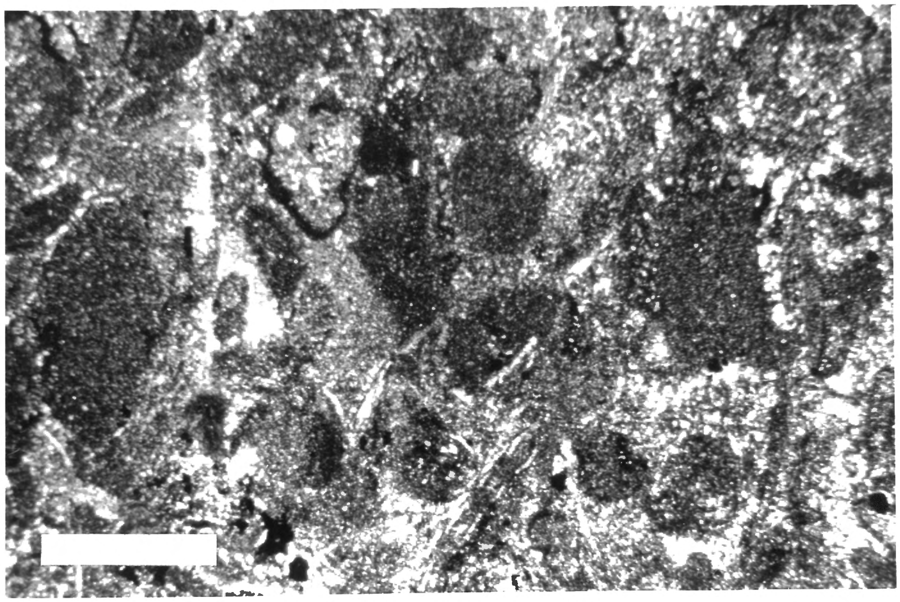


Fig. 3-14. Photomicrograph of silicified peloids in replacement chert (bar is about 1.5mm long).

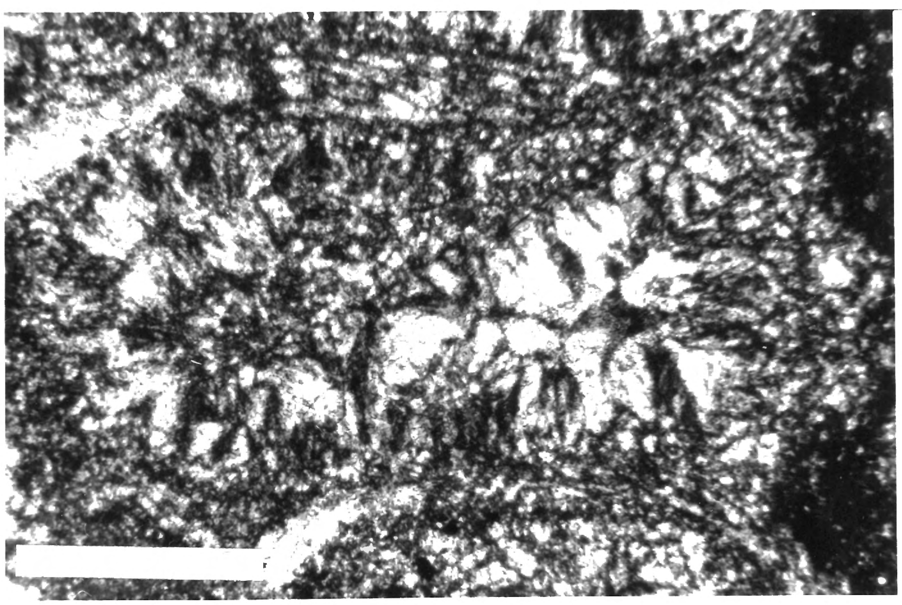


Fig. 3-15. Void-infilling textures in replacement c-hert (bar is about 0.5mm long).

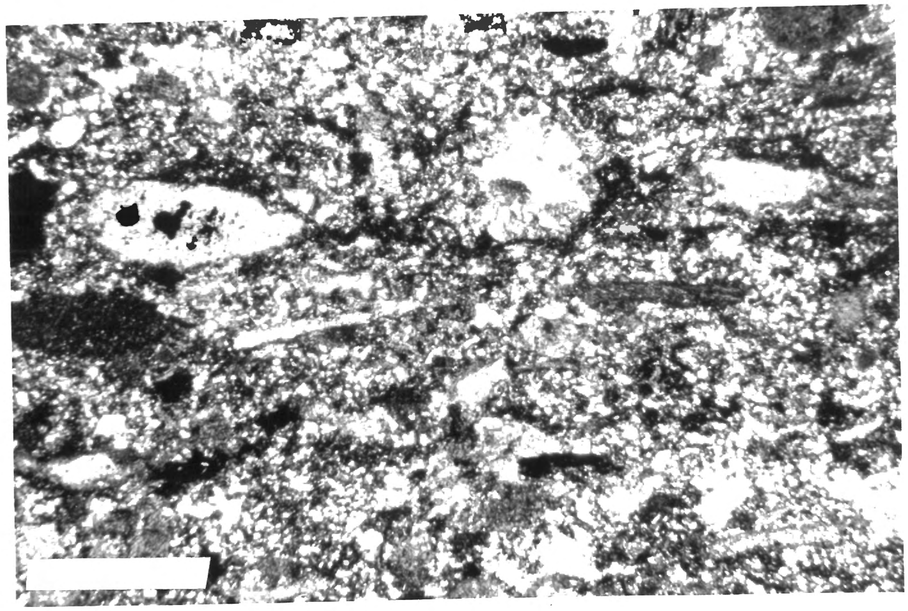


Fig. 3-16. Photomicrograph of wholly and partially silicified echinoderm fragments in replacement chert (bar is about 0.5mm long).

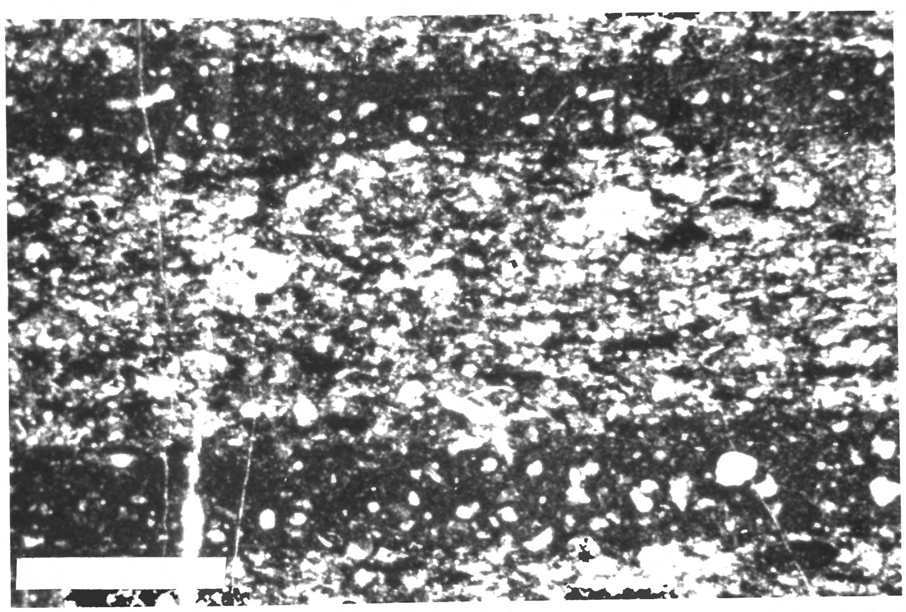


Fig. 3-17. Mm-scale planar lamination in replacement chert (bar is about 0.5mm long).

Void-infilling chalcedony forms spherical to oval radiating aggregates (Fig. 3-15) within pores of the matrix or bioclasts. Dolomite occurs as very finely crystalline to medium crystalline subhedral to euhedral rhombohedra. The larger dolomite crystals are extensively corroded.

Planar mm-scale lamination is well preserved. Calcareous-and organic-rich laminae alternate with silica-rich laminae.

Ghosts of peloids (Fig. 3-14) and bioclasts (Fig. 3-16) suggest that the rocks were lime packstones, grainstones, floatstones and rudstones before silicification. Bioclasts include echinoderms (Fig. 3-15) and ostracods with minor molluscs, brachiopods, bryozoa, sponge spicules and radiolaria.

6) LAMINATED DOLOMITE

Planar mm-scale lamination and the predominance of dolomite characterize laminated dolomite. It outcrops as resistant, thin to very thick bedded, buff brown to grey weathering and laminated dolomite (Fig. 3-18).

Laminated dolomite consists of 77-96% dolomite, 0-14% calcite and 0-9% quartz. Organic matter and pyrite are present in trace amounts. Dolomite is present as very finely crystalline, anhedral to subhedral and well sorted rhombohedra. Microcrystalline calcite and organic matter compose the matrix. Quartz is present both as microcrystalline to very finely crystalline, angular detrital grains and as a replacement of microcrystalline calcite.

Most beds show a planar mm-scale lamination which is caused by vertical variations in organic matter content (Fig. 3-19). Convolute and wavy laminae are rarely present.

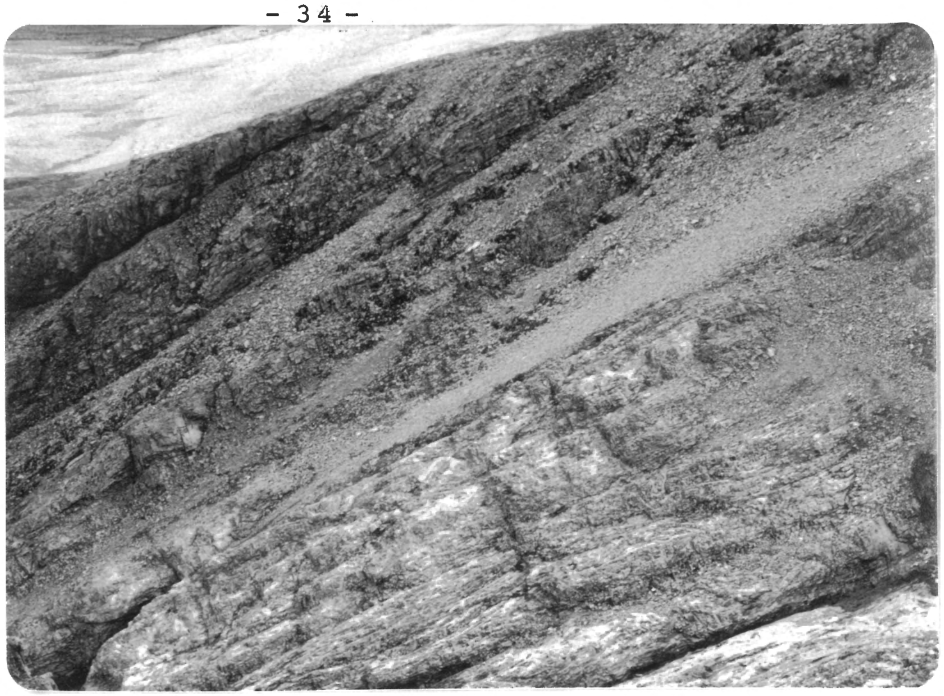


Fig. 3-18. Laminated dolomite in outcrop, section 2, West Irene Bay Cape Phillips Belt. Foreground section is about 20m thick.

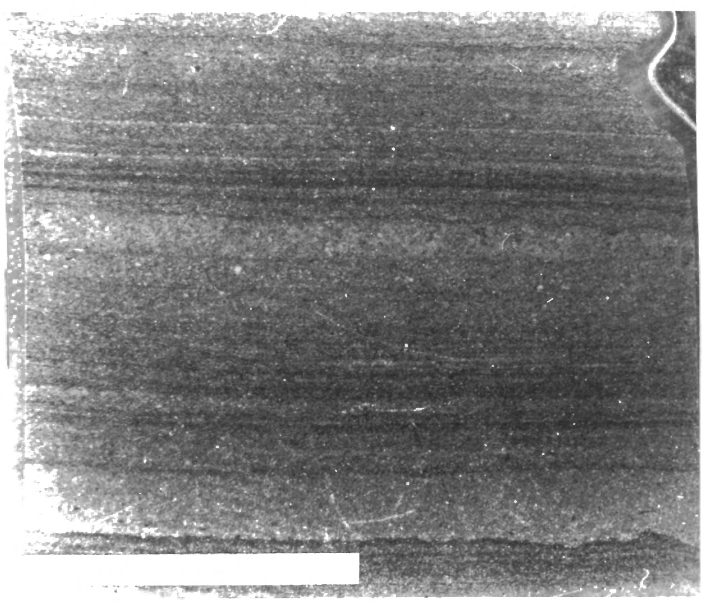


Fig. 3-19. Photograph of a thin section of laminated dolomite showing mm-scale planar lamination (bar is about 1.0mm long).

Ghosts of peloids are present. Bioclasts are rare and include ostracod and echinoderm fragments.

7) MASSIVE DOLOMITE

Massive dolomite crops out as resistant, cliff-or bluff-forming, pale grey to pale brown weathering dolomite. It comprises most of the Carbonate Buildup. Three sub-lithofacies are recognized: 1) vuggy massive dolomite; 2) intraclastic dolomite; and 3) bioclastic dolomite.

Vuggy massive dolomite comprises about 80% of the Carbonate Buildup. It is characterized by its low mountain-forming topography and the presence of large solution cavities up to 2m in diameter (Fig. 3-20). Vuggy and moldic pores account for 5-15% of hand specimens (Fig. 3-21). Moldic pores may often be unidentified fossils. In thin section, very finely to finely crystalline anhedral to subhedral dolomite crystals are seen.

Intraclastic dolomite occurs as a bedded breccia unit which gradationally overlies vuggy massive dolomite. The base of the unit consists of very thick bedded and resistant clast-supported beds of breccia. The clasts are angular and up to 2m in diameter (Fig. 3-22). Up section, the beds become progressively thinner, matrix-supported and the clast size decreases (Fig. 3-23). The lithoclasts consist of non vuggy massive dolomite, and fragments of peloidal and bioclastic-peloidal packstone and grainstone (Fig. 3-24). The matrix consists of finely crystalline to medium crystalline dolomite rhombohedra with minor angular, detrital quartz grains. Locally the matrix is laminated.

Fig. 3-20. Photograph of vuggy massive dolomite in outcrop showing large cavities. Cavity in the center of the photo is about 2m in diameter. Photograph is from section 1 of the Carbonate Buildup.

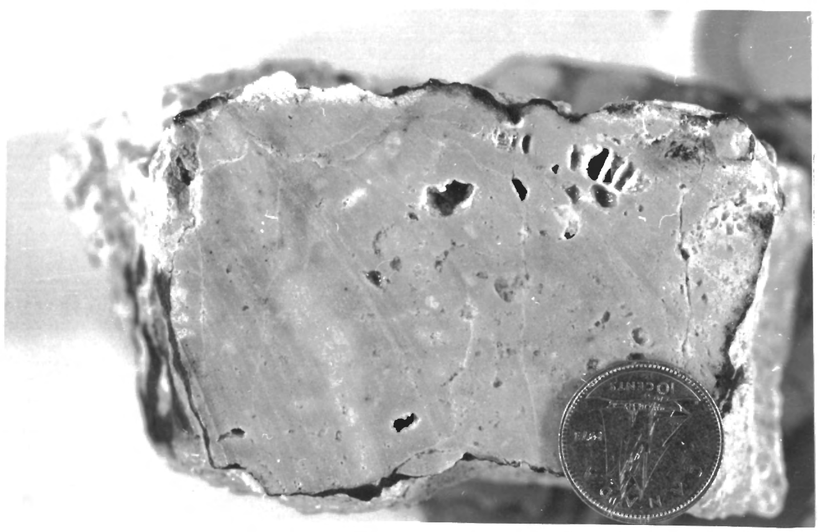


Fig. 3-21. Hand specimen of vuggy massive dolomite. Note the vuggy and moldic porosity (dime for scale)

Fig. 3-22. Photograph of intraclastic dolomite in outcrop, section 1, Carbonate Buildup (lens cap for scale).

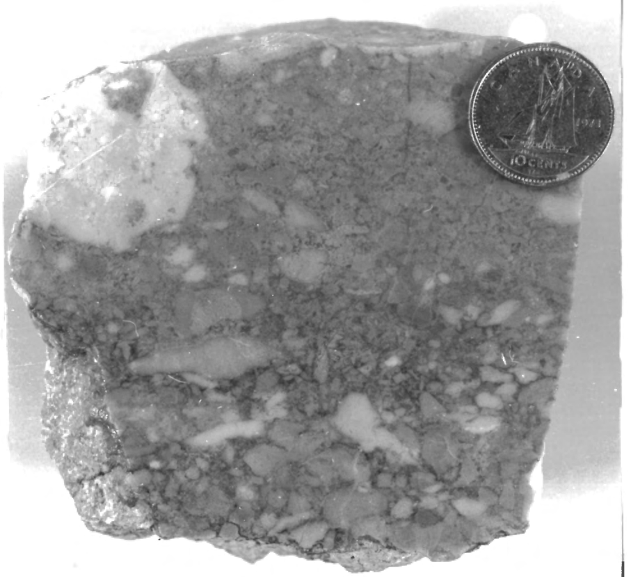


Fig. 3-23. Hand specimen of intraclastic dolomite (dime for scale).

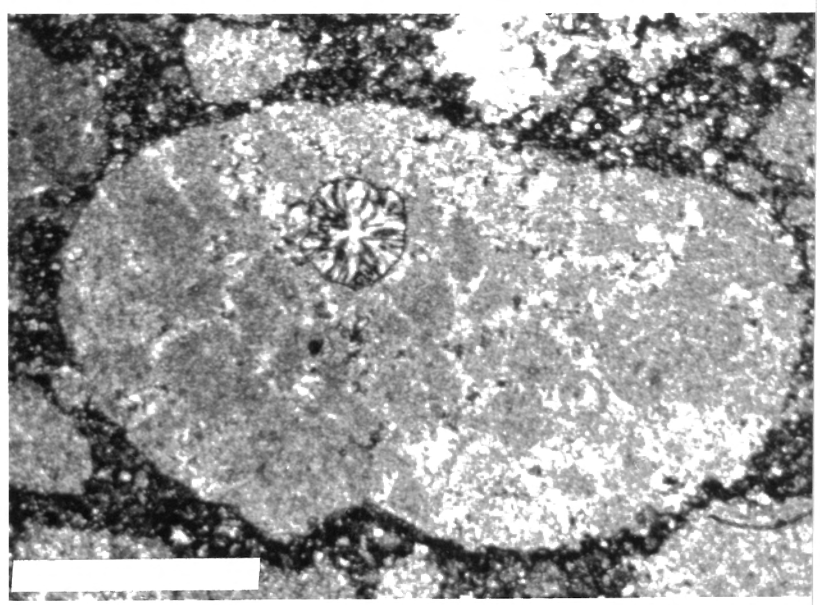


Fig. 3-24. Photomicrograph of intraclastic dolomite showing intraclast of peloidal grainstone in a dolomitic matrix. Note patch of silica replacement in the center of the picture (bar is about 0.5mm long).

Bioclastic dolomite is mostly present in the upper part of the Carbonate Buildup. It is milky white and exhibits 5-10% vuggy porosity. Partially dolomitized echinoderm fragments and intraclasts float in a dolomitic matrix.

CHAPTER 4

LITHOFACIES DISTRIBUTION

MAJOR SECTIONS

Four of the nineteen stratigraphic sections measured were sampled in detail. Comprehensive descriptions of the four sections are presented in Appendix 2. Each of the four major sections is described below to illustrate vertical lithofacies variation within the study area.

SECTION 1 (FIGURE 4-1)

This is the only section measured through the Carbonate Buildup. It is relatively thick and predominantly massive dolomite with minor quartzose mudstone, laminated limestone and massive limestone near the top. Proportions of lithofacies comprising the section are shown in Figure 4-1.

Most of the fossils have been rendered unrecognizable by dolomitization. However, the graptolite <u>Monograptus</u> <u>dubius</u> (Fig. A3-1, Appendix 3) initially occurs at 1140m.

The spatial relationships between the Carbonate Buildup and the Cape Phillips-Devon Island Formations in the area of section 1 are shown in Figure A2-1 (Appendix 2). The upper part of the Carbonate Buildup interfringers with the Devon Island Formation south of the measured section. The facies transition into the Cape Phillips Formation is not exposed. To the northeast, the entire section is progressively removed by the unconformity beneath the Lower Devonian Vendom Formation.

SECTION 2 (FIGURE 4-2)

This section corresponds to the eastward extent of the Cape

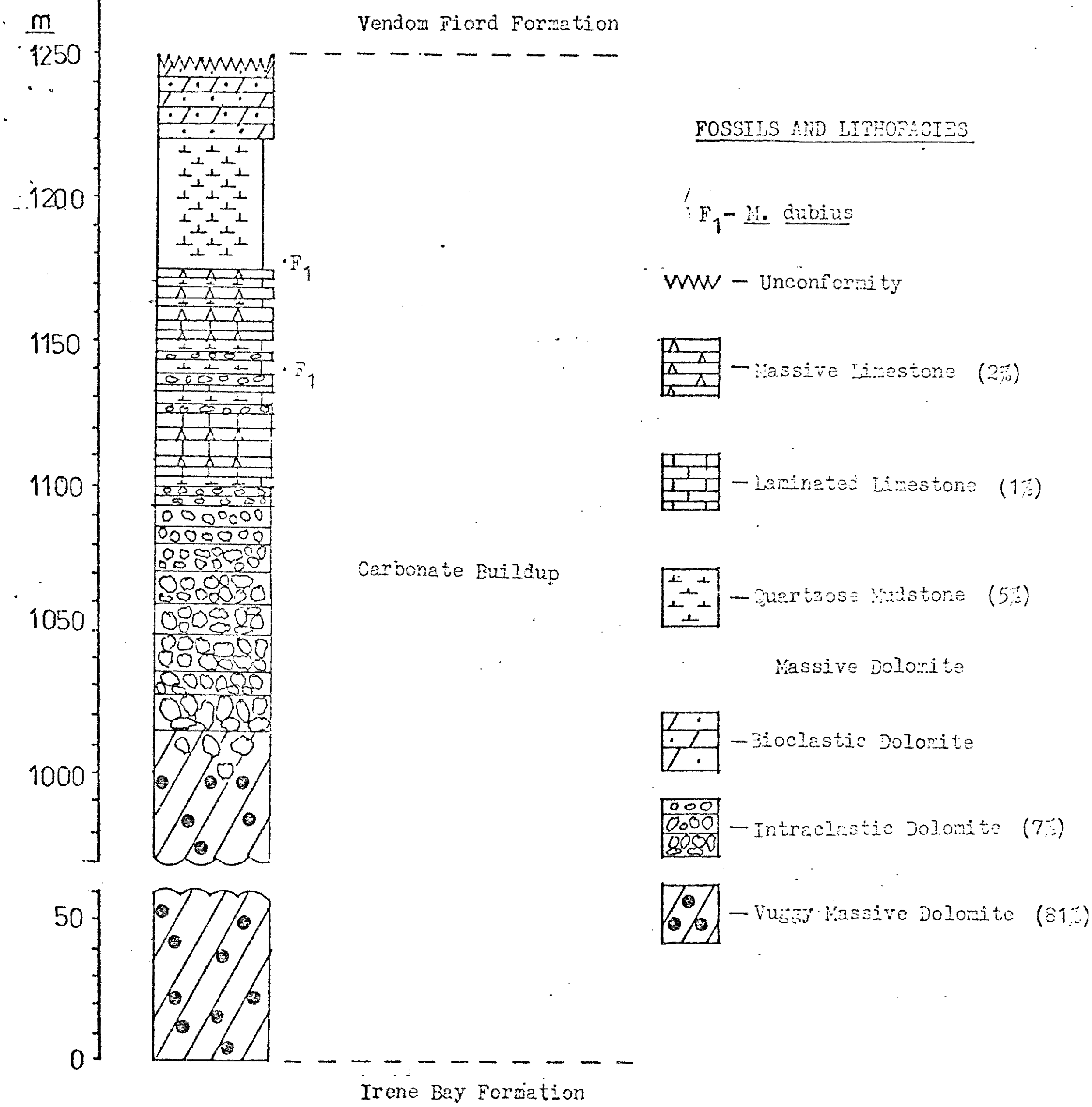


Figure 4-1: Section 1. Approximate proportions of lithofacies included. Recessive and resistant weathering patterns shown on column.

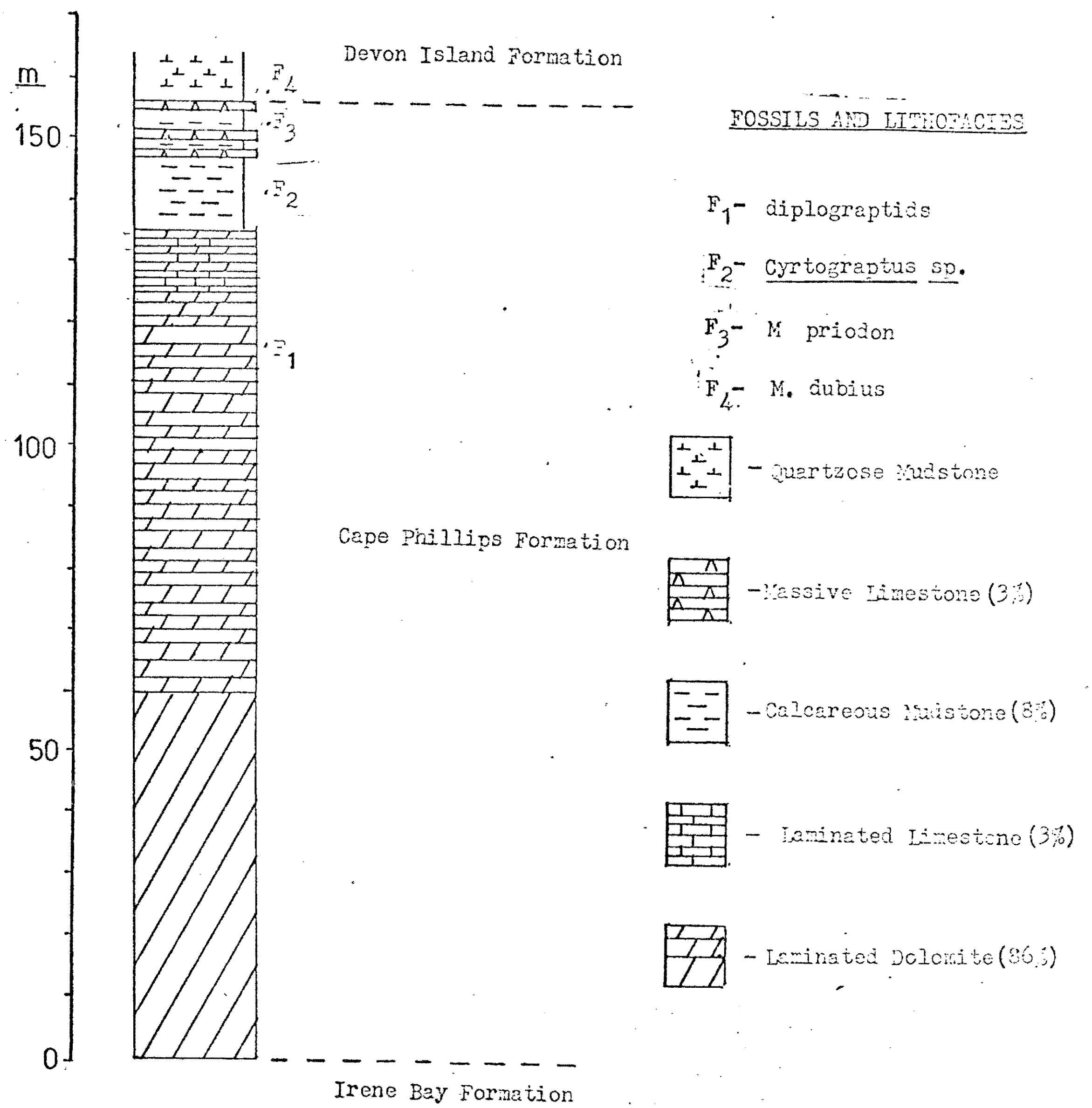


Figure 4-2: Section 2. Approximate proportions of lithofacies included. Recessive and resistant weathering patterns shown on column.

Phillips Formation in the study area (see Fig. 2-2 and Fig. A2-1). Laminated dolomite is predominant and it gradually gives way to minor laminated limestone, calcareous mudstone and massive limestone up section.

Graptolites are abundant in calcareous mudstone. This fauna is more abundant and diverse than in section 1.

SECTION 3 (FIGURE 4-3)

This is the thickest section measured in the Cape Phillips Formation. Laminated limestone is predominant. Calcareous mudstone constitutes a significant proportion while chert and laminated limestone are minor. Geology of this area is shown in Figure A1-2.

A distinctive and monotonous bedding sequence consisting of 65-75% medium to thick bedded laminated limestone interbedded with 25-35% thin bedded calcareous mudstone, is well developed in section 3, particularly in the basal 105m. "Rhythmite" is a general term that has been applied to this particular type of bedding sequence (Wilson, 1969).

Graptolites are abundant throughout the section in calcareous mudstone. The trilobite Pseudogygites latimariginatus (Fig. A3-8) occurs abundantly in the lowest 50m of the section. The trilobite fossils are not abraded, rarely whole and found randomly oriented on bedding planes of laminated and unlaminated limestone.

From 155m to 164m a distinctive bed of laminated limestone occurs between two thin chert successions. The graptolite Rastrites sp. (Fig. A3-2) occurs above and below the bed. This bed can be found at this stratigraphic horizon in almost every section west of section 2

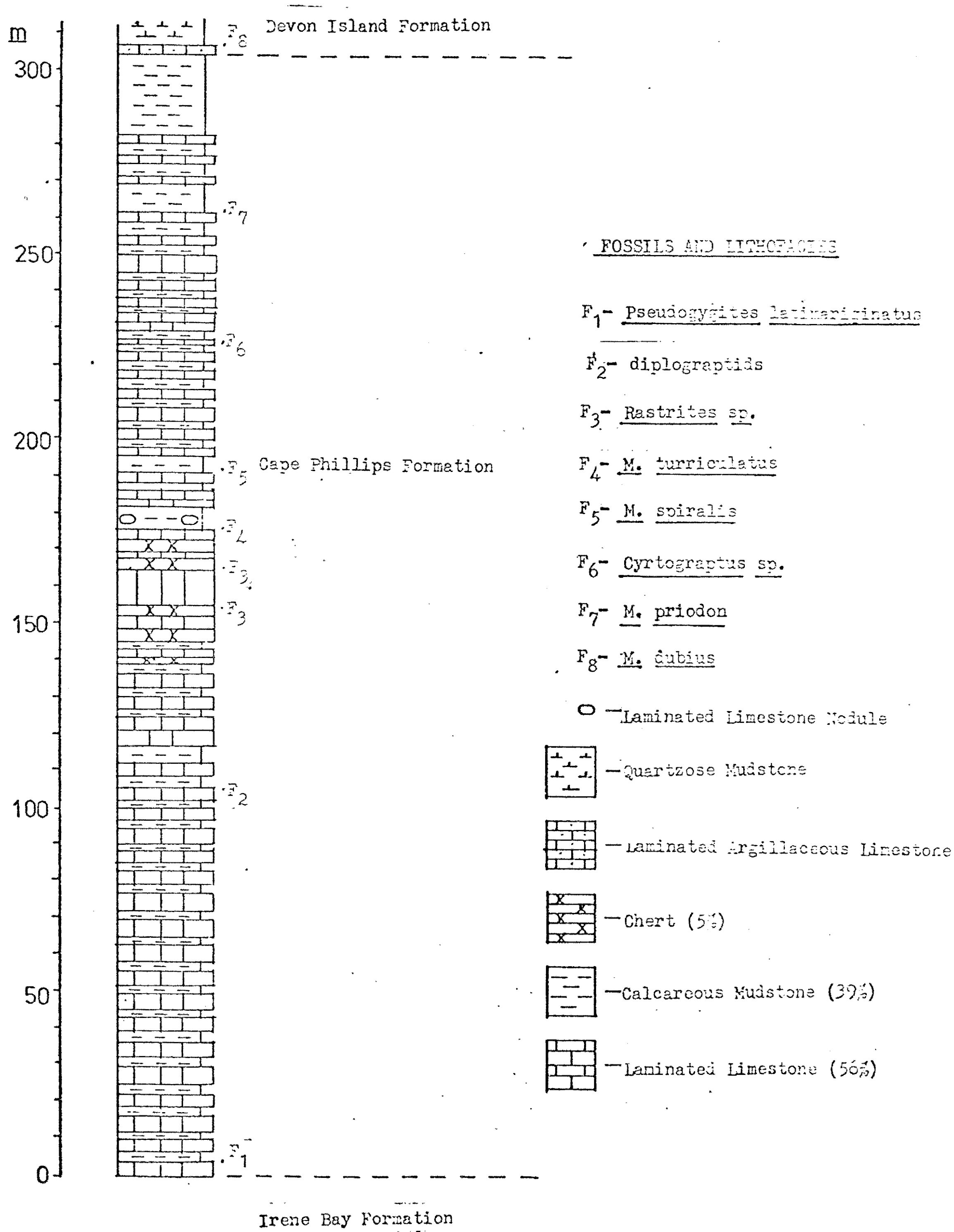


Figure 4-3: Section 3. Approximate proportions of lithofacies included. Recessive and resistant weathering patterns shown on column.

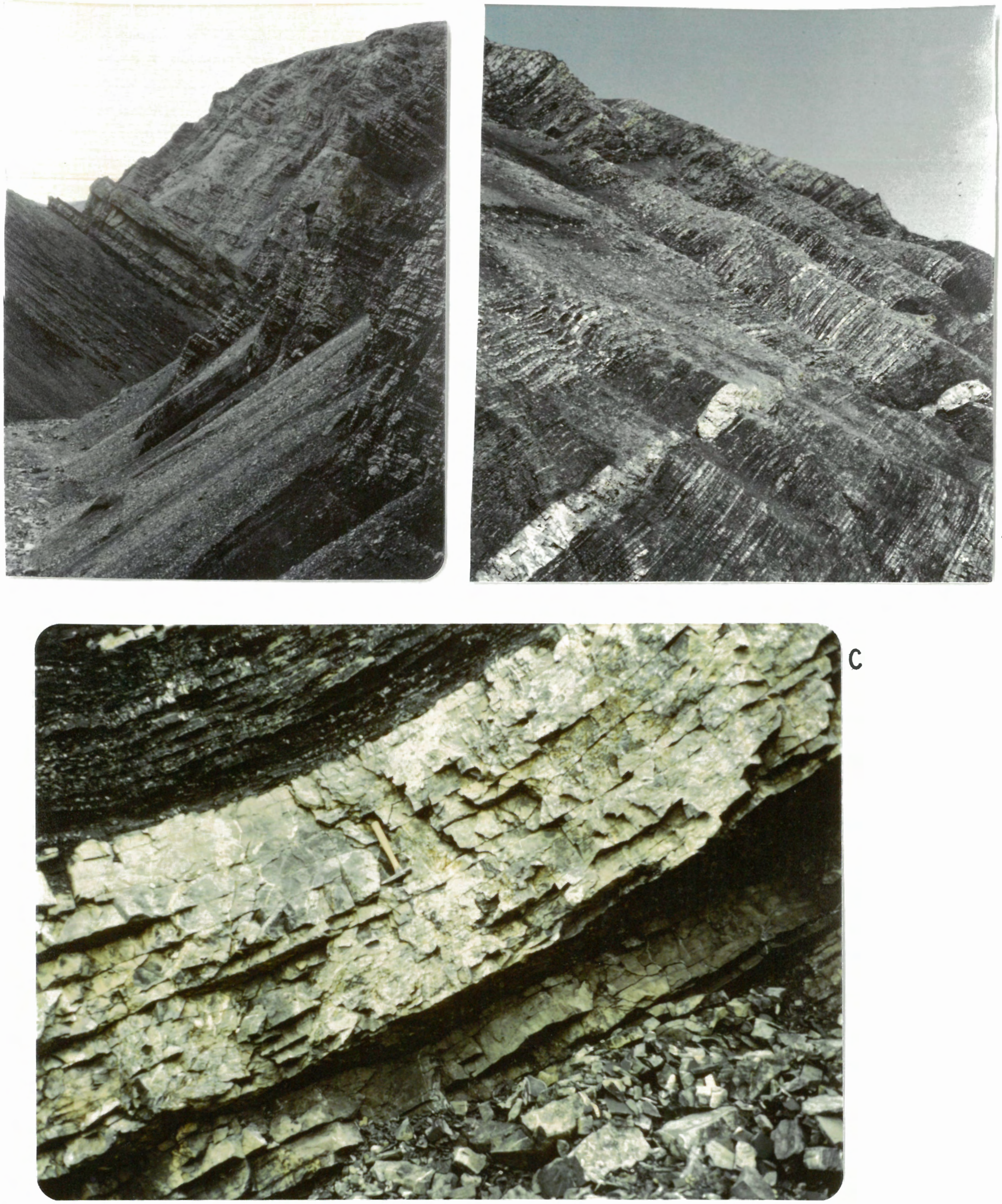


Fig. 4-4. The marker limestone bed.
A. Section 3, Huff Ridge Cape Phillips Belt. Foreground is about 20m thick.
B. Section 6, north of Trold Fiord. Section is about 50m thick.
C. Section 6, north of Trold Fiord. Hammer For scale (about 30cm long).

(Fig. 4-4). Therefore, this bed can be used as a significant lithologic marker and henceforth it is referred to as the marker limestone.

SECTION 6 (FIGURE 4-5)

This is the most westerly of the major sections (Fig. 2-2). Geology of the area is shown in Fig. A1-3. Calcareous mudstone comprises the largest proportion of the section. Laminated limestone is also important. The relative proportion of chert is greater than in section 2 and laminated argillaceous limestone is minor.

A poorly developed rhythmite succession is present relative to section 3. Comparatively, the marker limestone is thinner, ungraded and enclosed by thicker chert sequences.

Graptolites are very abundant in calcareous mudstone but trilobite fossils are rare.

CORRELATION BETWEEN STRATIGRAPHIC SECTIONS

Vertical and lateral distribution of the lithofacies in the nineteen sections of the study area can be examined using the graptolites for correlation. Graptolites were collected and identified in the field for the purpose of correlation between sections. In particular, Monograptus dubius (Fig. A3-1), Monograptus priodon (Fig. A3-2), Cyrtograptus sp. (Fig. A3-3), Monograptus spiralis (Fig. A3-4), Monograptus turriculatus (Fig. A3-5), Rastrites sp. (Fig. A3-6), and diplograptids (Fig. A3-7) were used with great success (Fig. 4-6).

Both the Cape Phillips Formation and the Carbonate buildup are conformably underlain in the study area by the Irene Bay Formation. The contact between the Cape Phillips and Devon Island Formation is marked

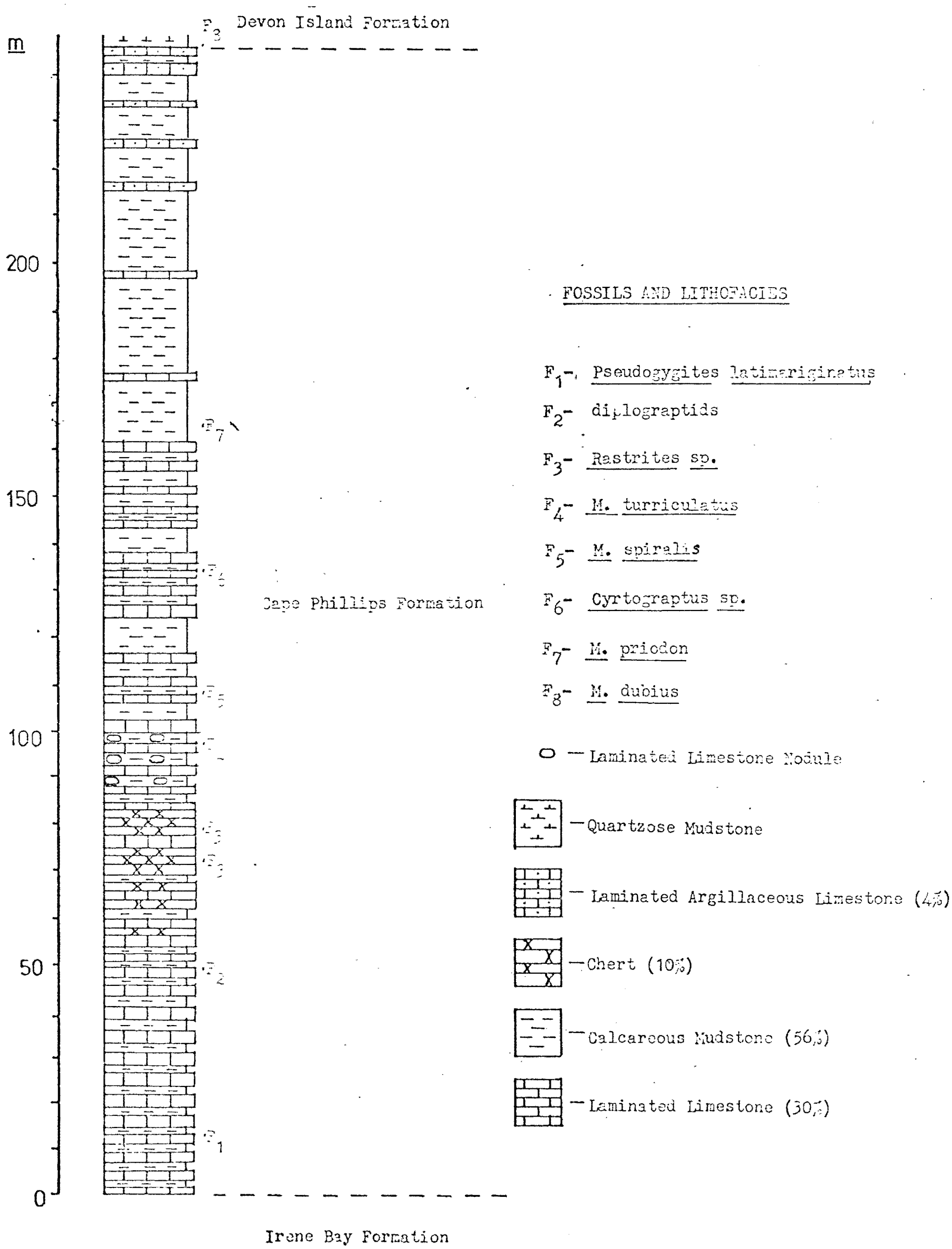


Figure 4-5: Section 6. Approximate proportions of lithofacies given. Recessive and resistant weathering patterns shown on column.

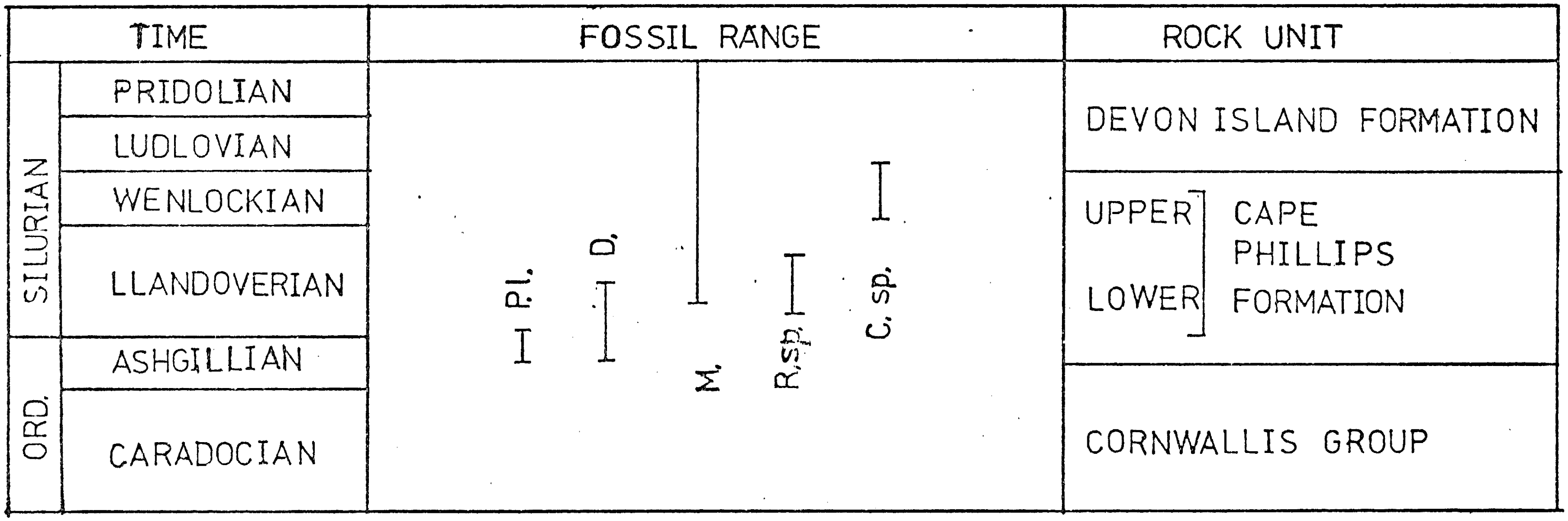


Figure 4-6: Relative ages of identified fossils (Modified from Morganti; 1979).

Legend

P.L. - Pseudogygates latimariginatus

D. - diplograptids

M. - Monograptids

R.sp. - Rastrites sp.

C.sp. - Cyrtograptus sp.

by the presence of quartzose mudstone and coincides with the occurrence of M-dubius in the absence of M. priodon. To better facilitate discussion and comparison, the Cape Phillips Formation is conformably divided into lower and upper parts (e.g. Fig. 4-7) based on the distribution of Rastrites sp.

Figure 4-7 shows that there are major westward changes in the strata which include: 1) a facies transition between sections 1 and 2; 2) thinning of the strata; and 3) lithofacies variations.

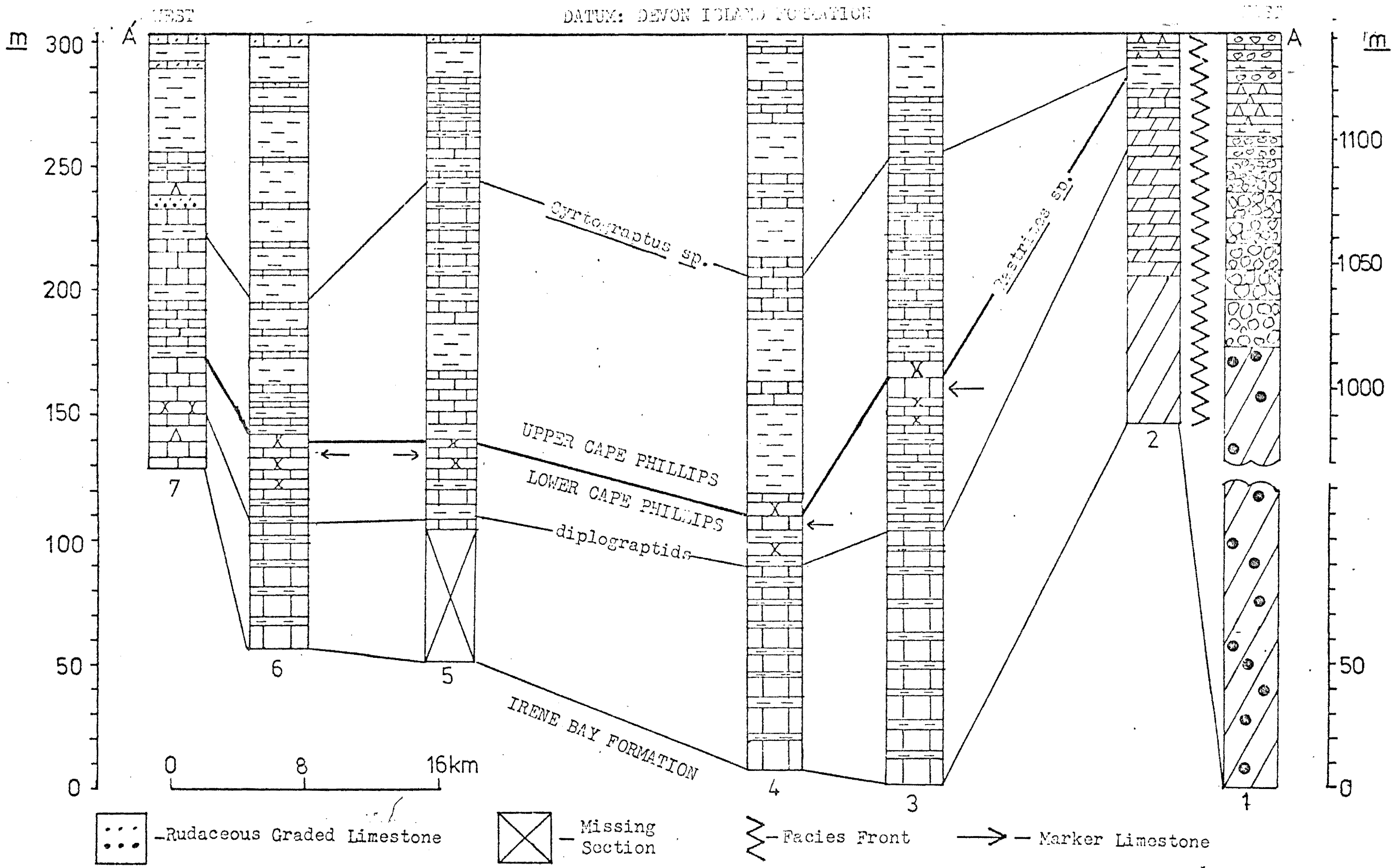
Correlations based on the occurrence of M. dubius shows that section 2 is about a seventh as thick as the age equivalent portion of section 1. This, plus its darker color, finer-grained nature and relatively abundant graptolite fauna suggests that section 2 is west of the facies front between shelf and basinal sediments.

Overall, the thickness of strata of Ashgillian to Wenlockian age decreases from 1140m in the east to 175m in the west. Section 2 is anomalous because it is only half as thick as section 3. Most of this difference is due to a five-fold increase in the thickness of the upper Cape Phillips in section 3.

Westward of section 3 most of the thickness decrease occurs in the lower Cape Phillips. The rhythmite in section 3 is 105m thick but decreases to 56m in section 6 and its age equivalent in section 7 is only 15m. Furthermore, the marker limestone decreases from 9m in section 3 to 2m in section 6. Meanwhile, the thickness of the upper Cape Phillips remains fairly constant.

While dolomite predominates in sections 1 and 2, it virtually disappears westwards of section 2 at the gain of laminated limestone, chert and mudstone. In turn, the proportions of mudstone and chert

Figure 4-7: Cross-section A-A'. See Figures 4-1, -2, -3 and -5 for symbols.



increase at the expense of laminated limestone. In the upper Cape Phillips, mudstone is predominant west of section 3 and it is the major rock type in sections 4 and 6. Section 7 represents a resurgence of laminated limestone at the expense of calcareous mudstone and chert on the west side of Trold Fiord.

Major north-south changes in the strata are illustrated in Figures 4-8, 9 and 10. These changes are similar to those described above. Figure 4-8 is a section along the strike of the Huff Ridge Cape Phillips Belt (Fig. 2-2). From north to south the thickness of the strata decreases slightly. Southward the proportion of calcareous mudstone increases at the expense of laminated limestone, particularly in the upper Cape Phillips. The proportion of chert increases slightly while the marker limestone thins and is not graded south of section 3. A minor resurgence of laminated dolomite is shown in sections 18 and 19.

A section along the strike of the East Trold Fiord Cape Phillips (Fig. 2-2) is shown in Figure 4-9. Southwards the strata decreases from 246m in section 6 to 140m in section 12 and the proportions of calcareous mudstone and chert increase to the south at the expense of laminated limestone.

The section in Figure 4-10 is drawn parallel to the strike of the West Trold Fiord Cape Phillips Belt. The strata here are comparatively coarser grained and more resistant. Figure 4-11 illustrates the contrasting character of the Cape Phillips Formation on each side of Trold Fiord. This change is due to a resurgence of laminated limestone, and massive and rudaceous graded limestone at the expense of both calcareous mudstone and chert. In contrast to the other Cape

Figure 4-8: Strike section B-B'. See Figures 4-1, -2, -3, -5 and -7 for symbols.

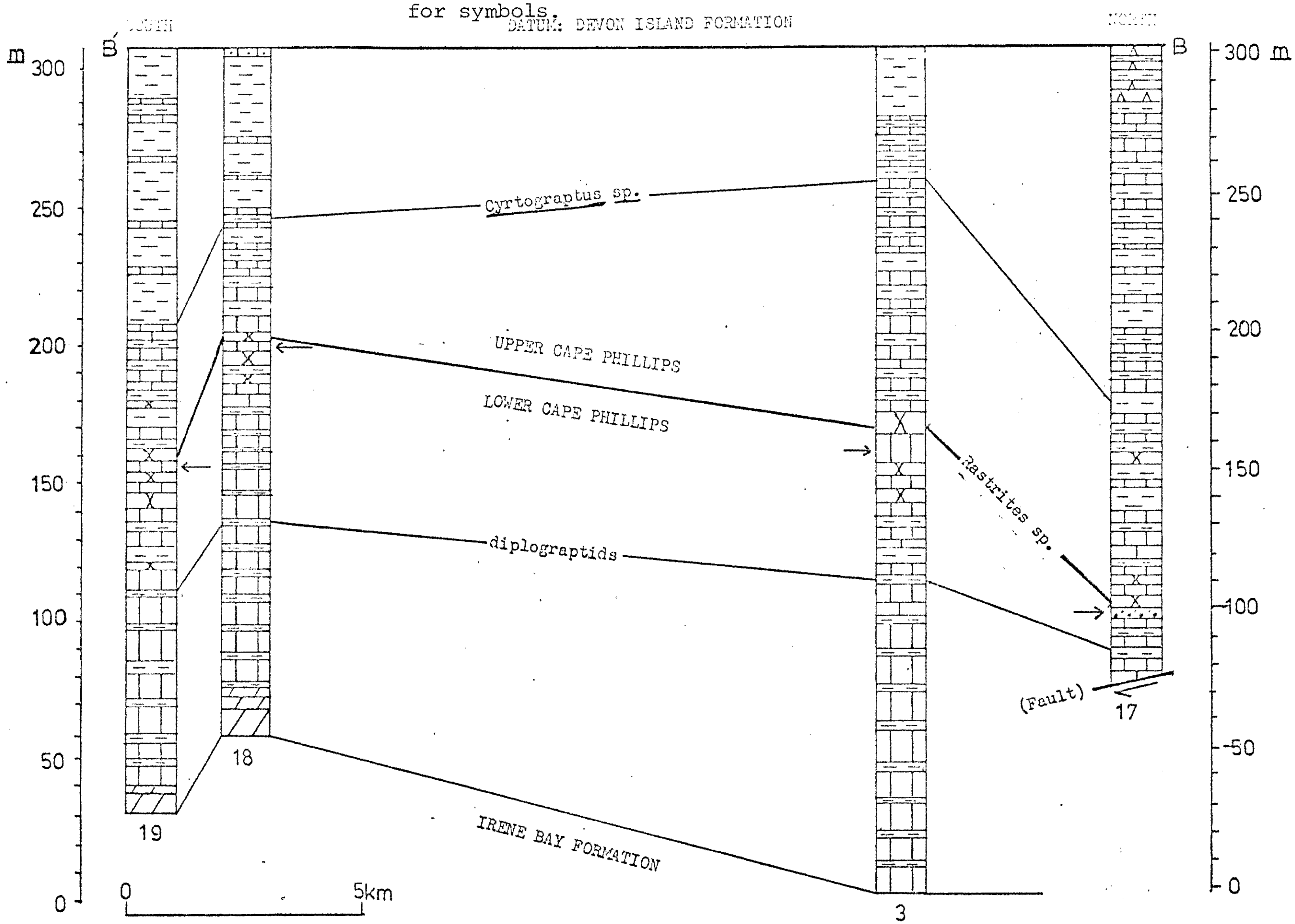


Figure 4-9: Strike section C-C'. See Figures 4-1, -2, -3, -5 and -7 for symbols.

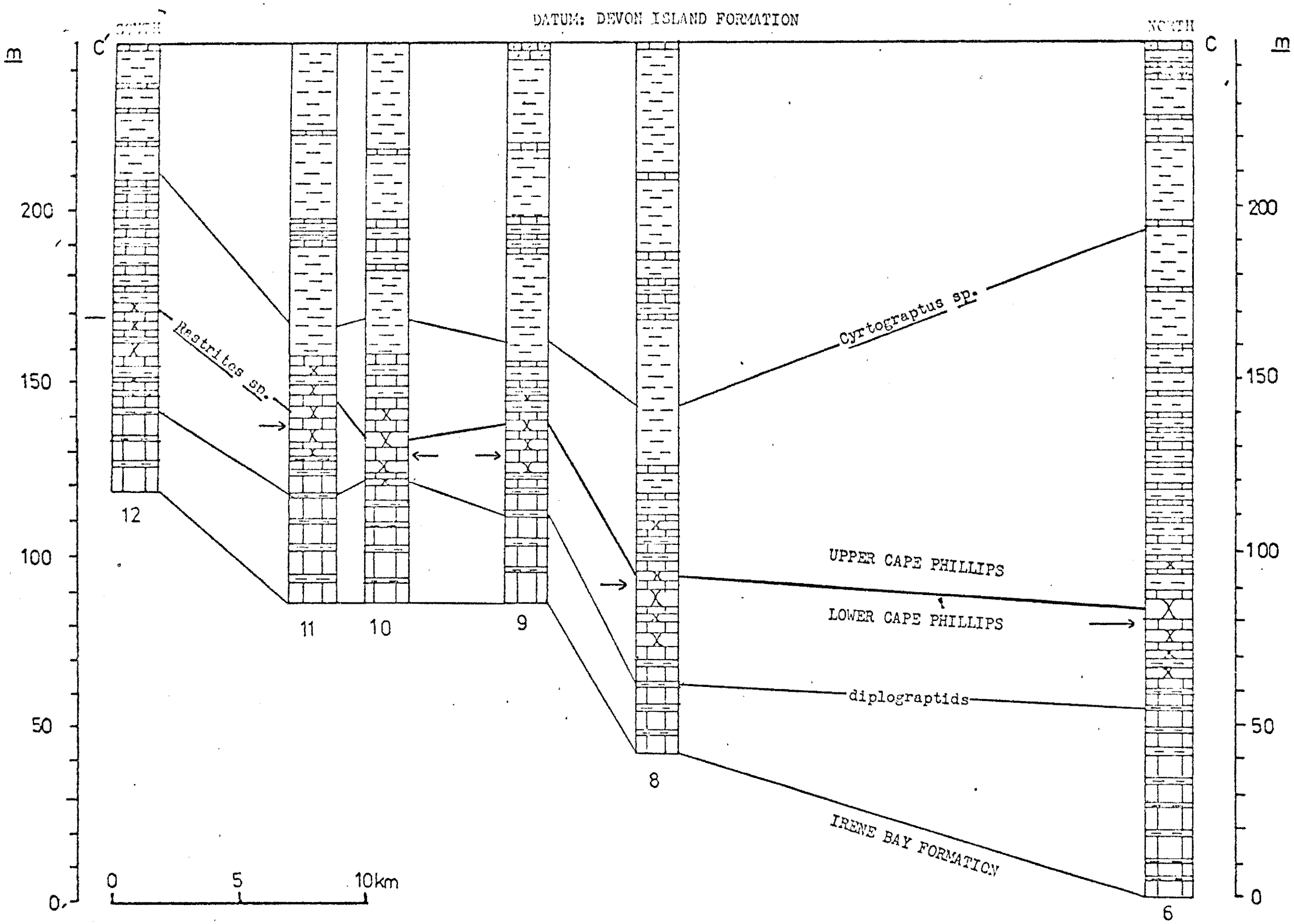


Figure 4-10: Strike section D-D'. See Figures 4-1, -2, -3, -5 and -7 for symbols.

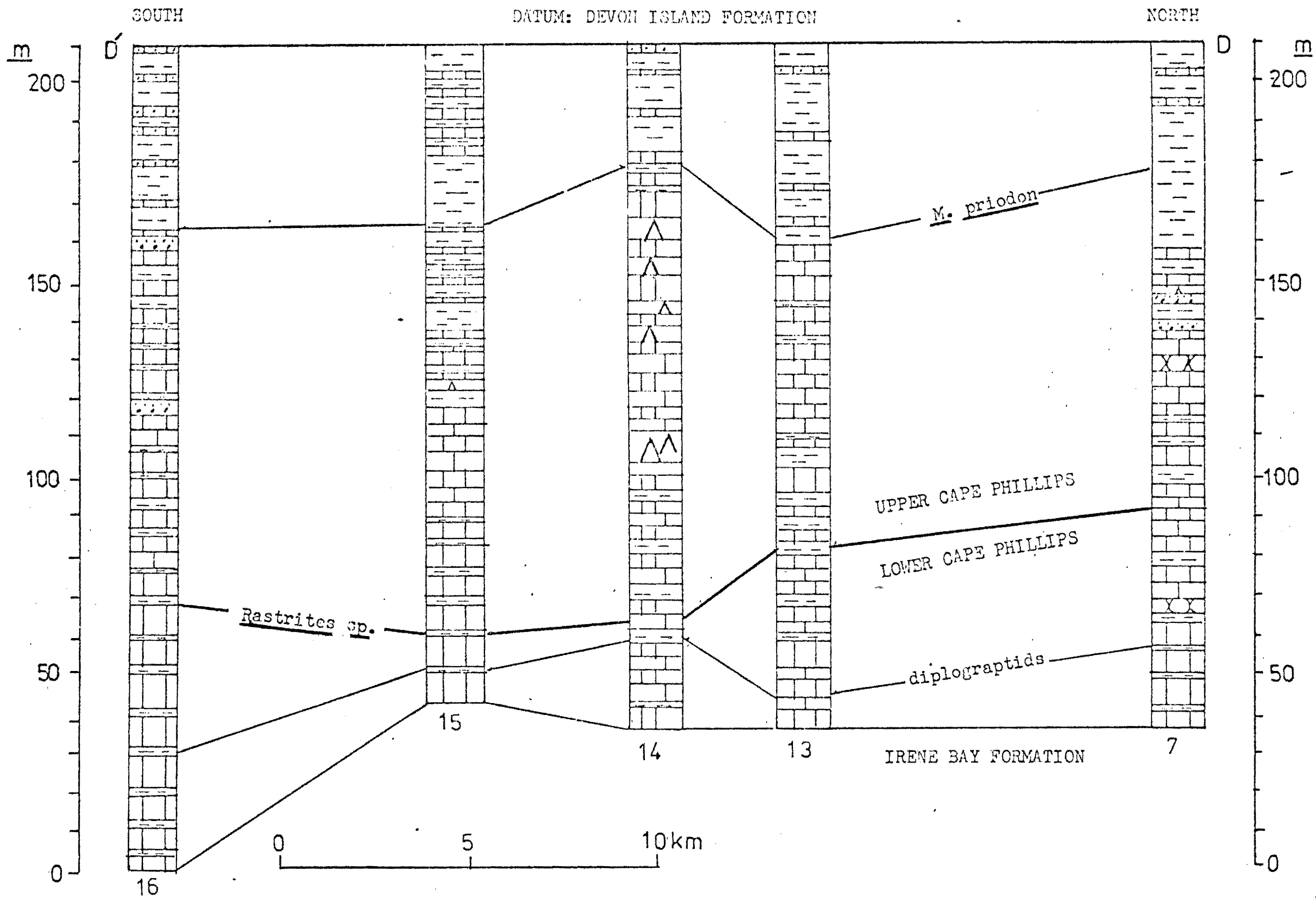
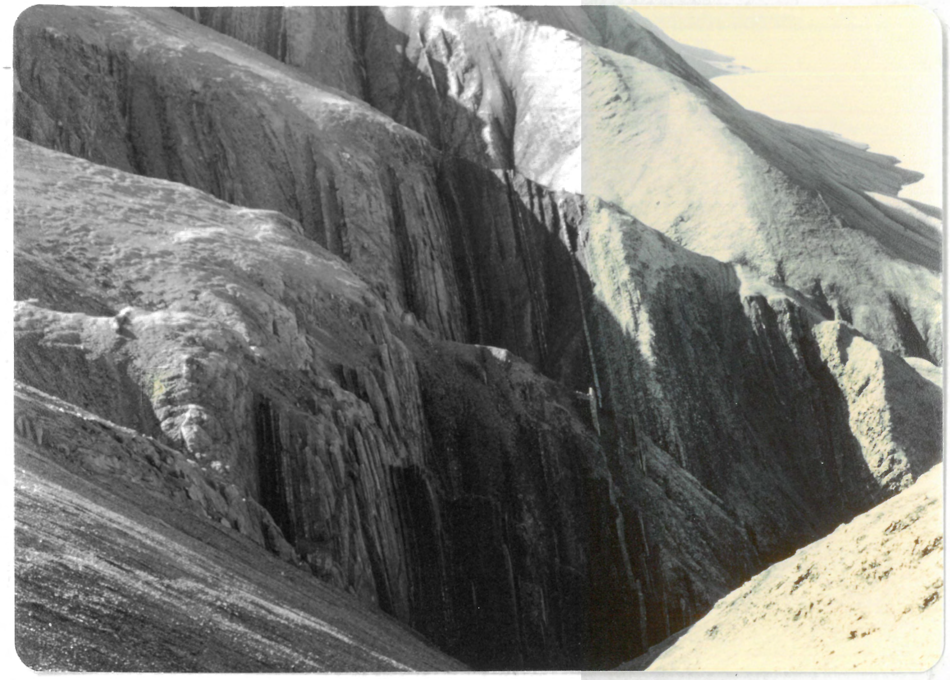


Fig. 4-11. Outcrops of the Cape Phillips Formation.

A



A. Section 11, East Trold Fiord Cape Phillips Belt. Section shown is about 200m thick. Note the vertical orientation of the beds and the recessive nature of the outcrop.

B

B. Photograph of the West Trold Fiord Cape Phillips Belt. The fiord is about 7km across and the relief on the far side is about 350m. The steep upper part of the hills consists largely of the Cape Phillips Formation. The strata here are overturned.

Phillips belts, the proportion of calcareous mudstone decreases southwards and the thickness of the strata increases. The lower Cape Phillips is comparatively underdeveloped here but rhythmite successions are present in the upper Cape Phillips.

LITHOFACIES ASSOCIATIONS

Each Cape Phillips belt described is characterized by a particular lithofacies association. These associations are summarized in Table 4-1 and discussed in detail in Chapter 6.

TABLE 4-1. Lithofacies Associations

	Measured Sections	Lithofacies	
		Major >10%	Minor
West Irene Bay	2	Laminated Dolomite	Laminated Limestone Calcareous Mudstone Massive Limestone
Huff Ridge	17, 3, 18, 19	Laminated Limestone Calcareous Mudstone	Chert Laminated Argillaceous Limestone
East Trold Fiord	6, 8, 9, 10, 11, 12	Calcareous Mudstone Laminated Limestone	Chert Laminated Argillaceous Limestone
West Trold Fiord	7, 13, 14, 15, 16	Laminated Limestone Calcareous Mudstone	Massive Limestone and Rudaceous Graded Limestone
Carbonate Buildup	1	Massive Dolomite	Quartzose Mudstone Massive Limestone Laminated Limestone

CHAPTER 5

ORIGIN OF LITHOFACIES

The origin of the lithofacies is interpreted in terms of: 1) sedimentary constituents and textures; and 2) stratigraphic distribution in relation to the shelf-slope model outlined in Chapter 2 (Fig. 2-4).

LAMINATED LIMESTONE

Features exhibited by this lithofacies include

1) Thin planar laminae are common
2) Wavy and small-scale cross laminae are present but rare
3) Bed thickness decreases directly with a decrease in grain size
4) Sorting is moderate to poor
5) Clasts include shallower water marine benthos. Deeper water benthos (Trilobites) are locally abundant. Pelagic organisms such as graptolites are rare
6) Lithoclasts may be present
7) Graded bedding is present but uncommon
8) Basal and upper bed contacts are sharp
9) General absence of sole marks or erosional marks of any kind.

These features suggest that the laminated limestone are limestone turbidites (see Flugel, 1982). The lack of erosional marks associated with these turbidites precluded paleocurrent determinations in the field. The differences between limestone and siliceous turbidites are examined by Flugel (1982, p. 510) and will not be elaborated here. Rare beds of laminated limestone contain graptolites which seemingly have been hydrodynamically aligned approximately east-west, suggesting that the turbidity currents were coming from the east or west.

There were two potential source areas of limestone turbidites of the Cape Phillips Formation: 1) a shallow-water carbonate platform (banks, reefs and atolls), or 2) forereef and upper slope environments. The forereef and particularly the upper slope source is suggested by the paucity of typical reefal bioclasts of this time frame, namely corals, algae and stromatoporoids (Wilson, 1975). Flugel (1982) pointed out that the most common internal structure of limestone turbidites is horizontal lamination. In addition, graded units are rare and the pelitic division E is never present.

At outcrop scale, the beds are planar and of uniform thickness along strike. However, on a regional scale (Figs. 4-7, 8, 9) the beds thin and become finer grained. Flugel (1982) and Davies (1977) indicate that turbidite beds should thin and become finer grained away from the source area. This suggests easterly and northerly sources for the turbidites of the Cape Phillips Formation east and north of Trold Fiord. Westerly and southerly sources are suggested for the West Trold Fiord Cape Phillips Belt.

Events such as periodic storms, earthquakes or slumps due to over-steepening triggered movements of unconsolidated and semi-consolidated sediment and generated downslope moving gravity flows such as turbidites.

The minimally abraded nature of the trilobite fauna of the Huff Ridge Cape Phillips Belt suggests that they represent parautochthonous benthos indigenous to this part of the basin. Turbidity currents probably originated in oxygenated water and the oxygen brought down into the basin during the Ashgillian must have been sufficient to support benthic life here. Elsewhere in the study area, trilobites are rare.

LAMINATED ARGILLACEOUS LIMESTONE

The depositional mechanisms were probably quite similar to those described above for laminated limestone. The argillaceous nature of these rocks, as well as that of the interbedded calcareous and quartzose mudstone, reflects a general increase of terrigenous input into the basin during the upper Wenlockian and Ludlovian. The beds of laminated argillaceous limestone are not noticeably thicker or coarser grained toward the east or north. Graptolites are generally absent from these rocks. It is assumed that the echinoderm and ostracod fragments, and sponge spicules were transported to the site of deposition as they are aligned parallel to bedding. It is concluded that this lithofacies was deposited by distal turbidity currents derived from an upper slope environment.

MASSIVE LIMESTONE AND RUDACEOUS GRADED LIMESTONE

Significant features of these rocks are listed below:

1) Thick massive beds with planar bases
2) Matrix support. Partial clast support in some beds
3) Little or no preferred orientation of clasts
4) Very poor sorting
5) Mixtures of angular and rounded clasts
6) Graded bedding (Rudaceous graded limestone only)
7) Irregular tops may be present

These data suggest two origins for this lithofacies: 1) massive limestone was deposited by debris flows and grain flows; and 2) rudaceous graded limestone were deposited by turbidity currents (Fig. 5-1).

Fig. 5-1. Photograph of a thin section of a limestone turbidite. The lower part is noticeably graded and consists of poorly sorted echinoderm fragments and lithoclasts. The upper part is better sorted and consists of fine-grained carbonate with angular lithoclasts and convolute lamination (bar is about 0.75cm long).

Massive limestone forms lenticular sheets and rarely channel deposits. A channel deposit in section 14 (Fig. 4-9) is a maximum of 7m thick and up to 20m wide along strike.

Flugel (1982) indicated that calcareous debris flows and grain flows are mostly found proximally to their source areas. Massive limestone is most prevalent in sections 2, 7 (Fig. 4-6) and 14 (Fig. 4-9).

Rudaceous graded limestone is coarser grained than laminated limestone, and is less prevalent in the study area. It occurs in sections 17 (Fig. 4-7), 7 and 16 (Fig. 4-9) and may be the proximal equivalent of laminated limestone. For example, the marker limestone in Section 17 is rudaceous graded limestone. However, in section 3 the marker limestone is graded grainstone (laminated limestone lithofacies) and in section 6, upgraded wackestone.

These gravity flows were probably triggered by the same mechanisms discussed above for laminated limestone. Indeed, debris flows and grain flows may have been precursors of many if not all of the turbidity currents (see Cossey and Ehrlick, 1979).

MUDSTONE

The dark, laminated and graptolitic calcareous mudstone was deposited by settling from hemipelagic and pelagic suspension and from turbid (nepheloid) layers. Studies on the origin of lime mud in Florida Bay, the Bahamas, Campeche Bank, and the Persian Gulf suggest that modern lime mud forms in large quantities in very shallow water (<30m) and that the rate of production is very high (Wilson, 1969).

Lime mud is mostly of organic origin, resulting from abrasion and disintegration of organisms and from inorganic precipitation. It can be carried into deeper water or shorewards. Currents generated by waves and tides may produce turbid layers which can occur at different levels in the water column. Moore (1969) suggested that turbid layers which form close to the sea bottom in outer shelf environments move down slope under the influence of gravity to form low density and low velocity turbidity currents which are not related to slumps or slides. The characteristic structure of their deposits is thin, planar lamination due to vertical variations in organic carbon content. Turbid layers well above the bottom of the sea are underlain by denser water which prevents settling, and sedimentation occurs at the margin of the supporting layers (Harlett and Kuln, 1973). It is at present difficult to separate deposits formed by hemipelagic setting from those of nepheloid layers. Deposition rates of mudstone were comparatively less than that of other lithofacies as shown by the abundance of graptolite fauna.

Increased terrigenous and clastic input into the basin during upper Wenlockian and Ludlovian times resulted in the deposition of quartzose mudstone by the mechanisms described above.

CHERT

Settling from pelagic and hemipelagic suspensions resulted in the deposition of radiolarian chert. The secondary and void-infilling textures of the replacement chert suggests an origin from silicification of calcite in laminated and massive limestone.

Today, while radiolaria are not restricted to deep water environments; radiolarian sedimentation is slow and effective only where other types of deposition are comparatively insignificant. These deposits may also be preserved in deeper water environments where calcium carbonate is dissolved or is not deposited due to the distance from source areas.

Radiolarian chert occurs in early to middle Llandoverian time over an extensive region from section 3 westwards (Fig. 4-6). This implies that carbonate sedimentation was periodically reduced during this time. The East Trold Fiord Cape Phillips Belt contains the maximum development of radiolarian chert which suggests that this was the deepest and most remote part of the basin. The relatively high proportion of carbonaceous organic matter in these rocks indicates very slow deposition in an environment of low oxygen tension where the organics would be preserved.

The radiolarian chert is locally fractured and brecciated. Steinitz (1970) described brecciation in Upper Cretaceous cherts of Israel and suggested that it was due to diagenesis. He made a convincing case for siliceous sediments remaining unlithified for much longer than the surrounding carbonates. Significant lithostatic pressure would have been exerted by the column of overlying sediments at the time of deformation. Plastic and nonplastic deformation events would result from an inter-layer diagenetic volume growth under conditions of considerable confining pressure. In the initial stages of this process, active plastic deformation would occur. This may account for folded laminae in Figure 5-2. As the volume growth continues in the remaining unlithified parts of the sediment, non plastic or brittle deformation of the lithified parts would occur. The expanding siliceous sediment may intrude between the fragments to form siliceous veins, the emplacement of which may in part represent forceful injection of sediment. Steinitz (1970) indicated

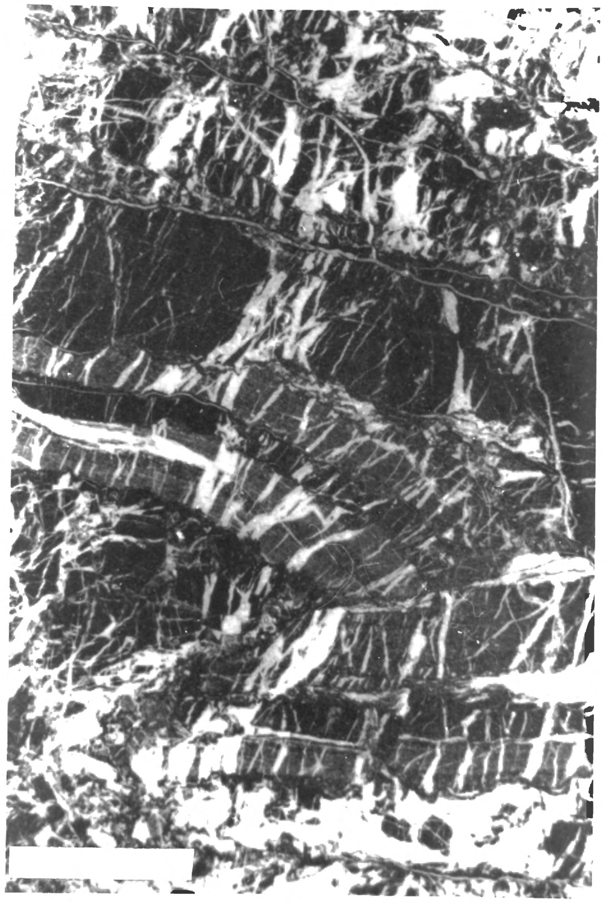


Fig. 5-2. Photomicrograph of deformed laminae in radiolarian chert. Note the folding and juxtaposition of the laminae in the center of the picture, and the extreme brecciation (bar is about 1mm long).

that the mechanisms for this volume growth during lithification was unknown at the time of writing. Alternatively, much of the brecciation may have occurred in response to tectonic deformation during the Devonian and Cenozoic orogenic events.

Replacement chert was probably derived from dissolution and reprecipitation of silica from opaline radiolaria and possibly siliceous sponge spicules. Replacement of carbonate by silica is indicated by the presence of silicified ghosts of calcareous matrix and bioclasts. Replacement must have occurred relatively early in the diagenetic history of the sediments before fluid flow was strongly impeded. The model of silicification presented here is based on the studies of Dapples (1959, 1967), Emery and Rittenberg (1952), Krauskopf (1959), Nemel et al. (1953), and Siever (1962). Decay of carbonaceous matter within the sediment lowered the pH of the pore water resulting in the dissolution of carbonate and precipitation of silica. Movement of silicification solutions was probably promoted by compaction and overburden pressure. The source of the silica may have been opaline-A radiolarians and perhaps sponge spicules. Dissolution of these would yield a pore solution supersaturated with quartz and cristobalite. Volcanic activity in the Pearya Geanticline during Upper Ordovician and Silurian time (Trettin, 1973) may in part have been the ultimate source of silica.

Most of the chert in section 6 is radiolarian, whereas most of the chert in section 3 is replacement chert. This suggests that silicification solutions migrated up dip from the deeper parts of the basin.

MASSIVE AND LAMINATED DOLOMITE

These lithofacies reflect diagenetic dolomitization of the Carbonate Buildup and its associated breccias.

The Carbonate Buildup may have been a reefal belt. Evidence for this includes its massive nature, and the presence of colonial corals (Favosites) and stromatoporoids in the breccia beds of the Devon Island Formation which interfinger with the Carbonate Buildup. McGill (1974) and Mayr (1974) reported the presence of dolomitized reefal buildups west of Vendorn Fiord, southeast of the study area.

The subhedral, angular and well sorted crystals in laminated dolomite suggest that it is not detrital. The presence of calcitic fossil fragments and lamination implies that dolomitization of laminated limestone produced laminated dolomite.

The distribution of dolomite is important in attempting to explain its origin. The occurrence of dolomite within the Carbonate Buildup and in the adjacent Cape Phillips Formation represented by section 2 contrasts with the calcite-dominated Cape Phillips Formation of the deeper water basin to the west. This implies that dolomitization was a process related to Upper Ordovician to Middle Silurian paleogeography in the study area.

At present, three models of dolomitization have been proposed: 1) burial compaction; 2) refluxing brines; and 3) mixing waters. The relative absence of significant quantities of dolomite in the deeper water sections suggests that dolomitization was not promoted by solutions derived from the burial compaction of the Cape Phillips Formation. The reflux model is also inappropriate because evaporitic minerals were not observed. Furthermore, features such as collapse breccias, evaporitic pseudomorphs, silicified or calcified evaporite nodules and crystal molds are absent.

The schizohaline model has been proposed by Land et al. (1975), Morrow and Kerr (1977) and Sodero and Hobson (1979) to account for dolomitization of the Allen Bay Formation. In the study area, the Carbonate Buildup does not display caliche zones, fenestral fabrics or desiccation cracks. However, huge solution cavities are present (Fig. 3-19). These may indicate that parts of the reefal belt were subaerially exposed for short periods of time. In addition, dolomitization must have preceded deep burial in order for the sediments to be porous enough to allow dolomitizing fluids to pass. These assumptions suggest that the schizohaline model is applicable to the study area. The major dolomitizing event took place as a result of the mixing of meteoric-derived groundwater and marine pore-water in the manner described by Dunham and Olson (1977). Substantial freshwater lenses may have formed beneath subaerially exposed parts of the carbonate platform. Lateral and vertical movement of these into the subtidally deposited sediment of the Cape Phillips Formation resulted in dolomitization. The maximum extent of dolomitization is marked by the dolomite to limestone lateral transition between section 2 and 3 (Fig. 4-6). The deeper water limestone was beyond the reach of the dolomitizing solutions. The lateral and vertical extent of dolomitization was probably controlled by the porosity, position of sea level and amount of hydraulic head available. The proximal distribution of laminated dolomite suggests that the porous and dolomitized breccias provided the principal distribution channels for the dolomitizing solutions.

Although the schizohaline model seems appropriate, the validity of its application can be questioned. For example, the solution cavities in the carbonate buildup are uncertain indicators of subaerial exposure. In addition, section 2 was further west before tectonic deformation brought it to within 1.5km of the Carbonate buildup. For it to have been dolomitized, the processes described above should have been operative over a lateral scale of several kms or even tens of kms. This is difficult to envisage.

To account for the presence of dolomite within the radiolarian and replacement cherts, and mudstone in the deeper water sections to the west, the model of Baker and Kastner (1981) is invoked. Dolomite in these sections is associated with recrystallized biogenic silica; it is a significant component of organic-rich marine sediments in modern deep sea environments (Baker and Kastner,1981). Based on experimental evidence, they propose that dolomite can precipitate rapidly when SO_4^{2-} concentrations are low. Microbial reduction in organic-rich sediments reduces SO_4^{2-} concentrations. Baker and Kastner (1981) indicated that SO_4^{2-} reduction fermentation or methanogenesis would provide HCO_3^- for the formation of dolomite in organic-rich and carbonate-poor sediments. Experimentally, they showed that the transformation of opal-A to Opal-CT may produce Mg^{2+} and OH^- - containing nuclei that are taken up during Opal CT formation.

Dolomite is then formed in chert when opal CT transforms to quartz and releases Mg^{2+}.

CHAPTER 6

SYNTHESIS

The Carbonate Buildup - Cape Phillips Formation facies transition can be subdivided into five major zones from east to west: 1) carbonate platform; 2) upper slope; 3) lower slope; 4) basin; and 5) lower slope (Fig. 6-1). These zone distinctions are based on the lithofacies associations presented in Chapter 4 (see table 4-1). Each lithofacies group is characteristic of an environment of deposition within the shelf-slope model framework of Figure 2-4.

CARBONATE PLATFORM

This zone is characterized by a massive and dolomitized reefal belt and associated fore-reef breccias. The westward boundary of this zone coincides with the facies transition into the basinal-rocks of the Cape Phillips Formation.

Only minor amounts of terrigenous material were deposited within the basin during the accumulation of the Cape Phillips Formation. Regional mapping did not indicate the presence of submarine fans, major channels or canyons within the basin. These features were not developed because the Carbonate Buildup was a line source of sediments. The extensive carbonate reefal belt prevented significant quantities of terrigenous material from entering the basin until upper Wenlockian and Ludlovian times when the Devon Island Formation was accumulating.

UPPER SLOPE

The upper slope zone is characterized by a relatively thin and coarse-grained succession predominantly of laminated dolomite, which is diagenetic after laminated limestone of turbiditic origin. These rocks are assumed to interfinger with breccia beds of the carbonate platform zone to the east. Debris flow deposits (massive limestone) contain fragments of peloidal and bioclastic packstone probably derived from the forereef area. The relatively minor mudstone and chert here suggest that sedimentation from pelagic and hemipelagic suspension or turbid layers was relatively unimportant.

In Chapter 4, it was concluded that the upper slope area was a source of gravity flows. The slumping and sliding of sediment basinward may account for the thinness of the strata here, particularly in the upper Cape Phillips.

Graptolites are fairly abundant in the upper part of the succession. However diversity is relatively restricted compared to deeper water zones to the west.

LOWER SLOPE

Lower slope lithofacies associations occur in two locations (Fig. 6-1). The eastern lower slope zone consists mostly of laminated limestone with calcareous mudstone (usually rhythmically interbedded) and minor chert. Massive limestone and rudaceous graded limestone are relatively rare.

The lower Cape Phillips is predominantly a thick rhythmite sequence. The upper Cape Phillips contains thinner rhythmite sequences and calcareous mudstone becomes increasingly predominant near the top. The Cape Phillips Formation is thickest in this zone. The abundance of laminated limestone and calcareous mudstone suggests that distal gravity flows and settling from suspensions were both volumetrically important processes.

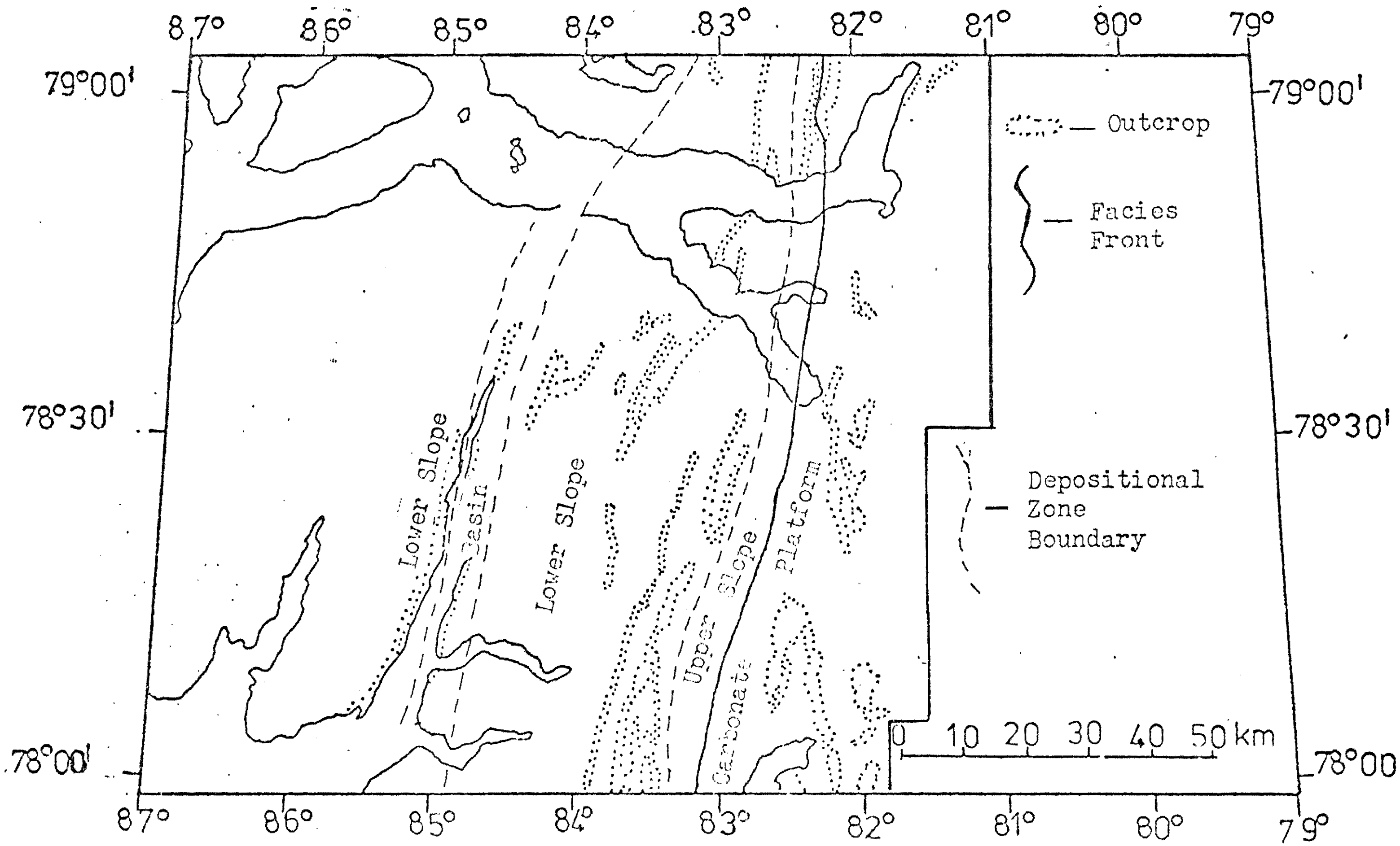


Figure 6-1: Paleogeographic map showing the depositional zones of the Carbonate Buildup-Cape Phillips Formation Facies Transition (Modified from Trettin, 1978).

Graptolitic fauna is both abundant and diverse. Benthic trilobites were abundant during the Ashgillian in this area.

In contrast, the western Trold Fiord lower slope zone consists of a thinner, more proximal assemblage. Laminated limestone is comparatively common here, and massive limestone and rudaceous graded limestone are significant. This implies that proximal and distal gravity flows are comparatively more important in this western zone. The lower Cape Phillips is thin and underdeveloped. Rhythmite sequences occur in the upper Cape Phillips but mudstone predominates near the top of the succession. In the eastern zone, the strata thinned and fined southward. Here the opposite occurs.

Graptolite fauna is comparatively less abundant and diverse, while trilobites are extremely rare.

Differences between east and west lower slope zones can be attributed to different source areas. Strata to the west are proximal to western or southern source areas.

BASIN

The basinal assemblage is characterized by the predominance of calcareous mudstone with laminated limestone and a thick development of chert. Massive limestone and rudaceous graded limestone are very rare. The assemblage emphasizes the importance of settling of fine-grained carbonate and siliceous detritus over sedimentation from distal gravity flows, which accounts for the relative thinness of the strata. The abundance of mudstone and thick development of chert reflects maximum depths and distances from source areas. Graptolite fauna here are most abundant and very diverse while trilobites are rare. It is

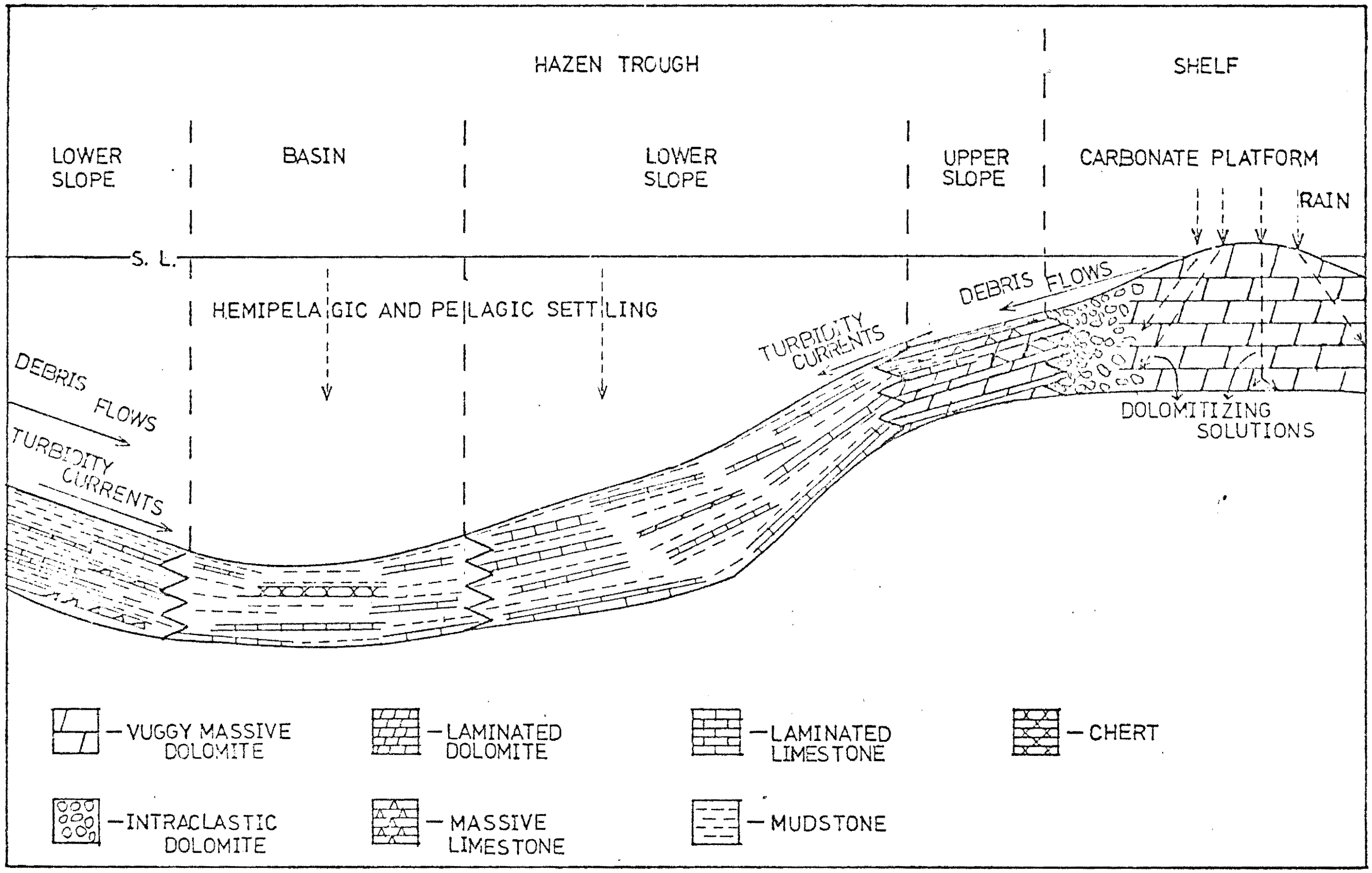


Figure 6-2: Schematic cross-section of proposed facies model.

concluded that the axis of the paleobasin passed almost north-south through this zone.

The cross-section in Figure 6-2 is a schematic illustration of the proposed depositional model of the Cape Phillips Formation.

RATES OF DEPOSITION

Characteristics such as mm-scale lamination, relatively high organic content and slow deposition at a rate of 6mm/1000 yrs. or less are typical of sediment-starved basins (Lineback, 1968, 1969; Conant and Swanson, 1961). Rates of deposition per stage of the Cape Phillips Formation were calculated using absolute ages from Braziunas (1975). Thicknesses of strata, based on the distribution of trilobites and graptolites (Morganti, 1979) were derived from section 3 for two reasons: 1) the Ashgillian here is well defined by the abundance of trilobites; and 2) it is one of the four major sections that were sampled in detail. The results are shown in Table 6-1. These show that the Hazen Trough may have been a sediment-starved basin only during the Wenlockian.

EVIDENCE OF DEEP WATER CONDITIONS

The regional zonal distribution indicates increasing water depths westward followed by an abrupt shallowing across what is now Trold Fiord. The following lines of evidence indicate that the Cape Phillips Formation was deposited in deep water:

1) The relatively high concentration of organic carbon suggests deposition from poorly oxygenated waters below wave base (Wilson, 1969).

2) The presence of beds with characteristics of turbidites and debris flows.

3) The Cape Phillips is a condensed age equivalent of the Carbonate

TABLE 6-1. Calculated Rates of Deposition of the Cape Phillips Formation

Stage	Duration (million yrs.)	Thickness of Strata (m)	Deposition Rate (mm/1000 yrs.)
Ashgillian	2.5	110	44
Llandoverian	10	140	14
Wnelockian	10	55	5.5
Total	22.5	305	12

Buildup.

4) The indigenous fauna is generally pelagic. The presence of mm-scale planar lamination indicates bottom conditions of low oxygen tension, precluding the existence of benthos throughout most of the deposition of the Cape Phillips Formation. The presence of parautochthonous trilobites in the eastern lower slope zone suggests that the onset of poorly oxygenated conditions here was post-Ashgillian. The isolated nature of the Hazen Trough precluded total mixing with the open sea which induced anoxicity in the basin.

DEPTHS

The absence of current structures, apart from those of turbidites, in the Cape Phillips Formation indicates that it was deposited below wave base. Taking wave base to be about 100m, this suggests that the shallowest portion of the basin edge was deeper than 100m. The stratigraphic relief between sections 1 and 2, based on the occurrence of the graptolite *M. dubius*, is 945m. This indicates water depths of at least 845m at the top of the Cape Phillips Formation in section 2. It is emphasized that this is only a crude estimate. This method was used by Yurewicz (1977) to estimate water depth during the deposition of the Rancheria Formation of New Mexico and West Texas. The maximum depth of the Hazen Trough during deposition of the Cape Phillips Formation was probably above the carbonate compensation depth of about 5,400m (Pettijohn, 1975).

The predominance of the distal basinal assemblage in the upper Cape Phillips, overlying the proximal lower and upper slope assemblages of the lower Cape Phillips is the result of both basin deepening and an eastward migration of the basinal lithofacies across the shelf. This transgression of the Cape Phillips - Devon Island Formation shelfward has been reported west of Vendom Fiord by McGill (1974) and Mayr (1974).

CHAPTER 7

CONCLUSIONS

1) The Cape Phillips Formation-Carbonate Buildup lateral facies transition can be subdivided into seven lithofacies. Six of these constitute the Cape Phillips Formation: laminated limestone, mudstone, massive limestone and rudaceous graded limestone, laminated dolomite, chert and laminated argillaceous limestone. The seventh, massive dolomite, comprises most of the Carbonate Buildup.

2) Laminated limestone, argillaceous laminated limestone and rudaceous graded limestone were deposited by turbidity currents. Massive limestones are debris and grain flow phenomena. Mudstone and radiolarian-chert were deposited from hemipelagic and pelagic suspensions and turbid layers. Replacement chert formed by the dissolution and reprecipitation of silica, after calcite. Dolomitization of the carbonate reefal belt and the adjacent Cape Phillips Formation formed massive dolomite and laminated dolomite respectively. Dolomitization may have occurred in a schizohaline environment.

3) Overall the strata thins and fines westward and southward, east of Trold Fiord. These changes reflect increasing distance from source areas to the east and north. On the west shore of Trold Fiord the strata is comparatively coarse, and fines and thins northward. This trend reflects increasing distance from source areas to the west and south.

4) Five depositional zones are recognized which run parallel to the axis of the paleobasin. From east to west these are: carbonate platform, upper slope, lower slope, basin and lower slope. Each zone is defined on the basis of distinctive lithofacies associations. Graptolite

fauna indicate that these zones are laterally equivalent.

5) The average rate of accumulation of the Cape Phillips Formation was 12mm/1000 yrs. Therefore the Hazen Trough probably was not a starved-sediment basin during this time.

6) The Cape Phillips Formation accumulated in depths of between 100m and 5,400m.

ACKNOWLEDGEMENTS

The writer is indebted to Petro-Canada (Coal and Minerals Division) who sponsored the field work for the thesis. I would like to thank Mr. J. Chris Harrison for his guidance and assistance during the field work.

The fossils used in this report were identified by Mr. J. Chris Harrison, Mr. R. Thorsteinsson and the writer.

The writer has been supervised by Dr. M. M. Gibling, Assistant Professor at Dalhousie University. The opportunity to discuss thesis related problems with him is greatly appreciated.

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WORK SCHEDULE

The following is a summary of the time spent on each aspect of the project.

FIELD WORK

A total of nineteen stratigraphic sections were measured during nineteen days of field work in the summer of 1982. Supervision and assistance were provided by C. Harrison, an exploration geologist with Petro-Canada, during most of the field work. All of the lithological samples were collected by the author. Most of the fossils were identified by C. Harrison with assistance from the author and R. Thorsteinsson of the G.S.C. Most of the maps of the study area were compiled and drafted by the author under the supervision of C. Harrison.

LAB WORK

During the last two weeks of September, 1982, hand specimens were described and submitted for thin sectioning. Throughout October and November of 1982, thirty-three specimens were crushed to 63 microns or less and analysed by X-ray diffraction (for 2 theta values of 2 to about 60°). The diffractograms were analysed as obtained.

Twenty-five thin sections were returned on December 3, 1982. These were examined over the Christmas break. By January 10, 1982, thirty more thin sections were returned. These were examined during the rest of January, 1982 with some assistance from Dr. M. Gibling and Dr. L. Jansa.

READING AND PHOTOGRAPHY

A significant amount of reading was completed during the first term in order to investigate the geology of other documented facies transitions of this type. During the early part of the second term (January and most of February), the reading material covered concerned more specific aspects of the project such as mechanisms of dolomitization.

Photographs of outcrops and rocks in the field were taken by the during the summer of 1982. Photomicrographs and photographs of the hand specimens and fossils were taken by the author during late January and early February of 1983.

The first draft of the project was prepared during the last week of January and the first week of February. This initial draft was critically reviewed by Dr. M.R. Gibling. The draft was rewritten and resubmitted on March 7. From March 8 to 21, the diagrams were drafted and the final manuscript was typed by Debbie.

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APPENDIX 1

ROCK ANALYSES

A total of 74 specimens were analysed for the present study. Quantitative and nonquantitative observations are tabulated in Table Al-2.

X-RAY ANALYSIS

Whole-rock X-ray diffractograms were obtained for those specimens indicated in Table Al-2. These diffractograms were analysed as obtained and it was found that seven minerals or mineral groups are present. These minerals and their values of 2 theta are:

calcite	29.4°
dolomite	30.9°
quartz	26.8°
mica/illite	8.8°
chlorite	12.6°
K-feldspar	27° to 27.5°
plagioclase	28°

The percentages listed for individual minerals or mineral groups in Table Al-2 reflect the height of the principal peak of that mineral multiplied by the corresponding intensity factor from Table Al-1. These percentages are related to the relative abundance of the minerals or mineral groups but not equal to it.

THIN SECTION ANALYSIS

Compositional analysis was carried out either by visual estimate in conjunction with X-ray diffraction for fine-grained samples or by visual estimate alone for coarser-grained samples. The relative abundances of

Table Al-1: Intensity factors for semiquantitative analysis of X-ray diffractograms (Cook *et al*, 1975).

TABLE 1
Minerals Actively Sought in Diffraction Data Analysis

Mineral	Window (°2θ, CuKα Radiation)	Range of D-Spacings (Å)	Intensity Factor[a]
Amphibole	10.30–10.70	8.59– 8.27	2.50
Analcite	15.60–16.20	5.68– 5.47	1.79
Anatase	25.17–25.47	3.54– 3.50	0.73
Anhydrite	25.30–25.70	3.52– 3.46	0.90
Apatite	31.80–32.15	2.81– 2.78	3.10
Aragonite	45.65–46.00	1.96– 1.97	9.30
Augite	29.70–30.00	3.00– 2.98	5.00
Barite	28.65–29.00	3.11– 3.08	3.10
Calcite	29.25–29.60	3.04– 3.01	1.65
Chlorite	18.50–19.10	4.79– 4.64	4.95
Clinoptilolite	9.70– 9.99	9.11– 8.84	1.56
Cristobalite	21.50–22.05	4.13– 4.05	9.00
Dolomite	30.80–31.15	2.90– 2.87	1.53
Erionite	7.50– 7.90	11.70–11.20	3.10
Goethite	36.45–37.05	2.46– 2.43	7.00
Gypsum	11.30–11.80	7.83– 7.50	0.40
Halite	45.30–45.65	2.00– 1.99	2.00
Hematite	33.00–33.40	2.71– 2.68	3.33
Kaolinite	12.20–12.60	7.25– 7.02	2.25
K-Feldspar	27.35–27.79	3.26– 3.21	4.30
Magnetite	35.30–35.70	2.54– 2.51	2.10
Mica	8.70– 9.10	10.20– 9.72	6.00
Montmorillonite	4.70– 5.20	18.80–17.00	3.00
Palygorskite	8.20–8.50	10.70–10.40	9.20
Phillipsite	17.50–18.00	5.06– 4.93	17.00
Plagioclase	27.80–28.15	3.21– 3.16	2.80
Pyrite	56.20–56.45	1.63– 1.62	2.30
Rhodochrosite	31.26–31.50	2.86– 2.84	3.45
Quartz	26.45–26.95	3.37– 3.31	1.00
Sepiolite	7.00– 7.40	12.60–11.90	2.00
Siderite	31.90–32.40	2.80– 2.76	1.15
Talc	9.20– 9.55	9.61– 9.25	2.56
Tridymite	20.50–20.75	4.33– 4.28	3.00
Gibbsite	18.00–18.50	4.93– 4.79	0.95

[a]The intensity factors are determined in 1:1 mixtures with quartz by obtaining the ratio of the diagnostic peak intensity of each mineral with the intensity of the diagnostic peak of quartz, which is assigned a value of 1.00. The detection limit in weight percent of the minerals in a siliceous or calcareous matrix can be obtained by multiplying the intensity factor by 0.12.

Table Al-2: Summary X-ray diffractional thin section analysis.

Sample	Section	Height (m)	Formation	Age	Method of Analysis	Calcite%	Dolomite %	Quartz %	K-feldspar %
1	6	0	Irene Bay	Ashgillian	Thin Section	100	—	—	—
2	6	18	Cape Phillips	Ashgillian	Thin Section	100	—	—	—
3	6	29	Cape Phillips	Ashgillian	Thin Section and X-rd	100	—	—	—
4	6	43	Cape Phillips	Ashgillian	Thin Section	100	—	—	—
5	6	45	Cape Phillips	Ashgillian	Thin Section and X-rd	68	18	14	—
8	6	50	Cape Phillips	Ashgillian	X-rd	87	3	10	—
10	6	56	Cape Phillips	Llandoverian	Thin Section and X-rd	4	—	96	—
11	6	59	Cape Phillips	Llandoverian	Thin Section and X-rd	44		56	—
12	6	58	Cape Phillips	Llandoverian	X-rd	71	2	20	7
13	6	77	Cape Phillips	Llandoverian	Thin Section and X-rd	90	[illegible]	8	—
14	6	75	Cape Phillips	Llandoverian	Thin Section	23	2	75	—
15A	6	79	Cape Phillips	Llandoverian	Thin Section	25	—	75	—
15B	6	79.5	Cape Phillips	Llandoverian	Thin Section	95	—	5	—
16	6	111	Cape Phillips	Llandoverian	X-rd	73	8	12	7
17	6	134.5	Cape Phillips	Llandoverian	Thin Section	25	—	75	—
18	6	149	Cape Phillips	Wenlockian	X-rd	66	3	26	5
19	6	240.5	Cape Phillips	Wenlockian	Thin Section	65	—	30	—
20	6	244	Cape Phillips	Wenlockian	Thin Section	54	—	30	—
21	6	248	Devon Island	Ludlovian	Thin Section	60	—	25	—
22	6	185	Cape Phillips	Wenlockian	Thin Section	90	—	10	—
23	6	187	Cape Phillips	Wenlockian	X-rd	19	7	74	—
24	6	247	Devon Island	Ludlovian	Thin Section and X-rd	—	14	58	—
25	6	61	Cape Phillips	Llandoverian	Thin Section	100	—	—	—
26	6	88	Cape Phillips	Llandoverian	X-rd	67	10	23	—
27	6	97.5	Cape Phillips	Llandoverian	X-rd	74	8	18	—
28	6	104	Cape Phillips	Llandoverian	X-rd	68	9	23	—
29	8	123	Cape Phillips	Wenlockian	Thin Section	90	—	10	—
30	8	143	Cape Phillips	Wenlockian	Thin Section	65	—	35	—
31	8	143.5	Cape Phillips	Wenlockian	Thin Section	65	—	15	—
32A+B	1	990	C. B.	?	Thin Section	—	100	—	—
33A	1	1070	C. B.	?	Thin Section	20	75	5	—
33B	1	1085	C. B.	?	Thin Section	39	60	1	—
33C	1	1095	C. B.	?	Thin Section	44	55	1	—

Table Al-2 cont'd.

Sample	Mica/Illite%	Chlorite %	Plagioclase%	Organic Content	Lithofacies
1	—	—	—	—	Bioclastic Wackestone
2	—	—	—	Low	Laminated Limestone
3	—	—	—	Low	Laminated Limestone
4	—	—	—	Low	Laminated Limestone
5	[illegible]	—	—	High	Calcareous Mudstone
8	—	—	—	High	Calcareous Mudstone
10	—	—	—	High	Radiolarian Chert
11	—	—	—	High	Radiolarian Chert
12	—	—	—	High	Calcareous Mudstone
13	—	—	—	Trace	Laminated Limestone
14	—	—	—	Low	Replacement Chert
15A	—	—	—	Low	Replacement Chert
15B	—	—	—	Low	Laminated Limestone
16	—	—	—	High	Calcareous Mudstone
17	—	—	—	High	Radiolarian Chert
18	—	—	—	High	Calcareous Mudstone
19	5	—	—	High	Laminated Limestone
20	16	—	—	Low	Laminated Argillaceous Limestone
21	15	—	—	Low	Laminated Argillaceous Limestone
22	—	—	—	Low	Laminated Limestone
23	—	—	—	High	Quartzose Mudstone
24	14	—	14	Low	Quartzose Siltstone
25	—	—	—	Trace	Rudaceous Graded Limestone
26	—	—	—	High	Calcareous Mudstone
27	—	—	—	High	Calcareous Mudstone
28	—	—	—	High	Calcareous Mudstone
29	—	—	—	Trace	Rudaceous Graded Limestone
30	—	—	—	Low	Laminated Limestone
31	—	—	—	Low	(20% Pyrite) Laminated Limestone
32A+B	—	—	—	—	(Vuggy) Massive Dolomite
33A	—	—	—	—	(Intraclastic) Massive Dolomite
33B	—	—	—	—	(Intraclastic) Massive Dolomite
33C	—	—	—	—	(Intraclastic) Massive Dolomite

Table A1-2 cont'd

Sample	Section	Height (m)	Formation	Age	Method of Analysis	Calcite%	Dolomite %	Quartz %	K-feldspar %
36	1	1103	C. B.	?	X-rd	24	12	37	10
37	1	1127	C. B.	?	Thin Section	100			
38	1	1153	C. B.	Ludlovian	Thin Section	80	—	10	—
39	1	1163	C. B.	Ludlovian	X-rd	9	11	32	18
40	1	1161	C. B.	Ludlovian	Thin Section	80	15	5	—
41	1	1222	C. B.	Pridolian (?)	Thin Section	10	90	—	—
42	2	20	Cape Phillips	Ashgillian	Thin Section		90	—	—
43	2	42	Cape Phillips	Ashgillian	Thin Section and X-rd	4	93	3	—
44	2	115	Cape Phillips	Llandoverian	Thin Section and X-rd	—	96	4	—
45	2	115.5	Cape Phillips	Llandoverian	Thin Section and X-rd	14	77	9	—
46	2	117	Cape Phillips	Llandoverian	Thin Section	10	70	20	—
47	2	125	Cape Phillips	Llandoverian	Thin Section and X-rd	49	24	20	7
48	2	133	Cape Phillips	Llandoverian	Thin Section and X-rd	—	40	60	—
49	2	135	Cape Phillips	Llandoverian	Thin Section and X-rd	29	4	67	—
50	2	150	Cape Phillips	Wenlockian	Thin Section	90	5	5	
51	2	165	Devon Island	Ludlovian	X-rd	3	3	49	—
54A+B+C	17	100–102	Cape Phillips	Llandoverian	Thin Section and X-rd	90	10	—	—
55	17	90.5	Cape Phillips	Llandoverian	Thin Section	65	30	5	—
56A+B+C	17	318	Devon Island	Ludlovian	Thin Section	80	—	15	—
60	7	101	Cape Phillips	Llandoverian	Thin Section	85	—	15	—
457	3	0	Irene Bay	Ashgillian	Thin Section	100	—	—	—
458	3	51	Cape Phillip	Ashgillian	Thin Section	90	10	—	—
459	3	50	Cape Phillips	Ashgillian	X-rd	89	7	4	—
460A	3	151	Cape Phillips	Llandoverian	Thin Section	10	15	75	—
460B	3	152	Cape Phillips	Llandoverian	Thin Section and X-rd	46	—	54	—
461A	3	154	Cape Phillips	Llandoverian	Thin Section and X-rd	87	9	4	—
461B	3	155	Cape Phillips	Llandoverian	Thin Section	10	10	80	—
462	3	156	Cape Phillips	Llandoverian	Thin Section	65	—	35	—
61	3	178	Cape Phillips	Llandoverian	Thin Section and X-rd	76	—	24	—
463	3	195	Cape Phillips	Llandoverian	X-rd	66	8	26	—
464	3	196	Cape Phillips	Llandoverian	Thin Section	25	10	65	—
465	3	181	Cape Phillips	Llandoverian	Thin Section and X-rd	85	1	14	—
466	3	226	Cape Phillips	Llandoverian	Thin Section and X-rd	78	6	16	—
467	3	252	Cape Phillips	Wenlockian	X-rd	73	7	20	—
468	3	280	Cape Phillips	Wenlockian	Thin Section and X-rd	6	12	82	—
[illegible]	3	306	Cape Phillips	Ludlovian	Thin Section	60	—	25	—

Table A1-2 cont'd.

Sample	Mica/Illite%	Chlorite %	Plagioclase%	Organic Content	Lithofacies
34	17	—	—	Low	Quartzose Mudstone
37	—	—	—	Trace	Massive Limestone
38	10	—	—	Trace	Laminated Limestone
39	16	14	16	Low	Quartzose Mudstone
40	—	—	—	Trace	Laminated Limestone
41	—	—	—	—	Bioclastic Dolomite
42	—	—	—	Trace	Laminated Dolomite
43	—	—	—	Trace	Laminated Dolomite
44	—	—	—	Trace	Laminated Dolomite
45	—	—	—	Low	Laminated Dolomite
46	—	—	—	Low	Laminated Dolomite
47	—	—	—	Low	Laminated Limestone
48	—	—	—	Low	Replacement Chert
49	—	—	—	Low	Replacement Chert
50	—	—	—	Trace	Massive Limestone
51	24	12	9	Low	Quartzose Mudstone
54A+B+C	—	—	—	Trace	Rudaceous Graded Limestone
55	—	—	—	Low	Laminated Limestone
56A+B+C	5	—	—	Low	Rudaceous Graded Limestone
60	—	—	—	Low	Rudaceous Graded Limestone
457	—	—	—	—	Bioclastic Limestone
458	—	—	—	—	Laminated Limestone
459	—	—	—	High	Calcareous Mudstone
460A	—	—	—	High	Radiolarian Chert
460B	—	—	—	Low	Replacement Chert
461A	—	—	—	Low	Laminated Limestone
461B	—	—	—	High	Radiolarian Chert
462	—	—	—	Low	Laminated Limestone
61	—	—	—	Low	Laminated Limestone
463	—	—	—	High	Calcareous Mudstone
464	—	—	—	Low	Replacement Chert
465	—	—	—	Low	Laminated Limestone
466	—	—	—	Low	Laminated Limestone
467	—	—	—	High	Calcareous Mudstone
468	—	—	—	High	Radiolarian Chert
469	13	—	—	Low	Laminated Argillaceous Limestone

of organic matter listed in Table A1-2 were estimated visually, and roughly correspond to the color of the fresh surface of the rocks. Black or dark grey rocks have relatively high concentrations of organic matter while pale grey or white rocks have only trace amounts.

APPENDIX 2

MAJOR STRATIGRAPHIC SECTIONS

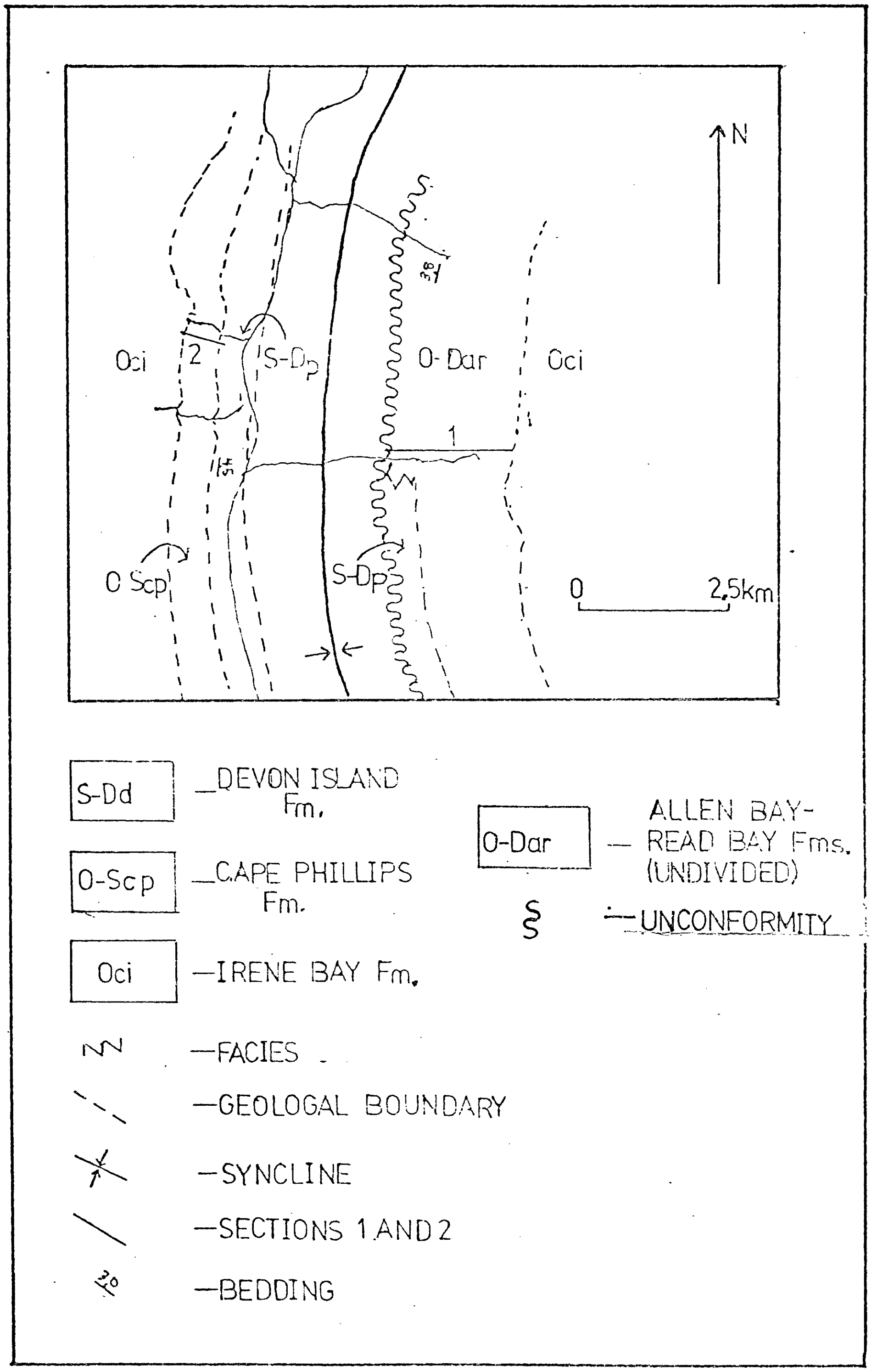
Four stratigraphic sections were systematically sampled and these are described in detail below.

SECTION 1 CARBONATE BUILDUP

The geology of the area around sections 1 and 2 is shown in Figure A2-1.

Thickness Interval (m)	Lithology
0-1015	- Cliff-forming, off-white to pale buff weathering, grey to off-white and light brown colored coarse grained and vuggy massive dolomite. Vuggy and moldic porosities account for 10-15% of hand specimens. Large fragments of dolomite are present near the top of this interval.
1015-1100	- Intraclastic dolomite succession. At base, angular fragments up to 2m in diameter but average closer to 30cm. The matrix is grey-green in color and locally laminated. Up section, the proportion and size of the fragments decreases, and becomes more calcitic. In the upper 20m, the clasts average about 5cm in diameter and float in a lime mud matrix.
1100-1105	- Thin bedded and platy greenish-grey weathering mudstone which is interbedded with thin beds of medium grey weathering, fine grained lime-

Figure A2-1: Regional geology of sections 1 and 2.



	stone (25-30%)
1105-1132.5	- Very thick bedded massive limestone: the beds are clast supported with 10-15% cobbles of dolomite and 5-10cm sized fragments of colonial corals, rugosa and crinoids. The upper 6m appears to be discontinuous.
1132.5-1157.0	- Platy, grey-green weathering quartzose mudstone with pyritic rusty spots. There are 10% interbeds of massive limestone and thin to medium bedded; fine-grained dolomite. Rare M. dubius.
1157.0-1167.0	- Thick to very thick bedded massive limestone.
1167.0-1225.0	- 90% platy to intensely fractured grey-green quartzose mudstone. The parting thickness of the mudstone decreases up section. Rusty spots are present. Medium bedded limestone beds (10%) are present; M. dubius is common.
1225-1251	- Buff to yellow weathering thick to massive bedded, coarse-grained bioclastic dolomite. Common colonial corals and rugosa. Angular unconformity at 1251m.

SECTION 2	WEST IRENE BAY CAPE PHILLIPS BELT
Thickness Inverval (m)	Lithology
0-60	- Very thick bedded, buff weathering, brown colored and fine-grained dolomite with low porosity. Very resistant in outcrop

and poorly laminated.

60-115.5 - Grey to buff weathering, petroliferous, medium to very thick bedded laminated dolomite. Thickness of bedding decreases up section. Diplograptids seen at about 84m.

115.5-135 - Consists of 65% thin to medium bedded, medium grey weathering laminated dolomite which is interbedded with 35% laminated limestone.

135-147 - Platy pale grey to grey-green weathering, dark grey colored calcareous mudstone with common M. priodon.

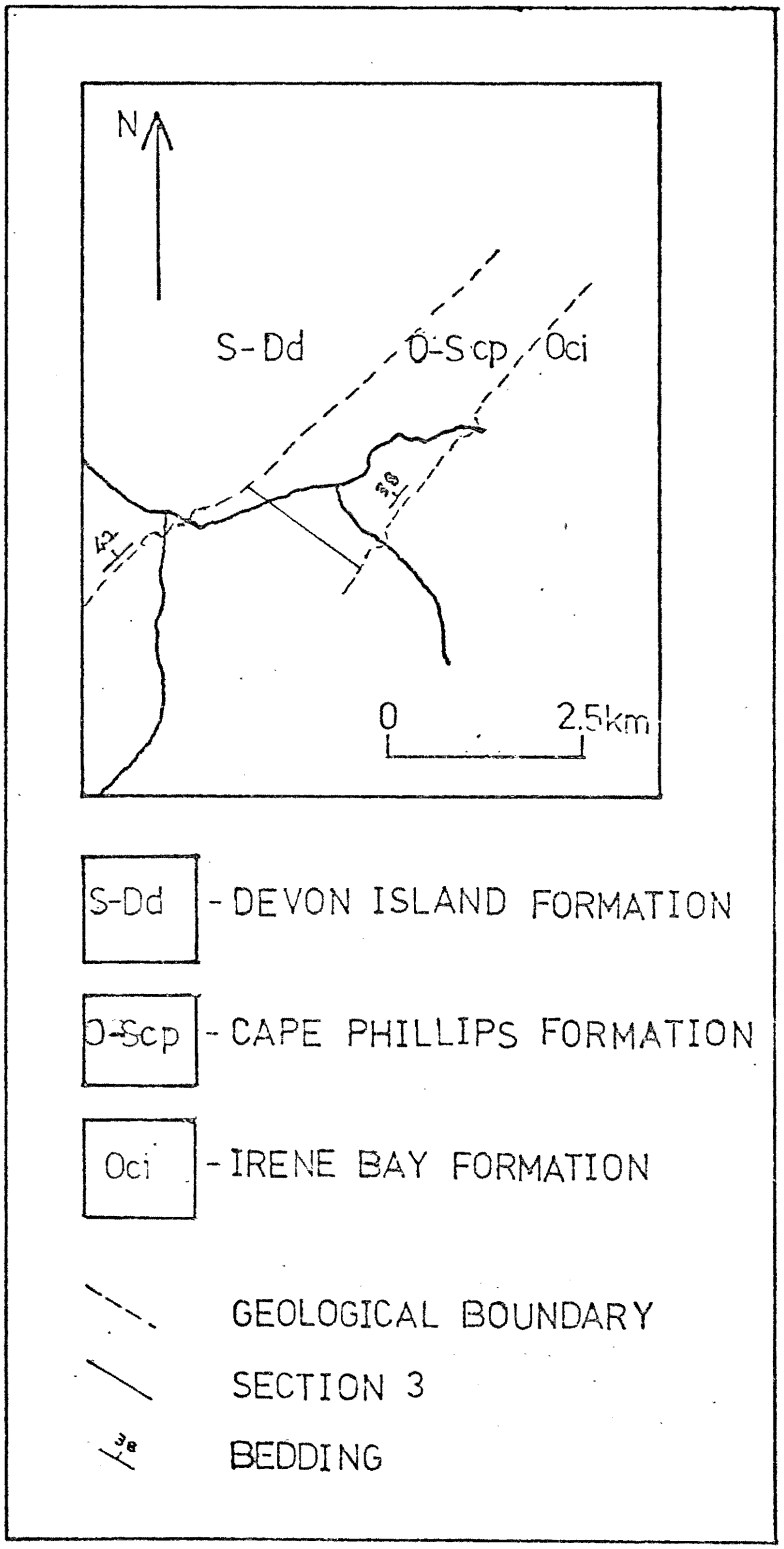
147-156 - Platy pale grey to grey-green weathering, dark grey colored calcareous mudstone with common M. priodon. The mudstone is interbedded with 15%, medium to very thick bedded, grey-brown weathering, matrix supported beds of massive limestone.

SECTION 3 HUFF RIDGE CAPE PHILLIPS BELT

The geology of the area around section 3 is shown in Figure A2-2.

Thickness Interval (m)	Lithology
0-105	- Dark brown to medium grey weathering, medium grey colored laminated limestone with 15-30% interbeds of platy to fissile black weathering, dark grey colored calcareous mudstone. Laminated limestone is thin to medium bedded. The trilobite Pseudogygites latimariginatus

Figure A2-2: Regional geology of section 3.



is very common and is found on the bedding planes of limestone. These beds are usually unlaminated. Diplograptids seen at 105m.

105-142 - Recessive dark brown to black weathering, dark grey colored fissile calcareous mudstone (30-40%) interbedded with thin to medium bedded laminated limestone (60-70%). Hard and brittle, black weathering chert occurs at 129m. The proportions of chert and mudstone increase up section at the expense of laminated limestone. Last trilobites seen at 105m.

142-152 - Platy to flaggy, laminated to thin bedded chert (20%) is interbedded with black weathering calcareous mudstone (50%) and brown weathering laminated limestone (30%). The proportion of chert increases to 70% at the very top of the interval.

152-153.6 - Resistant, buff weathering thick bedded laminated limestone bed.

153.6-155.5 - Resistant black chert (85-90%) with minor interbeds of fissile to platy calcareous mudstone.

155.5-164.5 - Marker limestone bed. Laminae are convolute at the base and become increasingly more planar up section. There are large fragments of chert present whose size decreases up section.

164.5-251.3 - In the basal 10m, chert is predominant. Up section the proprotion of laminated limestone and fissile to platy calcareous mudstone increases at the expense of chert. Laminated limestone comprises 60% of the succession and is medium to very thick bedded. Calcareous mudstone comprises 35% and is dark grey to black weathering and dark grey colored. M. turriculatus, M. spiralis and M. priodon are common. Nodular laminated limestone horizons are present at 178m and 179m.

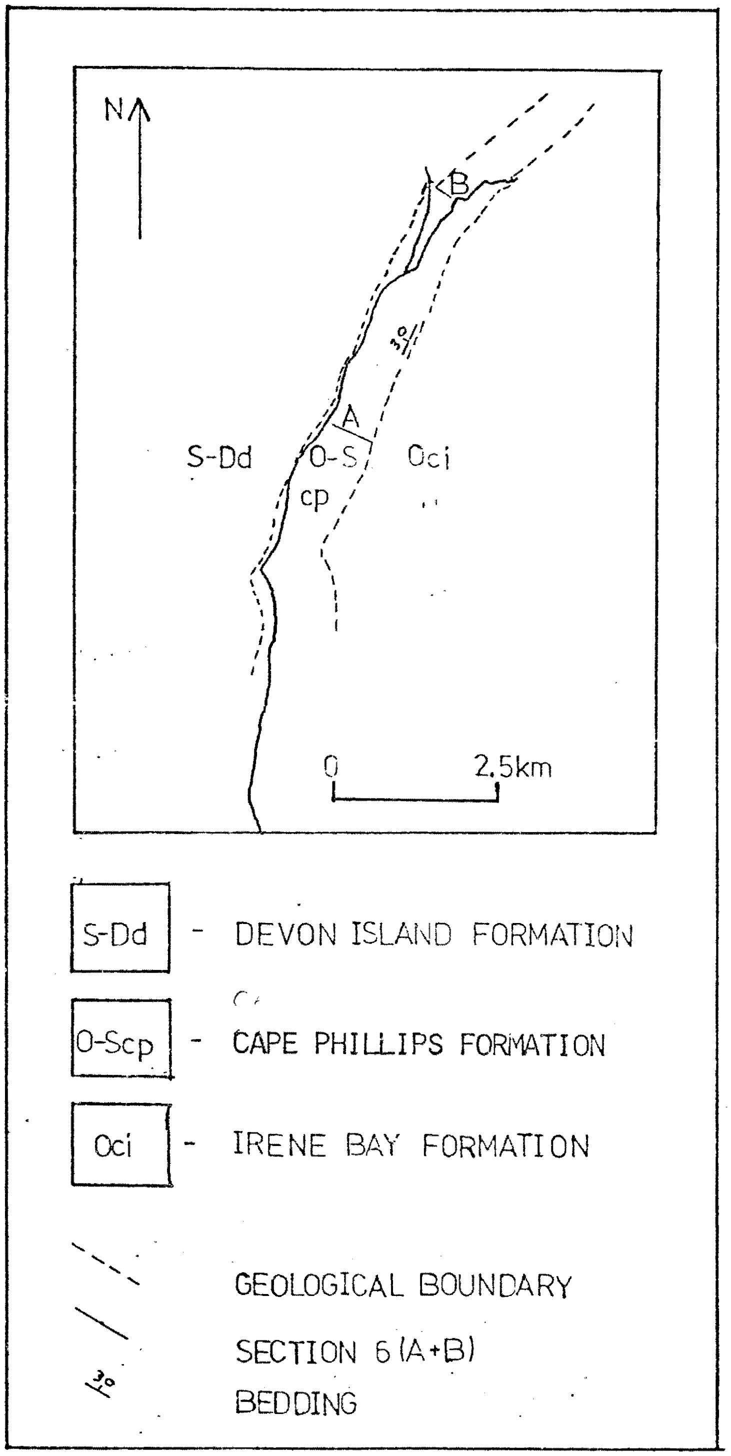
251.3-275.5 - Fissile to platy carbonaceous, black weathering, black colored calcareous mudstone (75%) interbedded with thin and medium bedded laminated limestone (25%). Cyrtograptus sp. and M. priodon common.

275.5-305 - Black, intensely fissile calcareous mudstone (95%) and minor thin bedded laminated limestone (5%) M. priodon common. Mudstone and laminated limestone become less calcareous up section.

SECTION 6 NORTH OF TROLD FIORD

The geology around section 6 is shown in Figure A2-3. This is a composite section. The initial 155m was measured at locality A and the rest of the section at locality B.

Figure A2-3: Regional geology of section 6.



Thickness Interval (m)	Lithology
locality A 0-54	- The succession consists of 65-75% medium bedded, buff to grey weathering laminated limestone interbedded with platy, black weathering, dark grey colored calcareous mudstone (25-35%). First tiolobite seen at 18m but they are relatively rare.
54-76.5	- Interval from 54 to 63m shows an increase in the proportion of calcareous mudstone at the expense of laminated limestone. At 63m, chert occurs. Up section the proportion of black weathering, dark grey colored chert increases to 95% at 76.5m. Chert is extremely brecciated and crumbles easily. Diplograptids present. Rastrites sp. near the top.
76.5-78.5	- Marker limestone bed. Brown to buff weathering, well laminated and dark grey colored limestone.
78.5-84	- 90% chert with thin and discontinuous beds of laminated limestone. Chert is thin bedded and brecciated. Nodules of laminated limestone at 79.5m. Rastrites sp. common at base.
84-115	- 60% platy, black calcareous mudstone interbedded with about 40% medium to thick bedded; buff to grey weathering laminated limestone. The lower 15m of this interval contains several horizons of laminated limestone nodules. M.

spiralis common.

115-160 - Fissile to platy black calcareous mudstone (60-80%) interbedded with medium to thick bedded, buff to grey weathering laminated limestone (20-39%). Minor chert laminae (1%). The proportion of calcareous mudstone increases upwards. M. spiralis and Cyrtograptus sp. common.

locality B 160-246 - Fissile to platy, black carbonaceous, calcareous mudstone (80-95%) interbedded with medium to thick bedded, buff to grey weathering, laminated limestone or laminated argillaceous limestone (above 216m) which weathers an orange-brown color (5-19%). Minor chert laminae occur in the lower 30m of this interval (about 1%). Up section laminated limestone and mudstone become less calcareous, and the proportion of mudstone increases. M. priodon is common.

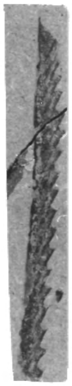
APPENDIX 3

IDENTIFICATIONS

Graptolite and trilobite fossils were collected in the field and tentatively identified in base camp for the purpose of relative age dating and correlation. The relative ages of the graptolites were derived from Lenz (1982) and Morganti (1979). The fossils identified and corresponding illustrations are listed below.

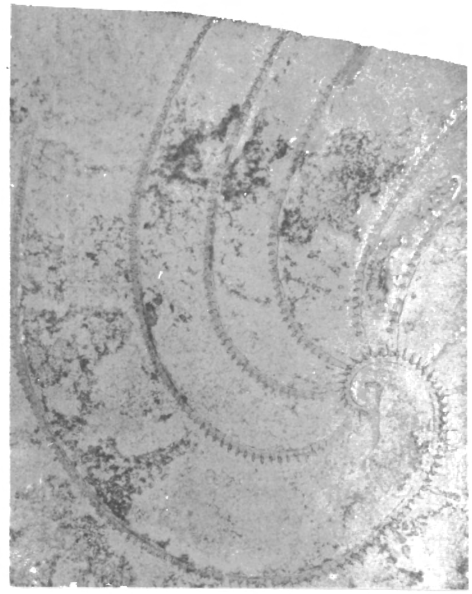
Monograptus dubius	A3-1
Monograptus periodon	A3-2
Cyrtograptus sp.	A3-3
Monograptus spiralis	A3-4
Monograptus turriculatus	A3-5
Rastrites sp.	A3-6
Diplograptids	A3-7
Pseudogygites latimariginatus	A3-8

These photographs are all to scale.



A3-1

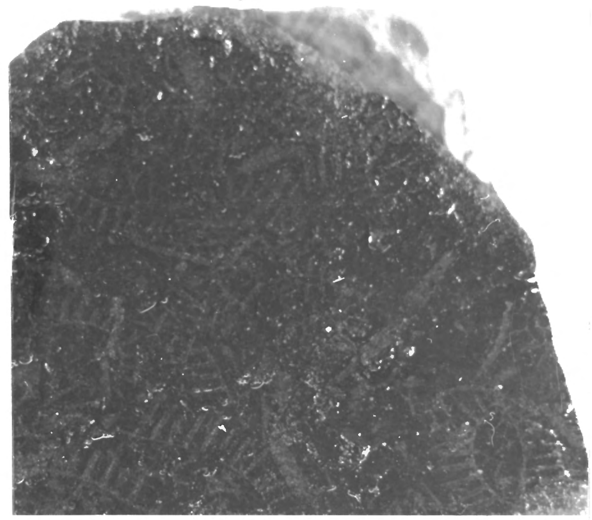
A3-2



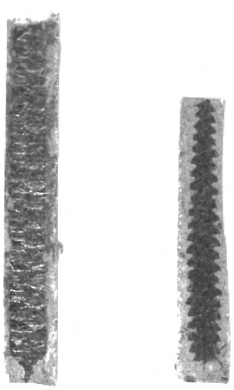
A3-3

A3-4

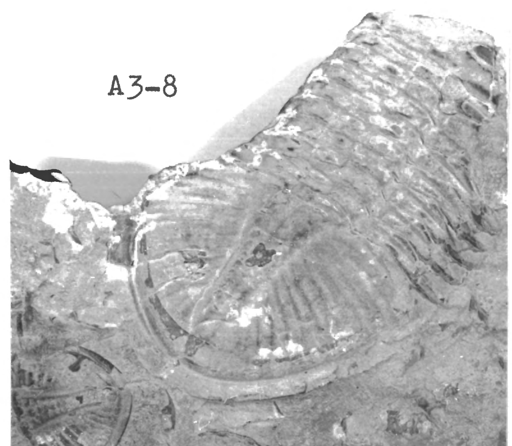
A3-5



A3-6



A3-7



A3-8