DEPOSITIONAL HISTORY OF MIDDLE CAMBRIAN TO LOWER ORDOVICIAN DEEP WATER SEDIMENTS, BAY OF ISLANDS, WESTERN NEWFOUNDLAND

CENTRE FOR NEWFOUNDLAND STUDIES

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~~DEPOSITIONAL HISTORY~~ OF MIDDLE CAMBRIAN TO LOWER ORDOVICIAN

DEEP WATER SEDIMENTS, BAY OF ISLANDS, WESTERN NEWFOUNDLAND

by

© Jack W. Botsford, M.Sc.

A thesis submitted to the School of Graduate

Studies in partial fulfillment of the

requirements for the degree of

Doctor of Philosophy

Department of Earth Sciences

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ABSTRACT

The Northern Head group is an upper Middle Cambrian to Lower Ordovician base-of-slope sediment apron, deposited downslope from a shallow-water carbonate platform, and now disposed in imbricate thrust slices within the Humber Arm Allochthon, western Newfoundland. The group encompasses the upper Middle Cambrian to upper Tremadoc Cooks Brook Formation and the upper Tremadoc to middle Arenig Middle Arm Point Formation. The discovery of numerous fossil localities has facilitated the erection of a stratigraphic framework, embodying several correlatable members. These subdivisions reflect a natural change in the depositional style upward, from carbonate to shale-dominated.

The Cooks Brook is characterized by abundant platform-derived, gravity-transported carbonate, and hemipelagic black shale, deposited in a deep water, poorly-oxygenated environment. Earliest sediments accumulated at the mouths of submarine canyons but were buried by debris flow conglomerate sheets and carbonate sand turbidites from an active, upslope shallow-water platform margin.

Gravity transport of carbonate sharply diminished in earliest Ordovician time but hemipelagic carbonate sedimentation persisted into late Tremadoc time.

The change to shale-dominated sediments of the Middle Arm Point reflects a new, low-relief margin upslope. Hemipelagic shale was accompanied by detrital, windblown dolomite and both were reworked by bottom currents. Diminished input of shelf and slope-derived organic carbon, and more vigorous marine circulation, resulted in

elevated Eh levels in the depositional environment which are indicated by 1) a pronounced increase in bioturbation, and 2) a new "suboxic" diagenetic regime, distinguished by widespread precipitation of Mn-carbonate and barite, largely within the stability field of hematite. Condensed sedimentation characterizes the middle of the Middle Arm Point, spanning the Tremadoc/Arenig boundary. Shale deposition continued until the collapsing margin was buried by sandstones of the overlying Eagle Island formation during middle Arenig time.

The Northern Head group and contemporaneous Cow Head Group were both part of an active carbonate margin until the Tremadoc. Their depositional and paleoceanographic histories diverged in late Tremadoc time, when a low-relief margin developed upslope from the Northern Head group while active carbonate sedimentation continued upslope from the Cow Head Group. This irregular carbonate margin morphology is suggestive of a basement-related structural juncture separating the two areas.

ACKNOWLEDGEMENTS

I wish to thank my supervisor, N. P. James, for his generous advice and encouragement throughout all aspects of this project. I also thank R. K. Stevens for sharing his wide-ranging knowledge in many thought-provoking discussions. The expertise of S. H. Williams, W.D. Boyce, R.K. Stevens and B. D. Erdtmann in fossil identification and biostratigraphic interpretation is gratefully acknowledged. I also wish to thank J. Waldron for offering his knowledge of the Bay of Islands area, and P. Cawood for helpful discussions and reading parts of the manuscript.

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The hospitality and friendship of the Penney family of Summerside is gratefully acknowledged.

Finally, I thank my wife, Adele Poynter, for her understanding, patience and support throughout this project.

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CHAPTER 1

INTRODUCTION

1.1 Introductory remarks

This is a geological investigation of an allochthonous, upper Middle Cambrian to Lower Ordovician deep-water carbonate sequence, the Northern Head group, situated in the Bay of Islands area, western Newfoundland.

Well-documented Lower Paleozoic deep-water carbonate sequences are relatively few. A long history of research has focussed on one such sequence in western Newfoundland, the Lower Paleozoic Cow Head Group. This has yielded considerable insight into the internal stratigraphy and depositional history, including styles of sedimentation, inferred relationship with the upslope carbonate platform, and changing paleoceanographic conditions.

Presumed equivalents to the south, in the Bay of Islands area, have been largely unstudied until now, but reflect a depositional history displaying similarities and important differences with the Cow Head Group. This equivalent carbonate and shale-dominated interval in the Bay of Islands comprises the Cooks Brook and Middle Arm Point Formations (Stevens, 1965), which together are informally termed herein the Northern Head group. Conventional wisdom has regarded the Northern Head group as the "distal equivalent" of the Cow Head Group, but because of difficulty of access and relative structural complexity, this interpretation has not been seriously investigated prior to this study. An alternative model, of lateral equivalence and contrasting depositional history is presented here.

This study 1) provides a basic stratigraphic framework for an area where stratigraphy has, in the past, been based largely upon reconnaissance investigations, 2) elucidates the depositional history of a unique deep-water carbonate sequence, and 3) provides a perspective for modelling the morphology and history of a Lower Paleozoic carbonate margin, as reflected in deep-water sediments, for over 100 km of its length.

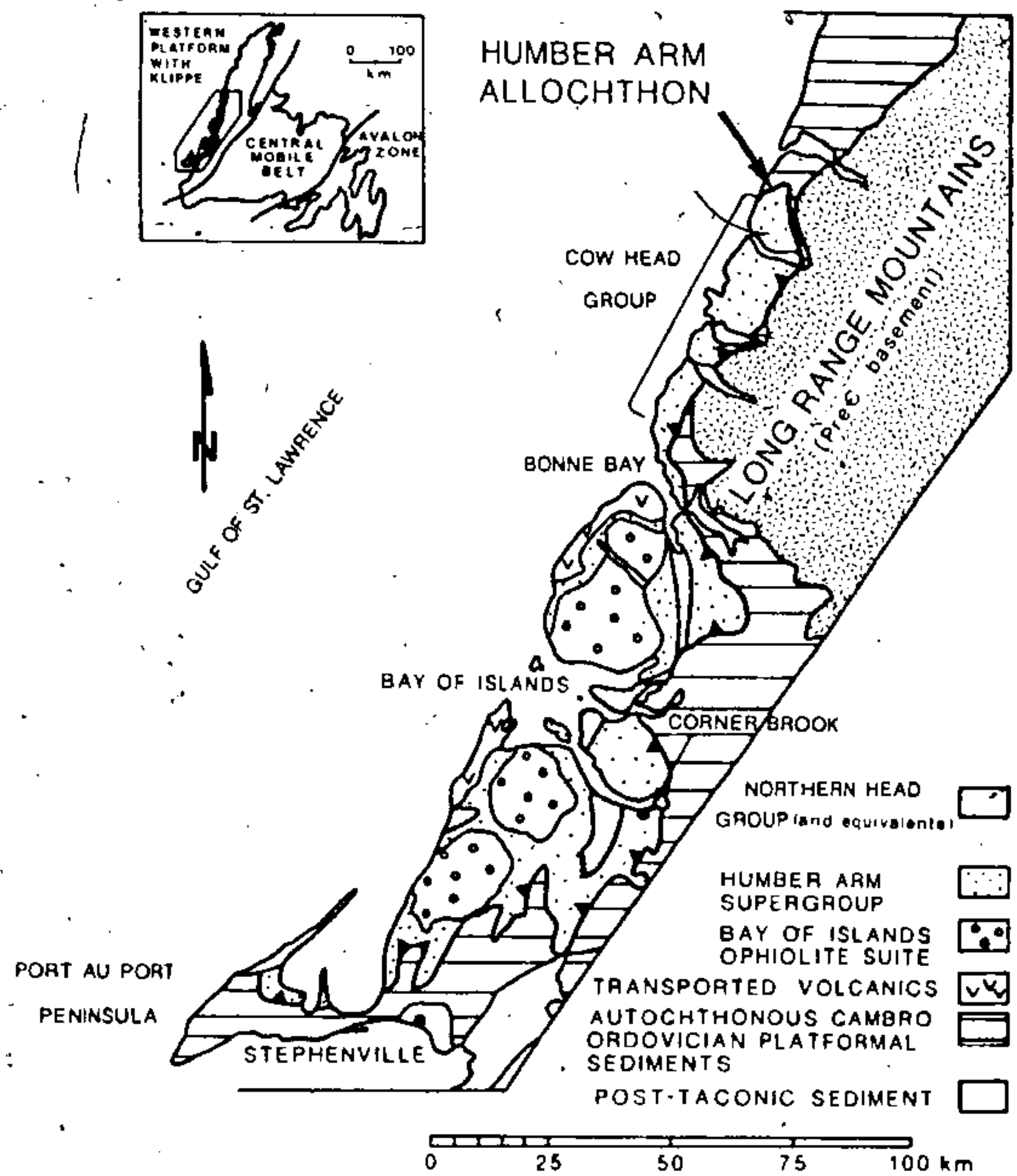
1.2 Regional geologic setting

The Northern Head group is situated within the westernmost portion of the Appalachian Orogen in Newfoundland (Humber Zone of Williams, 1978) which records the development and destruction of an Atlantic-type continental margin on the northern side of the late Precambrian-Early Paleozoic Iapetus Ocean (Stevens, 1970). The Humber Zone embodies a thick, autochthonous, Lower Cambrian to Middle Ordovician miogeoclinal succession, structurally overlain by two major allochthons which comprise partly coeval slope and rise sedimentary units plus ophiolite. These are the Hare Bay Allochthon to the north, and the Humber Arm Allochthon, which contains the Northern Head group, in the Bay of Islands area (fig 1-1). The westward emplacement of these allochthons represents the Middle to Late Ordovician Taconic Orogeny, interpreted to mark the initial closing of the Iapetus Ocean.

Possible equivalents of margin-related sedimentary units of the Humber Zone occur, highly deformed and metamorphosed, in the Fleur de Lys Supergroup of the Burlington Peninsula (Stevens, 1976;

Figure 1-1

Regional geologic setting of the Northern Head group within the Humber Arm Allochthon, western Newfoundland.


WESTERN PLATFORM WITH KLIPPE
CENTRAL MOBILE BELT
AVALON ZONE
0 100 km
HUMBER ARM ALLOCHTHON
COW HEAD GROUP
LONG RANGE MOUNTAINS
(PreЄ basement)
GULF OF ST. LAWRENCE
N
BONNE BAY
BAY OF ISLANDS
CORNER BROOK
PORT AU PORT PENINSULA
STEPHENVILLE
NORTHERN HEAD GROUP (and equivalents)
HUMBER ARM SUPERGROUP
BAY OF ISLANDS OPHIOLITE SUITE
TRANSPORTED VOLCANICS
AUTOCHTHONOUS CAMBRO ORDOVICIAN PLATFORMAL SEDIMENTS
POST-TACONIC SEDIMENT
0 25 50 75 100 km

Hibbard, 1984). The Humber Zone is bounded to the east by the Dunnage Zone, which represents vestiges of an oceanic domain (Williams, 1979).

Platform succession

Within the autochthon, a Lower to Middle Cambrian shallow-water siliciclastic and carbonate sequence, the Labrador Group, was deposited upon rifted Grenvillian basement. This is overlain by a thick (roughly 1500m) platformal carbonate sequence comprising the Middle to Upper Cambrian Port au Port Group (Chow, 1986), the Lower Ordovician St. George Group (Knight and James, 1987) and the Table Head Group (Klappa et al., 1980). The Table Head Group records foundering of the platform in the Middle Ordovician (ibid.) and is overlain by the thick Mainland Sandstone (Schillereff and Williams, 1979) and equivalents, interpreted to be easterly-derived during allochthon emplacement (Stevens, 1970).

Humber Arm Allochthon

The Humber Arm Allochthon is centered on the Bay of Islands area (fig 1-1) and comprises a basal package of sedimentary rocks, the Humber Arm Supergroup (Stevens, 1970), structurally overlain by the Bay of Islands Ophiolite Complex. Igneous and volcanic structural slices locally intervene within the allochthon (Williams, 1973) (fig 1-2).

The most complete sample of allochthonous sediments, partly coeval with their autochthonous counterparts described above, appears in the Bay of Islands area. A lower siliciclastic interval comprises the Summerside and Irishtown Formations (Stevens, 1965; Bruckner, 1966), regarded as Early to Middle Cambrian in age. This study is concerned with the overlying upper Middle Cambrian to Lower Ordovician interval which is dominated by resedimented carbonate. In the Bay of Islands area this is represented by the Cooks Brook and Middle Arm Point Formations (Northern Head group herein). This interval can be traced northward, through deformed equivalents in the Bonne Bay area (Quinn and Williams, 1982; Nyman et al., 1984) to the Cow Head Group, and extends southward, in a tectonized belt, to the Port au Port area (fig 1-1). Along its length it is conformably overlain by an easterly-derived flysch interpreted to have been deposited in advance of, and subsequently incorporated within, the westward-travelling allochthon (Stevens, 1970). This is termed the Lower Head Formation in the Cow Head area (Williams et al., 1985) and informally (this study) termed the Eagle Island formation in the Bay of Islands area (refer to Chapter 3).

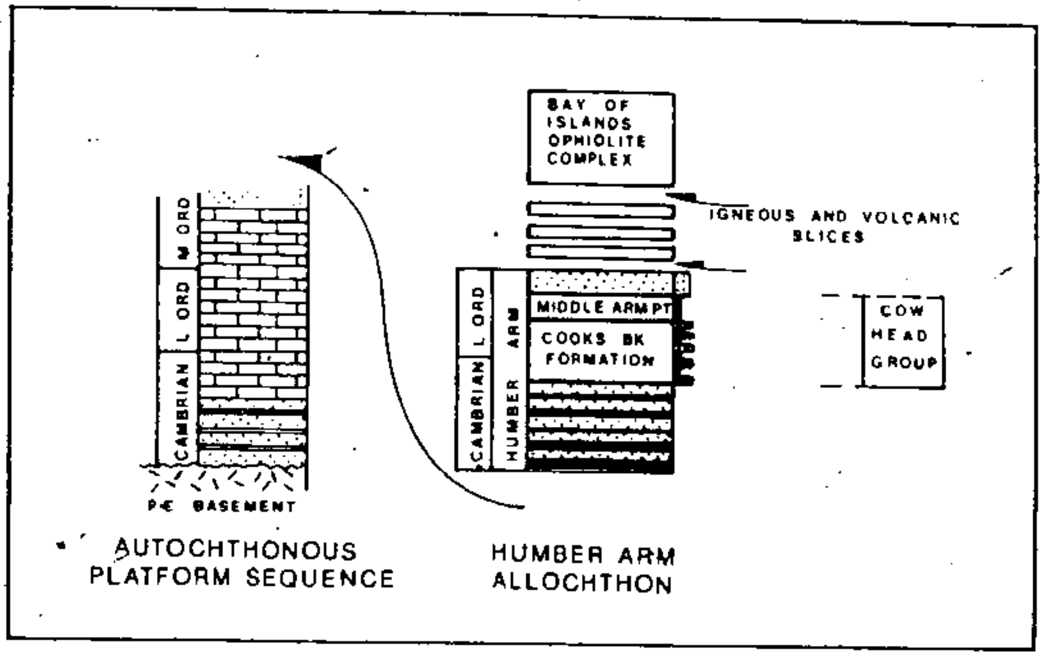
The Bay of Islands area represents the most complete transect through the structural succession of the Humber Arm Allochthon (cf. Williams, 1975), in terms of the Humber Arm Supergroup and the overlying Bay of Islands Ophiolite Complex. The northern part of the allochthon (Cow Head area) comprises only the Cow Head Group, bounded at the base by melange and conformably overlain by the Lower Head Formation, exposed in a series of steeply inclined, imbricated thrust slices.

Structural style of the Humber Arm Allochthon

The Humber Arm Allochthon records i) structures related to its westward (Taconic) emplacement, dominated by thrust imbrication, modified by ii) later compressional deformation, generally thought

Figure 1-2

Schematic diagram illustrating the tectono-stratigraphic setting of the Northern Head group (Cooks Brook and Middle Arm Point Formations); not to scale.



BAY OF ISLANDS OPHIOLITE COMPLEX
IGNEOUS AND VOLCANIC SLICES
M ORD
L ORD
CAMBRIAN
P€ BASEMENT
HUMBER ARM
MIDDLE ARM PT
COOKS BK FORMATION
COW HEAD GROUP
AUTOCHTHONOUS PLATFORM SEQUENCE
HUMBER ARM ALLOCHTHON

to reflect the (Devonian) Acadian Orogeny (Williams, 1979). At the north(eastern) boundary of the allochthon, this appears as pronounced uplift along high angle reverse faults which juxtapose Grenvillian basement of the Long Range Complex (plus portions of the cover sequence) with transported rocks of the Cow Head Group (Williams et al., 1986) (fig 1-1). In the Bay of Islands area folding and thrusting of easterly vergence at the eastern margin of the allochthon is regarded as the counterpart of this Acadian deformation (Cawood and Williams, in press). High angle normal faults which locally cut deformed sediments of the allochthon are tentatively assigned to the Permo-Carboniferous Alleghanian Orogeny (Williams, 1979; Bosworth, 1985; Waldron, 1985).

1.3 Review of previous work

Previous studies incorporating what is here termed the Northern Head group have dealt principally with regional stratigraphic considerations. The evolution of stratigraphic interpretations is summarized in Table 1-1.

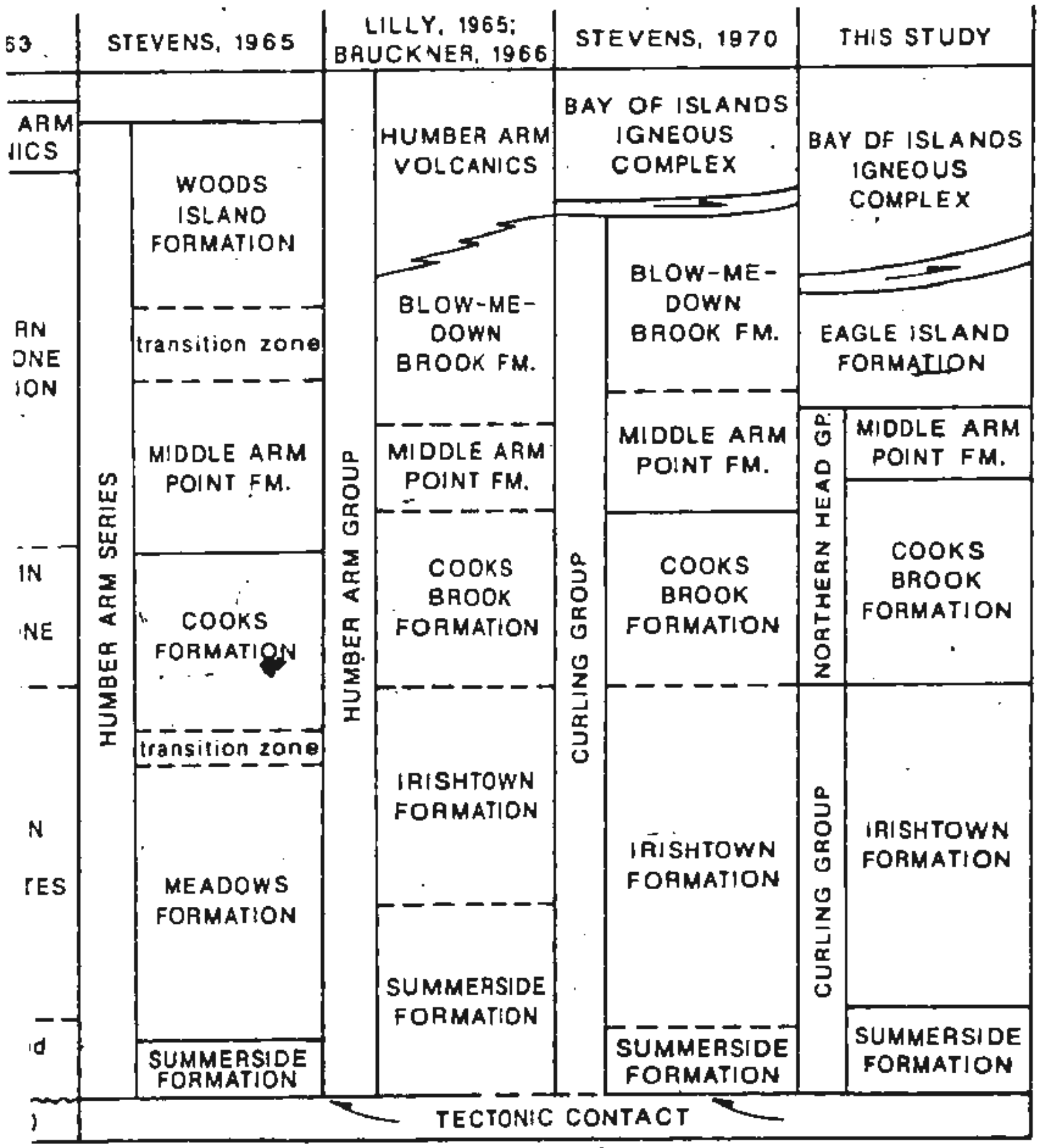
Rocks of the Humber Arm area were first mapped by Murray (1874) who broadly subdivided them into the Levis Shales, Sillery Sandstones and "Serpentines etc." using the nomenclature of Logan and based on similarities with the Eastern Townships of Quebec.

In a comprehensive study, Schuchert and Dunbar (1934) divided the sediments of western Newfoundland into a number of conformable series. Among these, they distinguished a Lower Ordovician Green Point Series, a Middle Ordovician Cow Head Breccia and a Middle to ?Upper Ordovician Humber Arm Series. The type section for the first

Table 1-1

Evolution of stratigraphic interpretation and nomenclature within the Bay of Islands area.

<table>
<tr><th colspan="2">SCHUCHERT & DUNBAR, 1934</th><th colspan="2">WALTHIER, 1949</th><th colspan="2">McKILLOP, 1963</th><th colspan="2">LILLY, 1963</th></tr>
<tr><td rowspan="6">HUMBER ARM SERIES</td><td rowspan="3">limestone conglomerate, thin-bedded limestone, dark shale</td><td rowspan="6">HUMBER ARM SERIES</td><td rowspan="2">UPPER HUMBER ARM (black shale and sandstone)</td><td rowspan="6">HUMBER ARM GROUP</td><td rowspan="3">'UPPER MEMBER' (shale)
calcirudites</td><td rowspan="6">HUMBER ARM GROUP</td><td>HUMBER ARM VOLCANICS</td></tr>
<tr><td>WESTERN SANDSTONE FORMATION</td></tr>
<tr><td>COOKS LIMESTONE</td><td>PENGUIN ARM LIMESTONE FM.</td></tr>
<tr><td rowspan="2">conglomeratic, arkosic quartzite</td><td rowspan="3">LOWER HUMBER ARM (shale, sandstone and conglomerate)</td><td>'MIDDLE MEMBER' (sandstone)</td><td rowspan="2">PENGUIN ARM QUARTZITES</td></tr>
<tr><td rowspan="2">'LOWER MEMBER' (shale)</td></tr>
<tr><td>red shale</td><td>undivided shales</td></tr>
<tr><td colspan="8">UNCONFORMABLE CONTACT (H.A. MIDDLE TO UPPER ORDOVICIAN)</td></tr>
</table>



63
ARM
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STEVENS, 1965
HUMBER ARM SERIES
WOODS ISLAND FORMATION
transition zone
MIDDLE ARM POINT FM.
COOKS FORMATION
transition zone
MEADOWS FORMATION
SUMMERSIDE FORMATION
LILLY, 1965; BRUCKNER, 1966
HUMBER ARM GROUP
HUMBER ARM VOLCANICS
BLOW-ME-DOWN BROOK FM.
MIDDLE ARM POINT FM.
COOKS BROOK FORMATION
IRISHTOWN FORMATION
SUMMERSIDE FORMATION
STEVENS, 1970
BAY OF ISLANDS IGNEOUS COMPLEX
CURLING GROUP
BLOW-ME-DOWN BROOK FM.
MIDDLE ARM POINT FM.
COOKS BROOK FORMATION
IRISHTOWN FORMATION
SUMMERSIDE FORMATION
THIS STUDY
BAY OF ISLANDS IGNEOUS COMPLEX
EAGLE ISLAND FORMATION
NORTHERN HEAD GP.
MIDDLE ARM POINT FM.
COOKS BROOK FORMATION
CURLING GROUP
IRISHTOWN FORMATION
SUMMERSIDE FORMATION
TECTONIC CONTACT

is at Green Point, (in what is now regarded as the distal facies of the Cow Head Group; cf. James and Stevens, 1986). The Cow Head Breccia was described from the area of the Cow Head Peninsula and was correlated with breccias lying above the Table Head Formation on the Port au Port Peninsula.

The Humber Arm Series was applied to the sedimentary rocks of the Bay of Islands, exposed in a "type section" which extended the length of the Humber Arm. This series was only crudely subdivided, as shown in Table 1-1 and was placed at the top of the Lower Paleozoic sequence in western Newfoundland and thought to be Middle to ?Upper Ordovician in age. The series was interpreted to extend from the Port au Port Peninsula to Bonne Bay and a faulted contact with the "much older" Green Point Series was interpreted in both of these areas. A shallow water depositional environment was suggested for the Humber Arm Series based upon sediment coarseness and apparent mudcracking (thought to be what is now regarded as tectonic extension fracturing; cf. Waldron, 1985).

The view of the "Humber Arm series" as a younger suite of rocks stratigraphically overlying the platformal carbonates of western Newfoundland persisted in subsequent studies (until re-interpreted by Rogers and Neale in 1963). Walthier (1949) recognized a broad tripartite division within the "Humber Arm series" and designated lower and upper siliciclastic and shale units separated by the "Cooks limestone tongue".

The stratigraphic divisions of Weitz (1953) first included the Summerside Formation, however his failure to recognize large scale folds and faults in the area and his grouping of highly disparate lithologies into single formations resulted in a stratigraphy which is fundamentally invalid and hence has not been included in Table 1-1.

Lilly (1963) used the term "Humber Arm group" to refer to Schuchert and Dunbar's "Humber Arm series" and regarded the contact of this group with the underlying carbonate sequence as a "marked unconformity". Lilly's stratigraphic divisions of the Humber Arm group include a broadly tripartite division of sedimentary rocks, with siliciclastics at the base (Penguin Arm quarzites), medial carbonate and shale (Penguin Arm limestone formation) overlain by siliciclastics of the Western Sandstone Formation. Volcanics now regarded as part of the Bay of Islands Ophiolite Complex were originally included by Lilly as part of the Humber Arm group and thought to immediately overlie the sedimentary sequence. Lilly's study was largely confined to the eastern part of the Bay of Islands (Penguin Arm, Goose Arm, Hughes Brook) where rocks now regarded as the oldest part of the Humber Arm Group (Summerside Formation) are not well represented. Hence the lowest unit presented in Lilly's subdivision of the Humber Arm group, termed "undivided shales" is thought to incorporate both rocks now regarded as the basal melange of the Humber Arm Allochthon and part of the Summerside Formation.

Mesoscopic and large-scale folding with axial plane cleavage was recognized in the area in the early studies of Walthier (1949), Weitz (1953), McKillop (1963) and Lilly (1963).

A major step in reinterpreting the regional geology and stratigraphy of the Bay of Islands area occurred in 1963, when

Rogers and Neale suggested that rocks of the Humber Arm Group are allochthonous and coeval with the Lower Paleozoic carbonate-dominated platformal sequence of western Newfoundland. This suggestion set the stage for the stratigraphic framework proposed by Stevens (1965) which forms the basis of the stratigraphic nomenclature now in common use.

Stevens regarded the Humber Arm Group as ranging from Early Cambrian to Middle Ordovician in age and divided the group into 5 formations, generally separated by transition zones (Table 1-1). Relatively minor modifications of nomenclature were incorporated in subsequent publications (Bruckner, 1966; Lilly, 1967) and these are detailed in Table 1-1. It is these 5 formations : the Summerside, Irishtown, Cooks Brook, Middle Arm Point and Blow-me-Down Brook formations which then appeared in common usage (e.g. Williams, 1973).

Recognition of the allochthonous nature of the "Humber Arm series" is inherent in the studies of Stevens (1965) and Bruckner (1966) where a gravity emplacement was favoured. Zones of "chaotic deformation" (Stevens) or "wildflysch" (Bruckner) were identified and thought to be related to this emplacement. East-verging structures were also recognized, as a later modification of the transported sequence.

In discussing the Bay of Islands and Hare Bay Igneous Complexes as transported ophiolite sequences Stevens (1970) introduced the term Curling Group to encompass the packages of transported sediment which underlie the ophiolite. This included the 5 formations listed above in the Humber Arm Allochthon (essentially the Humber Arm series or group of earlier workers) and presumed equivalents at Hare Bay. The term Humber Arm Supergroup was used to refer to all of the transported sediment in the 2 allochthons and included the Curling Group plus the Cow Head Group.

Regional-scale mapping and compilation was conducted in the Bay of Islands area by Williams (1973) and the Stephenville (Port au Port) area (Schillereff and Williams, 1979; Williams, 1981).

The structural history of the area has been elucidated in greater detail in the recent studies of Bosworth (1985) and Waldron (1985). A sequence of early, west-directed emplacement structures, overprinted by later deformation of easterly polarity has been recognized.

1.4 The study area

This study is focussed on the Northern Head group (Cooks Brook and Middle Arm Point Formations) and adjoining units and is centered in the Bay of Islands. This area is transected by the roughly N/S-trending belt of these upper Middle Cambrian to Lower Ordovician sediments (fig 1-1) and presents good coastal exposure. Equivalent rocks were examined to the north, in the Bonne Bay area, but are too highly deformed and too poorly exposed to be incorporated in any detailed aspects of this study. The same belt appears to the south of the Bay of Islands, extending to the Port au Port peninsula (fig 1-1) where it was investigated as part of this study. In this southern area, the tectonic style comprises relatively small stratigraphic intervals ("rafts") surrounded by a highly deformed shale-dominated lithologies within melange. Because of their suspect tectonic history, it is difficult to incorporate intervals in this southern region in a depositional framework and they are considered to be of more limited value than the principal study area, the Bay of Islands.

In the Bay of Islands, shoreline exposure along the Humber Arm and a small portion of Middle Arm is accessible by road. The remainder of the area is reached by boat, most conveniently from the town of Coxs Cove, on the southern shore of Middle Arm. Exposures in the Port au Port and Bonne Bay areas are readily accessible by road. Exposure between the Bay of Islands and Port au Port peninsula (i.e. Serpentine River mouth) is only accessible by boat or helicopter and was not visited in the course of this study.

Coastal exposure in the Bay of Islands is generally good. Inland exposure is confined to patchy stream sections, and is of limited value.

1.5 Aims and scope of this study

Prior to this study, knowledge of the Northern Head Group was limited principally to mapping conducted by R.K. Stevens in 1965. While the approach was remarkably thorough, this research was directed toward regional stratigraphy and structure. Only a handful of fossil localities had been located within the Northern Head group and questions of depositional history were not addressed.

The aims of this project are threefold:

1) To erect a workable stratigraphic framework, in order to facilitate i) internal correlation and ii) regional comparison, specifically with the Cow Head Group to the north. This can only be achieved in the context of a structural framework, which allows some confidence in internal correlation.

2) To synthesize the depositional history of this upper Middle Cambrian to Lower Ordovician interval through the integrated description and interpretation of i) sedimentologic, ii) ichnologic and iii) diagenetic and geochemical evidence.

3) To explore the relationship between the Northern Head group and the laterally equivalent and well-studied Cow Head Group to the north, and to use this perpective in attempting to model the morphology of the over 100 km-long portion of the ancient continental margin during Middle Cambrian to Early Ordovician time.

CHAPTER 2

STRUCTURAL GEOLOGY

2.1 Introduction

Reconnaissance geological mapping was conducted at the outset of this study to select areas suitable for more detailed stratigraphic and sedimentological investigation. This mapping was not conducted as a detailed structural analysis, but rather to provide a general structural framework to allow some confidence in correlation of sections. Many of the structural aspects of the area were pointed out to the author by J. Waldron (pers. comm., 1984) and the author is in general agreement with the structural history of the area, presented in some detail by Waldron (1985). This chapter summarizes pertinent aspects of the structural geology.

2.2 Regional setting

The Cooks Brook and Middle Arm Point Formations are situated in the upper part of a package of sedimentary rocks which occur at the structural base of the Humber Arm Allochthon. They are structurally overlain by the Bay of Islands Ophiolite Complex. Intermediate igneous and volcanic structural slices are present locally within the Allochthon.

Within the Bay of Islands the sedimentary tectono-stratigraphic package containing the Northern Head group is bounded to the east by the tectonic contact with the underlying platformal sequence, and to the west and northwest by a major melange zone (Companion Melange and equivalents; Williams, 1973) which occurs structurally below the metamorphic sole of the Bay of Islands Ophiolite Complex (fig. 2-1).

To the north, the Cow Head Group is structurally characterized by a regular series of southeast-facing, southeast-dipping belts interpreted to represent Ordovician thrust imbrication (Williams et al., 1986, and references therein).

2.3 Structural history

Four principal episodes of deformation are recognized in the Bay of Islands area (cf. Waldron, 1985): i) synsedimentary slope-related deformation, ii) west-directed thrusting, asymmetric folding and melange formation, regarded as emplacement-related, iii) folding and thrusting related to a deformational episode of easterly polarity and iv) gentle folding about E/W-trending axial planes, plus high angle faulting.

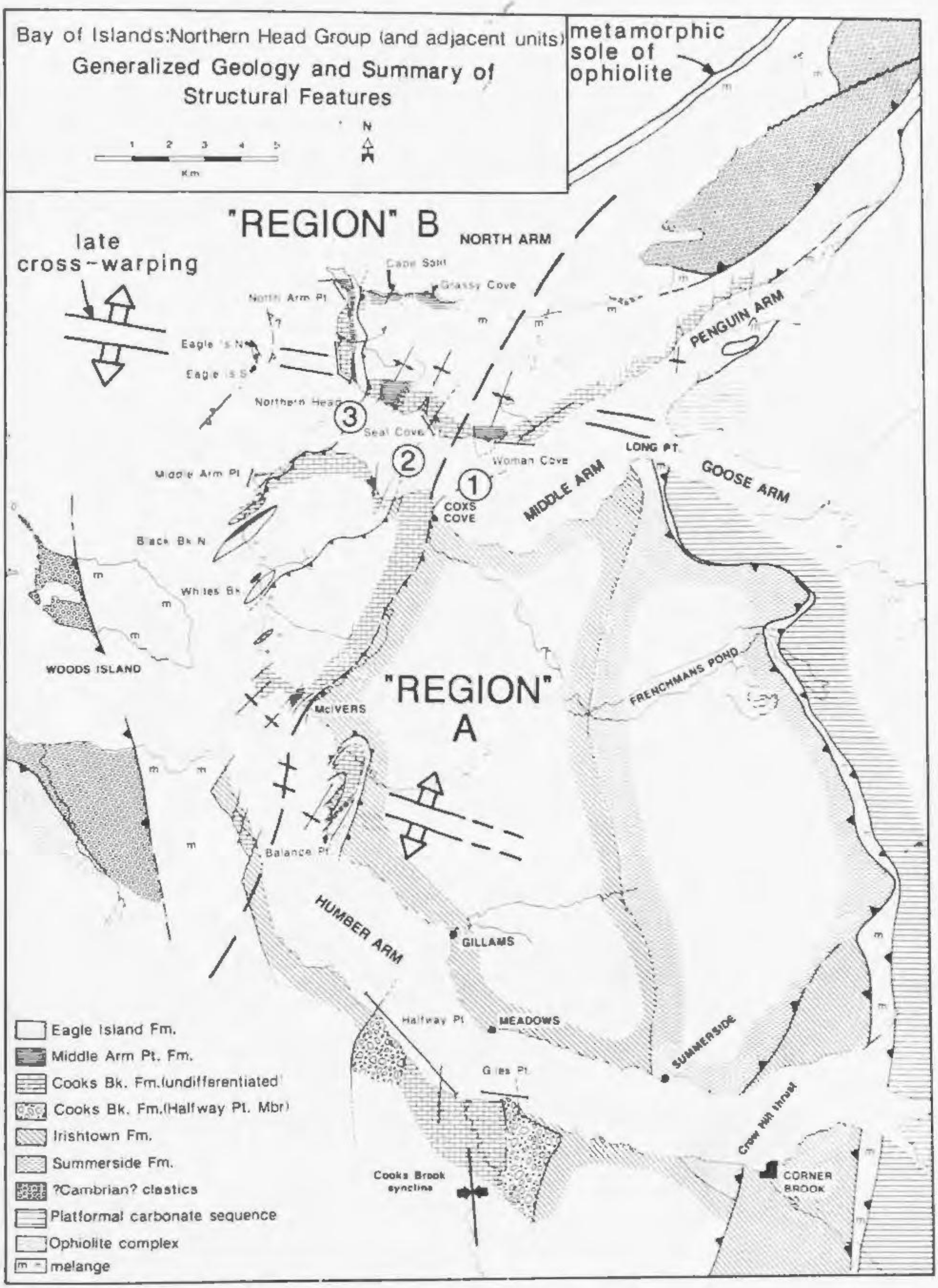
Two principal structural "regions" are apparent (fig 2-1). Region A, in the eastern portion of the area, exposes predominantly Summerside and Irishtown lithologies and displays the most intense deformation of easterly polarity, manifest as folding (e.g. Cooks Brook syncline), associated pronounced axial planar cleavage, and east-directed thrusting. In Region B, to the northwest, earlier west-directed structures are more apparent, since they have been less intensely overprinted by later deformation.

2.3.1 Synsedimentary deformation

Synsedimentary deformation is present in three intervals: i) matrix-supported, "chaotic" conglomerates which occur locally at the

Figure 2-1

Summary of structural features of the Bay of Islands study area. Region "A", in the east, displays the most intense deformation of easterly polarity, while in Region "B", to the northeast, earlier, west-directed structures are more apparent. Numbered thrusts are discussed in the text.


Bay of Islands:Northern Head Group (and adjacent units)
Generalized Geology and Summary of Structural Features
Km
N
metamorphic sole of ophiolite
"REGION" B
late cross-warping
NORTH ARM
PENGUIN ARM
Northern Head
Seal Cove
Woman Cove
LONG PT.
GOOSE ARM
MIDDLE ARM
COXS COVE
Middle Arm Pt
WOODS ISLAND
"REGION" A
FRENCHMANS POND
McIVERS
Balance Pt
HUMBER ARM
GILLAMS
Halfway Pt
MEADOWS
SUMMERSIDE
Crow Hill thrust
CORNER BROOK
Cooks Brook syncline
Eagle Island Fm.
Middle Arm Pt. Fm.
Cooks Bk. Fm.(undifferentiated)
Cooks Bk. Fm.(Halfway Pt. Mbr)
Irishtown Fm.
Summerside Fm.
?Cambrian? clastics
Platformal carbonate sequence
Ophiolite complex
melange

base of the Cooks Brook Formation (Halfway Point Member; refer to Chapters 3, 4), ii) intraformational truncation surfaces, which appear at a low angle to bedding, within a calcarenite-dominated portion of the Cooks Brook Formation (refer to Chapter 4: Calcarenite section), and iii) chaotic folding and faulting at the base of the Eagle Island formation, which locally involves the uppermost Middle Arm Point formation. All of this deformation is regarded as synsedimentary, and is discussed in Chapter 4.

2.3.2 West-directed structures

Evidence of west-directed deformation comprises i) thrusting, represented by east-dipping shear planes which result in the juxtaposition of stratigraphically contrasting units, commonly associated with ii) asymmetric mesoscopic folds with east-dipping axial planes, iii) melange zones which separate more intact thrust- or shear-bounded intervals. These features are clear within Region B and have been recognized within Region A, where they are refolded by later deformation.

a) Thrusts

Three NE/SW trending thrusts have been identified within Domain B. The first (fig 2-1, "1") juxtaposes lithologies of the Irishtown Formation, on the southeast with Cooks Brook lithologies to the northwest. The trace of this feature appears immediately west of the town of McIvers, on the Humber Arm, where it is marked by a thin zone of melange. The presence of several east-dipping shear zones, and generally west-directed asymmetric folds within Irishtown siltstones exposed in McIvers Brook suggests east-over-west movement along this feature. The thrust appears to be topographically-expressed in the valley extending northward from McIvers, and is traced northward to the west side of Coxs Cove, on Middle Arm. Here Irishtown siltstone structurally overlies folded Cooks Brook lithologies. The trace of the thrust has not been identified on the north shore of Middle Arm, and appears to trend into Penguin Arm (fig 2-1).

The Seal Cove/Brakes Cove thrust (fig 2-1, "2") is clearly expressed on the eastern side of Seal Cove (north shore Middle Arm), where it has emplaced basal Cooks Brook lithologies (including intensely pyritized limestone beds described in Chapters 3, 6) structurally above the Cooks Brook Upper Cambrian lime mudstone interval (Chapter 3) along a discrete, east-dipping surface. This is expressed, on the south shore of Middle Arm, as a roughly 10m wide melange zone at Brakes Cove, which separates an east-younging Irishtown/lower Cooks Brook succession (in the eastern, hanging-wall) from a zone of faulted and deformed Cooks Brook and Middle Arm Point lithologies (in the western, foot-wall). Numerous west-directed asymmetric folds appear in the hanging wall at Brakes Cove. The thrust is extrapolated southwestward to the vicinity of Whites Brook, but it cannot be reliably located along this shoreline, which is dominated by melange. Likewise, to the north, evidence of the thrust is not apparent within the melange which dominates the south shore of North Arm.

Along the north shore of Middle Arm, the Northern Head/Black Head thrust (fig 2-1, "3") is a near-vertical feature, presumably rotated to this attitude by later folding (see below). Here it juxtaposes highly deformed Cooks Brook limestone, on the east, with Eagle Island formation on the west. The thrust is extrapolated to the north, where a similar contact appears on the eastern side of North Arm Point, but is complicated by later, near-vertical faulting. The thrust is traced to the south shore of Middle Arm, in the vicinity of Black Head, where a broad zone of melange separates deformed Cooks Brook lithologies (on the east) from the Middle Arm Point/Eagle Island formation section at Middle Arm Point proper.

Based upon the spacing of the three thrusts described above, another thrust may separate Eagle Island from sections to the east, but the trace of this conjectural thrust does not appear on land.

b) Asymmetric folding

West-directed folding is characteristically tight to isoclinal and ranges in scale from less than 1m to roughly 100m in amplitude. Fold axial planes are generally gently east-dipping, however steeper attitudes are not uncommon (e.g. Eagle Island) and are thought to reflect rotation during subsequent deformation. Fold hinges are generally subhorizontal, but again, have suffered rotation locally through subsequent refolding. Shearing along larger scale fold limbs is common, particularly within shale-dominated Middle Arm Point and lowermost Eagle Island intervals (e.g. North Arm Point). Isolated, shear-bounded sub-horizontal fold hinges can be faintly discerned in the melange which dominates the shoreline south of Middle Arm Point (fig 2-1; see below).

c) Melange

Melange zones within the Bay of Islands constitute "mappable, internally fragmented and mixed rock bodies containing a variety of blocks, commonly in a pervasively deformed matrix" (Silver and Beutner, 1980). Compositionally, two types of melange are recognized in the area. Within the first, clasts of Cooks Brook, Middle Arm Point and Eagle Island formations can be recognized. These range in size from pebbles to huge rafts, several hundred meters on a side, and are surrounded by, or "float" within, a shale matrix. The Companion melange (Williams, 1973) is similar in style, but considerably thicker, and also contains blocks and clasts of basalt and diorite. This implies a difference in tectonic history which will be discussed below. This section concerns only the first type of melange, which occurs principally within Region B.

Melange zones within Region B are interpreted to have formed through tectonic processes of pervasive shearing and folding associated with west-directed thrusting. Shear-bounded "lozenges", up to 20m thick commonly appear within these zones. A more detailed discussion of melange genesis is presented by Waldron (1985).

An outcrop-scale and map-scale fabric is defined within these zones by i) an anastomosing, "phacoidal" cleavage which is common within the shale matrix, ii) the alignment of clast and block long axes, and iii) the axial planes of fold hinges, isolated by shearing, within the melange. This NE/SW trending melange fabric is parallel to the tectonic fabric defined by thrust-related shear planes and the axial planes of asymmetric folds, suggesting the consanguinity of all three processes.

Within the central portion of Region B (in shoreline exposure along Middle Arm) melange zones are generally thin (10 to 20m), are localized along thrust planes described above, and are bounded by progressively less deformed zones, toward the center of individual thrust slices, which contain individual measured sections. Toward the northeast and southwest extremities of Region B, (i.e. along the south shore of North Arm and the shoreline facing Woods Island), however, melange dominates and the structural style is one of intact sedimentary rafts isolated within melange. The same is true of the Port au Port area to the south. Lithologies from the upper part of the stratigraphic interval, i.e. Middle Arm Point and Eagle Island formations dominate this melange. Irishtown elements have not been identified and Cooks Brook components are rare. Several sections: Grassy Cove, Cape Split, Black Brook North, Rocky Point (Port au Port Bay) have been examined in rafts within this melange (fig 2-1).

2.3.3 East-directed folding and thrusting

East-verging structures: folding and associated axial-planar cleavage and thrusting are prominent within Region A, where they have been described by McKillop (1963), Stevens (1965), Bosworth (1985), Waldron (1985) and Williams and Cawood (1987). The most clearly recognizable east-directed thrust occurs at Crow Hill, in the vicinity of Corner Brook (Stevens, 1965; Bosworth, 1984; Waldron, 1985) where Summerside lithologies structurally overlie the Irishtown Formation along a west-dipping surface. This feature can be traced northward across the Humber Arm (fig 2-1).

Folds with steeply west-dipping axial planes occur on several scales in the "Cooks Brook syncline" on the south shore of the Humber Arm (fig 2-1; Geologic map: Appendix F). Folds appear parasitically on both limbs of the syncline and range in amplitude from less than 1m to over 50m, and complicate stratigraphic examination in this area (Appendix A). These locally refold earlier, west-directed structures. The associated steeply west-dipping axial planar cleavage is prominent here. It commonly appears as a pronounced planar fabric within matrix-rich, "chaotic" conglomerate of the Cooks Brook Formation, and can be demonstrated to crosscut bedding features locally (refer to discussion in Chapter 4: Conglomerate). The consistency of folding style on all scales in the Cooks Brook syncline suggests its formation during deformation of easterly polarity, postdating an original west-directed deformation.

To the north, along the north shore of Middle Arm, this deformational episode is represented by regular folding about NNE/SSW-trending, upright axial planes, which has resulted in the disposition of the anticline at Seal Cove, syncline immediately to the west, and Woman Cove syncline to the east (fig 2-1). It is this folding episode which has rotated the Northern Head/Black Head thrust, in particular, to its present near-vertical attitude. The pervasive axial planar cleavage typical of the Cooks Brook syncline is not present in this westerly setting. This folding extends to the east, along the north shore of Penguin Arm, but is less well-defined because of poor exposure and a paucity of stratigraphic markers. It does appear to repeat the Irishtown/Cooks Brook boundary several times, however. Fold amplitude may be accentuated by near-vertical faulting thought to occur on fold limbs in this area. In this transition eastward, associated cleavage becomes progressively more intense and locally crosscuts calcite-lined shears which are tentatively assigned to the west-directed deformational episode discussed above.

This fold episode cannot be discerned farther north, in the melange-dominated exposure along the south shore of North Arm.

2.3.4 Late deformation: gentle warping and near-vertical faulting.

Gentle folding about upright, E/W-trending axial planes has been documented in the Bay of Islands area by Waldron (1985). The principal effect of this folding episode is its interference with axes of the NNE/SSW-trending folds described above, to produce culminations and depressions. Such culminations are important in exposing key parts of the stratigraphic section at Northern Head, along trend to the west at Eagle Island, to the north at North Arm Point (fig 2-1). The Rattler window in Humber Arm is regarded as a similar culmination (Waldron, 1985) (see below).

High angle faulting represents the latest deformational event in the area (Bosworth, 1984; Waldron, 1985). This is of variable orientation, but is notable where it occurs about a roughly E/W trend, across the structural grain of the area. This occurs, for example, at North Arm Point, and southward along the cliff exposure at Northern Head, where displacement(s) of up to 30m disrupt the section, and result in considerable omission in the upper part. A similar NE/SW-trending fault appears on the eastern limb of the Woman Cove syncline, but does not appear to reflect much horizontal displacement. The timing of this faulting is unclear, but it has been tentatively related to Carboniferous deformation (Waldron, 1985).

2.3.5 Structurally distinctive areas: the Rattler Block

The Rattler Block is a domal feature comprising complexly-deformed Irishtown, Cooks Brook, Middle Arm Point and Eagle Island formation lithologies situated on the north shore of Humber Arm, in the vicinity of Rattler Brook (fig 2-1). This feature is bounded by a structurally overlying melange zone which separates it from surrounding Irishtown lithologies; it is regarded as a tectonic window (Stevens, 1965), an example of a structural culmination produced through the fold interference described above (Waldron, 1985). Deformation within the window is dominated by shearing, which appears to have produced considerable abbreviation of the stratigraphic section. The presence of this tectonic window is consistent with the interpretation of a gently dipping stack of thrust slices within the study area, and implies lateral movement of at least several kilometers along the overlying thrust surface. The basal portion of the Cooks Brook Formation exposed here displays a sedimentologic affinity with that in the Cooks Brook syncline (on the overlying thrust sheet) to the southeast (refer to Chapters 3, 4).

2.4 Summary

Early structures record synsedimentary, gravity-related deformation. A major episode of shearing, asymmetric folding and melange formation followed, accompanying thrust imbrication along (originally) gently east-dipping surfaces and related to initial westward emplacement of the allochthon. This has produced a "stack" of thrust slices which appear to have preserved the proximal/distal relationships of the sediments under investigation, in spite of later deformation. Subsequent tectonism of an easterly polarity is manifest by folding with upright to steeply west-dipping axial planes. This deformation increased in intensity eastward, accompanied by i) a pronounced axial planar cleavage and ii) east-directed thrusting in the eastern portion of the area. Fold interference produced by later gentle cross-folding has resulted in the disposition of these deformed sediments in a series of culminations and depressions. Late vertical faulting is of generally small displacement, but does complicate some stratigraphic sections through offset and local omission of section.

While this structural history presents a more complex picture than the regular, steeply-dipping thrust imbrication described from the Cow Head Area (cf. Williams et al., 1986), there is no evidence to suggest that structural mechanisms (such as out-of-sequence thrusting) have obliterated the fundamental proximal/distal or stratigraphic relationships within the Cooks Brook and Middle Arm Point Formations and related units. Folding episodes postdating initial thrust imbrication have been fortuitous from a stratigraphic viewpoint, in exposing stratigraphic sections which would otherwise have been poorly exposed in gently-dipping thrust sheets.

From a regional perspective, the promontories of North Arm Point and Middle Arm Point which expose the Northern Head Group are bounded to the north and south by structurally overlying ophiolitic massifs. Furthermore, sections which expose the lower part of the stratigraphic interval (i.e. Irishtown/Cooks Brook contact) occur in the central part of Domain B and pass, along strike to the NE and SW, into melange which is dominated by stratigraphically younger (Middle Arm Point and Eagle Island Sandstone) components. Hence the core of the Northern Head group exposure appears to represent a regional structural culmination, plunging beneath structurally overlying units to the NE and SW. This culmination was probably produced in the episode of late cross-folding described previously, and is coincident with a westward bulge in the allochthon/autochthon contact in the vicinity of Goose Arm (fig 2-1; Waldron, 1985).

2.5 Relationship with other structural elements

The Companion Melange, which bounds the study area to the west, is well-exposed at Woods Island and Frenchmans Cove (immediately to the south) and correlatives appear at the head of North Arm, bounding the study area to the north west) (fig 2-1). This zone is distinctive from the thin, emplacement-related melange zones described above, in i) its considerable width (roughly 2 km), ii) the presence of "exotic" volcanic and igneous blocks not present in the structurally underlying sedimentary sequence, iii) the regional disposition of the zone across the NE/SW emplacement-related structural fabric described above, and iv) the presence of ?Cambrian siliclastic rocks either within or separating the zone from the structurally overlying ophiolite complex. These aspects suggest that the assembly of the Humber Arm Allochthon in this area was not a simple process of sequential imbrication of sedimentary slices beneath an advancing ophiolite (cf. Stevens, 1970; Malpas and Stevens, 1977), but that some process of out-of-sequence thrusting or post-assembly readjustment contributed to the final disposition of structural elements of the allochthon in the Bay of Islands area. This may be related to the episode of east-directed deformation described above (cf. Bosworth, 1985). Regional aspects of the structural history of the Humber Arm Allochthon are presently under investigation (Williams and Cawood, in preparation).

In the Bay of Islands area, the Humber Arm allochthon is separated from deformed platformal carbonates to the east by melange, but this contact is commonly modified by high angle faults (Cawood and Williams, in press).

CHAPTER 3

STRATIGRAPHY

Introduction

This chapter consists of 3 parts: 1) a review and discussion of the regional stratigraphic nomenclature adopted in this study, 2) a detailed discussion of the systematic stratigraphy erected for the Northern Head group and 3) a discussion of biostratigraphic aspects.

3.1 REGIONAL STRATIGRAPHIC NOMENCLATURE

3.1.1 Introduction

While this study is focussed on the Cooks Brook and Middle Arm Point Formations, these must be placed within a meaningful regional stratigraphic framework. This framework should be one which best reflects overall patterns of sedimentation, which facilitates comparisons with along-strike equivalents (notably the Cow Head Group) and which preferably is as close as possible to that nomenclature in common use. The framework adopted herein is modified from that in common use, much of which, in fact, has not been formally published but has evolved from what appears in Stevens (1965; 1970) and Bruckner (1966), (refer to Table 1-1).

A schematic stratigraphic section through the sedimentary sequence exposed in the Bay of Islands is shown in figure 3-1 and illustrates the stratigraphic nomenclature adopted in this study. The most recent detailed examination and thickness estimate of several units within the Humber Arm Supergroup remains that of

Figure 3-1

Generalized stratigraphy of the Humber Arm Supergroup adopted in this study. The stratigraphic position of the Cow Head Group and Lower Head Formation are shown for comparison.
A legend of lithologic symbols employed throughout this study is shown in figure 3-1a.

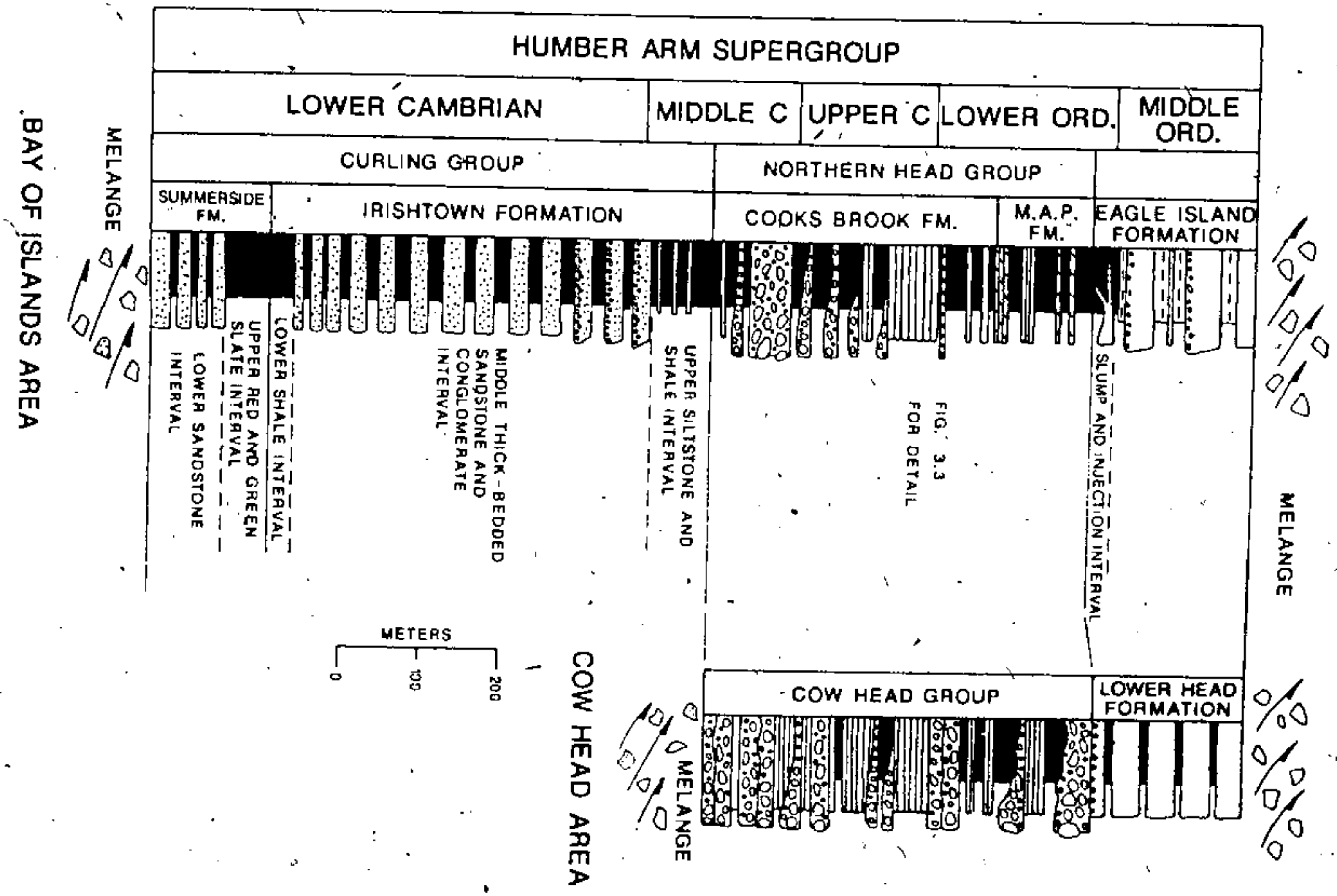
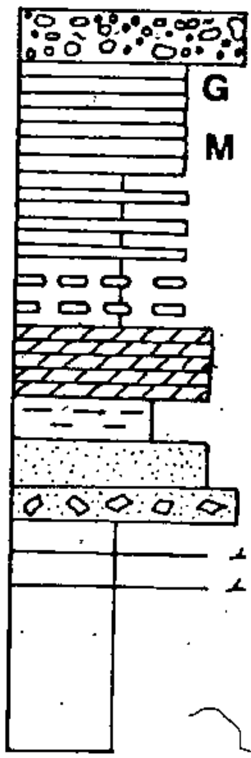

HUMBER ARM SUPERGROUP
LOWER CAMBRIAN
MIDDLE C
UPPER C
LOWER ORD.
MIDDLE ORD.
CURLING GROUP
NORTHERN HEAD GROUP
SUMMERSIDE FM.
IRISHTOWN FORMATION
COOKS BROOK FM.
M.A.P. FM.
EAGLE ISLAND FORMATION
LOWER SANDSTONE INTERVAL
UPPER RED AND GREEN SLATE INTERVAL
LOWER SHALE INTERVAL
MIDDLE THICK-BEDDED SANDSTONE AND CONGLOMERATE INTERVAL
UPPER SILTSTONE AND SHALE INTERVAL
FIG. 3.3 FOR DETAIL
SLUMP AND INJECTION INTERVAL
MELANGE
MELANGE
BAY OF ISLANDS AREA
METERS
0
100
200
COW HEAD AREA
MELANGE
COW HEAD GROUP
LOWER HEAD FORMATION

Figure 3-1a

Legend of lithologic symbols used throughout this study; "filled-in" (i.e. black) shale symbol refers to generally organic carbon-rich shale while uncoloured shale symbol refers to red and green organic carbon-poor shale.

Legend



Carbonate conglomerate

G Grainstone–packstone) Parted

M Mudstone–wackestone) limestone

Ribbon limestone

Nodular limestone

Dolostone

Siltstone

Sandstone

Conglomeratic sandstone

Shale: thin dolostone beds

Shale: black–blk green–gn

grey–gy red–rd

Chert	▼	Parallel laminations	≡
Quartz sand	Q	Ripples and cross laminations	
Pyrite	py	Graptolites	
Phosphate	ph	Trilobites	
Bioturbation		Brachiopods	
Younging indicator			

Stevens (1965) and revisions of some of these details are based upon the author's regional mapping done in the course of this study.

The term Humber Arm Supergroup (Stevens, 1970) is useful in referring to all of the sedimentary rocks in the Humber Arm and Hare Bay allochthons which conceptually form a tectono-stratigraphic package, bounded by major structural dislocation (generally major melange zones) and contrasting in nature with structurally underlying (generally platformal carbonates) and overlying (generally intrusive or volcanic) units. As such the Humber Arm Supergroup encompasses the Cow Head Group and the revised Curling Group and Northern Head group of this study.

3.1.1 Revision of the Curling Group

The term Curling Group (Stevens, 1970) was proposed to refer to the entire thrust-bounded package of sediments structurally below the Bay of Islands Ophiolite Complex in the Bay of Islands (and to incorpororate similar sediments in the Hare Bay Allochthon), but has not been widely used in the literature. The term serves to emphasize the overall difference between the allochthonous sedimentary sequences exposed in the Bay of Islands and the Cow Head region, which is really the result of regional-scale structural differences between the two areas. The package of allochthonous rocks in the Cow Head area is dominated by the Cow Head Group, but the stratigraphic base of this interval is not exposed. Presumed representatives of the underlying siliciclastic units have recently been mapped as huge blocks (of Irishtown Formation) within melange structurally underlying the Cow Head Group (Williams et al., 1985).

and have also been mapped in the vicinity of Bonne Bay to the south (Nyman et al., 1984). A more complete sample of the entire allochthonous sequence is preserved by the structural style in the Bay of Islands. However, in spanning this entire sequence, the Curling Group, as previously defined, lumps together discrete siliclastic-dominated and carbonate-dominated sedimentary intervals and does not readily facilitate lateral comparisons within the Humber Arm Allochthon. This appears to contravene the spirit of the North American Stratigraphic Code (1983), which states "Groups are defined to express the natural relationships of associated formations" (p. 858).

Hence the Curling Group is here revised, and restricted to include the siliciclastic-dominated interval which occurs at the stratigraphic base of the Humber Arm Supergroup. This encompasses primarily the Summerside and Irishtown Formations (as described below) within the Bay of Islands area. Both of these units are exposed in the vicinity of Curling, immediately west of Corner Brook (fig 3-2). The Curling Group is designated to also include other units demonstrated by ongoing mapping to have affinities with the Summerside/Irishtown interval, for example sandstones in the Blow-me-Down Brook and Woods Island area (discussed above). The Group is also intended to comprise lateral correlatives of the Summerside and Irishtown Formations, notably the Mitchells and Barters Formations in the Bonne Bay area (Nyman et al., 1984), pending the results of ongoing mapping and correlation (Quinn, in progress).

3.1.1.2 <u>The Northern Head Group</u>

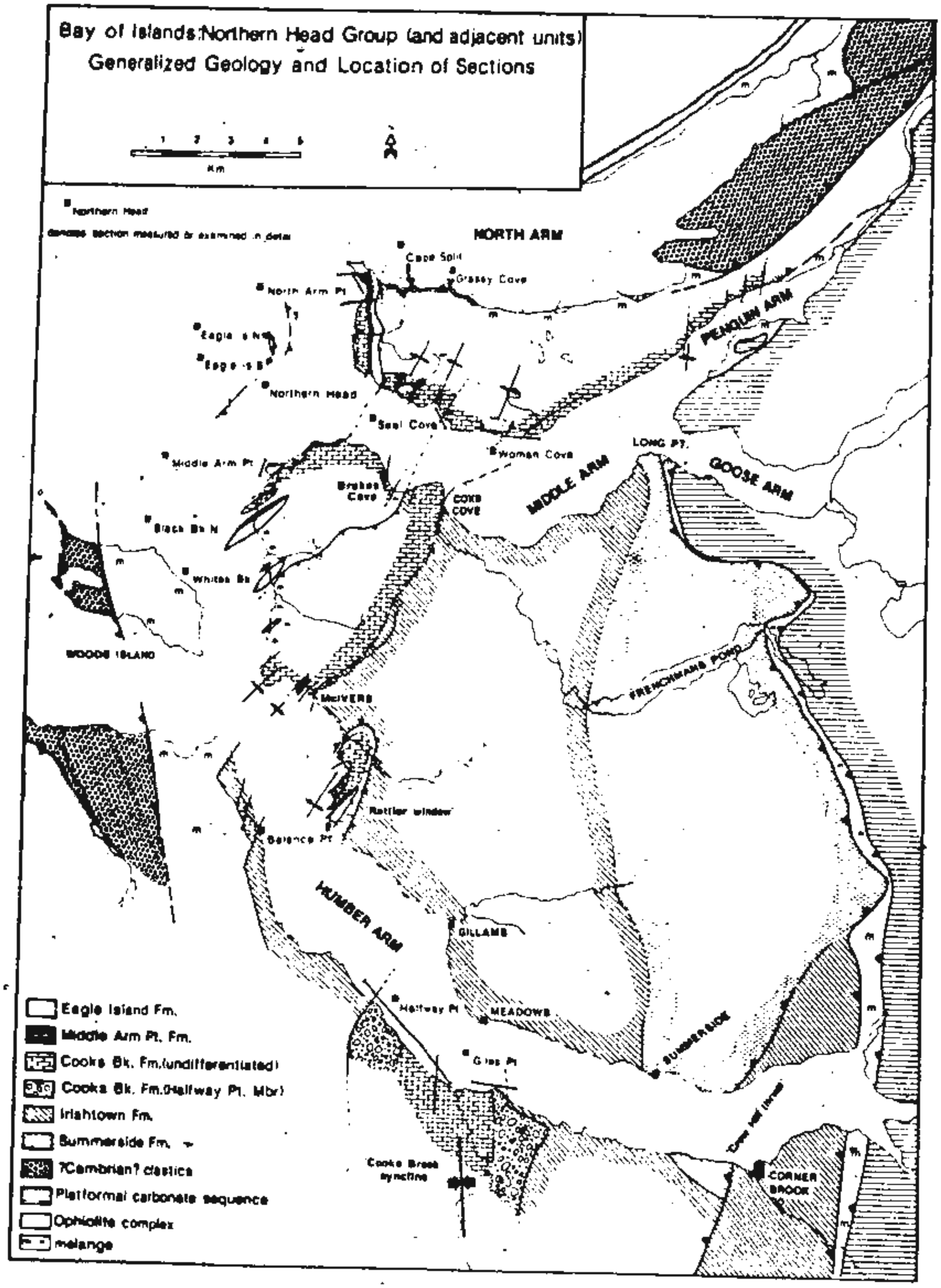
The overlying interval contains the Cooks Brook and Middle Arm Point Formations. The separation of these two formations in the Bay of Islands is demonstrated, in subsequent sections, to be valid and meaningful, but a term is needed to encompass the entire carbonate and shale-dominated interval which they represent.

To the north, the Cow Head Group contains two formations, each with several members, and is overlain by sandstones of the Lower Head Formation (James and Stevens, 1986). The Cooks Brook/Middle Arm Point interval is shown in this study to be intimately related to the Cow Head, in terms of age equivalence and lithologic similarity and the two are linked in a depositional model presented in Chapter 8. This perspective provides further impetus for a parallel nomenclature for the two areas.

Hence the term Northern Head group is informally adopted in this study to encompass the Cooks Brook and Middle Arm Point Formations, which are best exposed in the Bay of Islands and extend in a tectonized belt southward to the Port au Port Peninsula. The name is taken from the promontory of Northern Head, at the mouth of Middle Arm (fig 3-2), which exposes a thick and relatively continuous section spanning much of the Cooks Brook Formation and passing upward, through tectonized intervals, into the Middle Arm Point Formation to the east and north. The base and top of the Northern Head group are the base and top of the Cooks Brook and Middle Arm Point Formations respectively, as described in detail below. The Northern Head Group is overlain by sandstones of the Eagle Island Formation, also discussed below.

Figure 3-2

Bay of Islands: Northern Head group (and adjacent units), generalized geology and location of sections discussed in the text.


Bay of Islands:Northern Head Group (and adjacent units)
Generalized Geology and Location of Sections
Km
Northern Head
section measured or examined in detail
NORTH ARM
Cape Split
Grassy Cove
North Arm Pt
Northern Head
Seal Cove
Woman Cove
LONG PT.
PENGUIN ARM
GOOSE ARM
MIDDLE ARM
Middle Arm Pt
Brakes Cove
COXS COVE
Black Bk N
Whites Bk
WOODS ISLAND
FRENCHMANS POND
McIVERS
Rattler window
Galance Pt
HUMBER ARM
GILLAMS
Halfway Pt
MEADOWS
SUMMERSIDE
Giles Pt
Cooks Brook syncline
CORNER BROOK
Eagle Island Fm.
Middle Arm Pt. Fm.
Cooks Bk. Fm.(undifferentiated)
Cooks Bk. Fm.(Halfway Pt. Mbr)
Irishtown Fm.
Summerside Fm.
?Cambrian? clastics
Platformal carbonate sequence
Ophiolite complex
melange

The revised stratigraphic nomenclature adopted here is regarded as useful in regional mapping, in syntheses of continental margin evolution and in studies, such as this one, which focus on the nature of the margin over a selected stratigraphic interval. The use of this nomenclature for apparantly equivalent sedimentary sequences in the Hare Bay Allochthon has not been critically examined in this study.

3.1.2 THE CURLING GROUP

3.1.2.1 Summerside Formation

The Summerside Formation is composed of medium-bedded yellow to cream-weathering sandstone, green and red sandstone and highly cleaved green and red shale. The term was originally used by Weitz (1953) but was redefined by Stevens (1965) to refer to the above described lithologies which are well exposed at the village of Summerside. The unit is also exposed on the south side of the Humber Arm between Crow Hill and Church Cove (immediately west of Corner Brook), to the north along the shores of Frenchmans Pond and at Long Point in Middle Arm (fig 3-2).

This unit has generally suffered intense tight to isoclinal folding and associated steeply west-dipping cleavage which makes establishment of an internal stratigraphy and an estimate of stratigraphic thickness virtually impossible. Bedding is commonly transposed in less competent parts of the formation and great care must be exercised to separate bedding and cleavage. The author accepts Stevens' (1965) broad subdivision of the Summerside Formation into a lower arenaceous sequence and an upper red and green slate sequence. The lower unit is dominated by a yellow-weathering, thin to medium-bedded, medium to coarse quartzose litharenite with scattered pebble conglomerate, which passes upward into medium bedded red and green sandstones. This appears to be transitional with the overlying red and green slate, which locally demonstrates colour changes along strike. In the uppermost part this slate is transitional upward with bluish-weathering grey shale, and the appearance of thin quartzose sandstone beds within this shale is regarded as the base of the overlying Irishtown Formation.

The base of the Summerside Formation is regarded as everywhere a tectonic contact, for example at Crow Hill (fig 3-2) where the unit has been thrust eastward over the Irishtown Formation. Stevens (1965) estimated the thickness of the Summerside Formation as at least 300 feet (91 m). Bruckner (1966) suggested a thickness of 800 feet (244 m), however it seems likely that the lowermost dark shales mentioned in his account encompass parts of the Irishtown Formation and/or the basal melange zone of the Humber Arm Allochthon and this estimate is considered too large. The upper red and green shale interval within the Summerside Formation appears to be thicker at Frenchmans Pond (fig 3-2) than at Summerside itself and hence a thickness of 150m is tentatively suggested here.

At Long Point, in Middle Arm (fig 3-2), a thin interval of Summerside red and green shales stratigraphically overlies roughly 20m of pillow basalt at the structural base of the allochthon. A similar relationship is seen on Woods Island (fig 3-2) between sediments and volcanics there, suggesting a link between the

Summerside Formation and parts of the "Blow-me-Down Brook Formation" which is discussed further later in this chapter.

To the north, in the Bonne Bay area, presumed equivalents of the Summerside Formation are mapped as the Mitchells Formation (Nyman et al., 1984).

No fossils have been recovered from the Summerside Formation and it is tentatively regarded as Early Cambrian in age, because of its relationship with the overlying Irishtown Formation (see below).

3.1.2.2 Irishtown Formation

The Irishtown Formation comprises medium to thick-bedded quartz-rich sandstone, conglomeratic in part, intervals of grey to black shale and thin-bedded buff-weathering siltstone. This unit was mapped as the Meadows Formation by Stevens (1965) but this name was superseded by the term Irishtown Formation (Bruckner, 1966) which is now in common usage. This formation is widely exposed along the shores of Humber Arm and in Middle Arm (fig 3-2).

The internal stratigraphy of this unit is still not well understood and the most detailed attempt to subdivide the formation remains that of Stevens (1965), who proposed 6 informal "members" plus a transition zone into the overlying Cooks Brook Formation (p. 23). While only the upper part of the Irishtown Formation has received detailed examination in this study, it is felt that some of these divisions may reflect facies equivalents or structurally repeated intervals and a simpler gross stratigraphy for the Irishtown Formation is adopted here.

The base of the Irishtown is a thin interval dominated by bluish-weathering grey shales with thin beds of quartzose siltstone to fine sandstone and is transitional with the underlying Summerside Formation. This interval is approximately 30m thick and is best exposed at Davis Cove west of Summerside (fig 3-2) (cf. Stevens, 1965; pp. 23-24). Immediately overlying the transition zone is a thick interval dominated by thick-bedded quartzose sandstone with grey to black shale interbeds which extends west from Davis Cove to the west side of the village of Meadows (fig 3-2). It is the quartzites of this interval which form many of the rocky promontories along the Humber Arm. Areas where this unit is exposed are too numerous to list but good exposures include the prominent hill in downtown Corner Brook (and most of the roadcuts in and around the town) and the area from Davis Cove to Meadows on the north shore of Humber Arm (fig 3-2).

Sandstones within this interval demonstrate considerable variability in bedding style and are in part conglomeratic, but are everywhere quartz-rich. Beds are commonly 1 to 2m in thickness but amalgamated beds range up to 10m thick (e.g. roadside exposure immediately northwest of the village of Gillams; fig 3-2). Sandstones and conglomerates are interbedded with thinner intervals of quartzose siltstone and grey shale which is commonly orange-weathering. Shale-dominated intervals up to 3m occur within this unit. Thin carbonate units have been described from the middle of the Irishtown Formation by Stevens (1965) but where these have been examined (e.g. at Crow Hill) they are thought to occur toward the top the formation and to be related to the transition into the overlying Cooks Brook Formation. Lenses of conglomerate within the unit contain pebbles of igneous, metamorphic, sandstone and carbonate lithologies which appear to represent a sample of the Grenville basement and overlying Labrador Group of the autochthonous sequence (Jamea and Stevens, 1982). Good exposures of this conglomerate include the prominent hill in downtown Corner Brook, immediately west of the wharf at McIvers and numerous outcrops along the north shore of Penguin Arm (fig 3-2). These conglomerates seem to occur near the top of the quartzose sandstone interval, as suggested by Stevens (1965). Nowhere is this entire interval well exposed in an area where structural deformation can be accounted for, but it is probably best represented between Davis Cove and west of Meadows, on the north shore of the Humber Arm. The interval is estimated to be 450m in stratigraphic thickness.

The uppermost unit of the Irishtown Formation is composed of thin-bedded, commonly orange-weathering quartzose siltstone, scattered thin beds of sandstone and grey to black shale. This interval is best exposed immediately west of Halfway Point, east of Giles Point, at McIvers (on the shoreline and in the brook) and on the north shore of Penguin Arm (fig 3-2). The siltstone-dominated lithology appears to pass upward into a dark shale-dominated interval which is regarded as uppermost Irishtown Formation and is the only part of the formation exposed at the base of several sections through the lower Cooks Brook Formation in Middle Arm (section 3.2). This entire unit is commonly intensely folded and deformed but is tentatively regarded as approximately 75m in stratigraphic thickness.

The Irishtown Formation, then, comprises these 3 generalized intervals, with a total estimated stratigraphic thickness of 550m.

Early Cambrian trilobites, salterellids and archaeocyathans have been recovered from carbonate pebbles within Irishtown conglomerates (Walthier, 1949; McKillop, 1963; Stevens, 1965; James and Stevens, 1982). These, and the late Middle Cambrian fossils of the immediately overlying Cooks Brook Formation, suggest that the Irishtown Formation is late Early to Middle Cambrian in age.

Presumed lateral equivalents in the Bonne Bay area are mapped as Barters Formation (Nyman et al., 1984).

3.1.3 THE NORTHERN HEAD GROUP

3.1.3.1 Cooks Brook Formation

The internal stratigraphy of the Cooks Brook Formation is described in detail in section 3.2. The unit is composed of carbonate conglomerate, thin-bedded carbonate and shale. This formation is exposed in the "Cooks Brook syncline" between Halfway Point and Giles Point (and southward), in a broad band exposed west of McIvers and Coxs Cove which extends along the north shore of Middle Arm, and in tectonically isolated fragments within the "Rattler window", and immediately to the west, on the opposite shore of Humber Arm.

The Cooks Brook Formation overlies the Irishtown Formation in transitional contact and the base of the formation is placed at the first carbonate bed which appears above the black shale-dominated interval of the uppermost Irishtown. The basal contact is described in detail in section 3.2. The Cooks Brook is stratigraphically overlain by the Middle Arm Point Formation (described below).

The Cooks Brook Formation (as all units in the Humber Arm Supergroup) has been tectonically deformed and dislocated, so that the composite thickness and internal stratigraphy are assembled from a number of measured sections throughout the Bay of Islands area. Total composite stratigraphic thickness is approximately 350m. Similar rocks within the belt extending to the north into Bonne Bay have been mapped as McKenzies Formation (Nyman et al., 1984).

On the basis of contained fossils, the Cooks Brook Formation is regarded as late Middle Cambrian to Early Ordovician (Tremadoc) in age (section 3.3).

3.1.3.2 Middle Arm Point Formation

The Middle Arm Point Formation is composed of bedded, yellow-weathering silty dolostone, siliceous green shale with thin beds of dolostone, banded black and green shale, red and green shale and minor chert and pebble conglomerate. The internal stratigraphy of the formation is discussed in section 3.2. The interval is best exposed in sections from Middle Arm Point through Eagle Island and around the shoreline of Woman Head (the peninsula separating Middle Arm from North Arm). Similar intervals on and near the Port au Port Peninsula are also regarded as Middle Arm Point Formation. Similar, more highly deformed lithologies to the north have been included in the McKenzies Formation by Nyman et al. (1984).

The base of the Middle Arm Point Formation is defined as the base of a distinctively yellow-weathering 10 to 15m interval of bedded silty dolostone (Stevens,1965) where it stratigraphically overlies the Cooks Brook Formation. Details of this contact are provided in section 3.2. The Middle Arm Point is transitionally overlain by sandstones of the Eagle Island formation. Like the Cooks Brook Formation, the thickness of the Middle Arm Point Formation is assembled with the use of several structurally separated sections and is estimated as 120m, but appears to be somewhat variable according to the thickness of the uppermost part. A thickness of 1320 feet (402m) (including an overlying "transition zone") was originally estimated by Stevens (1965). This is thought, however, to incorporate numerous tectonic repetitions of the unit and to reflect a different interpretation of the nature of the overlying sandstone (see below).

Based upon contained graptolites the Middle Arm Point Formation is regarded as Early Ordovician in age, spanning the upper Tremadoc to middle Arenig Series (section 3.3).

Thus the Northern Head group as a whole ranges in age from late Middle Cambrian to Early Ordovician.

3.4 EAGLE ISLAND FORMATION

The informal term Eagle Island formation is introduced in this study to refer to the sandstone-dominated interval which stratigraphically overlies the Middle Arm Point Formation. The unit is composed of sandstone, ranging from thin to thick bedded, localized conglomerate, siltstone and grey shale plus local minor interbeds of red and green shale (similar to that of the Middle Arm

Point Formation) in the lowest part. The formation is generally exposed along the western margin of the Bay of Islands study area (fig 3-2).

This is the uppermost interval examined in this study and is part of an elongate, discontinuous belt of Lower to Middle Ordovician sandstone which overlies deep-water carbonate slope deposits (represented by the Cow Head Group and Northern Head group) and extends from the Cow Head area southward through Bonne Bay and into the Bay of Islands. Southward from this point and onto the Port au Port peninsula the interval is more highly tectonized and discontinuous. In the Cow Head area a similar sandstone is termed the Lower Head Formation (Williams et al., 1985; James and Stevens, 1986) and conformably overlies the Cow Head Group. In the Bonne Bay area the sandstone has been termed the Sellars Formation (Nyman et al., 1984). In the Bay of Islands and Port au Porr areas the sandstone conformably overlies the Middle Arm Point Formation and is regarded as a correlative of the above named sandstone units. The Eagle Island formation is most clearly comparable with the Lower Head Formation, but differs in character enough that a separate informal formation name is adopted here, pending further detailed study of these sandstones.

Sandstones assigned to the Eagle Island formation in this study were previously included within the Woods Island Formation (Stevens, 1965) and the Blow me Down Brook Formation (Brueckner, 1966). Subsequent studies have questioned the age and depositional setting of Blow-me-Down Brook sandstone in its type area (Stevens, 1983; Waldron, 1985; Quinn, 1985), stressing the apparent affinity with the ?Lower Cambrian Summerside Formation. The term "western sandstone" was informally adopted by Waldron (1985) (following Lilly, 1963) and nomenclature for this unit is still considered under revision. Hence sandstones designated herein as Eagle Island formation are removed from the Blow-me-Down Brook Formation and are those sandstone units which can be demonstrated to depositionally overlie the Middle Arm Point Formation (and equivalents) and are clearly Early to Middle Ordovician in age. This is the same sandstone informally termed "easterly derived flysch" by Waldron (1985).

The Eagle Island formation is the uppermost unit in the Humber Arm Supergroup and the upper boundary of the formation is everywhere tectonic (commonly melange). A minimum stratigraphic thickness of approximately 200m is indicated in the type section at Middle Arm Point.

A more detailed discussion of the distribution, sedimentology and paleontolgy of this formation is provided in ensuing sections.

3.2 SYSTEMATIC STRATIGRAPHY OF THE NORTHERN HEAD GROUP

Introduction

No single, continuous section exposes the entire Northern Head group. The stratigraphy has been assembled by correlating structurally isolated sections which span various parts of the entire interval. Reconnaissance mapping was initially conducted to identify the most intact sections and to establish their structural relationship (Chapter 2). A total of 12 sections, which together span the Northern Head group and adjacent units, were measured in detail. The location of these sections is shown in figure 3-2. Evidence has also been incorporated from more deformed areas, commonly "fault-bounded slivers", which have not been included within detailed sections.

A discussion of each measured section, including the resolution of local structural complexities, is provided in Appendix B. Large scale reproductions of measured sections are contained in Appendix A and simpified versions of these are brought forward where necessary.

Sections have been correlated on the basis of lithologic and biostratigraphic evidence. In some parts of the Northern Head group, members, which are demonstrably correlatable and considered useful for mapping purposes, have been informally defined. Useful marker horizons include the transitional contact with the underlying Irishtown Formation, a Cambrian conglomeratic interval (Brakes Cove member), a bedded dolostone unit at the base of the Middle Arm Point Formation (Woman Cove member), a distinctive siliceous green shale and dolostone unit (North Arm Point member) and the transitional contact with the overlying Eagle Island formation.

A west to east, proximal to distal polarity is indicated in the Northern Head group, although not as readily apparent as in the Cow Head Group (cf. James and Stevens, 1986), where the across-strike exposure is considerably greater. A schematic, composite stratigraphic section is shown in figure 3-3 as a guide to the stratigraphic intervals discussed in this section.

CAMBRIAN

3.2.1 <u>The lowermost Cooks Brook Formation (Irishtown/Cooks Brook Transition)</u>

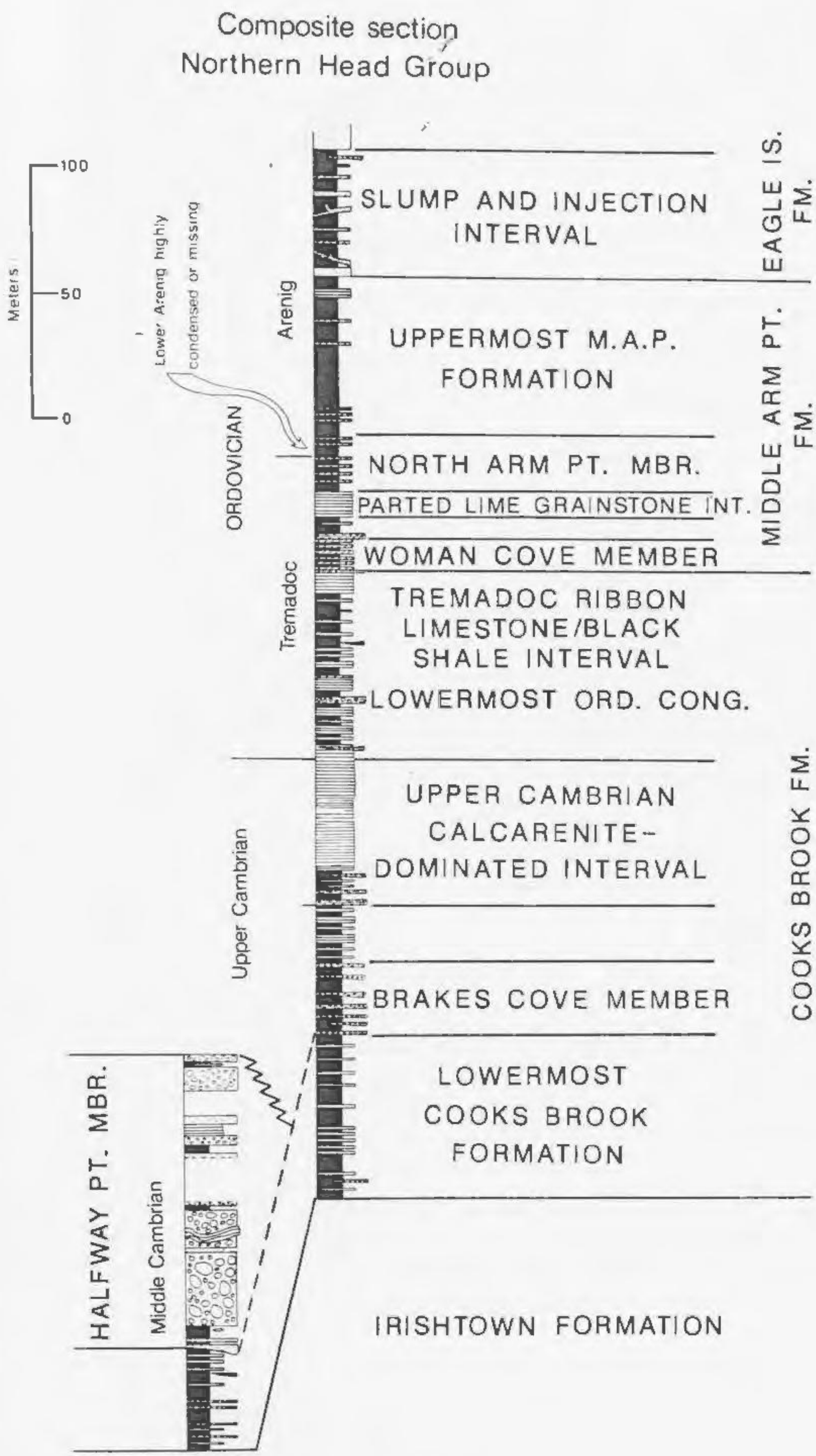
This is a distinctive interval which represents the transition from Irishtown siliciclastic sedimentation (?Middle Cambrian) into the carbonate-dominated Cooks Brook Formation (late Middle Cambrian and younger).

<u>Distribution</u>

The transition zone occurs on both limbs of the Cook's Brook syncline (fig 3-2). It is undisrupted in the type section at Halfway Point but is displaced by minor faults and folds at Giles Point. To the north, Irishtown shale appears in the core of an anticline at Seal Cove (Middle Arm) and the transition zone is intact on the eastern limb of this anticline. It is present but disrupted by faulting immediately to the south at Brake Cove and to the west at Northern Head. Further north, along regional strike, the zone is identical where observed in reconnaissance mapping of Middle Trout River Brook. This interval here forms the base of what has been informally termed the McKenzies Formation (Nyman et al.,1984),

Figure 3-3

Composite stratigraphic section and internal stratigraphy of the Northern Head group. Lithologic symbols as per fig 3-1a.



Composite section
Northern Head Group
Meters
100
50
0
Lower Arenig highly condensed or missing
Arenig
ORDOVICIAN
Tremadoc
Upper Cambrian
Middle Cambrian
SLUMP AND INJECTION INTERVAL
EAGLE IS. FM.
UPPERMOST M.A.P. FORMATION
NORTH ARM PT. MBR.
PARTED LIME GRAINSTONE INT.
WOMAN COVE MEMBER
MIDDLE ARM PT. FM.
TREMADOC RIBBON LIMESTONE/BLACK SHALE INTERVAL
LOWERMOST ORD. CONG.
UPPER CAMBRIAN CALCARENITE-DOMINATED INTERVAL
BRAKES COVE MEMBER
COOKS BROOK FM.
LOWERMOST COOKS BROOK FORMATION
HALFWAY PT. MBR.
IRISHTOWN FORMATION

clearly the equivalent of the Cooks Brook Formation.

<u>Lithology</u>

The base of the Cooks Brook Formation is defined at the first appearance of bedded limestone above the shale-dominated uppermost Irishtown interval previously described. At the type section at Halfway Point (fig 3-4) these beds are 20 to 50cm thick and are granule to pebble conglomerates, commonly graded and displaying a platy fabric. Parallel-laminated dolomitic grainstone locally caps these units or occurs as isolated beds. These carbonates are interbedded with dark grey to black shale, commonly laminated, which dominates the lowermost 10m and gives way upward to an interval of black/green/dolomitic banded shale.

At Giles Point one of the lowermost carbonate beds is a 50cm bed composed entirely of oosparite. The same lithology appears as clasts in immediately overlying conglomerates. Although described from several localities by Stevens (1965), oosparite has not been noted as bedded units in other sections which expose the base of the Cooks Brook Formation and is regarded here as an "accessory component" of the transition zone.

Abundant diagenetic pyrite is a ubiquitous accessory feature of the base of the Cooks Brook Formation (refer to Chapter 6).

<u>Paleontology</u>

The only fossils collected from this interval to date are indeterminate agnostids from thin limestone beds in Middle Trout River Brook.

Discussion

This interval, the transitional base of the Cooks Brook Formation, is remarkably similar everywhwere. It is overlain, however by units of different age, which suggests a localized and variously punctuated onset of carbonate sedimentation. This will be discussed further at the end of this chapter.

3.2.2 The Halfway Point Member

Distribution

This member is exposed on both limbs of the Cooks Brook syncline, at Giles Point and at the type section at Halfway Point. It also occurs in faulted exposure in the core of the "Rattler window", and as a raft in melange along the shoreline opposite Woods Island (fig 3-2).

Lithology

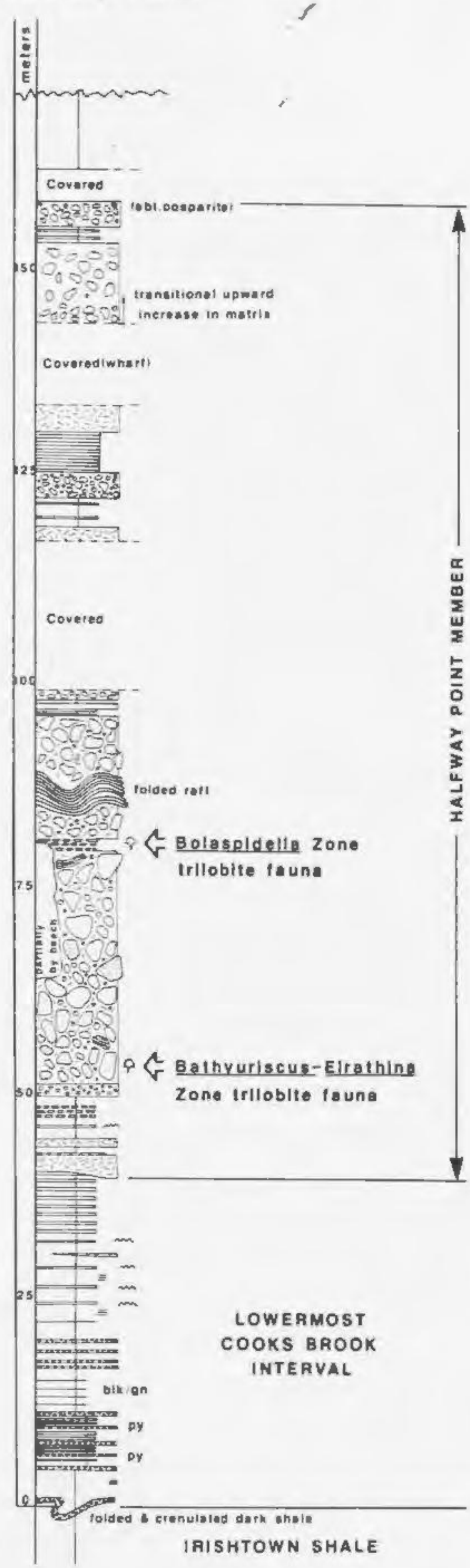
In the type section, at Halfway Point (fig 3-4) this interval is roughly 120m thick and is dominated by conglomerate. There are several individual conglomerate units within this interval, of variable style and thickness. Together, however, they form a conglomeratic interval which contrasts with overlying and underlying units and presumed lateral equivalents.

At the base of the Halfway Point member are several beds of platy conglomerate 1 to 2m in thickness. These are overlain by a roughly 50m thick unit of matrix-rich boulder conglomerate. Overlying this, in the upper part of the member are several conglomerate beds, 2 to 10m thick, of variable style and matrix content. Interbeds of parted lime grainstone and nodular to ribbon

Figure 3-4

Lower portion of the Halfway Point section, illustrating the lowermost Cooks Brook interval and the overlying Halfway Point member. Lithologic symbols as per fig 3-1a; "abt. oosparite" refers to abundant clasts of oosparite within conglomerate.

Halfway Point



limestone separate conglomerates throughout the entire interval.

The Halfway Point member as a whole, but particularly the medial massive conglomerate, is distinctive in 3 ways: 1) there is a very high proportion of dark shale matrix, 2) internal structure is commonly chaotic and includes large (3x10 m) chaotically folded rafts of bedded sediment, 3) individual boulders within the conglomerates are unique. This includes cobbles to boulders of the underlying Irishtown sandstone, abundant oosparite cobbles, and a distinctive white-weathering algal boundstone lithology which has not been noted outside of the Halfway Point member.

Paleontology

Trilobites have been recovered from boulders and from nodular bedded carbonate in the Halfway Point section (fig 3-4) and at Bound Head (Rattler Window) and are all late Middle Cambrian in age. Fauna from the lower part of the massive conglomerate are characteristic of the North American Bathyuriscus-Elrathina Zone and the Acado-Baltic Ptychagnostus gibbus Zone (pers. comm. A.R. Palmer to R.K. Stevens, 1979). Fauna from higher in the Halfway Point section, and Bound Head, are characteristic of the North American Bolaspidella Zone and Acado-Baltic Zone B3 (pers. comm. W.D. Boyce, 1985; Section 3-3; Appendix C). No fossils have been located from the uppermost part of this member.

3.2.3 The Brakes Cove Member

Distribution

The type section of the Brakes Cove member is at Northern Head, where contacts with underlying and overlying units are most clearly exposed (fig 3-5) and the member appears to be the most fossiliferous. Reference sections occur at Seal Cove and Woman Cove (fig 3-6). The interval is exposed at two localities in Brakes Cove, whence the name is derived, but the degree of deformation here obscures relationships with neighbouring units. The member is also exposed in Penguin Arm.

Lithology

The interval is roughly 12 to 15m thick and is characterized by pebble to cobble conglomerate units .5 to 2m thick, interbedded on a 3m scale with nodular to ribbon limestone. The conglomerates are lensoid, and thicker units appear to be amalgamations of 2 or 3 beds. The member is underlain by an interval of black, green and dolomitic shale with scattered thin beds of carbonate grainstone. At Northern Head it passes upward into a thick interval of parted to ribbon limestone, while at Seal Cove it is overlain by a shale-dominated lithology similar to that which underlies it.

Clasts within the conglomerates are roughly equally divided between lime mudstone and grainstone with sparse "exotic" clasts dominated by oosparite.

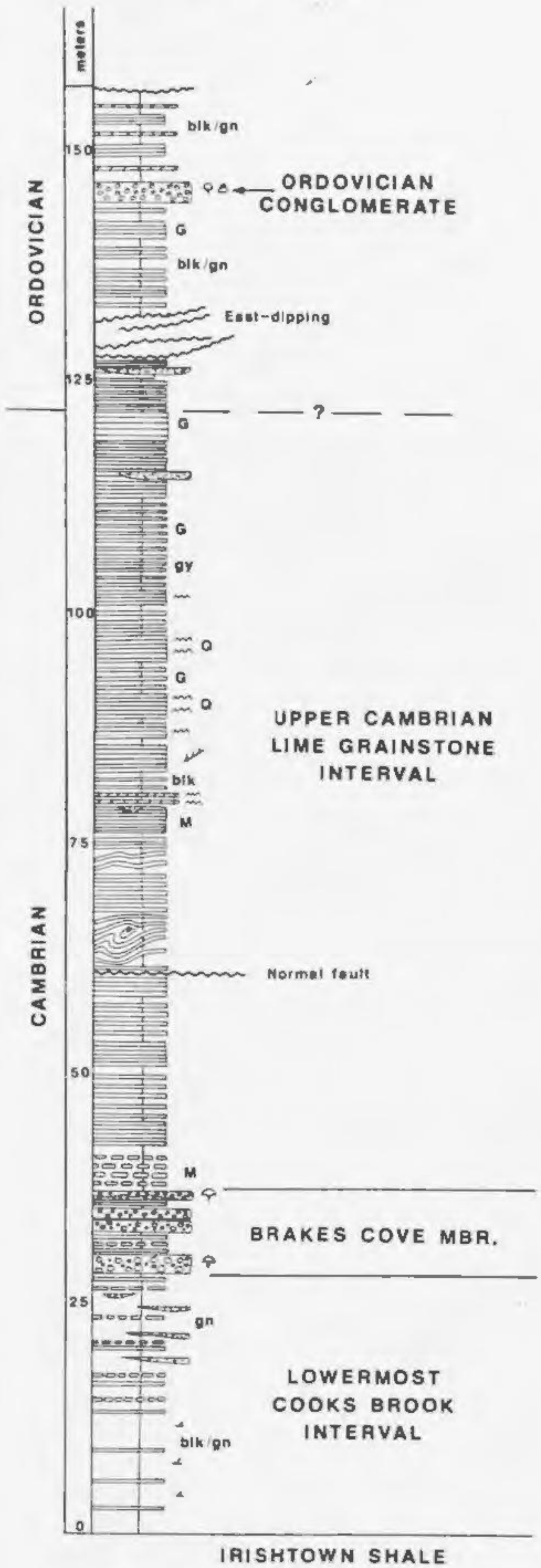
Paleontology

The conglomerates of the Brakes Cove member are the most richly fossiliferous in the entire area and have yielded a total of 49 trilobite and brachiopod-bearing boulders. These are dominated by

Figure 3-5

Lower portion of the Northern Head section, illustrating the lowermost Cooks Brook interval, the overlying Brakes Cove member, the Upper Cambrian lime grainstone interval, and the lowermost Ordovician conglomerate. Lithologic symbols as per fig 3-1a.

Northern Head



fossils characteristic of the North American Cedaria and Crepicephalus Zones (W.D. Boyce, pers. comm., 1985) and on this basis the Brakes Cove member is regarded as early Dresbachian (Late Cambrian) in age (Section 3-3).

3.2.4 Upper Cambrian facies contrasts

The Upper Cambrian is largely represented by a thick interval of bedded lime grainstone, but sections at Seal Cove and Woman Cove are overall more dominated by shale and lime mudstone (fig. 3-6).

a) Grainy facies (Northern Head)

Distribution

At Northern Head the Brakes Cove member is conformably overlain by a thick (100m) interval of parted to ribbon lime grainstone (fig 3-5). A similar interval appears in Brakes Cove, above the Halfway Point member in the Cooks Brook syncline, and is partially represented at Woman Cove.

Lithology

This interval is dominated by ribbon lime grainstone with scattered packages of parted lime grainstone and displays grey to green shale interbeds throughout. Grainstones commonly display abundant quartz silt, which is visible in thin section but not readily apparent in the field. Thin (20cm) very lensoid platy conglomerates are scattered through the sequence. Roughly 20m from the base of the interval at Northern Head a zone of chaotic folding occurs which may be slump-related (Chapter 4).

In the upper part of the interval, immediately east of the tip of Northern Head proper, highly rippled, dark, coarse lime grainstones appear. Beds here are up to 20cm thick, locally amalgamated and include scattered intraformational conglomerates. These grainstones contain the abundant quartz sand grains which are medium to fine and very well rounded. The sequence upsection is dominated by parted limestone with scattered 40cm conglomerare beds and continues to the major Ordovician conglomerate discussed below.

Paleontology

The only fossil locality contained within this grainy sequence is an indeterminate Dendroid assemblage (cf. Callograptus) from a black shale horizon immediately below the rippled grainstones described above. The sequence as a whole is regarded as Upper Cambrian since it is bracketed by the Dreabachian Brakes Cove member below and a conglomerate containing Lower Ordovician clasts above.

b) Shale/lime mudstone/conglomerate facies

Distribution

At Seal Cove and in part at Woman Cove the Upper Cambrian is more dominated by shale and lime mudstone than the sequence described above. It is also, however, punctuated by a second conglomeratic interval similar to the Northern Head member. Also, a very thin-bedded lime mudstone-dominated interval appears in the uppermost part of the Halfway Point section, in the core of the Cooks Brook syncline.

Lithology

At Seal Cove the Brakes Cove member is overlain by a roughly 35m interval dominated by interbedded black, green and dolomitic shale with scattered intervals of ribbon limestone. This is overlain by a conglomeratic interval similar to the Brakes Cove member, roughly 30m in thickness. The interval contains a number of lensoid pebble conglomerate units from 20 to 80cm thick which are interbedded with abundant green shale and 1 to 2m packages of nodular to ribbon limestone. This unit has been tentatively correlated with an interval at Woman Cove dominated by green shale and nodular limestone with a few thin lensoid conglomerates.

A sequence of parted to ribbon lime mudstone, estimated to be 55m thick, overlies this interval at Seal Cove. Limestones here are characteristically very thin bedded (1 to 2cm). A similar, but thinner, sequence appears at the top of the Halfway Point section, in the core of the Cook's Brook syncline.

Paleontology

The upper conglomeratic interval at Seal Cove has yielded a sparse trilobite fauna indicative of the North American Taenicephalus Zone (W.D. Boyce, pers. comm., 1985) and is regarded as lower Franconian.

The only Trempealeauan fauna encountered in this study occurs within a boulder in the Ordovician conglomerate at Northern Head. The uppermost lime mudstone and shale-dominated sequence has not yielded any graptolites as yet and is tentatively regarded as latest Cambrian in age.

3.2.5 Discussion of the Cambrian

Correlation of units in the Cambrian portion of the Northern Head group is shown in figure 3-6. As mentioned earlier, the transitional base of the Cooks Brook Formation appears remarkably similar everywhere but is overlain by units of different aspect and different age. In the most easterly exposure, in the Cooks Brook syncline, the thick, conglomeratic Halfway Point interval appears and is believed to be entirely late Middle Cambrian (*Bathyuriscus-Elrathina* and *Bolaspidella* Zones). In contrast, in sections to the northeast in Middle Arm the lowermost Cooks Brook interval passes upward into the Brakes Cove member which is Dresbachian (*Cedaria-Crepicephalus* Zone). Several alternatives might explain this apparent contrast:

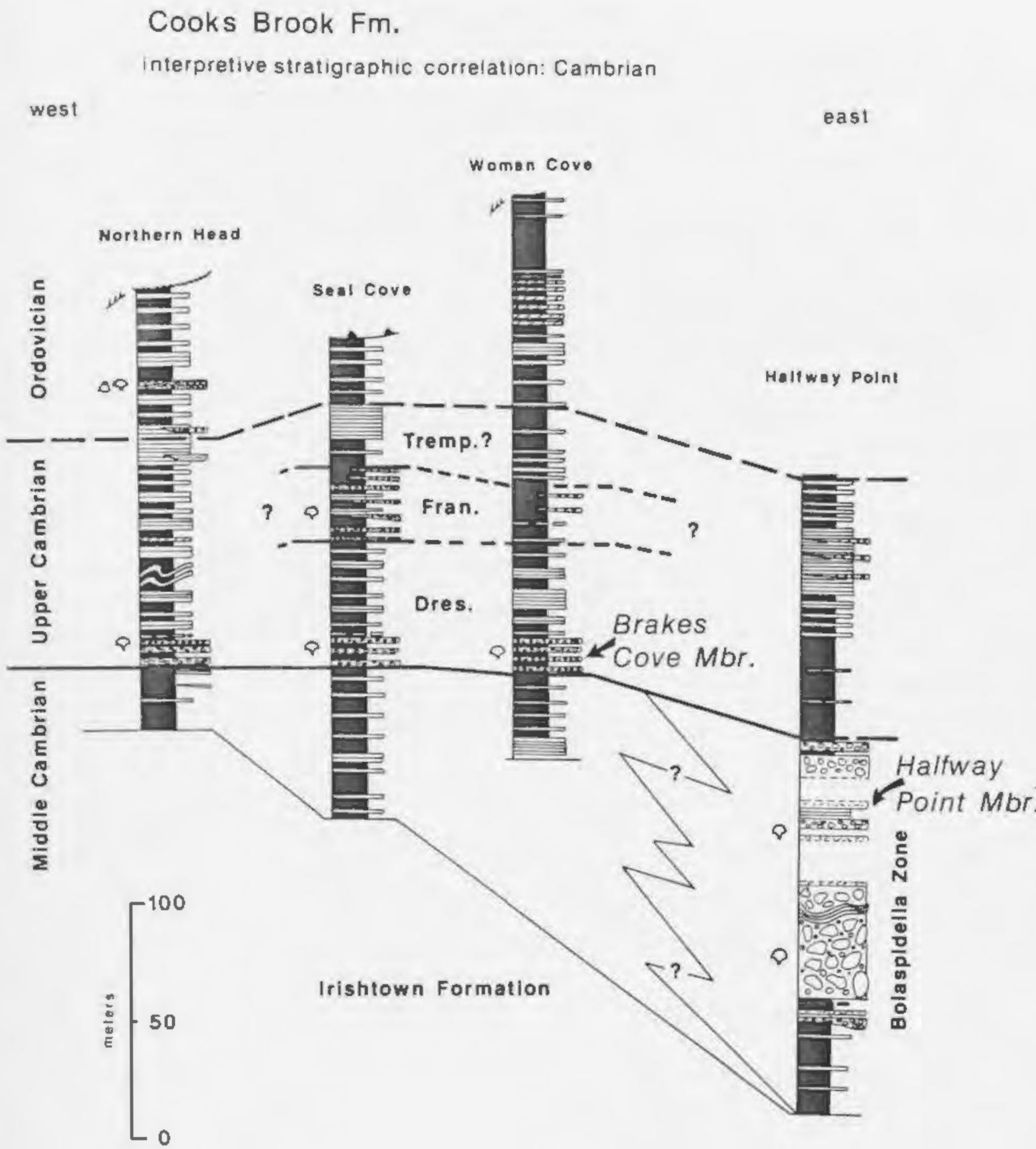
Option 1) The Cooks Brook syncline is out of place with respect to the west to east/proximal to distal polarity of the Northern Head group as a whole and has been structurally transported from an initial proximal setting to its present position. This places the Northern Head/Seal Cove sections in an initially more distal position and indicates that they received coarser carbonate sedimentation later, possibly under conditions of a prograding carbonate margin.

Option 2) More intense fossil collecting will uncover trilobites of Dresbachian age in the Halfway Point member, indicating that some or all of it is coeval with the Brakes Cove member and suggesting that these are facies equivalents of the same depositional event.

Option 3) The onset of carbonate sedimentation was localized and variously punctuated along the Cambrian margin. Hence deposition of

Figure 3-6

Cooks Brook Formation: interpretative stratigraphic correlation within the Cambrian. Lithologic symbols as per fig 3-1a..


Cooks Brook Fm.
interpretive stratigraphic correlation: Cambrian
west
east
Woman Cove
Northern Head
Seal Cove
Halfway Point
Ordovician
Upper Cambrian
Middle Cambrian
Tremp.?
Fran.
Dres.
?
Brakes Cove Mbr.
Halfway Point Mbr.
Bolaspidella Zone
Irishtown Formation
meters
100
50
0

the Halfway Point member occurred downslope from an active carbonate shelf in the late Middle Cambrian while shale-dominated sedimentation continued at Northern Head/Seal Cove until the Upper Cambrian deposition of the Brakes Cove member.

There is no evidence presently available to support options 1 nor 2. The third alternative represents the simplest and most straightforward model for correlating these units in the lower part of the Cooks Brook Formation. Conglomerates of the Halfway Point member have a distinctive style in their overall thickness, abundant matrix, chaotic sedimentary structures and incorporation of huge folded rafts of bedded carbonate and large blocks of the underlying Irishtown sandstone. These characteristics suggest that the Halfway Point member is an isolated unit, localized by depositional processes, and followed by later gravity depoaits (Brakes Cove member) along depositional strike in the Upper Cambrian. The postulated depositional setting of these units will be discussed in Chapter 8.

ORDOVICIAN

3.2.6 Lowermost Ordovician conglomerate

Distribution

The conglomerate is prominently exposed immediately east of the tip of Northern Head proper and this is the only locality which has yielded an Ordovician shelly faunal assemblage.

Lithology

It is a pebble to boulder conglomerate, 2m thick, which has planar boundaries and is not graded. It occurs within a sequence of parted to ribbon lime grainstones and immediately overlies the interval described in 3.2.4a) above (fig 3-5).

This is the youngest polymict conglomerate within the Northern Head group, since conglomerates upsection contain a preponderance of locally-derived clasts, deformed while soft. This unit, however, has a mixture of lime grainstones and mudstone with sparse clasts of oosparite and is, in this sense, similar in style to underlying Cambrian conglomerates.

Paleontology

Boulders within this bed have a Lower Ordovician trilobite and brachiopod fauna characteristic of the Missisquoia and Symphisurina Zones (W.D. Boyce, pers. comm., 1985). A single boulder containing a Trempealeauan fauna has been identified. Correlation of this unit with overlying graptolite-bearing units will be discussed in the next section.

Discussion

The Northern Head section above this bed is disrupted by normal faulting but overlying ribbon limestones are interpreted as being in normal stratigraphic sequence. Hence the conglomerate bed is regarded as lowermost Ordovician, immediately below the graptolite-bearing interval discussed in the following section.

3.2.7 Tremadoc ribbon limestone interval

Distribution

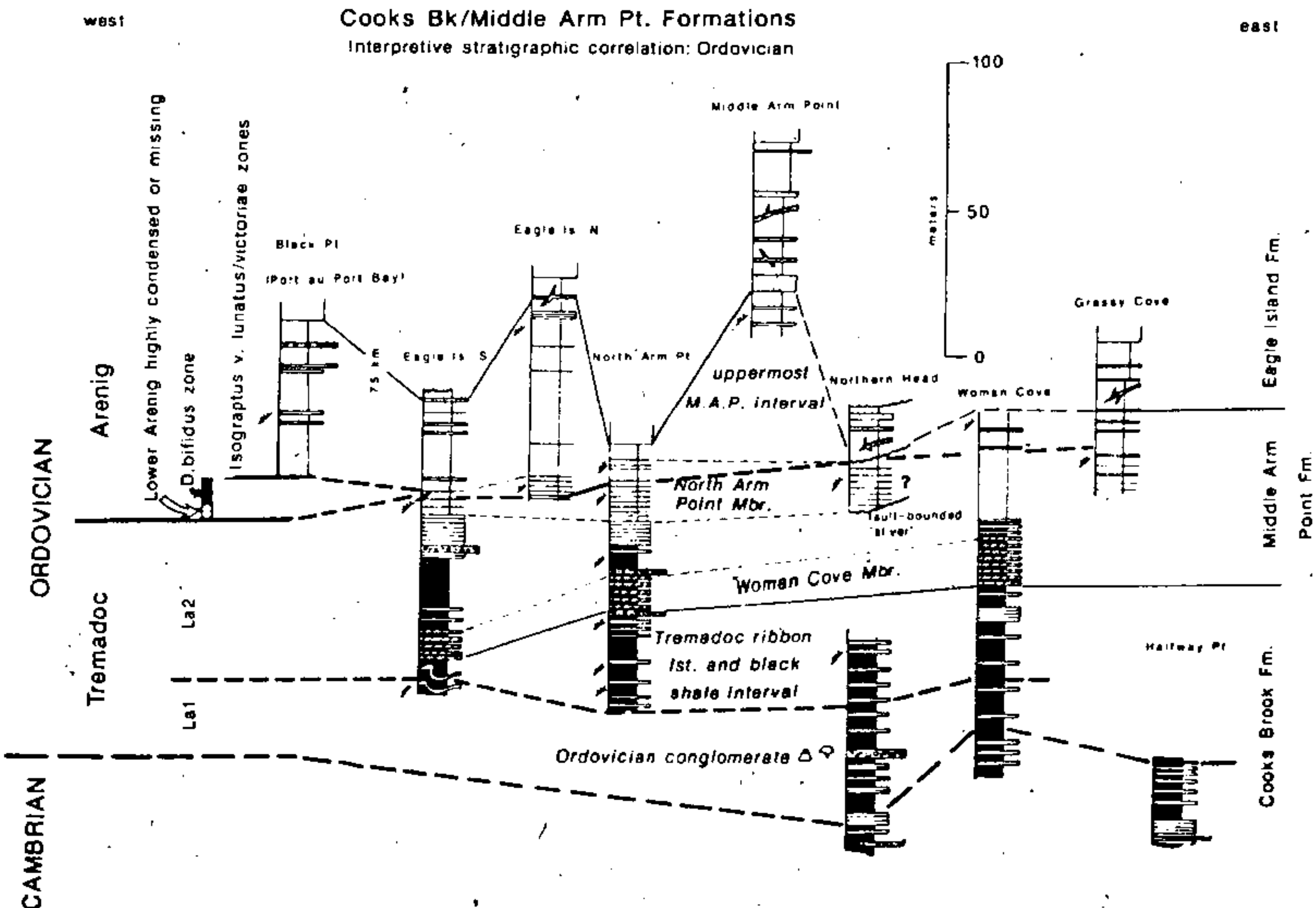
This unit occurs in the core of a complexely deformed anticline at the southern tip of Eagle Island, in the eastern continuation of the Northern Head section, in the cove between Northern Head and North Arm Point, and at the base of the North Arm Point section (fig 3-2). Each of these localities has yielded graptolites (Section 3-3). This unit is also tentatively correlated with a deformed interval of similar lithology at Woman Cove (fig 3-7) which has not yielded fossils to date. It also appears within a zone mapped as "highly deformed Cooks Brook Formation" in the vicinity of Black Head (east of Middle Arm Point; fig 3-2).

Lithology

This interval is somewhat deformed or only partially exposed wherever seen, hence its thickness is estimated as 30 +m. At Eagle Island exposure is limited and consists of a tightly folded interval of black shale, in beds up to 40cm thick, with 15 to 20cm thick interbeds of lime mudstone. The section here passes transitionally upward into the basal Middle Arm Point Formation (the Woman Cove member), however the degree of deformation at this locality makes relationships difficult to interpret. The fault-bounded ribbon limestone interval at Northern Head is of similar aspect: laminated dark shale ranging in thickness from 15 to 40cm interbedded with units of lime mudstone 15 to 25cm thick. A similar interval north of Northern Head passes upward into a highly deformed zone separating this section from North Arm Point to the north. At North Arm Point an 18m interval of this unit is exposed at the base of the section,

Figure 3-7

Cooks Brook and Middle Arm Point Formations: interpretative stratigraphic correlation within the Ordovician. Lithologic symbols as per fig 3-1a; predominantly red and green shale in the upper part of the section is shown uncoloured.


west
Cooks Bk/Middle Arm Pt. Formations
Interpretive stratigraphic correlation: Ordovician
east
100
50
0
meters
Middle Arm Point
Eagle Is. N
Black Pt
(Port au Port Bay)
Eagle Is. S
North Arm Pt
Northern Head
Woman Cove
Grassy Cove
Halfway Pt
uppermost
M.A.P. interval
North Arm
Point Mbr.
fault-bounded
sliver
Woman Cove Mbr.
Tremadoc ribbon
lst. and black
shale interval
Ordovician conglomerate
Lower Arenig highly condensed or missing
D.bifidus zone
Isograptus v. lunatus/victoriae zones
ORDOVICIAN
Arenig
Tremadoc
La2
La1
CAMBRIAN
Eagle Island Fm.
Middle Arm
Point Fm.
Cooks Brook Fm.

above low tide (fig 3-8). This interval is dominated by siliceous black shale with 5cm interbeds of lime mudstone at 30 to 40cm intervals. The shale is finely laminated and contains thin (< 1mm) extremely organic rich, "sooty" partings at roughly 5cm intervals. Lensoid pebble conglomerates up to 20cm thick occur within the lower 5m of exposure. An isolated 10cm banded chert is present in the uppermost 1m and contains lenses of pyrite up to 2cm thick. This interval passes upward into a unit of black and green shale interbedded on a centimeter scale.

The relationship of each of the structurally separated sections containing this interval is not clear due to the nature of exposures in the area. They are, however, regarded as intimately associated and equivalent or transitional based on contained faunas and lithologic similarity (fig 3-7).

<u>Paleontology</u>

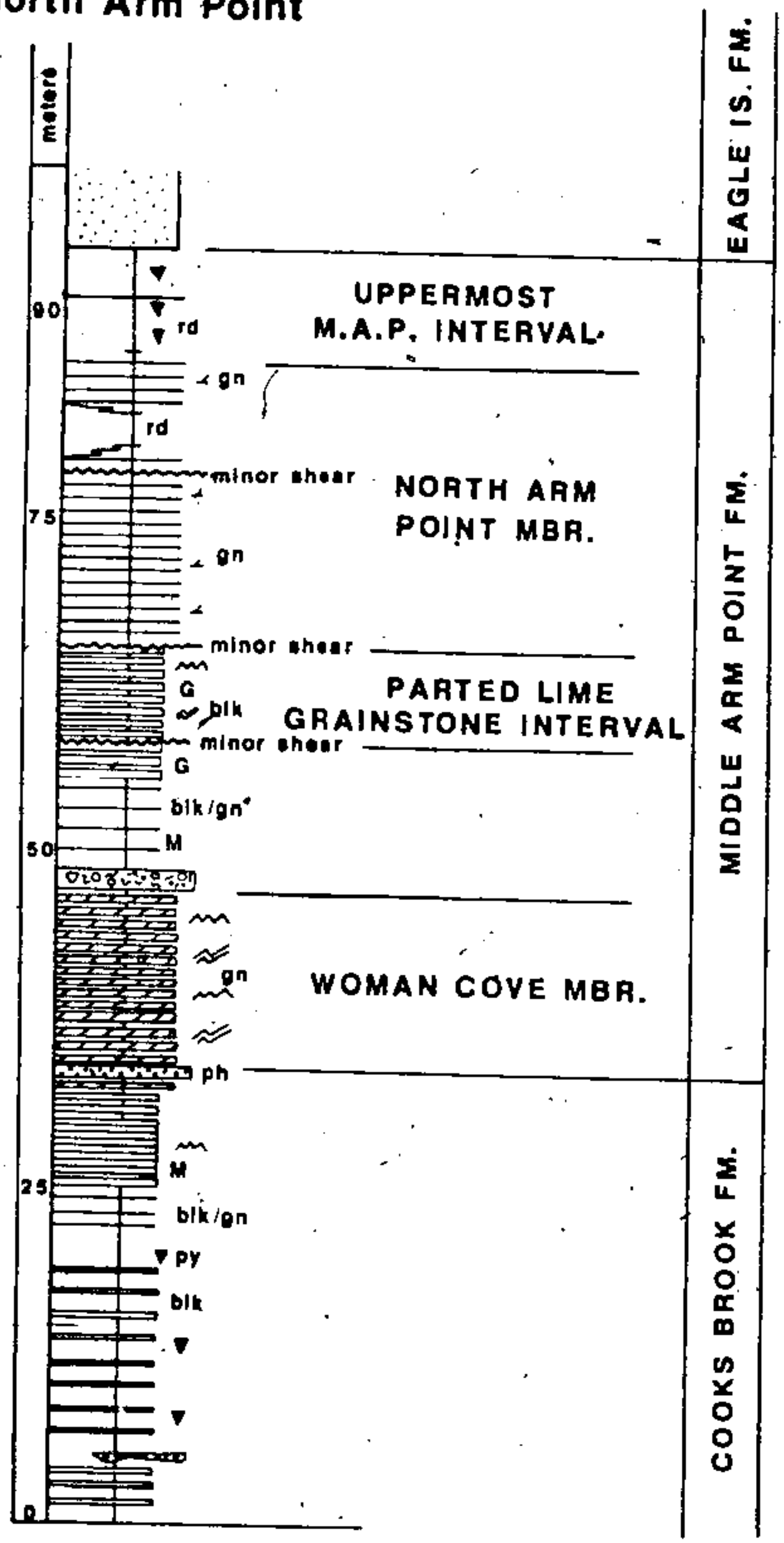
This interval at Eagle Island contains a classic Lancefieldian 1 (La1) graptolite fauna (Erdtmann and Botsford, 1986; Section 3. 3). Another La1 faunule has been recovered from the Black Head locality (Stevens, 1965).

The Northern Head interval contains an La2 fauna dominated by <u>Araneograptus</u> <u>murrayi</u> (B.D. Erdtmann, pers. comm., 1986). The deformed zone south of North Arm Point has yielded only a sparse collection of siculate dendroids, tentatively regarded as Early Ordovician. The North Arm Point interval is richly graptolite-bearing and contains an abundant La2 fauna throughout.

Figure 3-8

Upper portion of the North Arm Point section, illustrating the disposition of the Woman Cove member, parted lime grainstone interval, North Arm Point member, uppermost Middle Arm Point Formation, and Eagle Island formation. Lithologic symbols as per fig 3-1a.

North Arm Point



Discussion

At North Arm Point the top of this ribbon limestone and black shale interval is of La2 age, and is roughly 13m below the base of the Woman Cove member (the clearest nearby lithologic marker, see below). At Eagle Island South, however, the La1 graptolite locality occurs roughly 12m below the same dolostone package. The Woman Cove member is tentatively regarded as isochronous within the resolution of graptolite zonation (see discussion in that section) implying that the La2 interval is abbreviated or missing at Eagle Island. La2 zone graptolites have not been located there to date and it is possible that the interval has been tectonically abbreviated, given the amount of deformation present at Eagle Island South.

3.2.8 Woman Cove Member

This is the clearest lithologic marker within the entire Northern Head group and was proposed by Stevens (1965) as the base of the Middle Arm Point Formation. The interval is a clearly mappable unit, marks an overall change in depositional conditions and hence is regarded as a good formation boundary.

Distribution

This interval is continuously exposed in the type section at North Arm Point (fig 3-8) and is also well exposed at Woman Cove. The overall aspect at Eagle Island South is very similar but relationships with neighbouring units are suspect due to deformation. This interval, or parts of it, is exposed elsewhere in isolated tectonic slivers: along the north shore of Middle Arm between Northern Head and Seal Cove, south of Middle Arm Point, and at Big Head (Rattler window).

Lithology

The interval ranges from 12m in thickness at North Arm Point to 17m at Woman Cove. It is characterized by beds of silty dolostone generally ranging in thickness from 15 to 45cm interbedded with green shale in beds 5 to 15cm thick. Dolostone beds are distictively yellow-weathering, are commonly cross-laminated and characteristically highly bioturbated relative to the Cooks Brook Formation. Based on petrographic and other evidence they are interpreted as "detrital dolomite" units (Chapter 4).

Several related units appear in the west, at North Arm Point, which do not appear to the east at Woman Cove. Overlying the La2 interval at North Arm Point is a sequence, 13m in total thickness, comprising units of interbedded black and green shale, parted lime mudstone, and ribbon grainstone plus granule conglomerate which immediately underlies the Woman Cove member (fig 3-8). Dolomite first appears as grains, and locally dominates, current-rippled lenses within the uppermost grainstone beds. In contrast, at Woman Cove, the dolostone interval sharply overlies a unit of parted to ribbon lime grainstone.

Overlying the Woman Cove member at North Arm Point is a 1.5m pebble to cobble conglomerate dominated by clasts of silty dolostone, deformed while soft, and green shale clearly derived from the underlying dolostone interval. A similar unit occurs at Eagle Island South but is separared from the dolostones by an interval of black and green shale. At Woman Cove, the dolostone interval passes transitionally upward into bright green shale with isolated thin beds of lime mudstone and lenses of granule conglomerate up to 20cm.

Paleontology

At North Arm Point black shale within the ribbon lime grainstone unit, immediately below the dolostone, has yielded a non-diagnostic dendroid fauna. Black and green shale above the conglomerate contains a poorly preserved assemblage of Clonograptus sp. (R.K. Stevens, pers. comm., 1985). Green shales of the dolostone interval itself appear to be completely unfossiliferous. From the foregoing it is clear that the dolostone interval has not been precisely dated, but based on relationships with overlying and underlying units is regarded as late Tremadoc (La2). No evidence is presently available to suggest that the unit is time-transgressive.

3.2.9 Parted lime grainstone interval

Distribution

This interval is well exposed in the North Arm Point section, in the cove east of North Arm Point, and on Eagle Island (fig 3-2). Exposures on both sides of North Arm Point are identical and interpreted to be on opposite limbs of an isoclinally folded (and sheared) anticline.

Lithology

The unit is 7m thick at North Arm Point and approximately 10m thick at Eagle Island South. At North Arm Point (fig 3-~~8)~~ minor shears are evident at the lower and upper contacts of the interval but the transitional nature of lithologic change across these boundaries indicates that they are sedimentary and not tectonic. The unit is composed of lime grainstone, in beds 15 to 25cm thick interbedded with black, finely laminated shale at 5 to 10cm intervals. The lime grainstone is dark grey due to included organic carbon, displays scattered current ripples and is characteristically bioturbated. Similar characteristics are seen, but not as well exposed, at Eagle Island South.

Paleontology

The laminated black shale beds within this interval contain a non-diagnostic, dendroid-dominated fauna.

3.2.10 North Arm Point Member

Distribution

These rocks are best exposed in the type section at North Arm Point (fig 3-8) and also occur at Eagle Island (South and North) and in faulted exposure east of Northern Head. A similar lithology, with the same graptolite assemblage, is seen at Grassy Cove, in North Arm (fig 3-2).

Lithology

At the type section the North Arm Point member overlies the parted lime grainstone unit described above and measures 22m in total thickness up to an overlying unit of red chert and shale. The upper part is disrupted by shearing but appears to be transitional in that it incorporates meter-scale interbeds of the overlying red shale.

The member is mostly a siliceous green shale with minor thin dark shale interbeds (up to 3cm) and 15 to 20cm thick packets of silty dolomite which occur at roughly 50cm intervals. These units display irregular bedding at 2 to 5cm intervals, are commonly cross-laminated and locally silicified where they take on a reddish hue.

Paleontology

The collection of late Tremadoc graptolites from the base of the North Arm Point member, and Arenig assemblages from its uppermost part indicates that this interval spans the Tremadoc/Arenig boundary.

At i) North Arm Point, ii) a fault-bounded sliver east of Northern Head and iii) Grassy Cove (fig 3-2) the North Arm Point member contains a late Tremadoc graptolite assemblage dominated by Bryograptus, Adelograptus, Clonograptus and Kiaerograptus (S.H. Williams, pers. comm., 1984; 1985).

At North Arm Point a significant horizon of Arenig graptolites occurs in the uppermost part of the North Arm Point member, 12m above the late Tremadoc locality, 2m below the overlying red shale. The Tremadoc and Arenig graptolite occurrences are separated by the first appearance of thin red shale beds (fig 3-8) and a shear zone which introduces a shear-bounded packet of the (overlying) sandstone. (This has been removed when plotting stratigraphic sections). The upper Horizon contains a Didymograptus bifidus graptolite assemblage (S.H. Williams, pers. comm., 1985). Similar, but more poorly-preserved assemblages occur at Eagle Island South and North.

Discussion

These Tremadoc and Arenig graptolite assemblages come from an identical lithology which, at North Arm Point, dominates the entire interval from the top of the above described dark parted lime grainstone unit to the base of the overlying red shale and chert unit. It thus appears that the Tremadoc/Arenig boundary is contained within this "siliceous green shale plus silty dolomite" interval. Moreover, no graptolite assemblages representative of the lower Arenig *Tetragraptus approximatus*, *Tetragraptus akzharensis* nor *Pendeograptus fruticosus* Zones (Williams and Stevens, 1986) have ever been located anywhere within the Middle Arm Point Formation. These zones should appear between these two localities and even if the section as measured at North Arm Point is tectonically abbreviated, it appears on present evidence that the lower Arenig is condensed or missing within the Middle Arm Point Formation.

3.2.11 Uppermost Middle Arm Point Formation

Distribution

Complete sections of this interval occur at Eagle Island South, Eagle Island North and North Arm Point (fig 3-2). Fault-bounded portions of the interval are common, particularly the upper part which is in contact with the overlying sandstone. These include Black Point in Port au Port Bay (75 km to the south), Middle Arm Point proper, Black Brook north, Cape Split and Balance Point (fig 3-2). Where the base of this unit is seen it is transitional with the underlying North Arm Point member.

The section at Woman Cove exposes a substantial portion of the Middle Arm Point Formation but the overlying sandstone does not appear in the core of the syncline there, nor does the North Arm

Point member appear to be developed (fig 3-7).

The section at Grassy Cove (North Arm) is different in style (see below), since this "uppermost Middle Arm Point interval" is not clearly distinguishable and lithologies best assigned to the North Arm Point member are directly overlain by sandstones of the Eagle Island formation.

Lithology

This interval comprises 3 basic lithotypes:

1) a red shale-dominated lithotype which is either massive red shale, locally transitional into massive green, or occasionally interbedded red and green shale

2) thinly (cm scale) interbedded black and green shale, commonly with packets of thin-bedded carbonate at roughly 1m intervals.

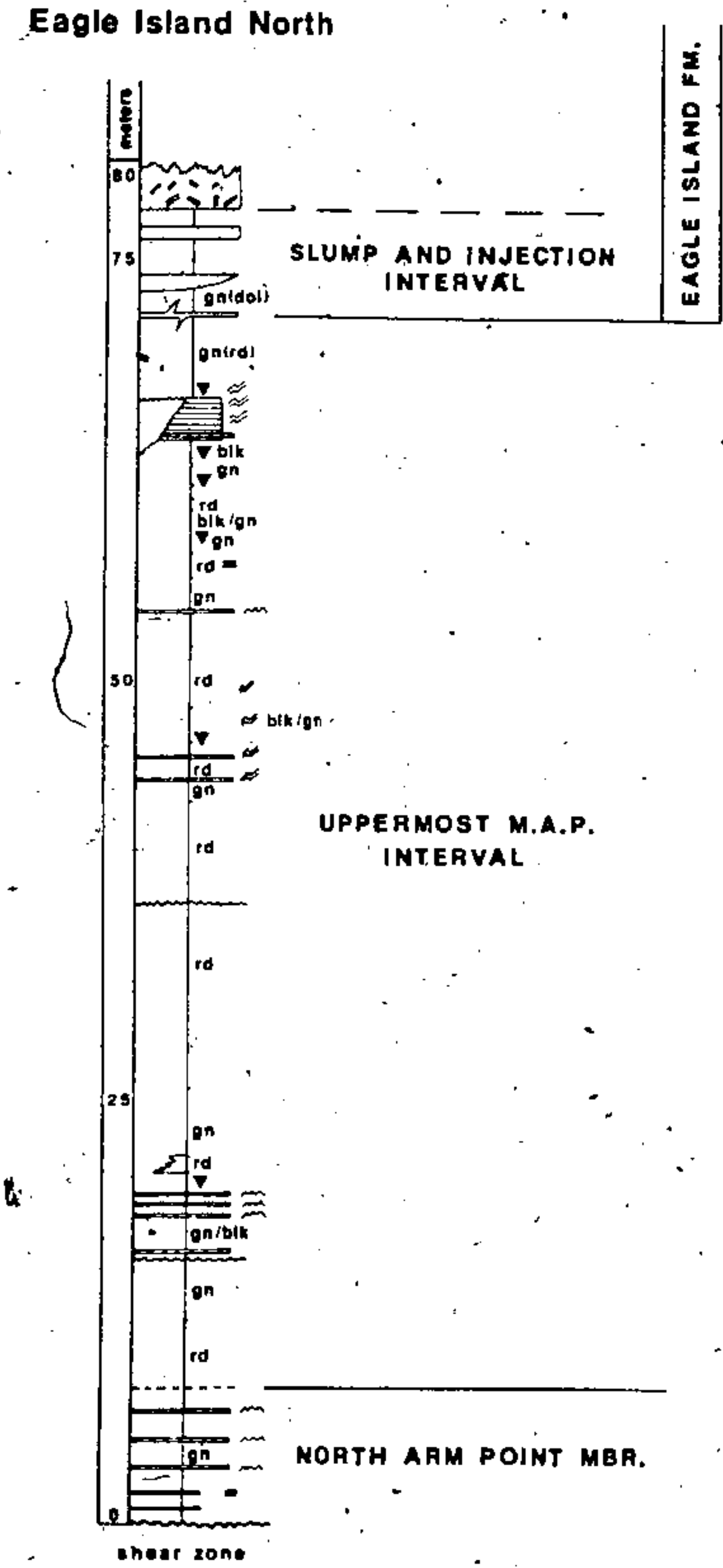
3) a green shale-dominated lithology which locally demonstrates a diffuse 5 to 10cm scale banding of dark shale and contains scattered packets of silty dolomite.

Red shale is confined to the western part of the area and occurs at Black Point (Port au Port Bay), Eagle Island and North Arm Point (fig 3-2). There is no systematic variation in the stratigraphic occurrence of these lithotypes, although the third is similar to, and may be locally transitional with the underlying North Arm Point member described above. The style of broad alternation of the first two lithotypes is well displayed in the Eagle Island North section (fig 3-9). This section also contains, in its upper part, a 2m bed of highly bioturbated lime mudstone which is not seen elsewhere.

At Woman Cove the entire interval is dominated by bright green shale with thin ribbon limestone beds common in the lower part and

Figure 3-9

Eagle Island North section illustrating the uppermost Middle Arm Point interval, and relationship with adjacent units. Lithologic symbols as per fig 3-1a.



Eagle Island North
meters
80
75
50
25
0
gn(dol)
gn(rd)
blk
gn
rd
blk/gn
gn
rd
gn
rd
blk/gn
rd
gn
rd
rd
gn
rd
gn/blk
gn
rd
gn
shear zone
SLUMP AND INJECTION INTERVAL
EAGLE ISLAND FM.
UPPERMOST M.A.P. INTERVAL
NORTH ARM POINT MBR.

units of banded black and green shale in the upper part. No red shale appears in this section.

Chert is common throughout the whole interval and consists primarily of pervasively silicified shale (Chapter 4).

The thick of this interval is variable (fig 3-7); 27m thick at Eagle Island South, 63m thick at Eagle Island North and only 7m thick at North Arm Point. At Black Point (Port au Port), the base of the interval is not seen and 54m are exposed. Likewise at Middle Arm Point 16m are exposed above low tide. It is possible that the deformation in this part of the section is responsible for some of the apparent variability in thickness. It is also quite likely, however, that the erosive depositional nature of the overlying sandstone has affected the thickness of the uppermost Middle Arm Point, as has been demonstrated in the Cow Head Group (James and Stevens, 1986).

Paleontology

This interval is regarded as spanning the Isograptus victoriae lunatus and Isograptus victoriae victoriae graptolite Zones (S.H. Williams, pers. comm., 1984; 1985; 1986). Banded black and green shales at Black Point have yielded a rich I. v. lunatus assemblage. Similar lithologies at Middle Arm Point contain a ?I.v. lunatus/victoriae fauna and pristine black and green banded shale immediately below the sandstone at Eagle Island North contains a good I.v. victoriae assemblage. The I.v. victoriae Zone continues into the overlying sandstone, as discussed below.

Black shales in the upper part of the Woman Cove section yield poorly preserved graptolite assemblages which are indicative only of the "lower Arenig" (S.H. Williams, pers. comm., 1984; 1985).

3.2.12 The Eagle Island Formation

Distribution

In the Bay of Islands study area exposures of this formation are generally confined to the west (fig 3-2) and are mapped at Eagle Island, North Arm Point, the type section at Middle Arm Point, east of Northern Head, in large rafts within melange south of Middle Arm Point (Black Brook North, Whites Brook), at Cape Split, Grassy Cove and highly deformed exposures nearby along the south shore of North Arm, and at Balance Point in the Rattler window.

In the Port au Port erea exposures of the sandstone are generally highly deformed. Sections at Black Point (Port au Port Bay) and Rocky Point (West Bay) are regarded as being the most intact.

Lithology

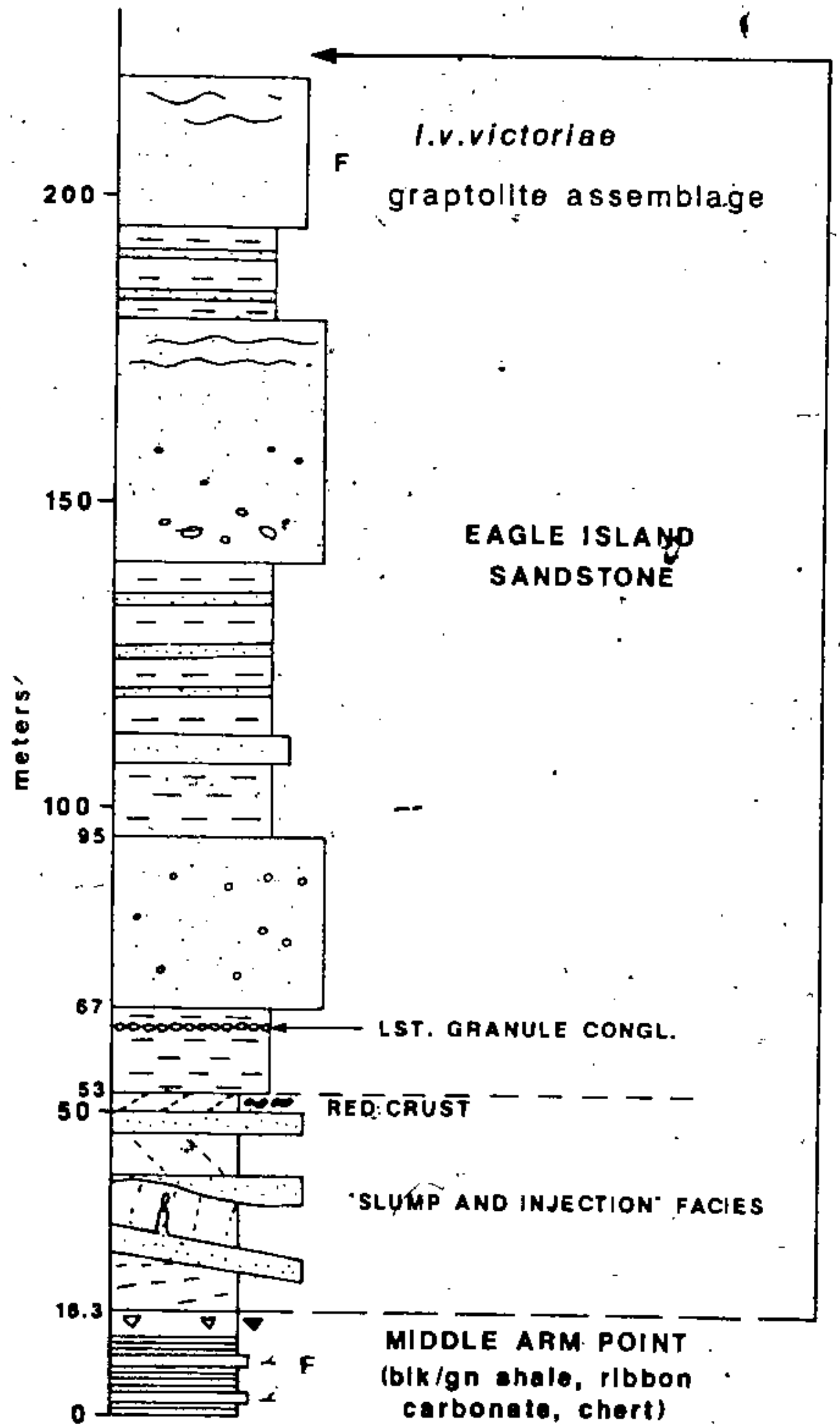
The Eagle Island formation is 203m thick in the type section at Middle Arm Point (fig 3-10). This figure is a minimum thickness since the depositional top of the formation is never seen and the upper boundary is everywhere either a discrete fault or melange zone.

The lower boundary of the unit with the Middle Arm Point is transitional. Grains of quartz and feldspar appear within sandy dolomite lenses in the uppermost part of the Middle Arm Point Formation (interval described above) and the basal contact of the Eagle Island formation is placed at the first occurrence of

Figure 3-10

Type section of the Eagle Island formation at Middle Arm Point. Lithologic symbols as per fig 3-1a.

MIDDLE ARM POINT SUMMARY



sandstone. A zone characterized by clastic injections is common at the base of the formation (Chapter 4).

Overlying bedded units of the Eagle Island formation display a wide variety of lithofacies which can be broadly characterized as : 1) thick massive sandstone (including conglomerate), 2) medium-bedded sandstone, 3) siltstone-dominated intervals and 4) shale-dominated interbeds. These are described in greater detail in Chapter 4.

Paleontology

Three graptolite occurrences have been located within the Eagle Island formation: at Rocky Point (West Bay) (originally located by R.K. Stevens), Black Brook North and Middle Arm Point. All of these contain an *Isograptus victoriae victoriae* Zone fauna (S.H. Williams, 1984; 1985), the same as the underlying uppermost Middle Arm Point interval. This is equivalent, in the Australian Zonal scheme (Thomas, 1960; VandenBerg,1981) to the Castlemanian 2 Zone.

3.3 PALEONTOLOGY AND BIOSTRATIGRAPHY

Introduction

Prior to this study only three fossil localities were known from the Cooks Brook and Middle Arm Point Formations. Based on these localities and the general similarity of geologic setting, the Cooks Brook and Middle Arm Point Formations have been broadly regarded as spanning the same interval as the Cow Head Group, that is late Middle Cambrian to Early Ordovician (Stevens, 1970; Barnes et al., 1982). A search for fossils was conducted in this study during the course of initial reconnaissance mapping and selected sections were subsequently searched in greater detail. This has yielded a total of thirty-four new fossil localities which span the Cooks Brook, Middle Arm Point and Eagle Island Formations, facilitating the erection of the stratigraphic framework presented in this chapter. The interpreted stratigraphic extent of these sections and disposition of fossil localities within them is shown in figure 3-11.

Biostratigraphy in this study relies heavily on zonation schemes established and stratigraphic insight gained in the Cow Head Group, which has received the attention of many workers since the pioneering studies of Kindle and Whittington in 1958.

Trilobites are relatively abundant in boulders within conglomerates throughout the Cambrian part of the Cooks Brook Formation and have proved very useful for sorting out the stratigraphy through that interval and into the lower Ordovician. Graptolites have been recovered throughout the Ordovician part of the Cooks Brook, Middle Arm Point and Eagle Island Formations and are the principal biostratigraphic tool through that interval.

3.3.1 TRILOBITES

3.3.1.1 Cambrian trilobites

Trilobites are the primary tool in Cambrian biostratigraphic zonation. Trilobite faunal assemblages are clearly environmentally controlled, resulting in a number of paleogeographic regions worldwide (Palmer, 1979). North American stages and biostratigraphic zones are summarized in Stitt (1971) and have evolved from schemes established by Howell et al. (1944), Lochman-Balk and Wilson (1958) and Palmer (1965). This zonation is based largely upon the distribution of polymeroid trilobites in relatively shallow water, shelf environments. Deeper water environments, on the other hand, are typified by an agnostid-dominated fauna and are better represented by the Acado-Baltic zonation scheme of Westergard (1946; 1947).

Both the Northern Head group and the Cow Head Group can be broadly regarded as "slope deposits". Conglomerates within the Cooks Brook Formation are like those of the Cow Head Group in that they are composed of boulders which have sampled a variety of environments, from shallow water shelf through marginal carbonate buildups to the deeper water slope. Hence individual conglomerate beds contain a mixture of trilobite faunal assemblages (and faunal provinces). This mixing was recognized in the Cow Head Group by Whittington and Kindle (1969) and has been addressed by the informal zonation scheme of Kindle (1981; 1982). Kindle's zonation is based upon a vast collection of trilobites (approximately 20,000 specimens), largely from the Cow Head Group, and represents the best summary of current understanding with which to compare the Cambrian trilobites of the Cooks Brook Formation. This scheme is based upon the representative assemblages of trilobites present in the mixture of boulders at successive stratigraphic levels and hence serves to meld the zonation schemes of the Acado-Baltic and North American faunal provinces (fig 3-12). A total of eight informal zones spans the late Middle and Upper Cambrian in the Cow Head Group. All of the Cambrian trilobite assemblages of the Cooks Brook Formation are referable to some of these zones; the other zones do not appear to be represented or have not been located to date.

Although boulders within individual Cooks Brook conglomerates are generally referable to the same zone, some mixing of stratigraphic ages is evident where a few boulders with older zonal assemblages appear. The youngest faunal assemblage is the dominant one in these cases and is regarded as the minimum age of the host conglomerate based upon present collections.

<u>Middle Cambrian</u>

Middle Cambrian trilobites are largely confined to the Halfway Point member of the Cooks Brook Formation which is exposed on both limbs of the Cooks Brook syncline (south shore Humber Arm) and at Bound Head (north shore Humber Arm). Boulders from the lower part of the massive conglomerate near Halfway Point yield trilobites of Zone 2. North American forms here are characteristic of the <u>Bathyuriscus</u>-

Figure 3-11

Interpreted stratigraphic extent of measured sections and disposition of fossil localities (numbers). Fossil locality numbers correspond to those used in Appendix C.

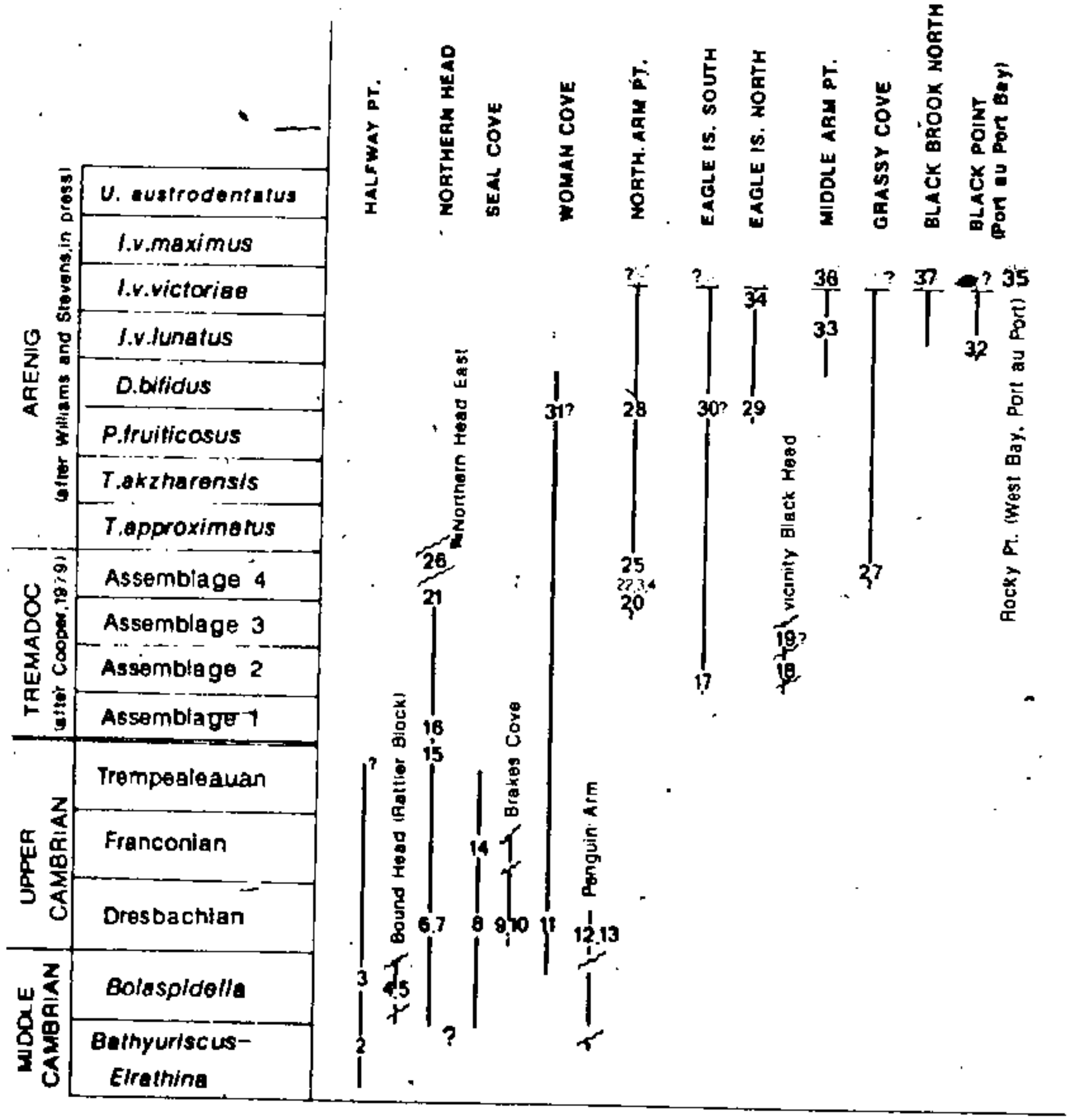
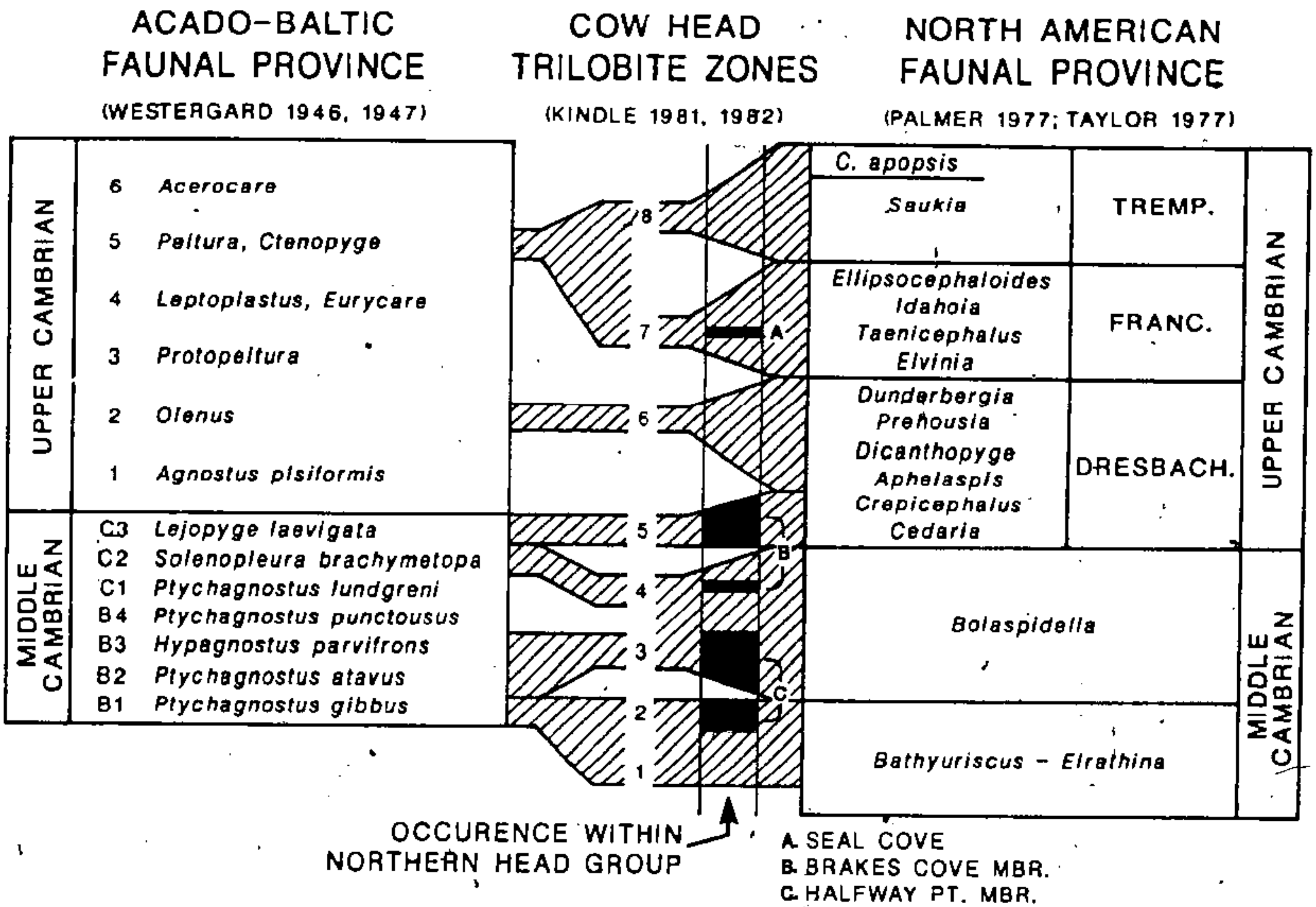

MIDDLE CAMBRIAN
UPPER CAMBRIAN
TREMADOC (after Cooper, 1979)
ARENIG (after Williams and Stevens, in press)
U. austrodentatus
I.v.maximus
I.v.victoriae
I.v.lunatus
D.bifidus
P.fruiticosus
T.akzharensis
T.approximatus
Assemblage 4
Assemblage 3
Assemblage 2
Assemblage 1
Trempealeauan
Franconian
Dresbachian
Bolaspidella
Bathyuriscus–Elrathina
HALFWAY PT.
NORTHERN HEAD
SEAL COVE
WOMAN COVE
NORTH. ARM PT.
EAGLE IS. SOUTH
EAGLE IS. NORTH
MIDDLE ARM PT.
GRASSY COVE
BLACK BROOK NORTH
BLACK POINT (Port au Port Bay)
Bound Head (Rattler Block)
Northern Head East
Brakes Cove
Penguin Arm
vicinity Black Head
Rocky Pt. (West Bay, Port au Port)

Figure 3-12

Gambrian trilobite zonation (Cow Head area) redrawn from James and Stevens (1986). The occurrence of trilobites from the Northern Head group is shown in the centre column.



ACADO-BALTIC FAUNAL PROVINCE
(WESTERGARD 1946, 1947)
COW HEAD TRILOBITE ZONES
(KINDLE 1981, 1982)
NORTH AMERICAN FAUNAL PROVINCE
(PALMER 1977; TAYLOR 1977)
UPPER CAMBRIAN
6 Acerocare
5 Peltura, Ctenopyge
4 Leptoplastus, Eurycare
3 Protopeltura
2 Olenus
1 Agnostus pisiformis
MIDDLE CAMBRIAN
C3 Lejopyge laevigata
C2 Solenopleura brachymetopa
C1 Ptychagnostus lundgreni
B4 Ptychagnostus punctousus
B3 Hypagnostus parvifrons
B2 Ptychagnostus atavus
B1 Ptychagnostus gibbus
8
7
6
5
4
3
2
1
A
B
C
C. apopsis
Saukia
TREMP.
Ellipsocephaloides
Idahoia
Taenicephalus
Elvinia
FRANC.
Dunderbergia
Prehousia
Dicanthopyge
Aphelaspis
Crepicephalus
Cedaria
DRESBACH.
UPPER CAMBRIAN
Bolaspidella
Bathyuriscus – Elrathina
MIDDLE CAMBRIAN
OCCURENCE WITHIN NORTHERN HEAD GROUP
A. SEAL COVE
B. BRAKES COVE MBR.
C. HALFWAY PT. MBR.

Elrathina Zone and representatives of the Acado-Baltic *Ptychagnostus gibbus* Zone are present (A.R. Palmer, pers. comm. to R.K. Stevens, 1979). Higher in the section, (at approximately 80 m), a unit of bedded nodular mudstone contains abundant *Bolaspidella* sp. A similar interval, plus individual boulders, at Bound Head contains this and other representatives of Zone 3 which are characteristic of the North American *Bolaspidella* Zone and Acado-Baltic Zone B3. The nodular interval which contains this fauna may be a large raft within conglomerate but appears to "cap" a conglomerate bed within a thick conglomeratic interval, and is regarded as *in situ* bedded sediment.

Trilobites of Zone 3 also appear within individual boulders at the Northern Head and Woman Cove Head localities described below.

Upper Cambrian

The Upper Cambrian Cooks Brook Formation contains distinctive and correlatable conglomeratic intervals which outcrop in sections at Northern Head, Seal Cove and Woman Cove and also appear at Brakes Cove and at localities along the north shore of Penguin Arm. The thickest of these intervals is also the most fossiliferous and the most widely correlatable and is termed the Brakes Cove member.

Single boulders with Zone 3 faunas have been collected at both the Northern Head and Woman Cove Head localities. Another single boulder from Woman Cove Head yields a Zone 4 fauna, with forms characteristic of the uppermost *Bolaspidella* Zone of the North American faunal province and Zone C2 of the Acado-Baltic faunal province. All of the other boulders collected from the Northern Head member at the localities listed above contain a Zone 5 fauna and are dominated by trilobites characteristic of the North American _Cedaria_ and _Crepicephalus_ Zones, at the base of the Dresbachian Stage.

Another conglomeratic interval occurs higher in the section at Seal Cove above an intervening sequence dominated by shale and thin-bedded carbonate. These conglomerates are thinner bedded and more pebble-dominated than those of the Brakes Cove member and are not as fossiliferous. Here a single boulder contains a Zone 7 fauna assigned to the North American _Taenicephalus_ Zone of the Franconian Stage and the Acado-Baltic Zone 5. This interval is tentatively correlated with a unit of thin-bedded conglomerate at Woman Cove which has not yielded any fossils to date.

Most of the Upper Cambrian of the Cooks Brook Formation is dominated by thick intervals of bedded lime grainstone and mudstone which have not yielded fossils to date. Trilobites characteristic of Kindle's Zone 6 and Zone 8 have not been recovered from the Cambrian interval and Zone 7 is poorly represented. A single boulder containing an uppermost Cambrian Trempealeauan fauna occurs within the Ordovician conglomerate described below.

3.3.1.2 _Ordovician trilobites_

North American Lower and Middle Ordovician biostratigraphy is based upon a zonation scheme established in a western Utah and Nevada reference area (Ross et al., 1982). Twelve trilobite-brachiopod faunal zones, designated A through L, span the Lower (Canadian or Ibexian) and Middle (Whiterock) Ordovician. The lowermost of these is the _Missisquoia_ Zone (A) which represents the base of the Canadian Series. This is overlain by the Symphisurina Zone (B). In terms of correlation with graptolite biostratigraphy, the base of the Tremadoc in the Cow Head Group is demonstrated to correlate with an horizon close to the boundary of these two zones (Fortey et al. 1982; Fortey, 1984).

Overlying the Upper Cambrian quartzose grainstones at Northern Head is a 2m conglomerate which is richly fossiliferous and yields a fauna typical of Zone A (Missisquoia) and Zone B (Symphisurina). A single boulder with a Cambrian Zone 8 fauna characteristic of the North American Saukia Zone (Trempealeauan Stage) has also been recovered. The underlying grainstones contain a non-diagnostic dendroid fauna and higher in the section a black shale interval yields the Tremadoc La2 graptolite fauna discussed below. The location of this Ordovician fauna demonstrates the relative continuity of the Northern Head section and confirms a tentative structural interpretation for the area, earlier confused because of the similarity in appearance of the Cambrian and Ordovician conglomerates here. This is the only locality where an Ordovician trilobite-brachiopod fauna has been identified. Few conglomerates occur higher in the section. These are generally pebble-dominated, commonly locally-derived and have not yielded any fossils to date.

3.3.2 GRAPTOLITES

The Australian graptolite zonation scheme has been used as the basis of correlation in the Cooks Brook and Middle Arm Point Formations as it has in the Cow Head Group (James and Stevens, 1986). In more detail, the graptolite zonation scheme employed here is a hybrid. The Tremadoc zonation scheme at Cow Head and indeed worldwide is currently under revision. Tremadoc fauna of the Cooks Brook and Middle Arm Point are best compared with the correlation scheme of Cooper (1979) (fig 3-13). A revised Arenig zonation scheme for the Cow Head Group has recently been proposed by Williams and Stevens (in press) and is employed here for the Arenig fauna from the Middle Arm Point and Eagle Island Formations.

Cambrian fauna and the Cambro-Ordovician boundary

While several measured sections (at Northern Head, Woman Cove and Seal Cove: fig 3-6) are interpreted as spanning the Cambro-Ordovician boundary, structural deformation and/or paucity of fauna do not permit accurate location of the boundary within the Northern Head group. A single locality, consisting of an indeterminate *Callograptus* sp. fauna has been found, at Northern Head, within a lime grainstone interval regarded as Upper Cambrian and approximately 60m below the prominent Lower Ordovician conglomerate.

3.3.2.1 Tremadoc

Cooper (1979) divides the Tremadoc into 4 assemblage zones, overlain by a 5th zone, dominated by *Tetragraptus approximatus*, which forms the base of the Arenig (fig 3-13). Assemblage 1

Figure 3-13

Sequence of graptolite assemblages, and their key taxa, in the Tremadoc and early Arenig, redrawn from Cooper (1979).

ARENIG	ASSEMBLAGE 5	*T. approximatus* *T. phyllograptoides* *T. acclinans* etc.
	Appearance of *Tetragraptus approximatus*	
TREMADOC	ASSEMBLAGE 4	*Clonograptus* (large), *Temnograptus, Adelograptus,* *Bryograptus, Klaerograptus,* *Tetragraptus, ?Didymograptus*
	Appearance of diverse graptolite fauna	
	ASSEMBLAGE 3	*Clonograptus* *Adelograptus*
	Appearance of *biradiate Anisograptids*	
	ASSEMBLAGE 2	*Anisograptus* *Triograptus*
	Appearance of *triradiate Anisograptids*	
	ASSEMBLAGE 1	*D. flabelliforme* s.l.
	Appearance of *Dictyonema flabelliforme* s.l.	

comprises *Dictyonema flabelliforme s.l.* alone. Assemblage 2 marks the appearance of an Anisograptid fauna and is dominated by *Anisograptus* and *Dictyonema*. Assemblage 3 comprises *Clonograptus*, *Adelograptus* and rare *Psigraptus*. Assemblage 4 comprises a much more diverse fauna, which commonly includes *Clonograptus* (many species), *Temnograptus*, *Kiaerograptus*, *Adelograptus*, *Bryograptus*, and more rarely large siculate *Dictyonema*, *Tetragraptus* and possibly *Didymograprus*.

No single, continuous section exposes a complete Tremadoc graptolite succession within the Cooks Brook Formation. Structurally separated sections which expose parts of the Tremadoc have been correlated, however, in a stratigraphic framework which appears to be consistent with the zonation scheme of Cooper.

The lowest Tremadoc fauna is located at Eagle Island South and comprises *Rhabdinopora enigma*, *Anisograptus compactus*, fragments of *Rhabdinopora scitulum* and abundant phyllocarids (Erdtmann and Botsford, 1986). This is very similar to the Australian La1 assemblage of Cooper and Stewart (1979) and represents Assemblage 2 of Cooper (1979).

A faunule comprising several species of *Dictyonema s.l.* plus ?*Anisograptus matanensis*? was reported by Stevens (1965) immediately to the southeast near Black Head and is also tentatively assigned to Cooper's Assemblage 2. This faunule is situated in a area mapped as "highly deformed Cooks Brook Formation" and was not relocated in this study. Within the same deformed zone, immediately southeast of Black Head, a faunule consisting solely of *Staurograptus* sp. is situated in an interval of interbedded black and green shale which can only be assigned to the "upper Cooks Brook Formation".

Black shale intervals mapped as higher in the Cooks Brook Formation yield a different faunal assemblage. At North Arm Point roughly 18m of a distinctive siliceous black shale-dominated interval is exposed above low tide and yields an abundant, but not very diverse graptolite fauna. This comprises large Dictyonema s.l., Adelograptus (Bryograptus) victoriae and Kaierograptus antiquus. No faunal change through the interval was discerned. At the top of the Northern Head section a deformed interval of black shale and thin-bedded lime mudstone contains Araneograptus murrayi (B.D. Erdtmann, pers. comm., 1986) and isolated fragments of indeterminate graptoloid siculae. Both of these faunal assemblages are comparable to the Australian La2 zone (Thomas, 1960; Cooper and Stewart, 1979) and are assigned to Cooper's Assemblage 4. The stratigraphic relationship of these two intervals cannot be determined but from lithostratigraphic considerations they are both regarded as "upper" Cooks Brook Formation. The shale interval at North Arm Point passes upward into a sequence of thin-bedded lime mudstone which is in turn overlain by the silty dolostone beds of the Woman Cove member. A similar transition is indicated at Northern Head but is disrupted and appears to be abbreviated by faulting.

The most intact section representative of the overlying Tremadoc interval is North Arm Point (fig 3-8). Graptolite localities within this section are as follows :

1) At approximately 32m nondiagnostic dendroids have been recovered from black shale interbeds within the lime mudstone interval at the

top of Cooks Brook Formation.

2) The Woman Cove member is roughly 13m thick and is capped by a 1.5m locally-derived conglomerate. This is overlain by a 7m interval dominated by thinly interbedded black and green shale. Here a black shale band (at approximately 52m) contains extremely delicate and poorly preserved Clonograptus sp.

3) This lithology passes transitionally upward into a roughly 9.5m interval of dark parted lime grainstone with thin interbeds of black, organic-rich shale. This shale contains,a non-diagnostic "rooted dendroid" fauna.

4) The uppermost part of the Tremadoc and transition into the Arenig is contained within the overlying, distinctive lithology. This is dominated by siliceous green shale with scattered thin beds of rippled silty dolostone, thin beds of dark shale and minor red shale. This distinctive interval, informally termed the North Arm Point member, can be correlated with other sections and is also fossiliferous where it appears at Eagle Island South and North, in a shear-bounded sequence east of Northern Head and at Grassy Cove. The Tremadoc fauna present (in the lower part of the member) is more diverse than that encountered previously and appears to represent a distinctive latest Tremadoc assemblage within the Cooks Brook Formation. At North Arm Point (73m) the assemblage comprises Adelograptus victoriae, ?Tetragraptus/ Temnograptus sp., Kiaerograptus sp., ?Clonograptus sp. and ?Bryograptus sp. (two-stiped). Similar faunal assemblages have been recovered from Northern Head East and Grassy Cove. This assemblage is distinctive and differs from the underlying La2 assemblages in the predominance

of extensiform graptolites and the absence of dendroids. This faunal difference may well be facies controlled, considering the contrast in host lithologies. This assemblage is regarded as latest Tremadoc and is assigned to the uppermost part of Cooper's Assemblage 4.

3.3.2.2 Arenig

The first appearance of Tetragraptus approximatus is a widely correlatable event and is generally regarded as the base of the Arenig (Cooper, 1979). Such is the case in the Cow Head graptolite zonation scheme of Williams and Stevens (in press) which is used in this study. This scheme is based upon the successive appearance and abundance of the zonal fossils: T. approximatus, T. akzharensis, Pendeograptus fruticosus, Didymograptus bifidus, Isograptus victoriae lunatus, I.v. victoriae, I.v. maximus and Undulograptus austrodentatus and is comparable with the Australian zonal scheme (Thomas,1960; VandenBerg, 1981) (fig 3-14).

The lowest diagnostic Arenig graptolite assemblage within the Middle Arm Point Formation is encountered within the North Arm Point member, at North Arm Point, approximately 13m stratigraphically above the latest Tremadoc assemblage described above. Shears are present between the two localities but lithologic similarities, and structural style here do not suggest omission of section and the North Arm Point member is regarded as a continuous interval.

This Arenig assemblage comprises Didymograptus bifidus (narrow-stiped), Isograptus cf. primulus, Tetragraptus ?bigsbyi, T. sp. (narrow-stiped), and one specimen of ?Pendeograptus pendens and is

Figure 3-14

Arenig graptolite zonation (Cow Head area), redrawn from Williams and Stevens (in press).

COW HEAD GRAPTOLITE ZONES	AUSTRALIAN ZONES AND STAGES THOMAS 1960 VANDENBERG 1981	
No fauna known	Da2	*G. intersitus* Zone
U. austrodentatus Zone	Da1	*G. austrodentatus* Zone
I. v. maximus Zone	Ya3	*A. crudus* Zone
	Ya2	*C. morsus* Zone
	Ya1	*O. upsilon* Zone
	Ca3	*I. v. maximus* Zone
I. v. victoriae Zone	Ca2	*I. v. victoriae* Zone
I. v. lunatus Zone	Ca1	*I. v. lunatus* Zone
D. bifidus Zone	Ch2	*D. protobifidus* Zone
	Ch1	*D. protobifidus* & *T. fruticosus* Zone
P. fruticosus Zone	Be4	*T. fruticosus* Zone (3 branch)
	Be3	*T. fruticosus* Zone (3 & 4 branch)
T. akharensis Zone	Be2	*T. fruticosus* Zone (4 branch)
	Be1	*T. fruticosus* & *T. approximatus* Zone
T. approximatus Zone	La3	*T. approximatus* Zone
Tremadoc	La2	*A. victoriae* Zone

assigned to the D. bifidus zone. Similar, but more poorly preserved assemblages occur at Eagle Island South and North. Although fossil localities are somewhat scanty in this lower Arenig interval, it is notable that no fauna indicative of the T. approximatus nor T. akzharensis zones have been recovered from the Middle Arm Point Formation. The presence of the above described D. bifidus zone fauna just 13m above the latest Tremadoc fauna suggests that the entire lower Arenig interval is contained within the North Arm Point member and hence appears to be highly condensed or missing. This is roughly synchronous with, but partly predates, a period of condensed sedimentation within the Cow Head Group where graptolite fauna of Zones Be2, Be3 and Be4 are contained within less than 20m of strata.

The absence of the North Arm Point member at Woman Cove is tentatively interpreted as a facies change. Here thin black shale beds within a banded black and green shale interval yield a poorly preserved fauna in which Pendeograptus pendens has been tentatively identified, suggesting only that this interval is "lower Arenig".

The uppermost Middle Arm Point Formation consists of interbedded units of thinly banded black and green shale, with scattered thin-bedded carbonate, and units of red and green shale. Thin black shale beds within this interval yield faunal assemblages representative of the I.v. lunatus and I.v. victoriae Zones.

In the Black Point section (Port au Port Bay) a 5cm black shale bed yields a rich assemblage comprising I.v. lunatus, Phyllograptus typus and large Pseudotrigonograptus ensiformis. This assemblage is assigned to the I.v. lunatus Zone. Pendeograptus(Tetragraptus) fruticosus has been reported from lower in the section (R.K.

Stevens, pers. comm., 1985) but was not relocated in this study.

At Middle Arm Point proper a poorly preserved faunule has been collected from a similar interval at the base of the section (at 5.2m) and is assigned to the I.v. lunatus or I.v. victoriae Zones.

At Eagle Island North (59m) a similar lithology yields I.v. victoriae, Xiphograptus bovis, ?Expansograptus/ Xiphograptus sp., and Pseudotrigonograptus sp. This is assigned to the I.v. victoriae Zone.

The interval containing the localities described above is immediately overlain by sandstone of the Eagle Island formation, which also contains fossil localities representative of the I.v. victoriae Zone. Specimens here are preserved within fine to medium sandstones as isolated individuals on bedding planes. I.v. victoriae and Tetragraptus sp. occur near the top of the Middle Arm Point section. At Black Brook North a similar locality yields I. victoriae cf. victoriae and Tetragraptus ?serra. The faunal assemblage at Rocky Point (West Bay, Port au Port) comprises Isograptus sp., Holmograptus sp. and Xiphograptus cf. bovis. These are the highest faunal assemblages known from the study area.

3.4 SYSTEMATIC STRATIGRAPHY AND BIOSTRATIGRAPHY: DISCUSSION

3.4.1 CAMBRIAN

3.4.1.1 Contrast between the Halfway Pt. and Brakes Cove members

The Halfway Pt. and Northern Head members are geographically separate (fig 3-2), but in their respective areas both are the lowest conglomeratic interval within the Cooks Brook Formation, overlying the transitional contact with the Irishtown Formation. Faunal evidence indicates that they are of different ages; the Halfway Point member is regarded as late Middle Cambrian while the Northern Head member is Dresbachian. Moreover the sedimentary style and composition of the two members are different (Chapter 4). The Halfway Point member is dominated by thick, massive, matrix-rich conglomerates with large folded rafts of bedded mudstone, boulders of the underlying sandstone, a distinctive algal boundstone lithology and abundant oolitic boulders. The Northern Head member contains thinner-bedded conglomerates of mixed composition with abundant shaly interbeds.

Hence conglomerate-dominated deposition appears to have been underway in the Halfway Point area while intervals of thin-bedded lime mudstone and shale were being deposited elsewhere. No direct link between the two areas has been established apart from the similarity and inferred correlation of the thick Upper Cambrian lime grainstone interval. More intensive collecting in the uppermost part of the Halfway Point member may yield a Dresbachian (or younger) fauna, linking deposition there with that of the Northern Head member. The observed abundance of oolitic boulders in conglomerates at the top of the Halfway Point member, however, suggests that the unit is homogeneous and that the two members are discrete.

3.4.1.2 <u>Timing of conglomerate deposition relative to the Cow Head Group</u>

Faunal evidence suggests a general synchroneity between the major conglomerates of the Cooks Brook Formation and some of those in the Cow Head Group. The Halfway Point member contains Zone 2 and 3 faunas which occur within the lowermost parts of the "basal debris sheets" (James and Stevens, 1986) of the Cow Head Group.

The laterally extensive Northern Head member contains a Zone 5 fauna which appears in Beds 1,2,3 and 4 in the Cow Head Group. These occur toward the top of the "basal debris sheets" and include megaconglomerates in Bed 3.

A Zone 7 fauna appears in the upper conglomeratic interval at Seal Cove, which is correlated with intervals of quartzose calcarenite in other sections through the Cooks Brook Formation. In the Cow Head Group a Zone 7 fauna is found in conglomerates in the lower half of Bed 6 within an interval also dominated by quartzose calcarenites.

The Lower Ordovician conglomerate of Northern Head contains a fauna characteristic of Zones A and B plus a fauna of Upper Cambrian affinity. Similar fauna occur within the predominantly conglomeratic Stearing Island member (James and Stevens, 1986) in a proximal setting in the Cow Head Group, and within the Broom Point member in more distal settings.

The Cooks Brook and Middle Arm Point Formations lack the laterally extensive conglomerates (and their contained fauna) which occur higher in the Ordovician in the Cow Head Group.

3.4.2 ORDOVICIAN

3.4.2.1 Biostratigraphic aspects

Comparison of Northern Head group graptolite faunas with those of the Cow Head Group indicates several points worthy of discussion:

1) Notwithstanding the tremendous difference in the number of man-hours spent collecting in the two areas, shales of the Northern Head group seem to be less fossiliferous than those of the Cow Head Group. Moreover, faunal diversity appears to be lower. Certainly the former are more deformed, and hence may have a lower "preservation factor", but the difference is thought to be original, and related to the paleogeographic relationship of the two sequences.

2) The character of the early Tremadoc faunal assemblages is somewhat different in the two sequences. Several relatively complete and fossiliferious sections span the Cambro-Ordovician boundary in the Green Point Formation of the Cow Head Group. The section at Broom Point North is a candidate for the international Cambro-Ordovician boundary stratotype while a richly graptolite-bearing section occurs at Green Point. In general these sections demonstrate an apparently evolutionary succession from rooted dendroids in the Cambrian upward into an early Tremadoc fauna dominated by several robust species of <u>Dictyonema</u> plus <u>Staurograptus</u> spp. At Green Point species of <u>Aletograptus</u> appear above this and are succeeded by

Triograptus spp. This is, in turn, overlain by an abundant and relatively diverse La2 fauna (James and Stevens, 1986).

While no such complete sections have been located in the Cooks Brook Formation, the La1 assemblage which has been described is dominated by the diminutive R. enigma, ?R. scitulum and Anisograptus compactus and is very similar to the Australian type La1 faunal assemblage. Moreover the La2 Araneograptus murrayi from Northern Head has not been reported from the Cow Head Group and is regarded as having affinities with the ?deep-water Baltic assemblages typical of Hunneberg (Erdtmann, pers.comm., 1986).

This apparent contrast between the fauna of the Cooks Brook Formation and the Cow Head Group is suggestive of association with a different, but not necessarily deeper water mass (cf. Erdtmann and Botsford, 1986). The presence of different water masses in the two areas would clearly depend upon the configuration of the Early Ordovician contintental slope and resulting differences in circulation. This would in turn govern the presence of nutrients and overall trophic levels and the attendant faunal communities. The possible significance of the biofacies differences discussed here will be further developed in light of paleogeographic models presented in Chapter 8.

3.4.2.2 General stratigraphic aspects

1) The Northern Head group is divided into two formations: the Cambrian and lowest Ordovician Cooks Brook Formation and the Lower Ordovician Middle Arm Point Formation. In the Cow Head Group, on the

other hand, this stratigraphic separation of formations is not recognized. Formations proposed within the Cow Head Group, the Shallow Bay and Green Point Formations (James and Stevens, 1986), represent proximal/distal facies equivalents which span the entire Cow Head interval. This difference in stratigraphic nomenclature reflects real differences between the two groups. Firstly, there is not the same degree of proximal to distal facies contrast within the Northern Head group, possibly because the across-strike exposure is not as great in the Bay of Islands. But more important, the change in depositional conditions which occurs within the Tremadoc in both areas is more marked and sharply focused in the Northern Head group. Here several parameters indicate a marked increase in the level of oxygen within the environment of deposition. This change first appears at the base of the Middle Arm Point Formation, in the Tremadoc, and is most pronounced at the Tremadoc/Arenig boundary within the North Arm Point member discussed below. The change is accented and represented in the Northern Head Group by the Woman Cove member, which will, in later discussion, be interpreted as a shelf-derived detrital dolomite interval. The member does not have a direct stratigraphic counterpart in the Cow Head Group, but instead is synchronous with the abrupt appearance of red shale and apparently oxidizing conditions in the distal sections there.

2) The lower part of the Arenig (equivalent to La3 plus most of the Bendigonian in the Australian zonal scheme) appears to be highly condensed or missing in the Middle Arm Point Formation. The lithology which seems to contain this interval over much of the area

is dominated by light green shale and rippled dolomitic siltstone. This is suggestive of a depositional environment which was relatively oxidizing, having preserved virtually no organic carbon while demonstrating moderate bioturbation, in a regime of some bottom current activity, which is reflected in the bedding style of the dolomitic siltstones. Condensed sedimentation is different in style and appears to have started somewhat later in the Cow Head Group. Here the La3 Zone is widely recognized and an interval characterised by silicified shale, phosphate granule conglomerates, chert and sparse carbonate spans Zones Be2, Be3 and Be4.

3) The sandstone which overlies the Middle Arm Point Formation appears to be older than its counterpart at Cow Head. Graptolites recovered from sandstones of the Eagle Island Formation and shales immediately below are assigned to the I.v. victoriae Zone, which is equivalent to the Caslemanian 2 Zone. In the Cow Head Group graptolites from shales above Bed 14 (and immediately below the Lower Head Formation) are assigned to the Darriwilian 1 Zone, while those from the sandstone itself may be as young as Darriwilian 2 or lowermost Llanvirn (James and Stevens, 1986). The Lower Head Formation does appear stratigraphically lower in some sections, particularly at Long Point, St. Pauls Inlet, where the highest graptolite fauna recovered from below the sandstone is Ca2. However, since no fauna has been recovered from immediately below the sandstone, nor from the sandstone itself, it is unclear whether this stratigraphic position should be attributed to erosional downcutting

or the earlier arrival of the sandstone here.

Sandstones of the Eagle Island and Lower Head Formations are broadly regarded as easterly-derived. The simplest interpretation of the biostratigraphic data would suggest that the relatively older Eagle Island Formation was deposited to the east of the Lower Head Formation and that the underlying Northern Head group was deposited in a more distal setting than the Cow Head Group. Deposition of the sandstones may be more complex than this however, and transgression of the sandstones along a tectonically-produced axis parallel to the continental slope may have resulted in the sort of age differential observed.

The above discussion provides separate pieces of evidence regarding the depositional setting of the Northern Head Group, its relationship with the Cow Head Group and the nature of Cambrian and Ordovician oceanic conditions which will be brought forward in models presented in the final chapter.

CHAPTER 4

SEDIMENTOLOGY

Introduction

Principal lithologic components of the Northern Head group: shale, chert, calcarenite, lime mudstone, dolomite and conglomerate are described separately in this chapter. Discussion of pertinent details from the Eagle Island Sandstone is included as a separate section. Interpretation of sedimentology is outlined within each section, and all are incorporated in a final discussion of the overall depositional setting. Stratigraphic nomenclature introduced in Chapter 3 is used throughout. Extensive reference is made to geographic localities (commonly measured sections) which are shown in figure 3-2.

Terminology

Sedimentologic terms employed in this chapter are generally simple and consistent with general usage (e.g. Blatt, Middleton and Murray, 1980); the descriptive grain-size scale is after Wentworth (1922).

The term mudstone or mud is generally employed here to refer to terrigenous, clay-dominated material, while lime mudstone or lime mud refers to carbonate-dominated material in the clay to silt fraction.

The descriptive terms "parted" and "ribbon" are adopted from recently-published studies of the Cow Head Group (James and Stevens, 1982; 1986; Coniglio, 1985), and refer to the bedding style of thin to medium interbedded carbonate and shale. "Ribbon limestone" consists of units of carbonate and shale of roughly equal thickness, while "parted limestone" is dominated by carbonate beds and displays much thinner argillaceous interbeds.

Colour designations used within the Shale section refer to the G.S.A. Rock Colour Chart (1980).

4.1 SHALE

Introduction

Shale is regarded in this study as a class of fine-grained argillaceous sedimentary rock, dominated by particles in the clay fraction but locally containing silt, as scattered grains or thin laminae.

This section is confined to shale sedimentology; shale diagenesis is treated in Chapter 6, and other aspects of shale geochemistry and mineralogy are discussed in Chapter 7.

Shale occurs in most Northern Head group sequences, as interbeds in conglomeratic, ribbon and parted limestone, and dolostones units. It also occurs as shale-dominated intervals with isolated beds of these lithologies. The overall nature of shale changes in two ways through the Northern Head group: 1) it becomes more abundant in the Ordovician as shale-dominated intervals increase and 2) dark (black or grey), generally well-laminated lithologies predominate below the Cooks Brook/Middle Arm Point boundary and green and locally red shale with more common massive intervals, predominates above. The broad colour change reflects a decrease in organic carbon content.

Shale also occurs as a matrix in conglomerates. Wherever shale is present in appreciable quantities in conglomerate matrix (e.g. Halfway Point member, Middle Arm Point conglomerate) it is clearly derived from immediately underlying sediments.

4.1.1 General description of shale occurrence

4.1.1.1 Irishtown shales

The majority of the Irishtown Formation is medium to thick-bedded quartzose sandstone (Chapter 3) and shale generally occurs as 10 to 40cm thick interbeds; shale-dominated intervals up to 3m occur locally. This shale is grey (N4)to black (N2), laminated on a millimeter to centimeter scale, and commonly contains thin beds of quartzose siltstone. Shale is most abundant in the uppermosr Irishtown (Chapter 3) and contains thin beds or lenses of characteristic, orange-weathering quartzose and dolomitic siltstone and very fine sandstone. This shale is also black to grey, laminated on a millimeter scale and generally highly fissile. It is commonly crenulated in response to regional tectonism (e.g. immediately west of Halfway Point; refer to Chapter 2).

4.1.1.2 Shales of the Cooks Brook Formation

Cooks Brook shale occurs in two principal groups based on colour: black (N2) to grey (N5), and green (10GY 5/2). Green shale includes a dolomitic, yellow-weathering variety (5Y 6/4). Where shale is present interbedded in other lithologies it is most commonly well-laminated and black to grey, but where interbeds are thicker (1m or more), commonly in conglomeratic intervals such as the Halfway Point member, it is banded black and green. Shale-dominated intervals in the Cooks Brook are either interbedded black and green shale (see below) or black and laminated. Both lithologies contain a variable component (roughly 15%) of thin-bedded carbonate.

Thick intervals of green shale alone are not present within the Cooks Brook Formation.

Laminated black shale is particularly conspicuous in the lower Tremadoc (Chapter 3), and is well exposed at the base of the North Arm Point section. Here thin beds (roughly 5cm) of lime mudstone punctuate the section at 30 to 50cm intervals and lensoid layers of lime mudstone (<1 cm) are scattered throughout (Plate 4-1a). Thin to very thin laminations are defined by organic remains and micrite. Thin, papery partings, composed solely of flattened organics (probably phyllocarids and graptolites) recur at roughly 5cm intervals. The shale is intensively silicified (see Chert, this chapter) and difficult to split along individual laminae, but almost every lamination examined contains abundant, intact graptolites.

The extreme regularity and parallelism of laminations, the lack of any current-related sedimentary structures and the preservation of delicate organic remains suggest that this shale interval was deposited by pelagic (organic remains) and hemi-pelagic (lime mud and detrital clay fraction) processes in a quiet-water setting. Diagenetic redistribution of carbonate has probably enhanced the thinly-laminated character.

4.1.1.3 Shales of the Middle Arm Point Formation

The internal stratigraphy of the Middle Arm Point Formation is described in detail in Chapter 3. Briefly, the formation consists of 1) a basal parted silty dolostone (Woman Cove member), overlain in some sections by conglomerate, 2) banded black and green shale, 3) an interval of dark, parted lime grainstone, 4) a unit of siliceous green shale with minor dark shale interbeds and scattered silty dolostone layers (North Arm Point member) and 5) an uppermost shale-dominated interval.

Shale interbeds in the Woman Cove member are bright green (10GY 6/4) and generally massive, with faint mottling suggestive of extensive bioturbation, similar to associated silty dolostones (refer to Dolomite section, this chapter). At Woman Cove these shale interbeds thicken progressively upward into an overlying interval of green shale. At North Arm Point the conglomerate which overlies the Woman Cove member has a green shale matrix and green shale ripups which were clearly derived from the underlying lithology.

The intense black colour (N1 to N2) of the shale interbeds in the parted lime grainstone interval (Chapter 3) is related to abundant organic carbon, evident in part as poorly-preserved graptolite and phyllocarid remains. This contrasts sharply with the overall paucity of organic carbon typical of most Middle Arm Point shales. The shale displays a "sooty" appearance on fresh surfaces and is very thinly laminated with a "papery" parting.

Shale in the North Arm Point member is predominantly siliceous and green (10GY 5/2) with thin beds of graptolite-bearing grey shale (5Y 3/2) scattered throughout. Intervals of discontinuous wavy stratification, defined by thin laminae and lenses of silty dolomite are abundant. These grade into ripple-laminated beds of silty dolomite, up to 20cm thick. The periodic influence of currents and bioturbation is evident throughout.

Shale-dominated intervals of the uppermost Middle Arm Point

Formation are described below.

4.1.2 Shale-dominated lithologic associations: description and postulated depositional mechanisms

Apart from the laminated black shale intervals of the Cooks Brook Formation discussed above, two principal, shale-dominated lithologic associations are present within the Northern Head group: 1) thinly interbedded black and green shale and 2) bedded to massive red and green shale. These commonly contain other lithologies described in this chapter (e.g. thin-bedded carbonate or silty dolostone) but it is the contrasting nature of shales within these associations which is considered important here.

4.1.2.1 Interbedded black and green shale, locally with accessory carbonate

Introduction

Based upon evidence presented in this section, the interbedded black and green shale association is interpreted to be the result of 1) turbidite deposition of organic-rich (black) mud, and 2) hemipelagic deposition of green mud. This mechanism is most clearly demonstrated where the association contains an accessory (detrital) carbonate component. Evidence for the same depositional mechanism is more subtly displayed where carbonate is absent.

Larger-scale cycles within this association are also thought to be related to periodic muddy turbidite sedimentation, and subsequent reworking.

General aspects

This association is characterized by rhythmic alternation of black and green shale. This includes a variety of bedding styles, from a thin (.5 to 2cm), very regular interbedding of black and green shale to a broader (10 to 30 cm), more diffuse alternation of internally well-laminated black and green shale (Plate 4-1b). Green shale is commonly yellow-weathering (5Y 6/4) because of disseminated, fine-crystalline dolomite. The third component is bedded carbonate, commonly silty, which occurs in laminations or thin beds, as part of the black and green rhythm, generally within the thicker, more irregularly-bedded variety. Black/green/carbonate units occur at the base of the Cooks Brook Formation at Northern Head, and as interbeds up to several meters thick within overlying intervals such as the Brakes Cove member. Thinly interbedded carbonate-free black and green shale is most prominent within the Middle Arm Point Formation, where intervals up to 5m thick are interbedded with the red/green shales described below (e.g. Eagle Island North, Woman Cove).

Internal structures

Carbonate-rich black/green shale

Coarse carbonate layers (composed of sand to granule grains) are not abundant in this lithology, but where present, occur as lenses with a scoured, irregular base (Plate 4-1c). Normal grading is ubiquitous. Internal structures are generally better displayed by silty units, and are either parallel laminations alone, parallel laminations passing upward into cross laminations, or cross laminations alone. Silty units are also normal-graded.

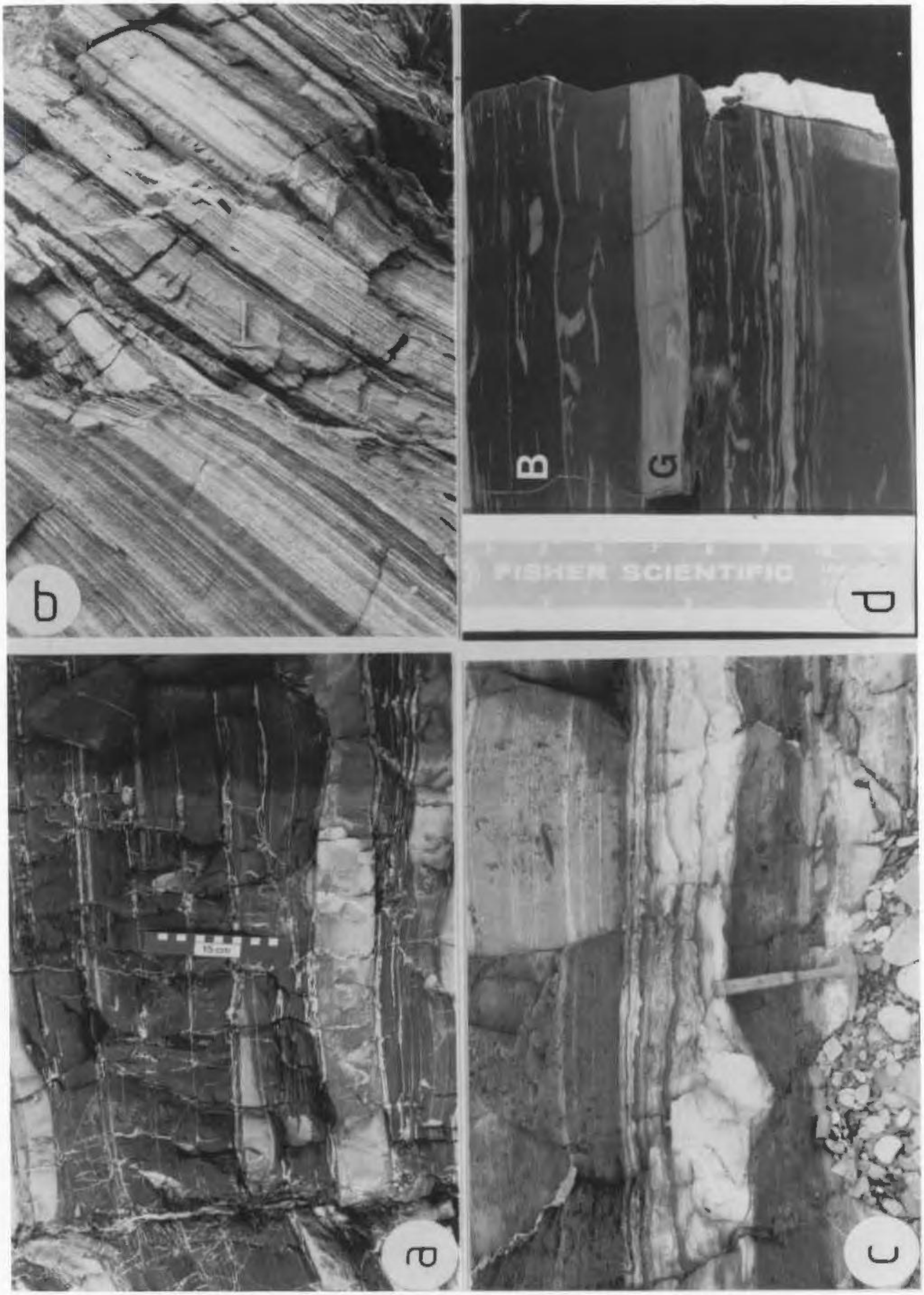
PLATE 4-1: BLACK AND BLACK/GREEN SHALES

a: Laminated, richly graptolite-bearing, Tremadoc (La2) black shale, with thin beds and lenses of micritic carbonate

b: Broadly interbedded black and green shale with scattered thin beds of carbonate; Cooks Brook Formation

c: Scoured, lensoid base of lime grainstone within black shale unit comprising black/green shale interval; basal Cooks Brook Fomation, Northern Head section

d: Interbedded black (B) and green (G) shale; black horizons are silty in part and display normal grading. Note truncation of burrow(s) at base of black horizon, and amalgamation of black horizons in upper part of slab.


b
B
G
FISHER SCIENTIFIC
d
a
c

The relationship between carbonate layers and black and green layering is important. Carbonate horizons are commonly associated with black shale. Silty carbonates commonly occur at the base of black shale layers, truncating structures such as burrows in the underlying green shale layer (Plate 4-1d) and grading upward into pure black shale. This, in turn, is in gradational contact with the overlying green layer. Amalgamated black layers, consisting of two or more graded units also occur (Plate 4-1d), and this style of amalgamation probably accounts for the presence of isolated carbonate lenses and layers within thicker black shale intervals (Plate 4-1c). There is little doubt that the diagenetic addition of carbonate, probably by marginal aggradation (cf. Coniglio, 1985) has enhanced the association of carbonate with black shale in the lithologic association described here (refer to Chapter 6). However, the abundant sedimentary structures within all of the grainy carbonates indicate that there is a <u>depositional</u> association of carbonate and black shale.

<u>Carbonate-free black/green shale</u>

In black/green shale intervals without silty carbonate layers sedimentary structures are present, but more difficult to detect. Black shales have a sharp base and subtle angular truncation of layering in the underlying green shales can be demonstrated locally (Plate 4-2a). Normal grading is generally difficult to detect in the field, but can be seen when the black shales contain silt. Black horizons may display a sharp contact with the overlying green horizon, but the contact is commonly gradational, and marked by increasing bioturbation. Green horizons generally display a higher

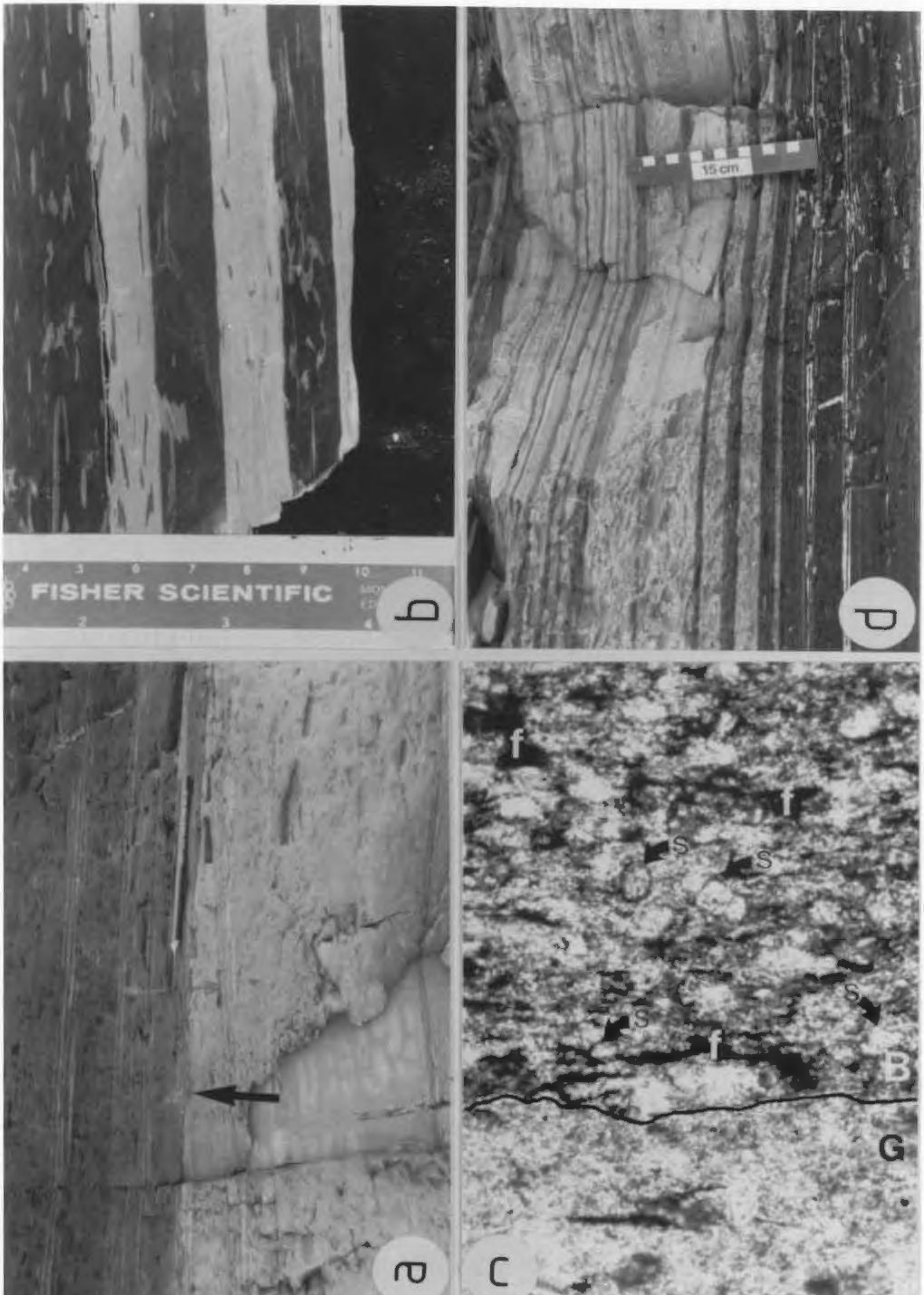
PLATE 4-2: BLACK/GREEN SHALES

a: Angular truncation of layering within green shale horizon at the base of black shale unit; note irregular nature of contact (arrow); lowermost Cooks Brook Formation

b: Thinly, regularly interbedded black and green shale displaying scattered burrows within both black and green horizons; Middle Arm Point Formation

c: Photomicrograph of base of black horizon (B), and uppermost portion of green horizon (G), within interbedded black/green shale interval (lithology of 4-2b above); note concentration of silt grains (s) and black organic "flakes" (f) within black horizon; field of view is .6mm in length.

d: Upward thinning and fading black layers, transitional upward into green horizon within Cycle "B"; lowermost Cooks Brook Formation, Northern Head section.



b
FISHER SCIENTIFIC
d
15 cm
a
c
f
s
B
G

level of bioturbation than black ones, but there is a spectrum of bioturbation levels which ranges from 1) bioturbation confined to green horizons to 2) burrows sharply crosscutting black horizons to 3) bioturbation present in both horizons (Plate 4-2b) to 4) extensively bioturbated but broad layering preserved to 5) massive (green) shale. An upward progression through this spectrum is seen locally where a black and green shale interval is overlain by extensively bioturbated red shales (described below) and is believed to reflect increasing levels of dissolved oxygen in the depositional environment (refer to Chapter 5).

Petrographic and geochemical evidence

In thin section, the colour of black shale is attributable to a concentration of opaque to semi-opaque, irregular flakes (up to 100 micrometers x 10 micrometers) flattened parallel to bedding. The ubiquitous upward decrease in concentration of these flakes through black horizons is sometimes profound enough to be apparent as a colour transition (from black N1 to grey N4) in the field or hand specimen but is generally too subtle. Although microanalysis has not been performed, these flakes are regarded as amorphous organic carbon. Indirect evidence is provided by organic carbon analysis of selected associated pairs of black and green layers (Table 4-1), which indicates variable, but appreciable, concentrations of organic carbon within black horizons and very low organic carbon content (close to the limits of detection; Appendix E) in green horizons. Moreover, graptolites and phyllocarids are found in black layers (Chapter 3) but never within green layers.

A compositional and grain size contrast is commonly apparent in

Table 4-1: Organic carbon content of selected black/green shale couplets.

Sample Number		Total organic carbon (wt. %)	
JB 39	(Eagle Is. N.)	.05	green
JB 38		.14	black
JB 48	(Lobster Cove Hd.)	.06	green
JB 47		.45	black
JB 70	(Cooks Bk.)	.10	green
JB 71		.34	black
JB 09	(Northern Hd.)	.05	green
JB 10		1.12	black
JB 31	(Middle Arm Pt.	.04	green
JB 30		.35	black
JB 15	(Black Bk. N.)	.07	green
JB 14		1.31	black
JB 35	(Eagle Is. S.)	.07	green
JB 34		.98	black

thin section, at the basal contact of black intervals. Underlying green shale is massive and dominated by chloritic clay flakes, while angular medium silt grains of carbonate, and locally siliciclastics, accompany the appearance of organic carbon flakes at the base of the black layers (Plate 4-2c). Carbonate grains may have been enlarged by diagenetic processes mentioned above, but their angular shape and the deformation of neighbouring organic flakes during compaction suggests that they are detrital. Where radiolaria are present they are either a) concentrated in the basal portion of black horizons or b) sparse in the black but prominently dispersed throughout the green horizons.

Where carbonate layers (with grains coarse enough for identification) occur within this lithologic association they reflect the composition of adjacent calcarenites. Common components include variably micritized, peloidal algal grains, abraded and overgrown dolomite rhombs and pelmatazoan and other bioclastic debris. Siliciclastic grains increase in proportion commensurate with their prominence in certain parts of the section, e.g. at the base of the Cooks Brook Formation at Northern Head.

Postulated depositional mechanisms

Carbonate-rich black/green shales commonly display many of the characteristics of fine-grained, silty to muddy turbidites (Stow and Shanmugan, 1980; Kelts and Arthur, 1981; Stow and Piper, 1984; Pickering et al., 1986).These include 1) basal scouring, 2) normal grading, 3) transitional relationships of parallel and cross laminations in the lower part and 4) transition into an overlying bioturbated interval. A more detailed comparison of similar lithologies from the Cow Head Group with models presented by these authors has been undertaken by Coniglio (1985) and will not be repeated here. Constituent carbonate grains have been derived, at least in part from shallow-water environments upslope (refer to <u>Calcarenite</u> section, this chapter) and are associated with organic carbon-rich shale, and both are regarded as redeposited.

Within carbonate-free black/green shale, black horizons commonly demonstrate 1) the basal truncation of underlying structures, 2) coarser modal grain size and 3) normal grading. These are considered to be essentially a finer-grained parallel to the sequence of structures described above, and these layers are regarded as muddy turbidites.

Intervening green horizons, on the basis of 1) elevated levels of bioturbation, 2) massive character, 3) localized presence of dispersed radiolaria and 4) transitional contact with underlying black horizons are regarded as hemi-pelagites. The transitional disappearance of organic carbon at the top of the black horizons is interpreted to be the result of relatively slow oxidation under ambient bottom-water conditions. Under such conditions the relative sharpness of this contact probably reflects slight temporal differences in sedimentation rate, or in the dissolved oxygen level of bottom water.

Very similar intervals of thinly interbedded black and green (Cretaceous) mudstones have been penetrated by DSDP drilling in the Atlantic (Dean et al., 1977; Meyers et al., 1984). These authors propose a similar model to that outlined in this study for the origin of these units, that is, periodic resedimentation of organic carbon-rich mud and subsequent burial by green hemi-pelagic mud layers under deep water conditions.

<u>Larger-scale cycles</u>

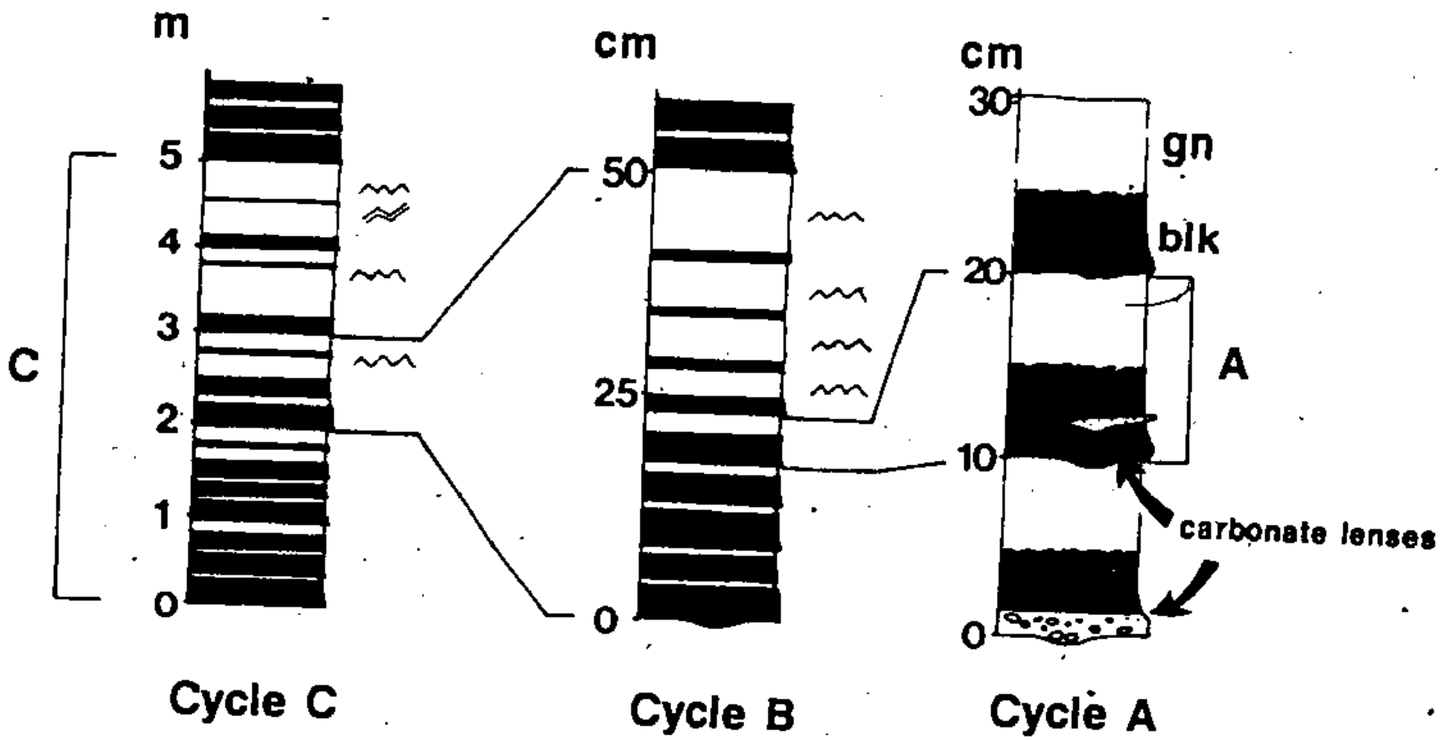
Where the black and green shale plus carbonate variety of this lithologic association is thickest and best-exposed, at the base of the Cooks Brook Formation at Northern Head, larger scale cyclic alternation of black and green is observed.

The alternation of thin beds of black shale (plus carbonate) and green shale, described above, is the smallest scale cycle present (Cycle "A", fig 4-1). Two orders of larger-scale cycles also occur.

The next order of cyclicity is represented by intervals roughly 50cm in thickness (Cycle "B", fig 4-1). These comprise a basal unit (15 to 20cm) of black shale (plus carbonate), with minor green shale horizons, which passes transitionally upward into an interval (25 to 35cm) of dolomitic, yellow-weathering green shale. The base of the black interval is generally sharp, with local, subtle, angular discordance upon the underlying green interval. Transition into the overlying green interval is by the thinning and fading black colouration of individual black horizons (Plate 4-2d). Green intervals are characterised by numerous irregular cross-lamination cosets defined by very fine silty dolomite, with scattered faint black horizons (Plate 4-3a). The diminished black colouration reflects the reduced organic carbon content. Organic carbon content within the basal black shale ranges up to 1.1% while it is at the

Figure 4-1

Schematic illustration of bedding cyclicity which occurs within interbedded black (plus carbonate) and green shale, prominently at the base of the Northern Head section. The largest scale cycle "C" is on the order of 5m thick, and comprises several smaller scale cycles "B" (each roughly 50cm thick). These diminish in overall organic carbon content through each Cycle C (refer to text). Cycle B comprises thinly-interbedded black and green shale, disposed in couplets (Cycle A) roughly 10cm in thickness. The relative proportion of black and green in each of these changes progressively through each Cycle B. Refer also to Plates 4-2d and 4-3a.


m
5
4
3
2
1
0
C
cm
50
25
0
cm
30
20
10
0
gn
blk
A
carbonate lenses
Cycle C
Cycle B
Cycle A

limit of detection within the green shale.

The third order of cyclicity (Cycle "C", fig 4-1) occurs in intervals of 3 to 5m thickness which comprise several sets of Cycle B. Within the lower 1 to 2m the black shale component within individual sets of Cycle B is both relatively thick and dark (rich in organic carbon). The relative proportion of cross-laminated green shale increases upward through each successive Cycle B (with a commensurate decrease in black shale), so that green shale dominates the upper half of each Cycle C (Plate 4-3b). In the uppermost part scattered, flattened burrows occur on some bedding planes, in a part of the stratigraphic section where bioturbation is generally very poorly developed (refer to Chapter 5).

Interpretation

Cycles B and C are interpreted to represent the same fundamental depositional mechanism as Cycle A. The basal part of each cycle represents the (punctuated) redeposited input of organic-rich mud, plus shallow-water carbonate grains, into the depositional environment, waning upward and followed by the deposition of hemipelagic, dolomitic green mud, in this case accompanied by current activity and localized bioturbation. No evidence of turbidite-related internal organization is noted within the green shale intervals and the abundant cross-laminations noted are best assigned to the action of bottom currents (cf. Stow and Lovell, 1979; Stow and Piper, 1984).

Similar cycles have been described from the Ordovician of Quebec and New York by Landing et al. (in press) who term them "Logan cycles". These authors ascribe cycle development to broad temporal oceanographic changes, related to sea level change, and suggest that the cycles are stratigraphically correlateble within their study area. Within the Northern Head group, such cycles are only developed in the interval described above, which is regarded as upper Middle Cambrian (Chapter 3). These cycles may be related to the periodic preservation of organic carbon (cf. Landing et al.) or the punctuated redeposition of organic carbon into the depositional environment. These alternatives are discussed, in light of overall depositional models, in the final chapter.

4.1.2.2 Bedded to massive red and green shale

This lithologic association is confined to the upper part of the Middle Arm Point Formation. It is volumetrically dominated by shale, but also contains lenses and beds of silty dolostone, packets of thinly-interbedded dolostone and lime mudstone, and beds of chert.

Black shale never occurs within this lithologic association. Intervals of massive red (10R 4/6) or green (10GY 5/2) shale, up to several m thick are abundant. These commonly display faint structures suggestive of thorough bioturbation, which are clearest where some burrows have been preferentially silicified. Levels of bioturbation are similar in red and green shales, but contrast markedly with the low levels generally observed in the black and green shales described above.

Massive shale commonly alternates with bedded or layered shale intervals which are of two principal types: 1) thin-bedded shale (generally <1cm) in hues of darker red (5R 2/6) to maroon (5RP 2/2),

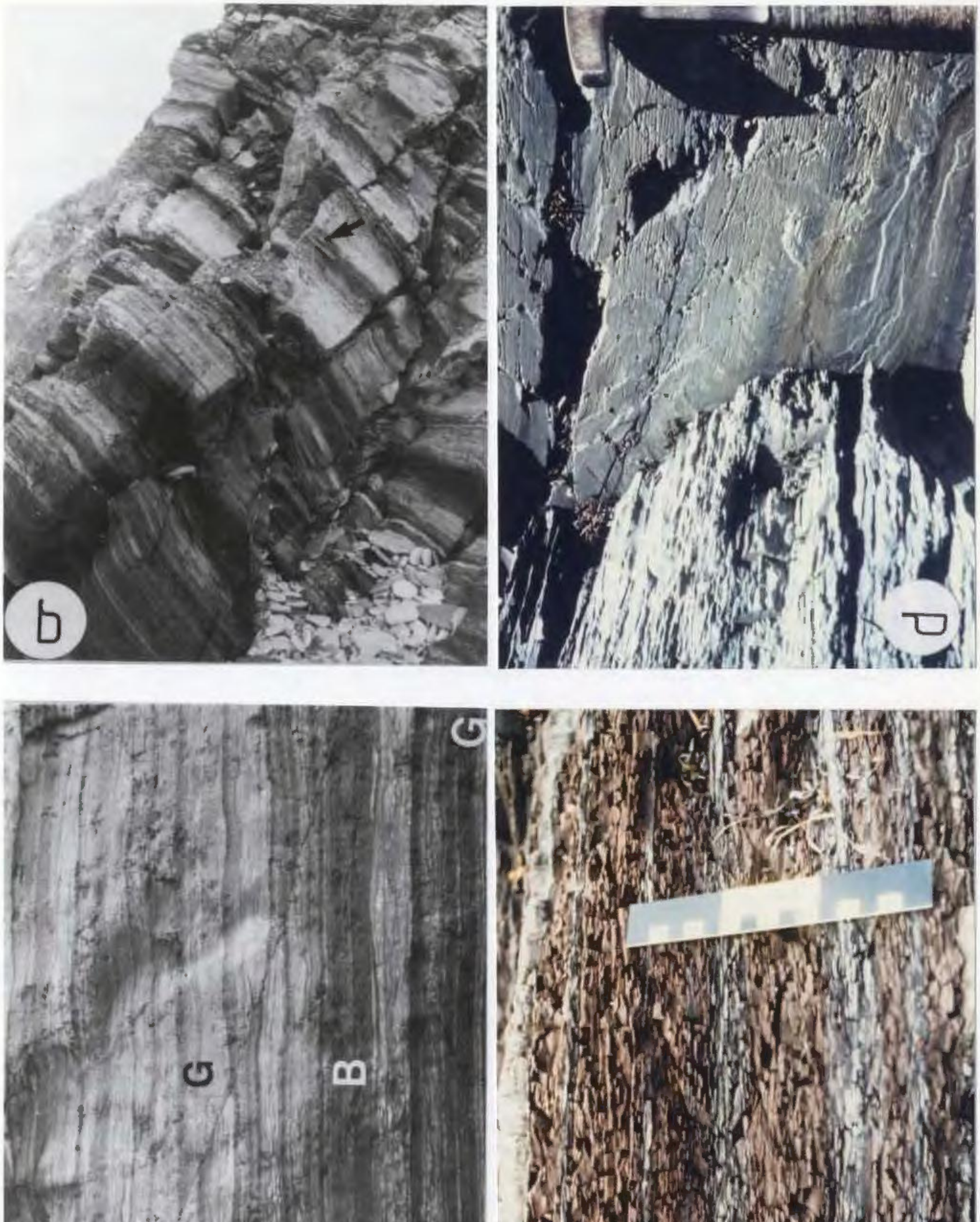
PLATE 4-3: SHALE LITHOLOGIES: BLACK/GREEN, RED AND GREEN

a: Dolomitic green shale interval within upper part of Cycle "B"; note numerous cosets displaying cross-lamination; 22mm coin for scale; lowermost Cooks Brook Formation, Northern Head section.

b: Single (approx. 5m) Cycle "C" displaying predominance of black shale at base (lower left) and dolomitic green shale at top (upper right); Hammer (arrow) for scale; lowermost Cooks Brook Formation, Northern Head section.

c: Variegated red shale displaying maroon laminae which are commonly Mn-rich; uppermost Middle Arm Point Formation, Eagle Island.

d: Broad colour variations within dominantly green shale; variations related to organic carbon content and modified by bioturbation; Middle Arm Point Formation, North Arm Point


b
d
G
B
G
a
c

plus accessory thin beds of carbonate (Plate 4-3c);

2) red and green shale characterized by a broader (4 to 5cm) layering defined by subtle colour variations. In green shale this broad layering consists of dark green (10GY 3/2) vs. light green (10GY 5/2) plus occasional olive-weathering layers (5Y 4/4) (Plate 4-3d). This may continue across a bedding plane transition into red shale, where the layering appears as an alternation of bright red (5R 5/4) and dull red (10R 3/4). This suggests that the layering is an original feature which has persisted through a subsequent (diagenetic) overall colour change. These units may have originated as black/green shale intervals, where bedding has been partially obscured by bioturbation. The cyclic appearance of burrowed horizons here overprints, partially disrupts and homogenizes an original layering caused by the episodic input and/or preservation of organic carbon. Episodic burrowed intervals are characteristic of this lithologic association, and are most readily apparent in massive light green shale, where they occur at 3 to 7cm intervals (Plate 4-4a). These borrowed horizons range up to 1.5cm in thickness and are highlighted by an associated, dark-weathering Mn-carbonate mineralization which occurs as a crust and burrow filling (refer to Chapter 6).

Associated diagenetic features

A diagnostic feature of this lithologic association is the occurrence of isolated, commonly maroon-weathering (5RP 2/2), bedding-parallel horizons of carbonate ranging from 1 to 3cm in thickness (Plate 4-3c). These layers have been diagenetically precipitated as a pervasive cement and partial replacement of the host shale by manganese and iron-rich carbonate. They are illustrated and discussed in greater detail in Chapter 6.

A related feature is disseminated manganese-rich carbonate crystals (up to .8mm) within massive shale (both red and green). Manganese is locally so abundant in this lithology that a silvery, metallic patina of pyrolusite is developed on exposed surfaces of shale. Lime mudstone beds occurring within red shale also locally display elevated concentrations of manganese.

Another diagenetic feature characteristic of this lithofacies is authigenic barite, which occurs as scattered crystals, 2 to 3mm in length, within massive green shale (refer to Chapter 6).

4.1.3 Red vs. green colouration in shale

Red and green shale may be thinly interbedded or locally laterally equivalent within the lithologic association described above. This colour contrast is considered to reflect, in part, depositional or early diagenetic conditions, and geochemical and diagenetic evidence is brought forward for discussion in this section.

Field Evidence and related interpretation

The red/green colour contrast is most commonly bedding parallel. The transition commonly separates thick (several meters or more) shale intervals dominated by contrasting colours, but layers of one colour as thin as 5 to 10cm may exist within the other. Also, faint relict red colouration is observed, at several localities, within intervals of green shale. As described in the Chert section (this

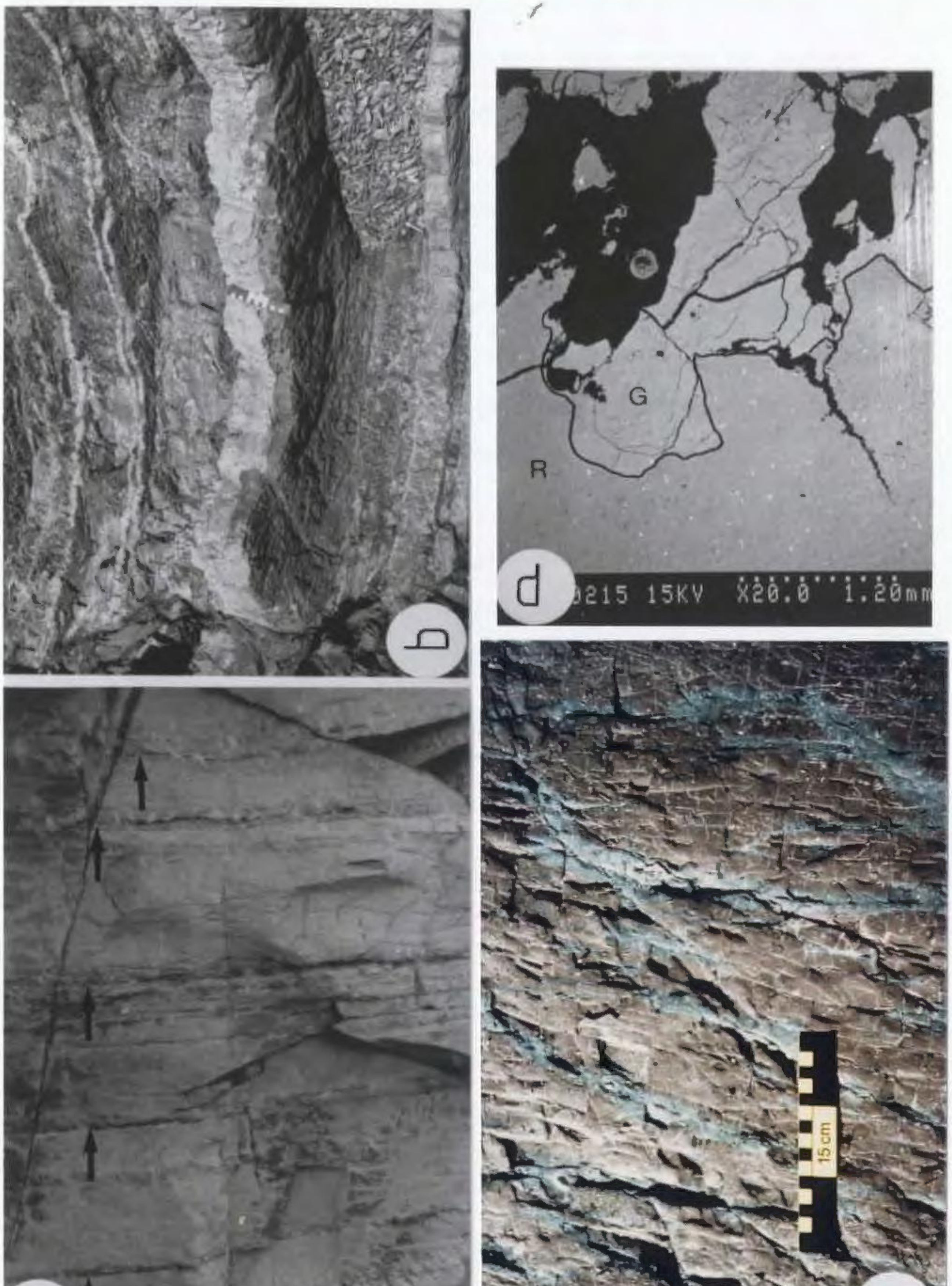
PLATE 4-4: RED AND GREEN SHALES

a: Burrowed horizons (arrows) within green shale; Middle Arm Point Formation, Woman Cove; 20mm coin for scale.

b: Chert beds within red/green shale interval; individual bed in center of photograph displays red base, green top; Middle Arm Point Formation, Black Point, Port au Port Bay.

c: Localized bleaching of red shale to green along a late fracture set; Middle Arm Point Formation, Black Point, Port au Port Bay.

d: SEM/EDAX photomicrograph (backscatter mode) showing the presence of disseminated aggregates of Fe oxide (bright specks) within red shale (R) host, and their absence within green shale burrow (G); dark areas were plucked from thin section during polishing



a
b
G
R
d
0215 15KV X20.0 1.20mm
15 cm
c

chapter) individual beds of chert (silicified shale) commonly preserve red/green colour changes within them, either as burrows (generally red burrows within a green host) or as bedding parallel transitions. Both red chert beds with green tops (Plate 4-4b) and green chert beds with red tops occur. Evidence presented in the <u>Chert</u> section, and in Chapter 6, suggests that silicification was an early diagenetic process which occurred during shallow burial. Since silica is present in this lithology as a pervasive cement, it is likely that once emplaced, it inhibited further diagenetic fluid movement and modification of the sediment. Hence silicification has probably preserved an original, very early diagenetic gradient, close to the sea floor, which was responsible for the red to green, or green to red, colour change. It is also possible that silicification itself was responsible for the colour difference, but since both polarities of colour change are preserved, this is considered unlikely.

Lateral red/green colour differences occur locally within individual, several meter thick, shale intervals (e.g. Middle Arm Point, Eagle Island North: Appendix A). The boundary between colours is irregular, and occurs at a high angle to bedding. This phenomenon is somewhat enigmatic, but a clue to its origin is suggested by a ?related feature. Within some intervals of red shale discrete late-stage fracture sets are the locus of a colour change to green, forming a zone roughly 1cm wide on either side of the fracture (Plate 4-4c). These are open fractures, which have likely been conduits for the downward percolation of groundwater in recent time, and the colour change is clearly a removal of red material associated with this process. Since field evidence indicates that the lateral colour changes described above are very late crosscutting features, they may have resulted from the more pervasive removal of red material, associated with recent groundwater movement in a similar manner.

Microscopic evidence.

The colour of "redbeds" is generally ascribed to the presence of intersritial iron hydroxide, chiefly hematite (reviewed in Chandler, 1980). Samples of red and green chert and shale from the Northern Head group were examined with the polarizing microscope and SEM in an attempt to establish the source, timing and location of pigmentation.

Particularly where silicified, red shales can be seen to derive their colour from thin grain coatings of hematite which are visible in thin section. The largest and most readily discernible coated grains are dolomite which have been subsequently surrounded by silica. Many of these coated dolomite crystals have been produced by the diagenetic overgrowth of an abraded core (refer to Dolomite section) and so, at least locally, coating by hematite occurred in the latter stages of the diagenetic sequence. Hematite has also been observed patchily distributed through the siliceous matrix with a granular texture and occasionally as flakes co-occuring with dolomite, detrital quartz and feldspar, in current-sorted laminae. These three styles of occurrence, of which the first is the most common, suggest that silicification postdated the formation of hematite in the sediment, whether originally deposited as such or produced *in situ* from an amorphous Fe oxide precursor. Diagenetic conditions must have remained within the stability field of hematite during silicification even if these occurrences are the result of redistribution processes.

The disposition of red pigmentation in shales could not be resolved with the polarizing microscope, so that i) lithified chip samples and ii) ultrasonically disaggregated samples of several pairs of associated red and green shales were examined under the SEM. Platy to hexagonal crystals (roughly .5 micrometers in diameter), occurring within hematite pigments, have been illustrated in SEM photomicrographs by McPherson (1980) and Welton (1984). Such crystals were not, however, detected in the samples examined in this study. Even under magnification of 17,000x disaggregated red and green shales appear identical, as mixtures of chlorite and illite clay flakes with clean surfaces. Hematite crystals could not be resolved in lithified chips but their presence may be masked by cementation. The presence of "free" iron in red shale has been detected, however, in some samples, as "clumps" or aggregates of amorphous iron oxide, up to 30 microns in diameter, visible using the SEM/EDAX in backscatter mode. In one sample in particular, these clumps are abundantly disseminated throughout a red shale host and absent in a contained burrow filled with green shale (Plate 4.4d).

Mineralogical and geochemical evidence

The clay mineralogy of associated red and green shale samples has been examined by XRD (Chapter 7; Appendix E). No discernable differences, in terms of the relative proportions of the principal clay mineral components, illite and chlorite, nor the mineralogy

Figure 4-2

A comparison of XRD diffractograms of red and green shale (neighbouring beds at Eagle Island North) illustrating the similarity in bulk mineralogy and the characteristic hematite reflection which is associated with most red shales.

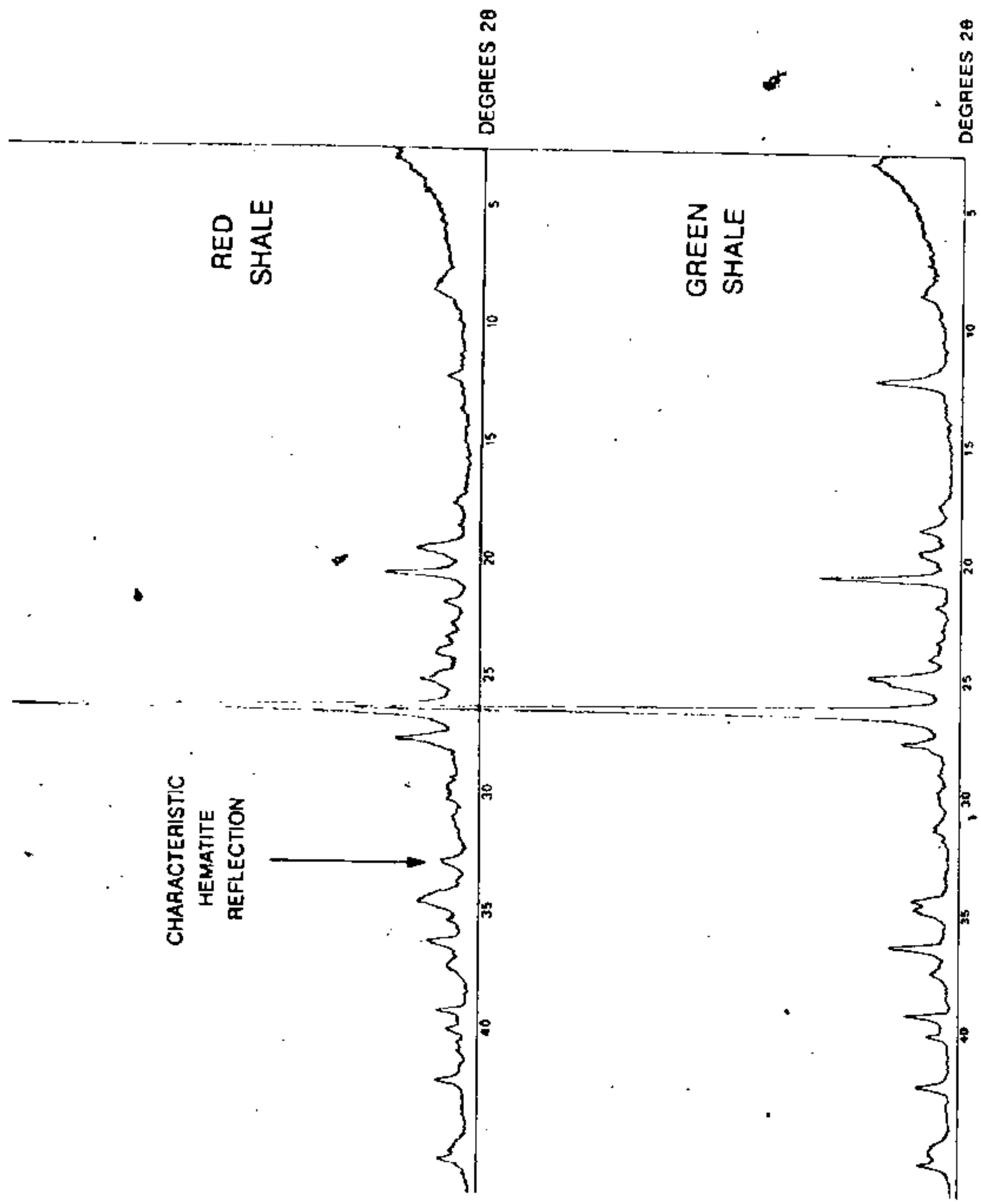

RED SHALE
GREEN SHALE
CHARACTERISTIC HEMATITE REFLECTION
DEGREES 2θ
DEGREES 2θ
5
10
15
20
25
30
35
40

Table 4-2

Ferrous/ferric iron ratios within selected pairs of red and green shale

Sample No. (red/green)	FeO	Fe2O3	Fe 2+	Fe 3+	Fe2+/Fe3+
	(all	expressed	in	wt. %)	
Middle Arm Point Fm.					
Middle Arm Point					
JB 1 red	1.97	2.97	1.53	2.07	.74
JB 2 green	3.92	2.19	3.05	1.53	1.99
Eagle Is. N.					
JB 36 red	1.88	4.68	1.46	3.27	.45
JB 39 green	4.54	1.51	3.52	1.06	3.32
Black Point					
JB 63 red	1.06	3.44	.82	2.41	.34
JB 64 green	1.09	.33	.85	.23	3.69
Summerside Fm.					
JB 82 red	2.52	4.86	1.96	3.40	.58
JB 81 green	4.94	1.76	3.84	1.23	3.12

(i.e. Fe content) of the contained chlorite, was detected. This was qualitatively confirmed by EDX identification and analysis of clay minerals during the search for hematite. Subtle diffractogram peaks indicating the presence of hematite were, however, detected in most of the red shales examined, but none are present in corresponding green shales (fig 4-2).

The average total Fe content of red and green shales is comparable; both contain approximately 6% total iron. Determination of ferric/ferrous ratios was conducted for three red/green pairs of Middle Arm Point shale, plus one pair from the Summerside Formation (Table 4-2). These data indicate that red shale is enriched in ferric iron, relative to green, by a factor of 6 to 10x, a comparable enrichment to that noted by Friend (1966) and McPherson (1980). Since there is no significant difference in whole rock mineralogy, these differences in ferrous/ferric ratios are attributed to the presence of "free" ferric oxide, which has resulted in the red colouration of some Middle Arm Point shales.

Red and green colouration in shale: summary and interpretation

The above evidence indicates that the red colour exhibited by certain shales in the Middle Arm Point Formation is due to the presence of hematite, which occurs as an extremely fine crystalline grain coating and locally as agglomerated masses and flakes within the matrix of shale and silicified shale. At least locally, the precipitation of this hematite occurred during the latter stages of the diagenetic sequence. The presence of relict red colouration within green shale intervals suggests the localized diagenetic transformation of this hematite to amorphous ferrous compounds. A limited amount of this transformation is shown to be recent. Red and green shale intervals are intimately associated within the same lithofacies, and it is unlikely that the two lithologies are derived from different sources.

The origin of such hematite is commonly thought to be either "detrital", i.e. introduced as pre-existing grain coatings, or "diagenetic", i.e. precipitated <u>in situ</u>. In the second case, the precipitation of hematite commonly proceeds through the dehydration of a precursor amorphous iron oxide (Van Houten, 1968), similar to limonite (Berner, 1969), and is an indication of oxidizing conditions. This is the importance of distinguishing the two origins. Models which invoke a "detrital" origin for (shaly) marine redbeds (Ziegler and McKerrow, 1975; Lajoie and Chagnon, 1973) suggest that hematite grain coating was originally produced under shallow marine to terrestrial conditions, subsequently resedimented into a deep marine setting and quickly buried, to avoid the removal of hematite under presumably reducing conditions in the deep marine environment. In this case no inferences can be drawn about the Eh level of the depositional environment. It is difficult to conclude how the iron which presently appears as hematite in the shales of the Middle Arm Point was introduced, as is generally the case in examination of redbeds (Van Houten, 1968; 1973). It is quite possible that iron was oxidized in the source environment before transportation to the deep-water site of deposition. It is clear, however, from the abundance of burrowed horizons and the overall sedimentologic style of the lithologic association containing red shale, that deposition and burial was not rapid and that the early diagenetic system was relatively open. The important point is that hematite participated in the early diagenetic sequence of these shales, was locally redistributed and remained stable, and in immediately adjacent parts of the sequence was removed. This indicates that depositional and early diagenetic conditions fluctuated about the stability boundary of hematite. The fact that silicification, as an early, near sea-floor process has preserved red/green colour changes suggests the presence of somewhat reducing pore waters (or possibly bottom waters ?) which were responsible for the removal of hematite. The relatively elevated Eh level of the depositional environment, as indicated by the presence of hematite, is commensurate with the increased levels of bioturbation and paucity of organic carbon evident in this part of the stratigraphic section and this relationship will be further exploted in subsequent chapters.

4.1.4 Relationship of lithologic associations within the Middle Arm Point Formation

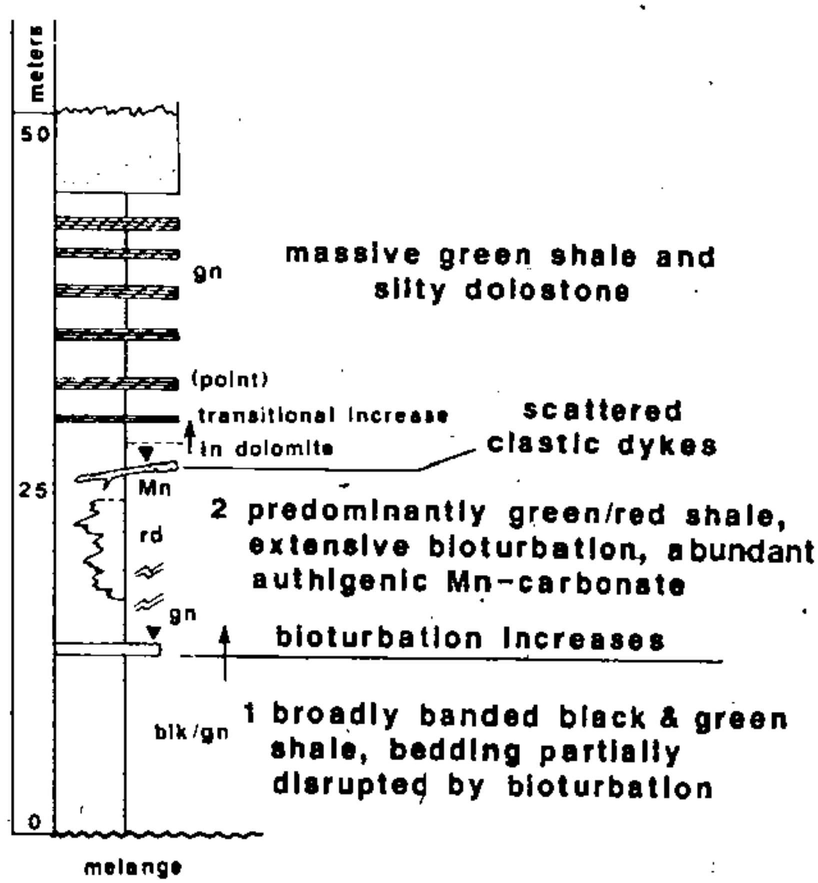
As mentioned above, 1) black/green and 2) red/green shale-dominated intervals are interbedded on a 1 to 5m scale within the uppermost interval of the Middle Arm Point Formation. The thinly interbedded black and green shale intervals are interpreted to represent the redeposition of organic carbon-rich muddy turbidites (black shale) plus hemi-pelagic deposition (green shale). Massive green and red shale intervals contain essentially no organic carbon, commonly display evidence of intense bioturbation, and based upon the variable preservation of hematite and other diagenetic features discussed in Chapter 6, record a variable, but elevated level of ambient dissolved oxygen in the depositional environment relative to other shale lithologic associations. The lower boundary of black/green intervals is generally sharp. The upper boundary is commonly more diffuse and upward increasing levels of bioturbation within black/green shale suggest an upward increase in the Eh level. This relationship is illustrated in the Cape Split section (fig 4-3). Here an interval of somewhat irregularly-bedded black and green shale, partially disrupted by bioturbation, passes transitionally upward into an interval of green and red shale, generally massive but with discrete bioturbated horizons and containing diagenetically-precipitated Mn-carbonate. This, in turn, is transitional upward into an interval of massive green shale with prominent silty dolostone beds overlain by sandstone of the Eagle Island Formation.

The two contrasting styles of shale-dominated deposition within the Middle Arm Point may be viewed in light of two different models: 1) Depositional conditions through this interval have fluctuated between two modes: i) a relatively low Eh level, which has preserved organic carbon and are now represented by thinly interbedded black and green shale and ii) relatively high Eh conditions which have resulted in the depoaition of the massive green and red shale. association. The driving mechanism of this fluctuation is "external" and somehow related to widespread oceanic conditions.

Figure 4-3

Measured section at Cape Split illustrating sedimentologic and diagenetic features interpreted to be associated with increasing levels of dissolved oxygen in the depositional environment, through an interval of the uppermost Middle Arm Point Formation. Lithologic symbols as per fig 3-1a.

Cape Split


meters
50
25
0
gn
massive green shale and silty dolostone
(point)
transitional increase in dolomite
scattered clastic dykes
Mn
2 predominantly green/red shale, extensive bioturbation, abundant authigenic Mn-carbonate
rd
gn
bioturbation increases
blk/gn
1 broadly banded black & green shale, bedding partially disrupted by bioturbation
melange

2) The massive green and red shale association represents "normal" depositional conditions at this time, which have been periodically interrupted by the input of organic carbon-rich muddy turbidites. These have, by their presence, temporarily altered the delicately balanced Eh level of the depositional environment and the return to "normal" marine conditions is represented by the transitional reappearance of the massive green and red shale association (cf. Dean and Gardner, 1982).

These two alternatives will be discussed in light of overall depositional and oceanographic models in the final chapter.

4.1.5 Summary

Organic carbon-rich, well-laminated black shale intervals are regarded as pelagic and hemi-pelagic, quiet-water deposits. The thickest and most conspicuous occurrence of this lithology is a correlatable lower Tremadoc interval (within the upper part of the Cooks Brook Formation) which provides evidence of distinctive depositional conditions at this time. The anomalous appearance, within the Middle Arm Point Formation, of abundant organic carbon within shale interbeds in a perted lime grainstone unit may be indicative of a temporary return to similar conditions.

Cycles of interbedded black and green shale are interpreted to reflect turbiditic redeposition of organic carbon-rich muds alternating with hemi-pelagic sedimentation. This style of sedimentation was ongoing throughout deposition of the Northern Head group and of a cyclic nature at the base of the Cooks Brook Formation. Shales of the Middle Arm Point Formation record a progressive increase in the level of dissolved oxygen in the depositional environment, punctuated by black and green intervals described above.

4.1 CHERT

Introduction

Chert is almost entirely confined to the Middle Arm Point Formation, particularly in the upper (Arenig) part. The only notable occurrence within the Cooks Brook Formation is within the Tremadoc black shale and thin-bedded carbonate sequence at North Arm Point. The majority of Northern Head group cherts are silicified versions of other lithologies, principally shale. Silicification appears to have been an early diagenetic phenomenon which has preserved sedimentary and biogenic structures and diagenetic features such as hematitic coatings. Dolomite is very common within these cherts, and dolomite grains are better preserved than within non-silicified dolostones.

4.2.1 Terminology

Since most of the Northern Head group cherts have originated by extensive silica cementation (and localized replacement) of pre-existing lithologies, a gradational boundary exists between the original host and end-member "cherts". In particular, the distinction between the field terms shale, siliceous shale and chert is somewhat arbitrary, and based broadly on the relative hardness (reflected in part as resistance to erosion relative to surrounding lithologies). Since these are field terms, attempts to quantify them are not applicable, but as a general guideline, those lithologies termed chert display an SiO_2 content of 80% or more compared with an average (this study) shale composition of 58.5% SiO_2. Siliceous shales lie between these values, are more resistant to erosion than surrounding shale, but can still be scratched with the hammer. This is distinct from the term <u>silicified</u> shale used below, which implies pervasive cementation, and commonly partial replacement, by silica.

4.2.2 Biogenic components

Radiolaria are the most common siliceous biogenic component and occur within roughly 1/3 of the chert samples examined. They are generally preserved as spherical bodies, roughly .1 mm in diameter and filled with fine-crystalline silica. In a few samples delicate ornamentation can be seen and a "net-like" internal structure has been observed under cathodoluminescence. Siliceous sponge spicules are less abundant and are only present in lithologies with abundant radiolaria. The relative paucity of spicules may thus be related to preservation rather than initial abundance.

Radiolaria never constitute more than 15% of any chert. Densely-packed "radiolarites" (cf. Grunau, 1965; Barrett, 1982; Gortner and Larue, 1986) are not present. Radiolaria are commonly concentrated in one of three ways:

1) In thin current-sorted laminae mixed with dolomite crystals of roughly the same size.

2) In individual horizons within banded black and green shale sequences.

3) In pellets within burrows.

4.2.3 Principal types of chert

Shale and silty dolostone are the two principal Northern Head group lithologies which become so extensively silicified as to form chert. Conspicuous by its absence is the nodular and replacement chert associated with limestone in the Cow Head Group (Coniglio, 1985; James and Stevens, 1986). Likewise, the characteristic chert "crusts" which cap (principally Ordovician) conglomerates within the Cow Head Group (ibid.) are not developed. This style of silicification, however, does occur as a siliceous matrix in some calcarenite units overlying Halfway Point member conglomerates (refer to Calcarenite, Conglomerate sections). A somewhat similar mode of "bed-top" silicification is present in silty dolostones (refer to Dolostone section) and is discussed below.

4.2.3.1 Silicified shale

Where chert occurs in the uppermost Cooks Brook Formation (North Arm Point locality mentioned above) the host shale is black and rich in organic carbon. This shale is broadly silicified but contains thin (< 1mm) very organic-rich, non-silicified partings at roughly 5cm intervals. A single 10cm layer of translucent, relatively pure chert occurs in the upper part of this interval. This layer displays centimeter scale banding which appears to be relic bedding and includes scattered, lensoid horizons of pyrite up to 2cm thick. In thin section this chert is dominated by structureless, fine crystalline silica. This texture, and the above-described features suggest that the layer originated by extensive replacement along a discrete horizon, where it has almost entirely replaced thin beds of shale.

Silicified shale is a characteristic component of the uppermost Middle Arm Point Formation, where it is best developed immediately below the Eagle Island formation. At several localities (Middle Arm Point, Eagle Island North) it forms blocky-weathering intervals, up to several meters thick, of massive silicified shale, which is predominantly green. In other sections (North Arm Point, Black Point), discrete 3 to 10cm beds of chert (silicified shale) occur at 30 to 70cm intervals within units of red and green shale. These cherts are both red and green, and have preserved or "frozen" diagenetic red/green colour variations. At North Arm Point, for example, green cherts predominate and preserve red burrows within them (refer to Shale section above).

The early onset of silicification is suggested by rounded silicified clasts within carbonate conglomerates and angular "rip-up" clasts of (Middle Arm Point) chert in conglomeratic horizons in the overlying Eagle Island formation.

Silicified shales display a subtle matrix of dark isotropic or very weakly birefringent silica in thin section which surrounds and cements clay and silt particles. Samples (from Middle Arm Point and Eagle Island), which are massive in hand sample, display, in thin section, subtle structures suggestive of burrowing which predate silicification. Brecciation of shale followed by cementation by crystalline quartz and localized fine-crystalline quartz veins is also present, similar to that described from bedded cherts by Wise and Weaver (1974).

Samples where quartz cementation is common display 2 stages of crystal growth within pores. The first is an acicular pore-lining, while the second is a pore-filling chalcedonic quartz which is commonly, but not always, length-fast. Silica also coats or rims carbonate grains and locally completely replaces carbonate.

In several cases burrows appear to have been the loci of more intense silicification which can be observed 1) within the host sediment along the margin of the burrow and 2) as clear, silica-dominated areas within otherwise red sediment-filled burrows.

4.2.3.2 Silicified dolostones

Scattered silty dolostones have been extensively silicified and appear as resistant "chert" horizons up to 10 cm thick (Plate 4-5a) within some shale-dominated sequences (the Middle Arm Point Formation). Examples of partially silicified dolostones, where silicification is confined to individual bed tops, are described in the Dolomite section.

In thin section, dolomite commonly appears as abundant, euhedral crystals within individual, mm-scale laminae and locally within graded beds up to 1cm in thickness. In the graded beds dolomite is accompanied at the base of the bed by fine sand-size grains of quartz and feldspar, phosphate and locally radiolaria.

In the case of individual laminae dolomite, angular, detrital quartz and feldspar grains and radiolaria have undergone the same size-sorting during deposition. These laminae commonly appear as light-coloured intervals within red shale. This indicates that i) the velocity of the current which deposited the lamina was high enough to remove clay, ii) the red hematite stain is confined to the clay fraction and iii) at least some of the silica present was introduced as a detrital component (radiolaria). Burrows preserved within these cherts commonly contain a much higher proportion of detrital components than the generally clay-rich host sediment.

4.2.4 Summary and Interpretation

Northern Head group cherts are principally the result of extensive cementation and localized replacement of pre-existing shales and dolostones. They are largely confined to the Middle Arm Point Formation in the Arenig part of the section. Partially recrystallized radiolaria are associated with roughly one third of the chert samples examined.

Field evidence indicates that in many cases silicification has occurred early, possibly at or near the seafloor. This includes:

i) the incorporation of rounded, silicified clasts within carbonate conglomerates, and the presence of angular "rip-up" clasts of (Middle Arm Point) chert in conglomeratic horizons of the overlying Eagle Island formation.

ii) the presence of uncompacted silicified burrows within intervals of shale and silty dolostone; in this case the burrows may have acted as permeable and porous locations for the precipitation of silica from pore-waters during early diagenesis.

iii) the "bed-top" silicification displayed by silty dolostones within the Middle Arm Point Formation, where extensive silica cementation is confined to the uppermost part of each individual thin bed within a thin-bedded interval of silty dolostone. Similar processes have been noted within red and green shale intervals, where silicification has apparently arrested and preserved

PLATE 4-5: CHERT, CALCARENITE LITHOLOGIES

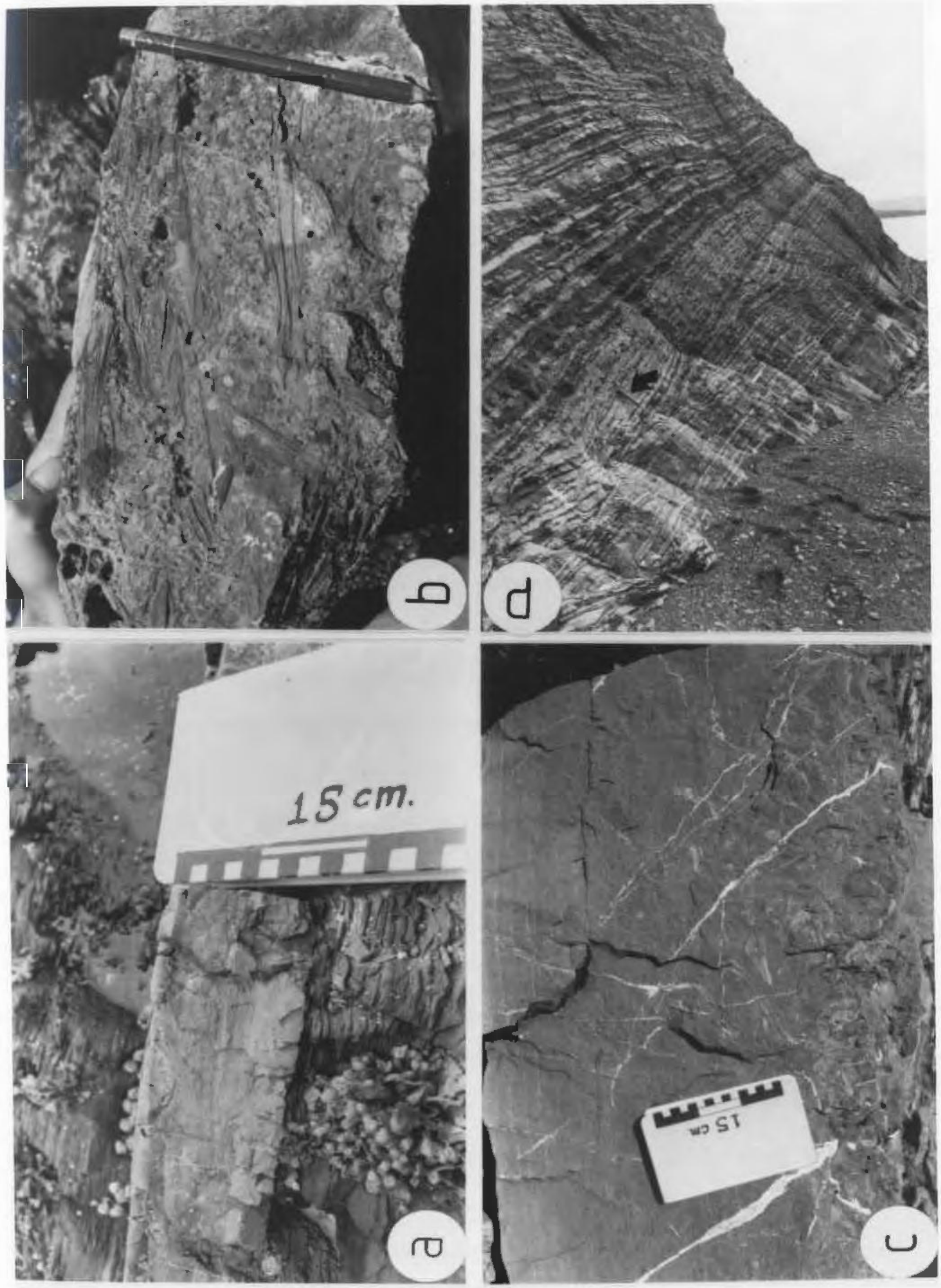
a: Resistant chert bed within a shale interval, formed by the silicification of silty dolostone; Middle Arm Point Formation, Black Brook North.

CALCARENITE

b: Conglomerate lens dominated by tabular clasts of locally-derived, parallel to cross-laminated calcarenite; Upper Cambrian calcarenite-dominated interval.

c: Graded bed, grading from conglomerate at base to parallel-laminated calcarenite at top; "graded-stratified conglomerate" of Hiscott and James (1985); Upper Cambrian calcarenite-dominated interval.

d: "Intraformational truncation surface" attributed to gravity-sliding within the Upper Cambrian calcarenite-dominated interval; Northern Head; hammer (arrow) for scale.



b
d
a
15 cm.
c
15 cm

diagenetic red/green colour changes.

The origin of the microcrystalline silica cannot be conclusively demonstrated but the association with radiolaria in various stages of recrystallization (and the scattered presence of siliceous spicules) strongly suggests derivation by early diagenetic recrystallization of biogenic silica. Studies of Tertiary to Recent pelagic siliceous deposits indicate that the transformation of biogenic silica (opal A) through an intermediate cristobalite (opal CT) to quartz is a solution/reprecipitation process which is dependent upon time, temperature and concentration of impurities (ionic species and clays; Lancelot, 1973) in the precipitating medium (summarized in Calvert, 1974; Wise and Weaver, 1974). Silica solution and redistribution in pore waters during this process (cf. Suess, 1979) could readily have resulted in the style of pervasive cementation and localized replacement observed in cherts of the Northern Head Group. Relic radiolarian tests (now preserved as spherules of microcrystalline quartz) probably represent a small fraction of the original siliceous biogenic debris present, preserved by local variations in pore water chemistry. There is no evidence of volcanogenic input of silica into the cherts of the Northern Head group, neither in significant amounts of siliceous volcanogenic debris nor as hydrothermal fluids.

Chert is more widespread in the Cow Head Group than in the Northern Head group, by volume, in the variety of its occurrence, and in stratigraphic distribution (Hubert et al., 1977: James and Stevens, 1986) In both cases the occurrence of chert does increase significantly in the Ordovician, but is much more widespread in the

Tremadoc in the Cow Head Group than it is in the Northern Head group. Possible reasons for this contrast between the Northern Head Group and Cow Head Group are discussed in the final chapter.

4.3 CALCARENITE

Introduction

Calcarenite beds are distributed throughout the Northern Head group, but dominate the Upper Cambrian portion of the Cooks Brook Formation and are generally sparse within the Middle Arm Point Formation. Calcarenite beds range from less than 5cm to roughly 40cm in thickness and occur in several different ways, as 1) isolated interbeds (together with shale) within other lithologies, such as conglomeratic intervals, 2) thin "caps" on some conglomerate beds and 3) the principal component of parted limestone intervals. The clearest example of the latter is the roughly 100m thick Upper Cambrian calcarenite-dominated section described in Chapter 3 and referred to below.

Calcarenite units range in grain size from coarse silt to coarse sandstone and in texture from packstone to wackestone. Modal grain size is fine sand. Granule conglomerate is different, and is discussed in the conglomerate section.

4.3.1 Composition

The most common component of Northern Head group calcarenites is well-rounded peloids. In the finer size range (15 to 50 micrometers) these are featureless micrite. Peloids range up to coarse sand size, where "structure grumuleuse" (Bathurst, 1971) is common observed, and where, in the least-recrystallized examples, Girvanella and Epiphyton can be distinguished. Nuia is a less common component.

Siliciclastic grains are a ubiquitous component of Northern Head calcarenites. The siliciclastic component ranges up to 25% in individual calcarenite beds near the base of the Cooks Brook Formation. Here flakes of detrital mica (a characteristic component of the immediately underlying Irishtown lithologies) accompany rounded grains of quartz and feldspar. Quartz grains here are medium to coarse sand, and are characteristically highly fractured and corroded and appear similar to those comprising sandstones in the underlying Irishtown Formation.

Angular siliciclastic silt is a pervasive minor component, both within grains (scattered throughout peloidal micritic grains) and matrix. This silt becomes conspicuously abundant in the Upper Cambrian part of the Cooks Brook Formation. It is too fine to be readily apparent in the field, but can be seen in thin section to represent up to 40% of the rock, where it is commonly sorted in individual laminae. Within an interval of particularly coarse uppermost Cambrian calcarenites this silt is accompanied by very well rounded medium to coarse quartzose sand, which commonly displays frosted surfaces.

Dolomite is another common component of the calcarenites and occurs as 1) individual crystals with euhedral (frequently ferroan) overgrowth, and 2) clumps of non-ferroan dolomite interpreted to be dolomitized intraclasts. Dolomite is discussed in detail in a later section.

Trilobite and brachiopod fragments and rounded, commonly overgrown pelmatazoan fragments are present as a minor component in many calcarenites.

Unlike many Cow Head Group calcarenites (James and Stevens, 1986), ooids are extremely rare in calcarenites of the Northern Head group.

4.3.2 Bedding styles and lithologic associations

4.3.2.1 Cooks Brook calcarenites

Calcarenite dominates a roughly 100m thick interval within the Upper Cambrian portion of the Cooks Brook Formation (Chapter 3). Although calcarenite beds are variable, the majority are roughly 5 to 25cm thick, and display i) a broadly channelized to planar base, ii) parallel laminations in the lower part, commonly passing upward into iii) a ripple-laminated upper part. Massive calcarenite beds are also present but are uncommon. Shale interbeds range from less than 1cm to 5cm between calcarenites, although amalgamated calcarenite beds are common.

Thin pebble to cobble conglomerates are associated with this lithology, particularly in the thick Upper Cambrian calcarenite-dominated interval. These conglomerates range from 10 to 30cm in thickness and are generally lenses less than 1m wide. They are composed of tabular clasts of parallel to cross-laminated calcarenite, clearly derived from the surrounding lithology (Plate 4-5b). These units are not graded, and commonly display a planar base and irregular top (with projecting clasts).

The most extensive exposure of the Upper Cambrian calcarenite-dominated interval is present along the roadside in the core of the Cooks Brook syncline (immediately west of Cooks Brook). Two modal thicknesses of calcarenite beds occur here: thick (40cm) and thin (5 to 10cm). Locally thin beds of lime mudstone appear within the thin beds. These two bedding styles occur in units 3 to 5m thick, which commonly alternate. This bedding feature cannot be discriminated as thickening or thinning upward, since the contact between units is sharp and not gradational. The lensoid conglomerates described above are most common within the thicker bedded units.

Amalgamated calcarenite units, locally up to 5m thick, also occur within this interval. Uncommon beds, up to 50cm thick, grade from conglomerate at the base to parallel-laminated calcarenite at the top (Plate 4-5c). These are similar to those termed "graded-stratified conglomerate" by Hiscott and James (1985) and James and Stevens (1986).

Planar discontinuity surfaces, at a low angle to bedding, occur within the Upper Cambrian calcarenite interval (Plate 4-5d), commonly just above chaotically folded horizons. This is most readily apparent at Northern Head. These are identical to the "intraformational truncation surfaces" described from the Cow Head Group (Coniglio, 1985; James and Stevens, 1986) and attributed to gravity-induced sliding of sediment.

Calcarenite "caps" on conglomerate beds are most commonly noted in the lower part of the Cooks Brook Formation. These units range from 2 to 5cm in thickness. Internal structure is variable and ranges from massive to entirely parallel-laminated to parallel-laminated grading up into cross-laminated to entirely cross-laminated. These units are similar to, but generally thinner, than those described from the Cow Head Group (Hubert et al., 1977; Coniglio, 1985; James and Stevens, 1986). Calcarenite caps overlie only matrix-rich conglomerates and are compositionally identical to the matrix of the associated conglomerate.

4.3.2.2 Middle Arm Point calcarenites

Calcarenite is uncommon within the Middle Arm Point Formation, but occurs conspicuously within a 7 to 10m interval of dark parted limestone (refer to Chapter 3; fig 3-8). Calcarenite beds, 15 to 25cm thick, are interbedded with black, finely laminated shale at 5 to 10cm intervals. The calcarenite is dark grey due to included organic carbon, displays scattered current ripples and is characteristically bioturbated.

The modal grain size of these units is .8mm and they range from medium to coarse sand. Compositionally, they are similar to the granule conglomerates which occur higher in the section, in the abundance of algal micrite or sparite grains dominated by *Girvanella* and *Epiphyton*, and the presence of accessory rounded phosphate grains.

4.3.3 Calcarenites: Interpreted source and depositional mechanisms

4.3.3.1 Postulated source

Peloidal grains are the dominant component of Northern Head Group calcarenites and are interpreted to have been largely derived from calcified algae. A similar composition has been noted in the calcarenites of the Cow Head Group (Coniglio, 1985; Coniglio and James, 1985; James and Stevens, 1986). Based upon the widespread occurrence of these redeposited algal grains (and boulders of calcified algae within conglomerates) these authors reconstruct the

Lower Paleozoic shallow-water carbonate margin as one dominated by Girvanella, Epiphyton and Renalcis, shedding sediment dominated by these calcified algae into deeper water. The nature of the Northern Head group calcarenites is consistent with this interpretation.

The nature and stratigraphic position of siliciclastic grains within calcarenites in the lowermost Cooks Brook Formation are consistent with derivation from a waning siliciclastic source at the close of Irishtown sedimentation.

The notable prominence of siliciclastic grains within the Upper Cambrian Northern Head group calcarenites is very similar to that described from the Cow Head Group (James and Stevens, 1986). Based on grain shape and texture, and overall size distribution (angular silt and frosted sand grains) this quartzose material is regarded by these authors as eolian in origin and this is accepted here. This input of siliciclastic material appears to have been continuous through the deposition of the Northern Head Group, with local maxima related to events recorded on the platform (see final chapter).

4.3.3.2 Depositional mechanisms

The internal sequence of sedimentary structures, broadly channelized base and normal grading demonstrated by the majority of the Northern Head group calcarenites suggest that these units have been deposited by turbidity currents. Although the classic Bouma sequence is not developed, these units commonly display the Tbce divisions and have many of the features of medium-grained turbidites as summarized by Pickering et al. (1986). Predominantly massive calcarenite beds have been described from the Cow Head Group by

Coniglio (1985), who regarded them as proximal turbidites. Cross stratification on the tops of Cow Head Group calcarenites was interpreted by Hubert et al. (1977) to represent the action of contour currents, but in the Northern Head group calcarenites this structure is interpreted as part of the Bouma cycle, and no evidence of contourites has been observed in this lithology (cf. Conoglio, 1985; Hiscott and James, 1985).

Likewise, the calcarenite caps on conglomerate beds were interpreted by Hubert et al. (1977) as contourites. It is clear from observations outlined above that each calcarenite cap is genetically related to the associated conglomerate. Since the calcarenite units commonly display partial Bouma sequences, it is considered most likely that these units represent turbidites, whose deposition is part of the gravity-driven emplacement of the underlying debris flows (cf. Krause and Oldershaw, 1979; Hiscott and James, 1985).

The thin, lensoid conglomerates in the Upper Cambrian calcarenite interval display the characteristics of localized debris flows. The association of these conglomerates with thicker bedded calcarenite units is suggestive of a more "proximal-style" depositional setting (cf. Walker, 1967) as opposed to the thinner bedded calcarenite/lime mudstone units with which they alternate. This alternation of units does not appear to reflect a pattern of thickening or thinning upward consistent with the facies distribution described from a submarine fan setting (Mutti and Ricci Lucchi, 1978; Walker, 1978). Rather the alternation indicates a periodic increase in sediment supply from upslope, possibly driven by tectonic control (cf. Macdonald, 1986) but thought to more likely represent punctuated, small-scale progradation of the upslope carbonate margin.

The appearance of the calcarenite interval within the overall shale-dominated Middle Arm Point Formation is anomalous. This interval represents the input of largely shallow-water-derived carbonate grains (and organic carbon-rich mudstone) into an interval otherwise indicating restricted input from the platform margin. Evidence suggesting the depositional mechanism of beds within this interval has been partially obscured by bioturbation, but beds here most closely resemble other calcarenites interpreted as turbidites.

4.4 LIME MUDSTONE

4.4.1 Introduction and distribution

Lime mudstone is scattered throughout the Northern Head Group, as i) isolated thin beds within shale, ii) component beds interbedded with, or transitional with, calcarenite units and iii) thin-bedded intervals of parted to ribbon limestone. In each of these modes beds range from continuous to nodular.

Units, up to 1m thick, of thin-bedded, generally nodular lime mudstone characteristically occur with shale intervals in the Brakes Cove member.

Where lime mudstone is associated with the Upper Cambrian calcarenite interval described previously, it appears as isolated thin beds (< 5cm) or thin-bedded packets, up to .5m thick, which are scattered in a non-systematic fashion throughout the interval.

Lime mudstone is conspicuous in the uppermost Cambrian part of the section, and in an overlying (Tremadoc) interval associated with black shale. The Cambrian occurrence appears at Seal Cove, Woman Cove and at Halfway Point/Giles Point, and consists of a roughly 25m thick interval, dominated by lime mudstone and contrasting texturally with the underlying calcarenites. Lime mudstone here occurs in beds 1 to 3cm thick, interbedded with cream-weathering, marly calcareous shale, lending a massive appearance to the outcrop.

The Tremadoc interval is dominated overall by black shale (see Shale section, this chapter) but contains varying amounts of thin-bedded to lensoid lime mudstone and is transitional, in part, into ribbon limestone (Plate 4-1b). Mudstone beds are featureless to faintly, thinly laminated.

Within the Middle Arm Point Formation, lime mudstone occurs as a component of other lithologies (e.g. thin-bedded dolostone/mudstone couplets; refer to Dolomite section), but is particularly conspicuous in an isolated interval within the uppermost Middle Arm Point at Eagle Island North. This 3m thick unit is isolated within shale, and consists of lime mudstone, in beds 5 to 15cm thick, with minor shale interbeds. This unit displays a sharp base and is transitional, through a nodular interval, into overlying shale. The entire lime mudstone interval is intensely bioturbated (see Chapter 5).

4.4.2 Composition

Most lime mudstone units are wackestones. They commonly appear to be fine-grained equivalents of many calcarenites, because they contain scattered peloids, angular siliciclastic silt, isolated dolomite rhombs, and minor bioclastic grains. Individual beds containing abundant radiolaria are also present. The lime mudstone component which dominates is recrystallized (microspar) and is of uncertain origin. Sparse laminations within these units are defined by concentrations of clay mineral flakes or siliciclastic silt. These lime mudstone units are not graded, although locally, silt-filled scours are present at the base of individual beds.

4.4.3 Possible origin of lime mudstone units

The origin of lime mudstone units in the Northern Head Group is enigmatic, and is obscured by particle size, by recrystallization, and by the paucity of diagnostic sedimentary structures. This problem has not been addressed in detail in this study, but based upon i) analogy with the calcarenite units with which lime mudstone beds are locally intimately associated including ii) the presence of micritic peloids mentioned above, the source of this lime mud is thought to most likely be the disintegration of shallow-water-derived calcified algae. This suggestion has been advanced based upon more detailed investigation of similar lithologies in the Cow Head Group (Coniglio and James, 1985; Coniglio, 1985; James and Stevens, 1986). Because of the absence of calcareous plankton in the Early Paleozoic, lime mud through this interval, even if diagenetically redistributed, must have its ultimate origin on the carbonate platform.

The depositional mechanism(s) of many lime mud units in the Northern Head group is equivocal. Possibilities include i) dilute turbidity currents, ii) hemipelagic settling or iii) redeposition by contour current. Where mudstones are associated with coarser-grained units (refer to Dolomite, Calcarenite sections) a turbidite-related origin can commonly be demonstrated. In other cases, the absence of any sedimentary structures, apart from scattered parallel laminations, and the association with thinly parallel-laminated shale suggest quiet-water deposition by a process of hemipelagic settling. No evidence of contour current reworking or deposition has been noted.

The importance of diagenetic carbonate precipitation and marginal aggradation in ribbon lime(mud)stone intervals in the Cow Head Group has been stressed by Coniglio (1985). Marginal banding locally within Northern Head group mudstone units suggests the action of similar processes, and this is briefly examined in Chapter 6.

4.5 DOLOMITE

Introduction

Dolomite is present throughout the Northern Head group but is particularly abundant within the Middle Arm Point Formation, where bedded dolostone units are common. Lower in the section, within the Cooks Brook Formation, dolomite occurs as a scattered minor component of several lithologies (calcarenites, conglomerate matrix and shales). The nature of these occurrences is described below, in stratigraphic sequence.

Dolomite occurs within the Northern Head group as i) transported grains, or a replacement of transported grains, and ii) as a cement. This section is focussed on the former, while diagenetic aspects of dolomite are treated in Chapter 6.

4.5.1 Dolomite within the uppermost Irishtown Formation

The characteristic orange-weathering appearance of black to grey shale and siltstone in the uppermost Irishtown Formation is due to the presence of abundant, medium silt-size, euhedral, highly-ferroan dolomite. This is sorted into cross laminations, and is accompanied by abundant quartz, feldspar and mica of similar size.

4.5.2 Dolomite within calcarenites of the Cooks Brook Formation

Dolomite is ubiquitous within calcarenites of the Cooks Brook Formation and locally comprises up to 15% of this lithology. As mentioned in the Calcarenite section, dolomite occurs here as i) scattered individual subhedral ~~to~~ euhedral crystals (30 to 60 micrometers) and ii) "clusters", ranging up to .4mm, of euhedral crystals. The first variety is most commonly ferroan while the second is generally non-ferroan. The "clustered" variety of dolomite has clearly occurred by the progressive replacement of (dominantly micritic) grains and intraclasts, and is noted in various stages of replacement throughout the Northern Head Group. This is illustrated in partial, and complete stages of development in Plate 4-6a) and b) respectively. This replacement is present within both grains in bedded sequences, and in clasts within conglomerate, and is regarded as an early diagenetic product.

4.5.3 <u>Middle Arm Point dolomite</u>

There are three principal types of dolomite in the Middle Arm Point Formation:

1) The dramatic appearance of dolomite in the Northern Head group occurs as the Woman Cove member (base of the Middle Arm Point Formation).

Higher in the section, dolomite occurs within

2) isolated thin beds and lenses, locally associated in "packages" and

3) units comprising thinly interbedded silty dolostone and lime mudstone.

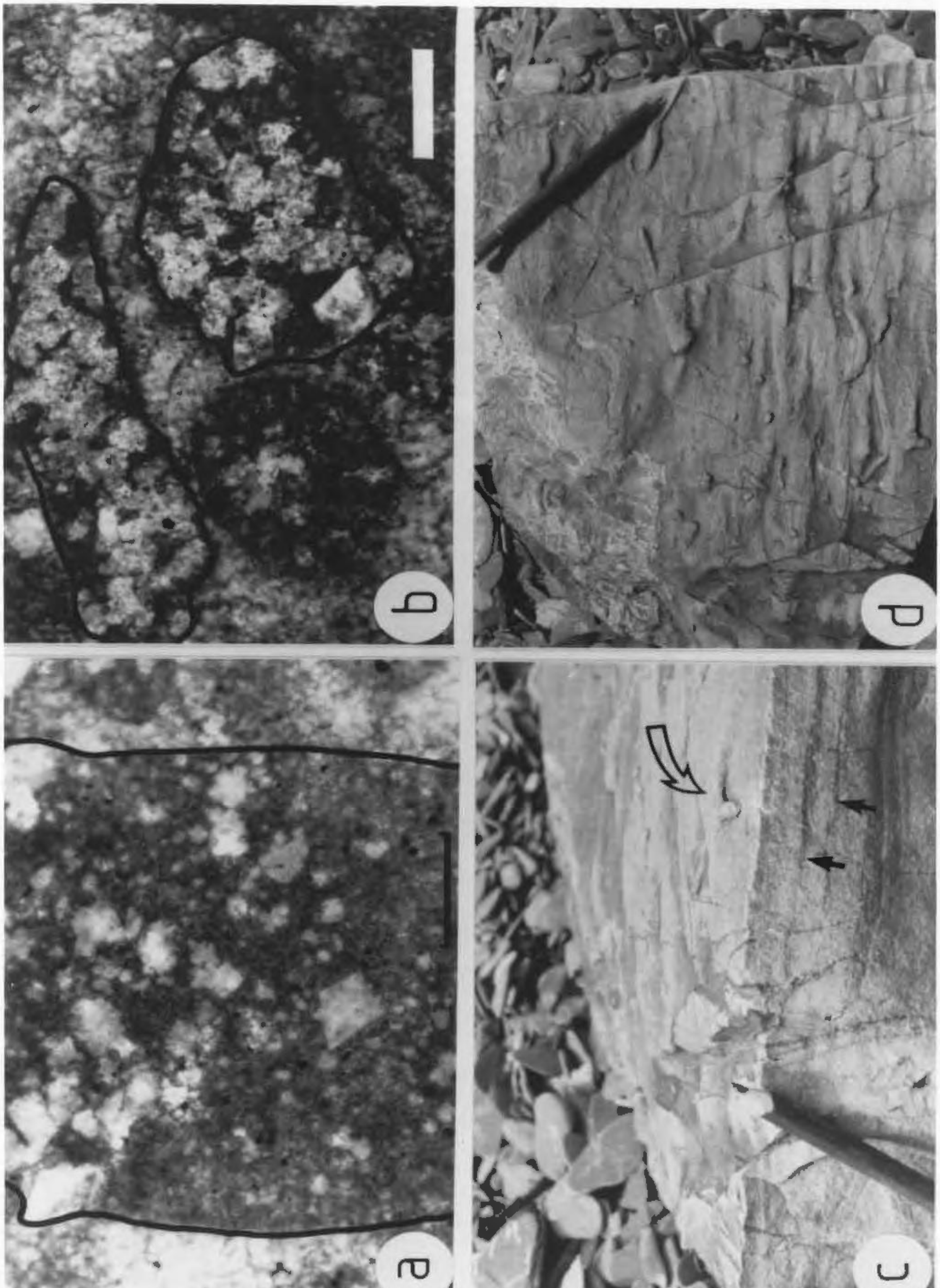
PLATE 4-6: DOLOSTONE LITHOLOGIES

a: Photomicrograph illustrating incipient dolomite replacement of micritic grain (outlined); clast within conglomerate, Brakes Cove member (Cooks Brook Formation); scale bar is .1mm.

b: More advanced replacement of micritic grains (outlined) by dolomite; scale bar is .1mm.

c: (Overturned) portion of silty dolomite bed displaying individual sets of dolostone separated by thin shale laminae (small arrows). Burrows on base (here upper surface) of bed have locally initiated down-current scouring (large arrow).

d: Flute casts and bioturbation on the base of silty dolostone bed (illustrated in previous photo); burrows are crudely aligned parallel with flute casts, and have locally initiated scouring downcurrent.


a
b
c
d

4.5.3.1 Woman Cove Member

The Woman Cove member ranges from 12 to 15m in thickness and is dominated by beds of characteristically buff-weathering silty dolostone.

Dolostone beds are 5 to 10cm thick and interbeds of grey to green shale commonly thicken upward, from 2cm at the base to 5cm near the top of the interval. Shale interbeds are structureless. Individual dolostone beds are generally entirely cross-laminated and ungraded. Beds may contain several centimeter-scale sets of cross laminae, separated by thin shaly laminae (Plate 4-6c). Each successive set may display a slightly different current orientation, different from the adjacent one by up to 45 degrees. Flute casts are present on the base of some beds (Plate 4-6d). Parallel-laminated and massive units occur locally. Thicker beds may display convolute lamination. Bedding surfaces are slightly wavy and irregular, but are laterally continuous over distances of 5 to 10m (Plate 4-7a).

Bioturbation is conspicuous and is generally best developed in the lowermost 5m. Palaeophycus and Cylindrichus trace fossils are abundant (Plate 4-7b), both parallel to, and crosscutting bedding (refer to Chapter 5). On some bedding surfaces elongate scoured areas, similar, and parallel, to nearby shallow flute casts extend "down-current" from the exposed tip of a burrow (Plate 4-6c,d). These clearly illustrate that burrows predated, and affected currents which were transporting and/or depositing silty dolomite.

Dolostone beds in the uppermost several meters of the Woman Cove member (well exposed at Woman Cove proper) and higher in the Middle Arm Point Formation have red-weathering, silicified tops. These

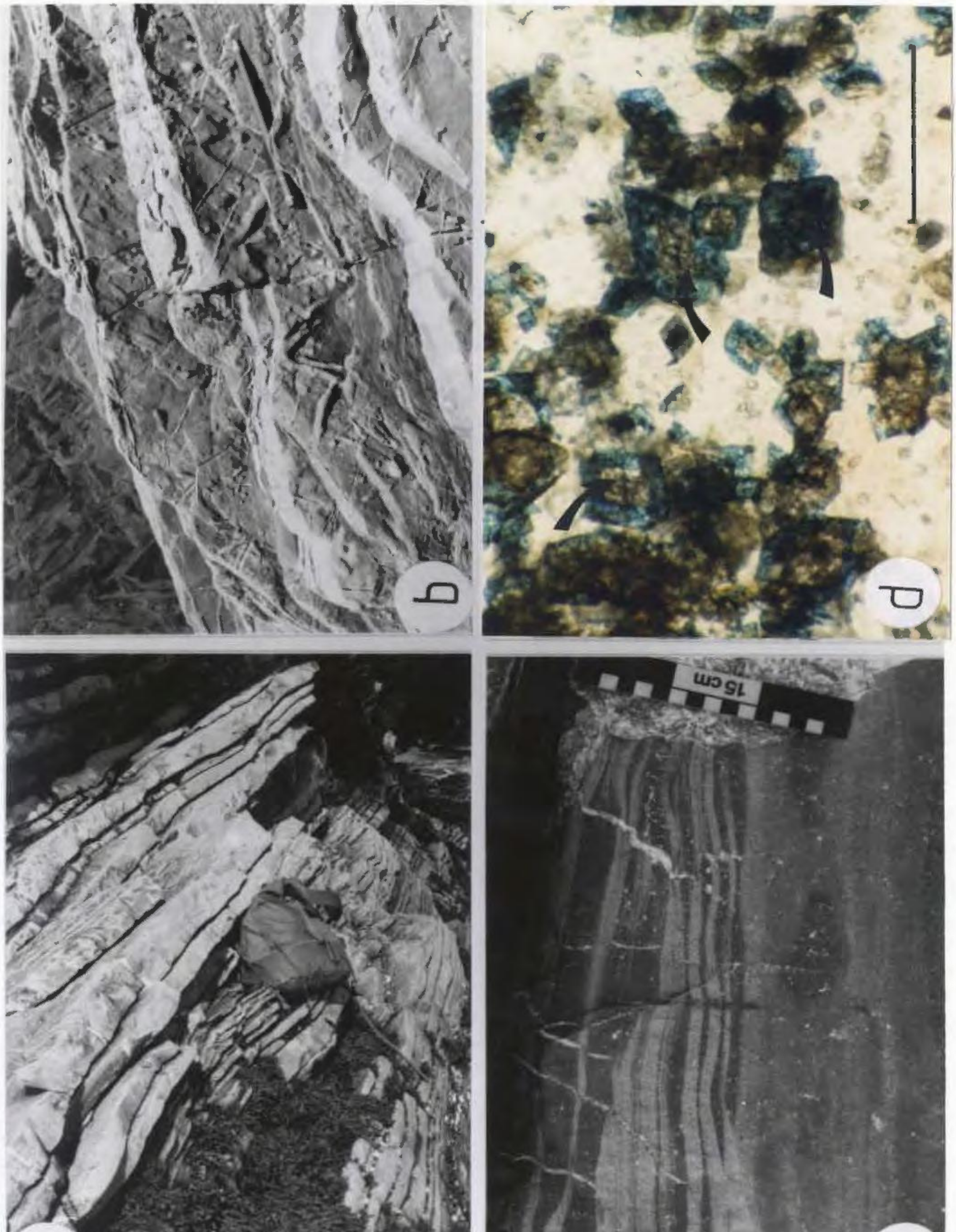
PLATE 4-7: DOLOSTONE LITHOLOGIES (continued)

a: Parted silty dolostone beds at the base of the Woman Cove member; Woman Cove

b: Bioturbation, dominated by Palaeophycus (plus ?Cylindrichnus) on the base of silty dolostone beds; Woman Cove member, Eagle Island

c: Transitional appearance of silty dolostone (light tone) within dark lime mudstone; base of Woman Cove member, North Arm Point

d: Photomicrograph of silty dolostone displaying abraded, detrital cores (arrows) with euhedral, ferroan overgrowth (blue); dolomite surrounded by pervasive silica cement; scale bar is 1mm.


a
b
c
d
15 cm

intervals of silicification range up to 2cm in thickness, highlight current laminations, and are thought to reflect a process of early cementation (refer to Chert, this chapter, and Chapter 6).

The base of the Woman Cove member is transitional at Woman Cove and North Arm Point. Here thin beds (1cm thick) of dolomite silt to sand are interbedded with dark lime mudstone over an interval of approximately 1m (Plate 4-7c). Dolomite beds are cross-laminated, irregular or lensoid and display a sharp, locally-scoured base and a gradational contact with the overlying lime mudstone.

Dolostones of the Woman Cove member are a densely-packed mosaic of dolomite rhombs, commonly containing scattered angular silt grains of quartz and feldspar. A very fine crystalline silica cement is present and varies from patchy to pervasive. Individual dolomite rhombs range in size from medium silt to fine sand. Many display inclusion-rich cores which are commonly abraded and overgrown by euhedral, commonly Fe-rich rims (Plate 4-7d). The irregular truncation of internal zoning, visible under cathodoluminesence, can locally be seen at the margin of this core. The variable composition of this dolomite, and other diagenetic features, are treated in Chapter 6.

4.5.3.2 Upper Middle Arm Point dolomites

Higher in the Middle Arm Point section dolomite occurs as:
1) thin beds or lenses, commonly isolated, within red or green shale-dominated sequences. Locally, in the uppermost part of the Middle Arm Point, these thin beds occur as 25 to 40cm thick packages, within green shale.

2) a component of alternating dolostone/lime mudstone couplets, bedded on a centimeter scale in 1m thick packages isolated within shale-dominated intervals.

In the first case, dolostone units are commonly current-rippled and locally display a scoured base filled with coarse grainstone. Most samples are a mixture of euhedral (overgrown) to anhedral, commonly abraded dolomite grains, with 5 to 10% quartz and feldspar grains scattered throughout. Modal grain size varies from coarse silt to fine sand. Grains are commonly segregated into well-sorted laminae, which range in thickness from .1 to several millimeter and alternate with, or occur within, a muddy matrix. Thicker, grainy laminations display a sharp and locally scoured base.

Individual beds within the packages of thin-bedded dolostone in the upper part of the Middle Arm Point range up to 5cm in thickness, and are cross-laminated throughout. Individual bed tops are highlighted by reddish-weathering silicification similar to that described in the Woman Cove member.

Distinctive grains of intergrown chert and ferroan dolomite occur within dolostone units in the upper part of the Middle Arm Point (Plate 4-8a). These are identical to those in carbonate granule conglomerates slightly higher in the Middle Arm Point and lowermost Eagle Island Sandstone (refer to Conglomerate section). These distinctive grains are confined to this (Arenig) part of the Northern Head Group. Their origin is discussed at the end of this section.

Several red shale intervals contain dolostone units which display a pervasive, very fine intercrystalline hematitic stain which coats grains and locally fills pores. This appears to have been excluded from clay matrix-rich domains. Hematite surrounds overgrown dolomite grains and evidence from silicified dolostones suggests that this coating was contemporaneous with silica cementation and occurred in situ.

4.5.3.3 Dolostone/lime mudstone couplets

This lithology is characteristic of the uppermost part of the Middle Arm Point Formation, where it occurs in green shale-dominated sequences. Silty dolostone and lime mudstone commonly alternate as centimeter-scale beds which comprise carbonate-dominated packages up to 1m thick (Plate 4-8b). Dolostone units are locally current rippled, discontinuous and lensoid.

Petrographic and field evidence suggests that the thin-bedded alternation of limestone and dolostone is, at least in part, depositional in origin. Dolostone intervals have sharp, locally scoured bases and normal grading up to a transitional contact with the micrite. Angular quartz and feldspar silt grains are distributed throughout the dolomite horizons but appear only rarely within micrite bedlets.

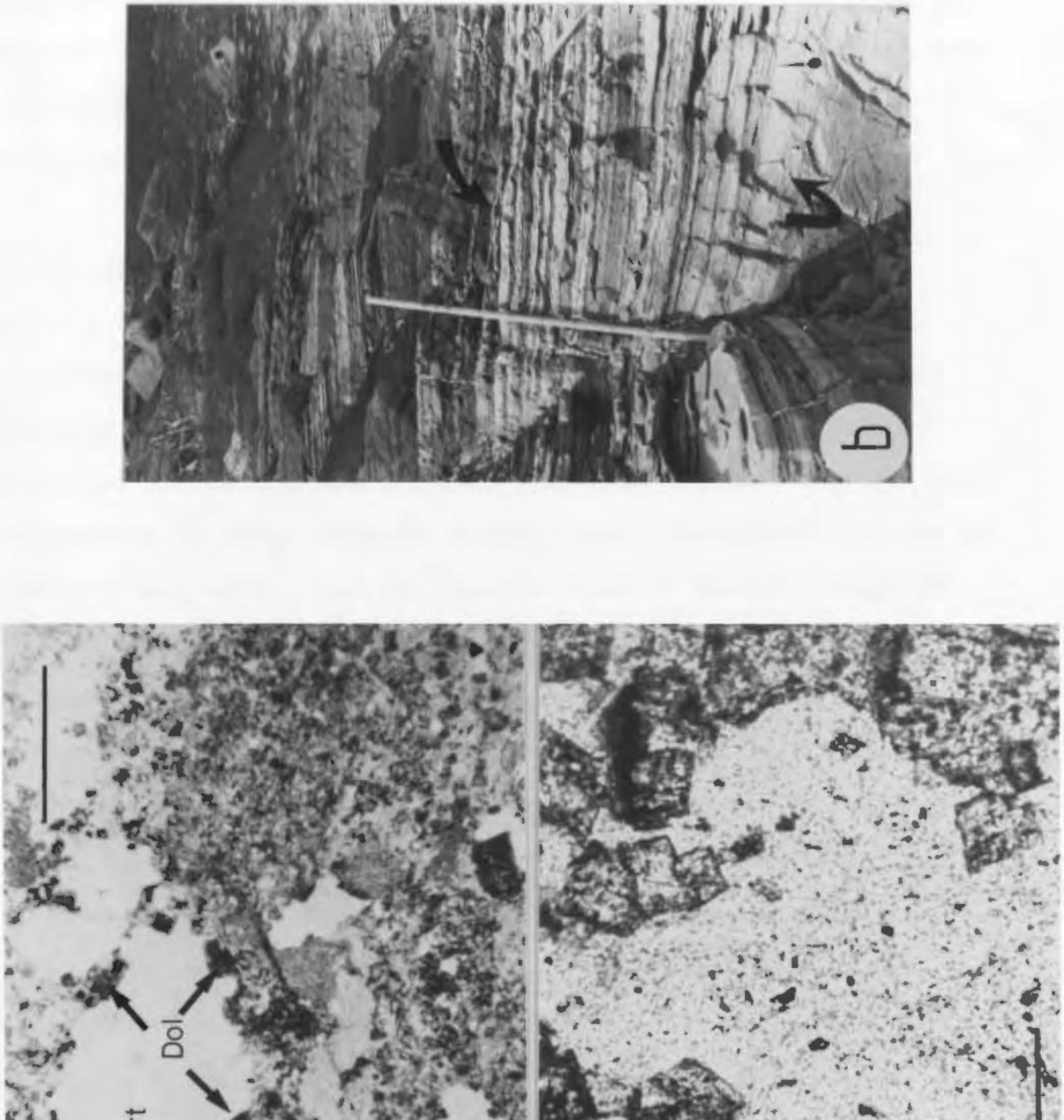
Individual dolomite rhombs range up to coarse silt and commonly display an abraded, irregular core, commonly overgrown by a ferroan rim. Smaller rhombs are generally totally ferroan and tend to be anhedral. One sample of a dolostone/lime mudstone couplet contains dolomite rhombs, as described, within the dolostone bedlet and contains rounded, abraded, non-ferroan dolomite grains entombed

PLATE 4-8: DOLOSTONE LITHOLOGIES (continued)

a: Photomicrograph illustrating a distinctive chert/dolomite grain typical of those noted within silty dolostones and granule conglomerates of the uppermost Middle Arm Point Formation, and thought to be derived from the coeval, platformal Aguathuna (compare with 4-8c below); scale bar is 1mm.

b: Carbonate "package" within shale-dominated interval (arrows indicate base and top), consisting of thinly interbedded silty dolostone and lime mudstone (darker tone); pole is 1m in length.

c: Photomicrograph of finely intergrown microcrystalline chert/dolomite from the platformal Aguathuna Formation, Daniels Harbour area; note the similarity of this lithology with chert/dolomite grains described from the Middle Arm Point Formation (4-8a above); scale bar is .1mm.


b
a
Chert
Dol
c

within the lime mudstone bedlet, which are not overgrown. This suggests 1) that the micrite was present early in the diagenetic history, probably deposited as a bedlet of lime mud, before 2) the ferroan overgrowth of detrital dolomite grains and that 3) the lime mud encompassed similar detrital dolomite grains which were effectively sealed off from this phase of diagenesis.

4.5.4 Dolomite: Discussion and Interpretation

4.5.4.1 Origin of the dolomite

Abraded, inclusion-rich cores, with irregular boundaries and euhedral (commonly Fe and Mn-rich) overgrowths, are the norm in dolomites of the Middle Arm Point. This abraded core, and the common association of these dolomite crystals with siliciclastic grains of similar size, within gravity-deposited beds or laminae, suggests that these dolomites have been redeposited, and are detrital. This origin may encompass both eroded grains of previously lithified dolostone, and dolomite transported directly from its penecontemporaneous site of shallow-water formation (cf. Sabins, 1962). Similar examples of detrital dolomite have been described and illustrated in the literature (Sabins, 1962; Amsbury, 1962; Scholle, 1971; Young and Doig, 1986) and direct analogues have been described from the Cow Head Group by Coniglio (1985). The ferroan rim displayed by these crystals is not abraded, and represents the in situ growth of dolomite under diagenetic conditions discussed in Chapter 6.

The lack of internal structure within the core has been taken as indicative of a synsedimentary as opposed to a lithified source for detrital dolomite of this kind (Sabins, 1962). A structureless, cloudy and inclusion-rich core is the norm in dolomites of the Middle Arm Point; however, the small modal particle size of most of these precludes any strong inference as to original source.

Although discussion of the relationship of features of the Northern Head group with events recorded on the coeval shallow-water carbonate platform is largely reserved for the final chapter, a clear potential source for the dolomite of the Middle Arm Point Formation is the contemporaneous Aguathuna Formation. This peritidally-deposited unit contains abundant buff-weathering dolostone and localized evaporitic units (Levesque, 1977; Pratt, 1979; Knight and James, in press). In thin section, portions of these evaporitic units are very similar to, and appear to be the likely source of, the distinctive chert/ferroan dolomite grains described above (Plate 4-8c). This suggests that at least some of the input into the dolostone units of the Middle Arm Point Formation was derived from a coeval, shallow water source area.

The replacement of calcitic intraclasts and peloids by dolomite has been documented and discussed above, and volumetrically appears to be the most important in the Cambrian part of the section. The dolomite rhombs produced during this process are generally non-ferroan, which suggests that they formed away from (prior to) the <u>in situ</u> diagenetic growth of ferroan dolomite. The in-transport disaggregation of the loosely cemented clusters produced by this replacement may have been one source of the many isolated dolomite rhombs common in the same part of the section.

4.5.4.2 Postulated depositional mechanisms of silty dolostone beds

The features of the Woman Cove member silty dolostone beds outlined above suggest that these units do not fall within the spectrum of classical turbidites (summarized in Walker, 1984; Pickering et al., 1986). The combined features of irregular bedding contacts, extensive cross-lamination and widespread bioturbation predating or coeval with current activity suggest that if these beds were originally turbidites, they have been extensively reworked by later current activity. In fact, these features, combined with the silt to fine sand size and good sorting displayed by these units, are compatible with the characteristics of sandy contourites as outlined by Stow and Lovell (1979) and summarized by Pickering et al. (1986). The same is true for the packages of thin-bedded silty dolomite described from the uppermost part of the Middle Arm Point Formation.

On the other hand, the scoured, channelized base and grading commonly displayed by the isolated dolostone beds described above are consistent with deposition by turbidity currents.

The field and petrographic evidence presented above suggests emplacement of the dolostone/lime mudstone couplets described above as turbidites. The scoured base of dolostone beds and the transition upward into lime mudstone suggest that each couplet was deposited as one unit. Each of the principal components of this lithology, the dolomite, the siliciclastic silt, and the lime mud are most likely shelf-derived. Thus it appears that each couplet represents an original mixture of shallow-water components which has been differentiated during turbidity current transport and deposition.

In summary, input of detrital dolomite was continuous throughout the deposition of the Northern Head group. Replacement of calcitic intraclasts was a volumetrically more important source of this dolomite in the Cooks Brook Formation while abraded-core, ferroan-rimmed dolomite is representative of the Middle Arm Point. This change in population is roughly coeval with the appearance of buff-weathering dolomite on the carbonate platform upslope (Aguathuna Formation). Within the Middle Arm Point, the input of other allodapic carbonate constituents was greatly diminished, and current re-worked, bedded dolostone units are a conspicuous component.

4.6 CONGLOMERATE

Introduction

The relative abundance, sedimentologic style, and composition of carbonate conglomerates changes stratigraphically through the Northern Head group. In general, conglomerates decrease in abundance and thickness upward. The stratigraphically highest thick, polymict conglomerate occurs in the basal Ordovician and overlying conglomerates are generally thin and commonly locally-derived. Beds of conglomerate dominate some intervals within the Cambrian part of the Cooks Brook Formation. Two such intervals, the Halfway Point member and the Brakes Cove member, are considered to be sufficiently distinctive and correlatable to be of stratigraphic use.

4.6.1 Conglomerates of the Halfway Point member

In the type section, the Halfway Point member is roughly 120m thick and dominated by conglomerate (Chapter 3; fig 3-4). Eleven major, individual conglomerate units, of variable style and thickness, constitute this interval. The conglomerates can be broadly characterized as i) well-bedded, or ii) chaotic. At the base of the Halfway Point member are several beds of platy conglomerate 1 to 2m in thickness. These are overlain by a roughly 50m thick, chaotic, matrix-rich boulder conglomerate. The upper part of the member is composed of several conglomerate beds, 2 to 10m thick, of variable style and matrix content. Interbeds of parted lime grainstone and nodular to ribbon limestone separate conglomerates throughout.

"Well-bedded" conglomerate units range in thickness from 1.5 to 4m and generally display sharp, planar lower and upper bedding contacts. Sorting is usually moderate to poor and grading is not evident. The amount and type of matrix is highly variable, even between adjacent conglomerates. In some units matrix is sparse (roughly 5%) while in others it is abundant (roughly 20%). In general there is an upward increase in matrix through individual beds. This is particularly evident where the matrix contains abundant silty dolomite and is transitional upward into a silty dolomitic cap, up to 5cm thick, which overlies several of these units. Conglomerate matrix is generally composed of grey to green mudstone, with a variable silty dolomite component, which in some beds comprises most of the matrix.

Clasts range in size from pebbles to boulders. Clast shape is variable, and dependent upon lithology. Algal boundstone and oolitic boulders are generally rounded, while most lime mudstone and some lime grainstone boulders are tabular, reflecting the original thin-bedded nature of these lithologies. Fabric is generally poorly-defined within these units; even beds or portions of beds dominated by platy clasts display only a weak planar fabric parallel to bedding and imbrication is extremely rare.

Clast composition: The two principal clast types are lime mudstone (30 to 45%) and lime grainstone, commonly rippled (25 to 45%). Clasts composed of granule to pebble conglomerate are also locally abundant, comprising up to 20% of individual beds. The distinctive components of Halfway Point member conglomerates are clasts of: 1) oolitic limestone (5 to 15%), 2) white-weathering algal boundstone (tr. to 5%) and 3) quartzose sandstone. These lithologies are most abundant in the lower two thirds of the Halfway Point member and absent in the uppermost beds.

Oolites are predominantly oosparite. Ooids range from 0.4 to 2mm in diameter and are generally not flattened. Cores are commonly replaced by blocky, equant spar. The algal boundstone has a clotted texture, with structures suggestive of Epiphyton in less recrystallized areas, and contains irregular domains of micrite or microspar. The sandstone is a quartz arenite, and is identical to that of the underlying Irishtown Formation.

"Chaotic" conglomerate dominates the medial portion of the Halfway Point member and is distinctive in 4 ways: 1) there is a very high proportion of dark shale matrix, 2) internal structure is commonly chaotic on a hand specimen to outcrop scale, 3) the lithology includes large (3x10m) chaotically folded rafts of bedded sediment (Plate 4-9a), and 4) the proportion of "exotic" lithologies described above is greater than in nearby "well-bedded" conglomerates.

The matrix of this conglomerate is black to dark grey, slightly calcareous mudstone (dominated by semi-opaque clay particles), which commonly constitutes 40% of the rock. It locally contains abundant (up to 25%) angular siliciclastic grains (predominantly quartz), ranging from medium silt to fine sand, plus mica (up to 10%). A "swirling" fabric, suggestive of matrix flow is common. Where the matrix is abundant, clasts "float" within, and are locally injected by (Plate 4-9b), a cleaved dark shale and the rock has the

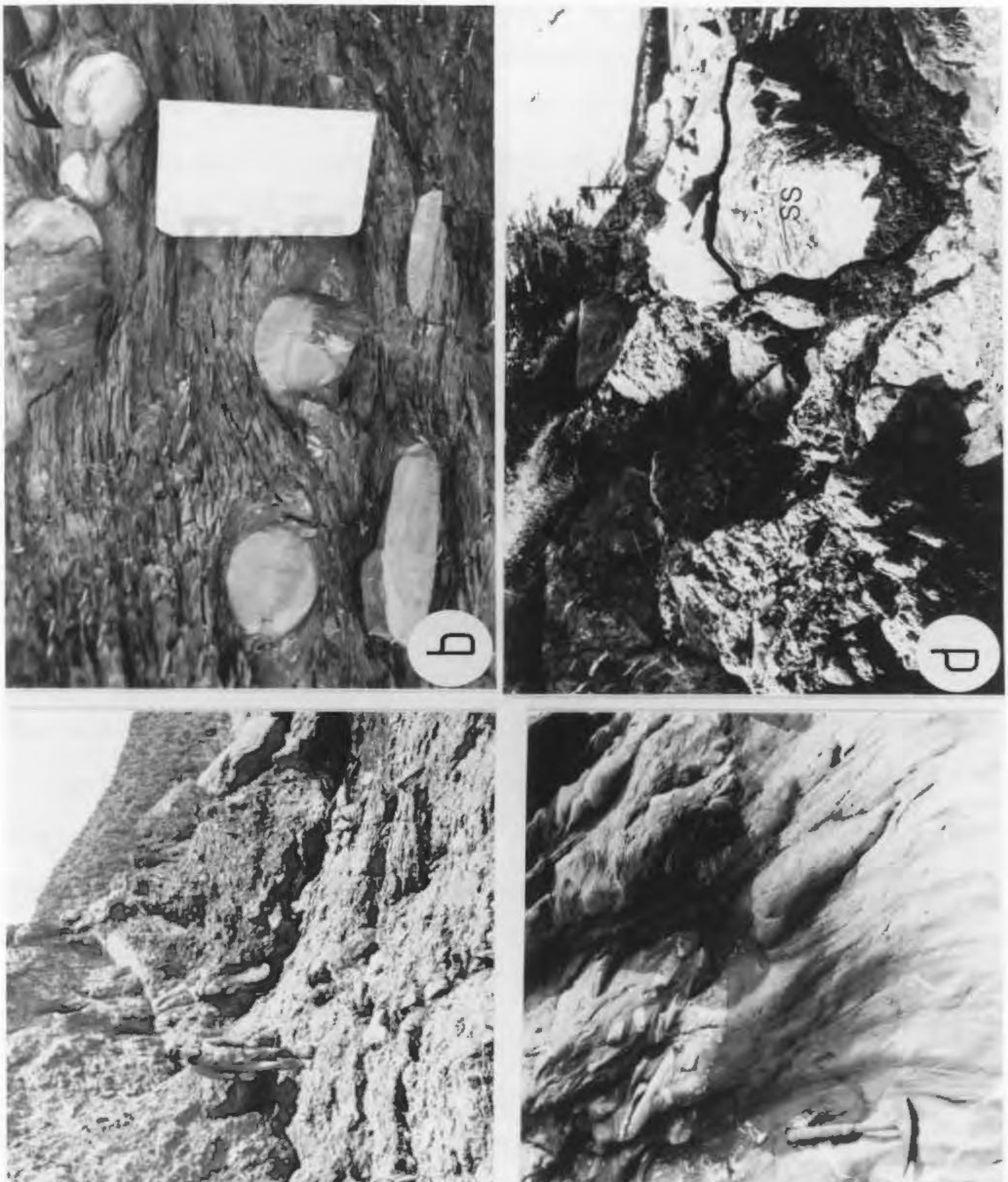
PLATE 4-9: CONGLOMERATE LITHOLOGIES: HALFWAY POINT MEMBER

a: "Chaotic" conglomerate, Halfway Point member; note folded raft of thin-bedded limestone (left).

b: Limestone clasts floating within a cleaved shale matrix, "chaotic" conglomerate, Halfway Point member; note "pull-apart" style of clasts and matrix injection (arrow, uppermost right).

c: Base of individual "chaotic" conglomerate overlying shale-dominated interval; vertical planar fabric (roughly parallel to hammer) is cleavage related to regional folding.

d: Large boulder of quartzose sandstone (ss, outlined) within Halfway Point member conglomerate; sandstone is interpreted to have been derived from underlying Irishtown Formation; hammer at top for scale.


a
b
c
d
ss

appearance of a typical tectonically-formed melange. Pull-apart structures ranging from ductile boudinage to brittle extension fracture are evident in clast shape here (Plate 4-9b).

Clasts in most of this conglomerate are rounded and no fabric is apparent. Within some domains, however, the alignment of platy clasts parallel to a pervasive phacoidal cleavage in the matrix has resulted in a pronounced planar fabric. This fabric is axial planar to the mesoscopic and macroscopic upright folds of the Cooks Brook syncline (Chapter 2). Locally matrix cleavage can be seen to "overprint" a chaotic disposition of clasts, or crosscut crude bedding features within matrix-rich conglomerate (Plate 4-9c) and the planar fabric described is thought to be related to the deformation which formed the Cooks Brook syncline.

Rafts of bedded sediment are generally thin-bedded to nodular lime mudstone which range in size up to 3 x 10m. Numerous boulders of algal boundstone and oolitic limestone, as well as boulders, ranging in size up to roughly .75 x 1m, of buff-weathering quartzose sandstone (Plate 4-9d) are also present within the chaotic conglomerate.

4.6.2 Conglomerates of the Brakes Cove Member

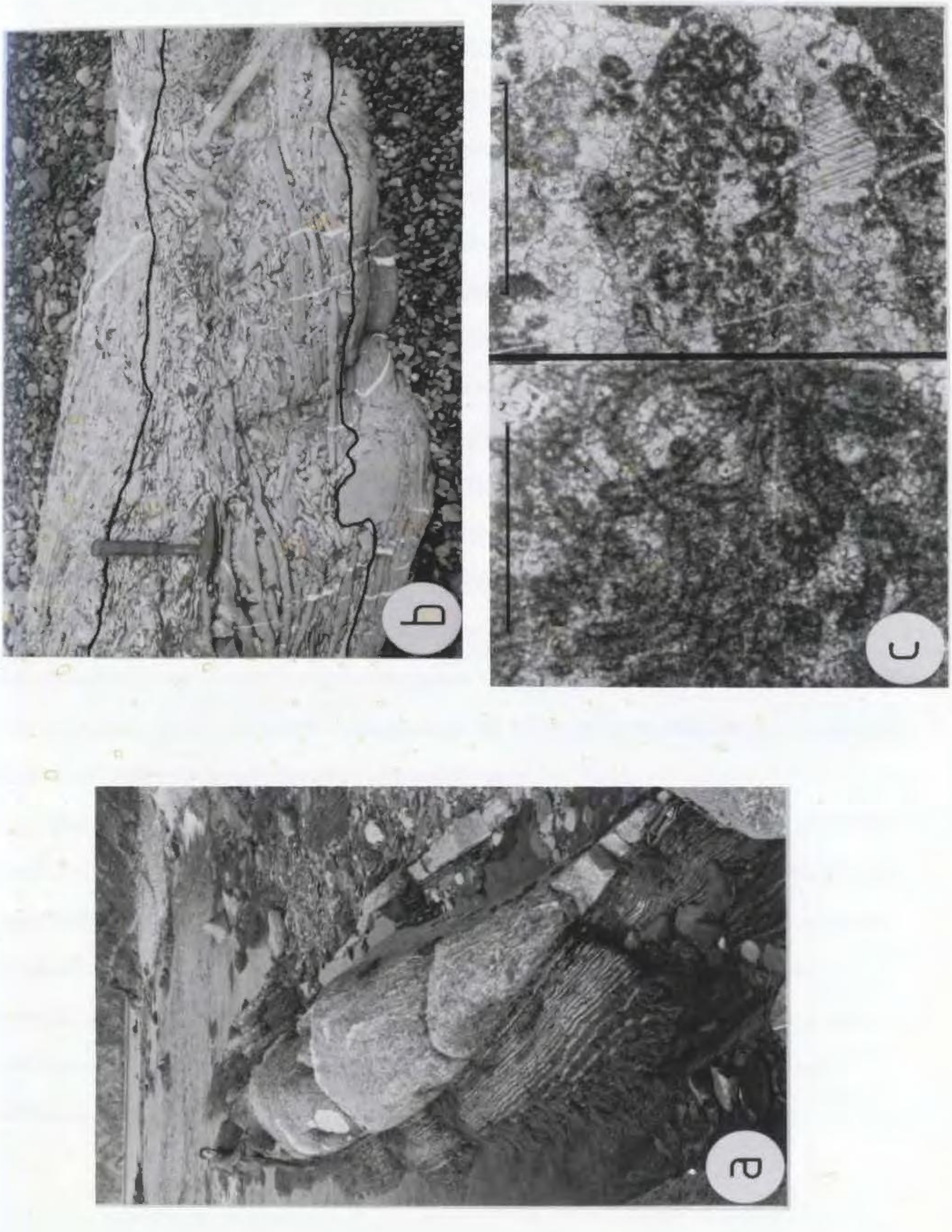
Like the Halfway Point member, the Brakes Cove member overlies the transitional base of the Cooks Brook Formation. In areas where the Brakes Cove member is exposed, however (Chapter 3), underlying and associated beds are thin-bedded and shale-dominated. At the transitional base of the member conglomerate beds are thin, 20 to 30cm in thickness, distinctly lensoid and surrounded by shale.

PLATE 4-10: CONGLOMERATE LITHOLOGIES: BRAKES COVE MBR., GRANULE CONGLOMERATE (Middle Arm Pt. Fm.)

a: Lensoid conglomerate bed within Brakes Cove member; Northern Head; top to right

b: Individual conglomerate bed within Brakes Cove member displaying 3 "subunits": i) basal matrix-poor interval, ii) intermediate matrix-rich interval, and iii) upper matrix-poor interval; Northern Head section.

c: Photomicrograph(s) of Girvanella algal structure within a rounded grain contained within granule conglomerate of the uppermost Middle Arm Point Formation; left portion of photograph is detail of right. Scale bar on right is 1mm, on left is .2mm.


b
c
a

Compositionally they are dominated by pebbles of lime mudstone. Above this interval conglomerate beds range from .5 to 2m in thickness are distinctly lensoid (Plate 4-10a). These units are composed of lime mudstone and lime grainstone pebbles to cobbles. "Exotic" lithologies are a very minor component; both white-weathering algal boundstone and sandstone are absent and oolitic limestone is rare. Conglomerate composition and fabric is variable, both between adjacent beds and within beds. Tabular clasts, which dominate some units, are generally composed of lime mudstone and fine lime grainstone. Coarser lime grainstone cobbles are generally the best rounded and it is these which yield most of the trilobites in the Brakes Cove member (Chapter 3). Individual beds comprise up to three subunits which display a slightly different clast composition and proportion of matrix (Plate 4-10b). The boundaries of these subunits are irregular and it is not clear whether the bed, as a whole, is a "welded" composite of discrete deposits or a single unit, differentiated during deposition.

The matrix of these conglomerates is grey to green mudstone with variable proportions of silty dolomite. The percentage of matrix is generally low, ranging from 5 to 15%. Several conglomerate beds are capped by thin (1 to 3cm) intervals of rippled lime grainstone. Conglomerates of the Brakes Cove member are interbedded with green shale, thin beds of lime grainstone, nodular lime mudstone and ribbon limestone.

4.6.3 Upper Cambrian conglomerates

The Brakes Cove member is overlain by a thick interval of calcarenite, described in a preceding section. This sequence contains numerous thin, localized conglomerates throughout, intimately associated with calcarenite beds and previously discussed in the Calcarenite section. At Seal Cove a conglomeratic interval similar to the Brakes Cove member occurs within the overlying shale-dominated sequence. Conglomerates here differ from the Brakes Cove member conglomerates only in that they are finer-grained (composed predominantly of pebbles) and thinner (less than .75m).

4.6.4 Basal Ordovician conglomerate

This is an isolated, 2m thick conglomerate which occurs within a sequence of parted to ribbon lime grainstone at Northern Head. The bed displays sharp, planar lower and upper contacts. Clast size ranges from pebble to boulder and grading is not evident. Composition is different from conglomerates of the Brakes Cove member in the increased percentage of oolitic clasts (roughly 15%) and in the appearance of quartz-bearing lime grainstone clasts (15%+); this lithology appears in thin to medium beds immediately below this conglomerate.

4.6.5 Middle Arm Point Formation

Two types of conglomerate are present within the Middle Arm Point Formation: 1) pebble to cobble conglomerate, with abundant locally-derived clasts, in the lower part of the formation, 2) thin-bedded granule conglomerate in the uppermost part of the formation.

4.6.5.1 Lower conglomerates

The first conglomerate immediately overlies the Woman Cove member at North Arm Point. It is a 1.5m thick unit composed of pebbles to cobbles of silty dolostone (30%) and green shale (30%), both commonly soft-sediment deformed, plus lime mudstone (15%) and lime grainstone (10 to 15%) in a matrix of green shale. The clasts of silty dolostone and green shale, and the matrix, are derived directly from the underlying Woman Cove member. The unit has an irregular lower bedding contact and planar upper contact and is of equal thickness over the outcrop area. This unit is correlated with a similar conglomerate exposed on Eagle Island which is very similar in composition, and contains abundant green shale clasts. The Eagle Island conglomerate bed, however, is separated from the Woman Cove member by a roughly 15m thick interval of green and black shale.

A distinctive conglomerate, with some similar characteristics, occurs in deformed strata between Northern Head and Overfall Brook. The stratigraphic position of this unit is uncertain, but it occurs within lithologies mapped as deformed lower Middle Arm Point Formation. This conglomerate is on average .5m thick and of irregular thickness over the 10m of exposure. It is characterized by 1) an abundant green shale matrix (approx. 30%), 2) the predominance of very well rounded pebbles with scattered angular boulders and 3) the presence of elongate, soft sediment-deformed green shale blocks up to .2 x 1m in size. Pebbles are predominantly green shale and lime mudstone. The boulders are coarse sand to granule conglomerates composed of very well rounded algal grainstone. Nuia and Epiphyton are common.

Another conglomerate, with some similar characteristics, occurs within a shale-dominated interval, stratigraphically higher in the Middle Arm Point Formation, at Black Point (Port au Port Bay). This unit is roughly 1m thick and is characterized by an abundant green shale matrix (approx. 40%), containing very well rounded pebbles, composed predominantly of black, phosphatized lime mudstone and chert. The bed demonstrates irregular, gradational boundaries with the surrounding green shale.

Approximately 8m stratigraphically lower in this section is a different conglomerate which is distinctive in composition. It is a 30 to 40cm thick pebble conglomerate with an irregular base and planar top, capped by a lime grainstone several centimerers thick. The matrix is composed of lime grainstone and is relatively sparse, comprising roughly 10% of the conglomerate. The pebbles are composed of lime mudstone (30%), lime grainstone (25%), black, phosphatized lime mudstone (20%), chert (predominantly green; 20%) and uniquely igneous (gneissic?) lithology (<5%). Many micritic clasts display "structure grumuleuse" and where these are only slightly recrystallized Girvanella can be resolved. In a few calcium phosphate clasts a relic structure strongly suggestive of Girvanella tubules, within an overall faintly clotted fabric, can be seen. This suggests that these clasts formed by the phosphatization of algal boundstone.

4.6.6 Granule conglomerates of the Middle Arm Point Formation

Thin beds of carbonate granule conglomerate are a volumetrically small but conspicuous component of the upper part of the Middle Arm Point Formation and lowermost part ("slump and injection" interval) of the Eagle Island Sandstone. These beds commonly occur as isolated units within shale-dominated intervals. They are generally 3 ro 10cm thick, lensoid, and commonly have an irregular, channelized base and planar top. Most beds display normal grading. These units are locally overlain, in welded contact, by 1 to 2cm units of rippled silty dolostone. Abundant granules of black phosphate (ranging up to 15%) are abundant.

Most granules are very well rounded but some display an irregularly scalloped profile which appears to be the result of very late dissolution associated with stylolitization. The components of these granule conglomerates commonly include the following, in order of relative abundance:

1) Algal-dominated grains which range from biosparite to biomicrosparite to biomicrite. Girvanella is the most common algal component and can be clearly observed, commonly surrounded by micrite, in grains which have been little recrystallized (Plate 4-10c). A similar characteristic fabric implies the presence of Girvanella in more highly recrystallized grains. Similar examples of Epiphyton are less common and Nuia occurs as an accessory component in some samples.

2) Bioclastic debris is dominated by rounded pelmatozoan grains. Trilobite and brachiopod fragments are a common accessory component and constitute up to 15% of some samples.

3) Phosphate grains are semi-opaque and brown to green in plane light. Microanalysis indicates that these are carbonate hydroxyapatite (collophane) (cf. Nriagu and Moore,1984). They occur as both well-rounded and irregular grains which have been ductiley deformed and squeezed around other grains. The latter grains, in particular, commonly display included, euhedral crystals of non-ferroan dolomite, up to 30 micrometers, scattered throughout.

4) Micrite grains with siliciclastic silt are generally well-rounded and composed of featureless micrite with rounded to angular silt grains of quartz and feldspar dispersed throughout.

5) Siliciclastic components range in size from angular silt, distributed throughout the matrix, to well-rounded coarse sand. Quartz, and lesser amounts of feldspar, are the two principal components.

6) Chert and intergrown dolomite grains are an important accessory component of many granule conglomerates. These grains are generally very well-rounded and constitute up to 5% of some samples. They are the same distincive grains which occur within dolostone units at roughly the same stratigraphic interval. They have been described and illustrated in the Dolomite section, where their interpreted significance is discussed.

The matrix of these granule conglomerates constitutes 25 to 40% of individual samples. It is generally composed of green, chlorite-rich mudstone and commonly contains abundant silt-size dolomite, quartz and feldspar. It is clear in one sample, with particularly abundant matrix that this has baen derived from the compaction and melding of numerous soft grains of mudstone, initially 2 x .5 mm in size.

Dolomite within the matrix of these conglomerates generally displays the abraded core and ferroan overgrowth typical of Middle Arm Point dolomite (refer to Dolomite section).

4.6.7 Interpreted depositional mechanisms of conglomerates

Conglomerates of the Northern Head group clearly represent gravity deposits and broadly demonstrate many of the characteristics of debris flows. Variability in sedimentary style and composition suggests differences in source area, depositional mechanisms and depositional setting.

Five principal types of conglomerate have been recognized in the Northern Head group:

1) Chaotic, matrix-rich conglomerate of the Halfway Point member

Characteristics:

i) abundant matrix which is very similar to shale of the underlying uppermost Irishtown Formation

ii) abundant "exotic" clasts, in particular blocks of the underlying Irishtown sandstone

iii) large folded rafts of bedded sediment

iv) chaotic fabric.

Interpretation:

The characteristics of this conglomerate broadly fit the definition of a debris flow i.e. the deposit of a sediment gravity flow in which clasts have been supported by the finite yield strength of the matrix, grain interaction, pore fluid pressure and buoyancy (Middleton and Hampton, 1973; 1976; Schultz, 1984). The chaotic fabric and presence of folded rafts of bedded sediment suggest that processes of slumping were operative in the deposition of this conglomerate. The presence of Irishtown sandstone within the lower part of this deposit suggests basal erosion, which may also have been responsible for the incorporation of large amounts of Irishtown shale as a matrix. The other "exotic" clasts in this conglomerate are thought to be derived from the shallow water platform margin (James and Stevens, 1986). This unit displays many of the characteristics of the "chaotic slump deposits" (Facies F) described from siliciclastic submarine fan deposits by Mutti and Ricci Lucchi (1978).

2a) Thick, planar-bedded, non-graded conglomerates

Distribution:

These occur in the lower and upper portion of the Halfway Point member, in the lowermost Ordovician.

Characteristics:

i) sharp, planar upper and lower bedding contacts

ii) broadly lensoid over distances of roughly 10m

iii) not graded

iv) variable amounts and type of matrix

v) variable clast composition (tabular vs. rounded).

Interpretation:

The characteristics of this conglomerate type closely fit the "classic" debris flow deposit (Middleton and Hampton, 1973; 1976) which has been been studied in more detail, and more finely subdivided, in the Cow Head Group (Hubert et al., 1977; Hiscott and James, 1985; Coniglio, 1985; James and Stevens, 1986). This conglomerate type has been subdivided by James and Stevens (1986) based upon variations in clast type and bedding style, but such detail is not considered warranted in this study. The generally thick and planar-bedded nature of these conglomerates is suggestive of a more sheet-like geometry compared with 2b) below.

2b) Lensoid, pebble-dominated, non-graded conglomerates

Distribution:

These units appear most prominently in the Brakes Cove member and the overlying conglomeratic interval at Seal Cove.

Characteristics:

i) generally thinner than 2a) above

ii) dominated by pebble-sized clasts

iii) distinctly lensoid geometry.

Interpretation:

These units may be gradational with 2a), but their character is suggestive of a more localized and intermittent style of deposition. They are similar to the "limestone chip conglomerate" of Hiscott and James (1985), which were interpreted to represent "fingers" of debris related to a single flow.

3) Conglomerates of the Upper Cambrian lime grainstone interval (see discussion in Calcarenite section, this chapter)

Characteristics:

i) generally thin (10 to 30cm)

ii) highly lensoid, with irregular, channelized base downcut into underlying grainstone and commonly flat top

iii) low clast diversity; dominated by tabular pebbles to cobbles of surrounding lithology

iv) generally matrix-poor.

Interpretation:

This style of conglomerate is interpreted as locally-derived, channelized debris flow deposition associated with minor progradational events in a turbidite-dominated interval.

4) Shale-rich conglomerate (lower Middle Arm Point)

Characteristics:

i) abundant clasts of shale, and shale matrix

ii) abundant silty dolomite clasts (locally-derived)

iii) broadly channelized base

iv) not graded.

Interpretation:

This conglomerate type displays many of the characteristics of a debris flow deposit, but is unique in that it has clearly eroded and incorporated underlying lithologies and contains a markedly diminished percentage of other lithologies derived from upslope. It is regarded as the product of a more localized style of debris flow deposition.

5) Granule conglomerates of the upper Middle Arm Point

Characteristics:

i) isolated within shale-dominated intervals

ii) very thin-bedded (3 to 10cm)

iii) highly lensoid; channelized, irregular base and flat top

iv) commonly display normal grading

v) locally display rippled siltstone caps

vi) component grains well-rounded

vii) abundant algal grains; phosphate.

Interpretation:

The grading and scoured base commonly displayed by this conglomerate type are not consistent with deposition by simple debris flow, such as the conglomerates described above. These units may conceivably represent "distal debris flows", as described by Shanmugan and Benedict (1978) but are thought to most closely resemble turbidites.

4.6.8 Further discussion of conglomerates: depositional setting and compositional variation

4.6.8.1 Significance of compositional variation

Reconstructions of the Cambrian carbonate platform margin (James, 1981; James et al., 1983; James and Stevens, 1986) indicate a setting dominated by stacked ooid sand shoals and calcified algal bioherms, so that the "exotic" lithologies described in this section are regarded as direct input from shallow water. White-weathering algal boundstone clasts are confined to the Halfway Point member, (upper Middle Cambrian), the stratigraphically lowest conglomerate in the Northern Head group. A similar distribution occurs in the Cow Head Group (James and Stevens, 1986). Oolitic limestone clasts are relatively abundant in the Halfway Point member, sparser in the Brakes Cove member and reappear in their highest stratigraphic occurrence in the lowermost Ordovician conglomerate.

Phosphatized clasts are conspicuous constituents of conglomerates in two intervals: i) the lowermost Cooks Brook Formation and ii) Ordovician conglomerates generally, and specifically granule conglomerates in the uppermost Middle Arm Point Formation. In the first case, pebbles are phosphatized shale, commonly conspicuous as the only component in this interval to escape extensive replacement by pyrite. In the Ordovician, pebbles and granules are phosphatized limestone, as discussed previously.

Conglomerates in the lower part of the Middle Arm Point Formation contain a high percentage of locally-derived shale matrix and locally-derived clasts, and reflect the overall pattern of decreasing input of shallow water lithologies in the Ordovician.

The localized occurrence of gneissic clasts at Rocky Point (Port au Port Bay) is enigmatic, but appears to reflect the localized unroofing of crystalline basement, possibly related to (Arenig) faulting along the platform margin.

The granule conglomerates of the uppermost Middle Arm Point Formation are remarkable in their delivery of clearly shallow water, algal-dominated lithologies into a shale-dominated part of the section, immediately underlying the sandstones of the Eagle Island

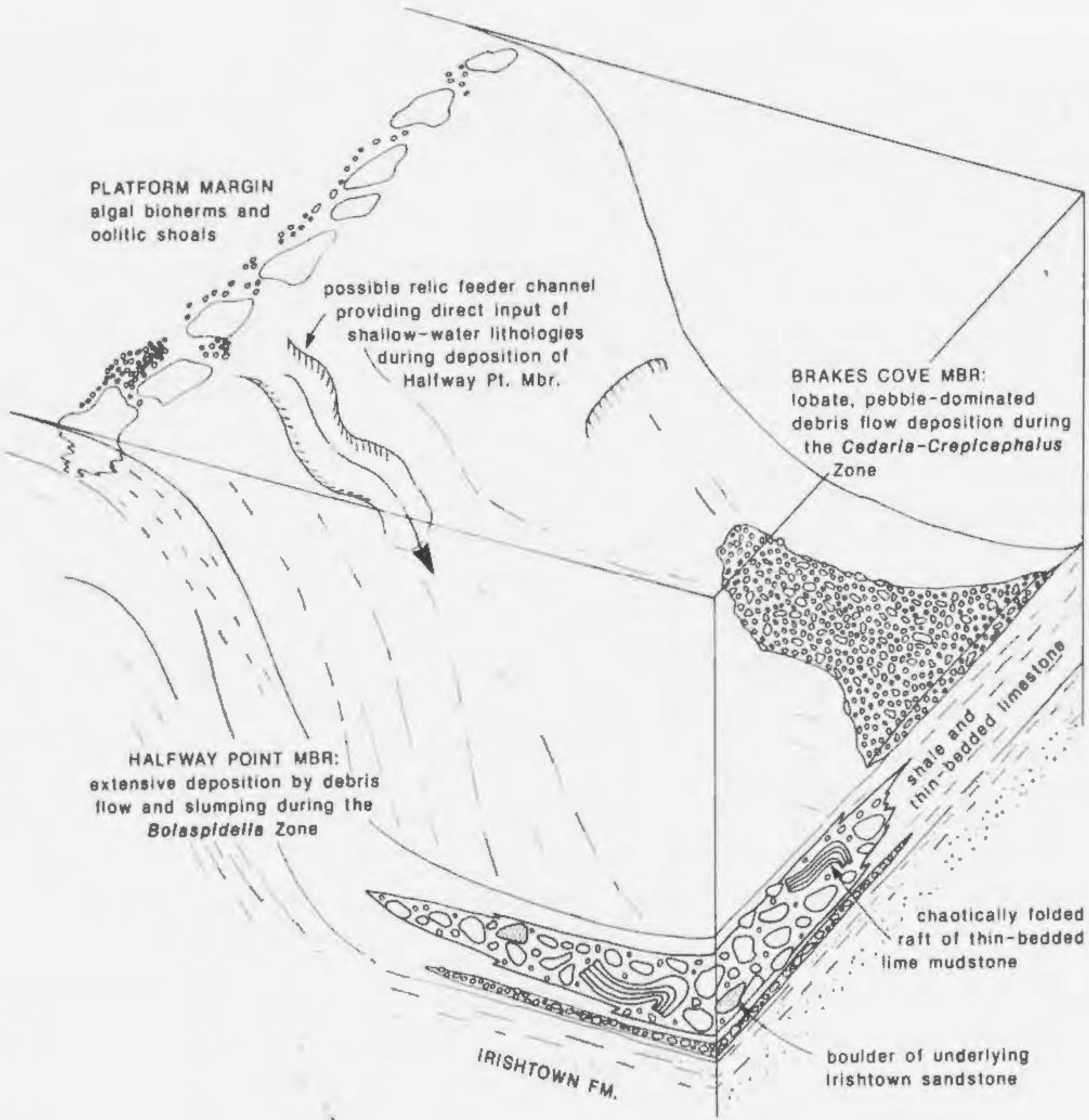
Formation. These granule conglomerates represent, in a sense, the final input from the carbonate platform into a "starved" or "distal" type of depositional environment, and hence may represent tectonic instability on the margin immediately predating sandstone deposition.

4.6.8.2 Postulated relationship of the Halfway Point and Brakes Cove Members

As has been pointed out in Chapter 3 (Stratigraphy), the Halfway Point member and Brakes Cove member both overlie the transitional base of the Cooks Brook Formation, but are of different age and different sedimentologic style. The Halfway Point member comprises type 1 and type 2 conglomerates, interpreted as erosive slump deposits and debris flows. Moreover the Halfway Point member is characterized by its conspicuous shallow water-derived components while the Brakes Cove member contains appreciably fewer such clasts. This suggests that deposition of the Halfway Point member took place on some kind of depositional "axis" or depocentre which promoted the early onset of a coarse, "proximal-style" of sedimentation which received appreciable input of sediment from shallow water sources. The localized nature, erosive style of deposition (presence of sandstone boulders), and construction of the Halfway Point member by processes of large-scale slumping and reiterative debris flow emplacement are consistent with deposition in a channel or possibly submarine canyon setting (cf. Stanley and Unrug, 1972; Normark, 1974). The Brakes Cove member, on the other hand, appears to have been in an "off-axis" setting, which received redeposited carbonate

Figure 4-4

Schematic illustration of the postulated relationship between Halfway Point and Brakes Cove members (in the lower part of the Cooks Brook Formation).


PLATFORM MARGIN
algal bioherms and
oolitic shoals
possible relic feeder channel
providing direct input of
shallow-water lithologies
during deposition of
Halfway Pt. Mbr.
BRAKES COVE MBR:
lobate, pebble-dominated
debris flow deposition during
the Cedaria-Crepicephalus
Zone
HALFWAY POINT MBR:
extensive deposition by debris
flow and slumping during the
Bolaspidella Zone
shale and
thin-bedded limestone
chaotically folded
raft of thin-bedded
lime mudstone
boulder of underlying
Irishtown sandstone
IRISHTOWN FM.

sediment later, in the form of (type 2) debris flows, generally thinner and finer and with much less shallow water input. The postulated relationship of these two units is summarized in figure 4-4. It is possible that the submarine topography which existed at the end of Irishtown deposition influenced the onset of the Cooks Brook sedimentation. Although the depositional setting of the Irishtown Formation has not been studied in detail, bedding styles and overall geologic setting are not inconsistent with a submarine fan setting (James and Stevens, in prep.). In this case, a submarine canyon within a pre-existing (Irishtown) depocentre may have acted as a natural conduit for early, erosive, and slump-dominated deposition of the Halfway Point member while the Brakes Cove member was deposited later, off-axis, in a lower-relief setting.

4.7 EAGLE ISLAND FORMATION

Introduction

The detailed sedimentology of the Eagle Island formation is outside the scope of this study. A generalized description and discussion of selected aspects are provided here, since they pertain to the depositional setting of the uppermost Middle Arm Point Formation.

The Eagle Island formation is 203m thick in the type section at Middle Arm Point (Chapter 3), which represents a minimum thickness since the upper boundary is everywhere tectonic. The base of the unit commonly comprises an interval of sandstone injections within a (Middle Arm Point) shale host. This also includes sandstone beds (generally less than 40cm) which demonstrate grading and a vertical sequence of sedimentary structures which suggest that they are turbidites. This basal interval is overlain by a variety of bedded sandstones, siltstones and shales.

4.7.1 "Slump and injection" interval

The basal portion of the Eagle Island formation is usually an interval of: i) folded and rotated blocks of uppermost Middle Arm Point sediments (Plate 4-11a) and ii) widespread injection with dykes and sills of sandstone (Plate 4-11b). Sandstone injections are locally folded and rotated but also crosscut folding, indicating that injection and early deformation were coeval. Sills generally range from 20cm to 1.5m in thickness, while dykes attain a maximum thickness of 15cm. The recognition of sills is based upon their 1)

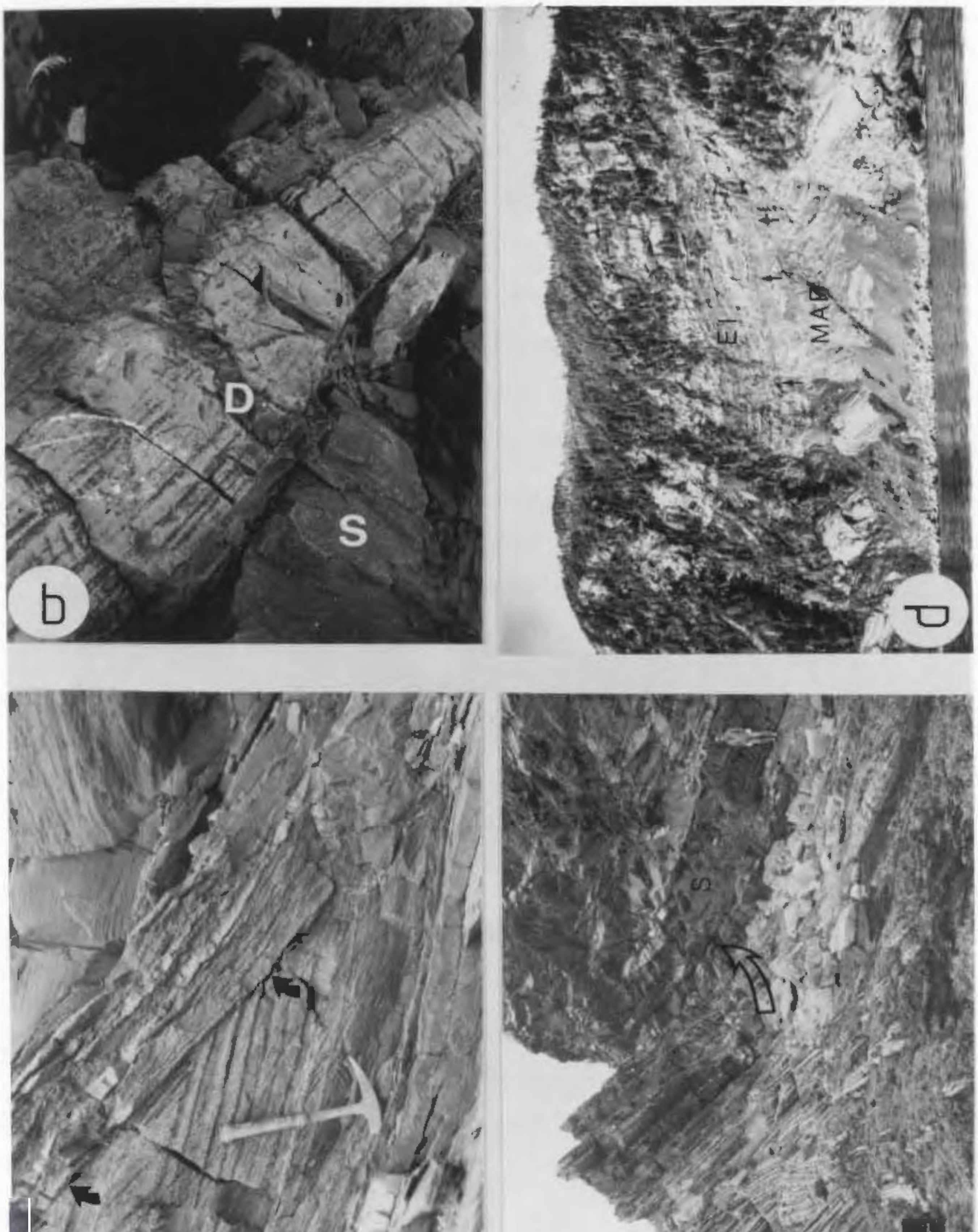
PLATE 4-11: EAGLE ISLAND FORMATION: FEATURES OF SLUMP AND INJECTION INTERVAL

a: Folded and rotated blocks of shale within basal "slump and injection" interval, Eagle Island formation; angular discontinuity (arrows) separates a rotated shale block from overlying interval with abundant siltstone and sandstone.

b: Sandstone sill (s) and dyke (d) crosscutting bedded interval of silty dolostone and shale ; "slump and injection" interval, Eagle Island formation.

c: Uppermost Middle Arm Point Formation (lower left, up to arrow) and basal Eagle Island formation at Middle Arm Point; black unit behind figure (s) is highly lensoid in nature, and interpreted as thick sill at base of sandstone.

d: Gently dipping and virtually undeformed Eagle Island formation (E.I.) overlying chaotically faulted and folded Middle Arm Point lithologies (M.A.P.); arrows indicate contact; vicinity Overfall Brook, north shore of Middle Arm.


a
b
D
S
c
S
d
EI
MAB

consanguinity with clearly crosscutting dykes, 2) complete lack of internal structure, 3) sharp and planar bounding surfaces, 4) marked lateral thickness variation, i.e. abrupt disappearance of 1.5m units over several meters with no evidence of associated channeling and 5) abrupt changes or "steps" in local stratigraphic position (cf. Hiscott, 1979). A particularly thick (maximum 5.2m) sandstone unit occurs at the base of this interval at Middle Arm Point (Plate 4-11c) and contains an isolated 1m x 0.4m size block of the host green shale and silty dolomite "floating" within it. The depositional mechanism of this unit is somewhat enigmatic, but it satisfies all of the above criteria and is tentatively regarded as a sill. Sills over 3m thick have been reported from a similar setting in the Ordovician Tourelle Formation of Quebec (Hiscott, 1979).

This interval is highly variable in thickness: 36.7m at Middle Arm Point, approximately 75m at Black Brook North, 5.4m at Eagle Island North, approximately 60m in a fault-bounded unit east of Northern Head, 4m at Cape Split and 8m at Grassy Cove. Elsewhere, at Black Point (Port au Port Bay), Eagle Island South, and North Arm Point the Middle Arm Point Formation is directly overlain by bedded sandstone; the slump and injection interval is absent.

The contact between the basal Eagle Island formation and the underlying Middle Arm Point Formation is almost everywhere gradational, and the boundary between the two is placed at the first occurrence of sandstone (Chapter 3).

?Slump-related deformation of the Middle Arm Point

An enigmatic but important contact between the Eagle Island Formation and deformed Middle Arm Point lithologies is prominently exposed in a cliff on the north shore of Middle Arm, roughly halfway between Overfall Brook and Northern Head proper. Here, gently dipping and virtually undeformed conglomerate, sandstone and shale of the basal Eagle Island formation sharply overlie extensively faulted and chaotically folded parted lime mudstone and shale (Plate 4-11d). These deformed lithologies are most similar to the uppermost Middle Arm Point interval at Woman Cove but also contain stratigraphically lower elements viz. the North Arm Point member "sliver" referred to in Chapter 3. This contact dips gently eastward and is exposed on the shoreline several hundred meters to the east, immediately west of a thrust which juxtaposes deformed Cooks Brook lithologies and those just described. The sandstone/shale interval at the base of the Eagle Island formation is here thrown into tight to isoclinal east-dipping asymmetric folds associated with the thrust deformation and this style of deformation is widespread along this portion of the shoreline (refer to Chapter 2). It is this deformation which makes the above-described contact enigmatic, since it is unclear whether the contact is 1) purely tectonic and probably associated with the thrusting episode, 2) depositional or 3) depositional, modified by tectonism. If it is purely tectonic then a younger unit (Eagle Island Sandstone) has been emplaced upon older (Middle Arm Point) lithologies along a (presently) gently dipping surface, and this implies local complexities in the thrust mechanism. Late veining is noted along the contact, where it can be reached in the cliffside away from the thrust. Given the marked contrast between chaotically deformed lithologies below the contact and virtually undeformed basal Eagle Island interval above the contact, away from the thrust, however, options 2) or 3) seem more likely. This suggests that locally the basal Eagle Island formation interval was deposited upon <u>already deformed</u> Middle Arm Point lithologies.

The top of the "slump and injection" interval is most commonly gradational, with chaotic deformation decreasing upward while the relative proportion of sandstone beds which demonstrate scoured bases, grading and other internal structures increases to 100%. At Middle Arm Point, however, and immediately to the south at Black Brook North, the top of this interval is an angular discontinuity, where chaotically folded shale, dolostone and chert is sharply overlain by an undeformed interval of thin-bedded sandstone or siltstone (Plate 4-12a), which passes upward into thick, massive beds of coarse sandstone.

<u>Basal Eagle Island formation interval: interpretation</u>

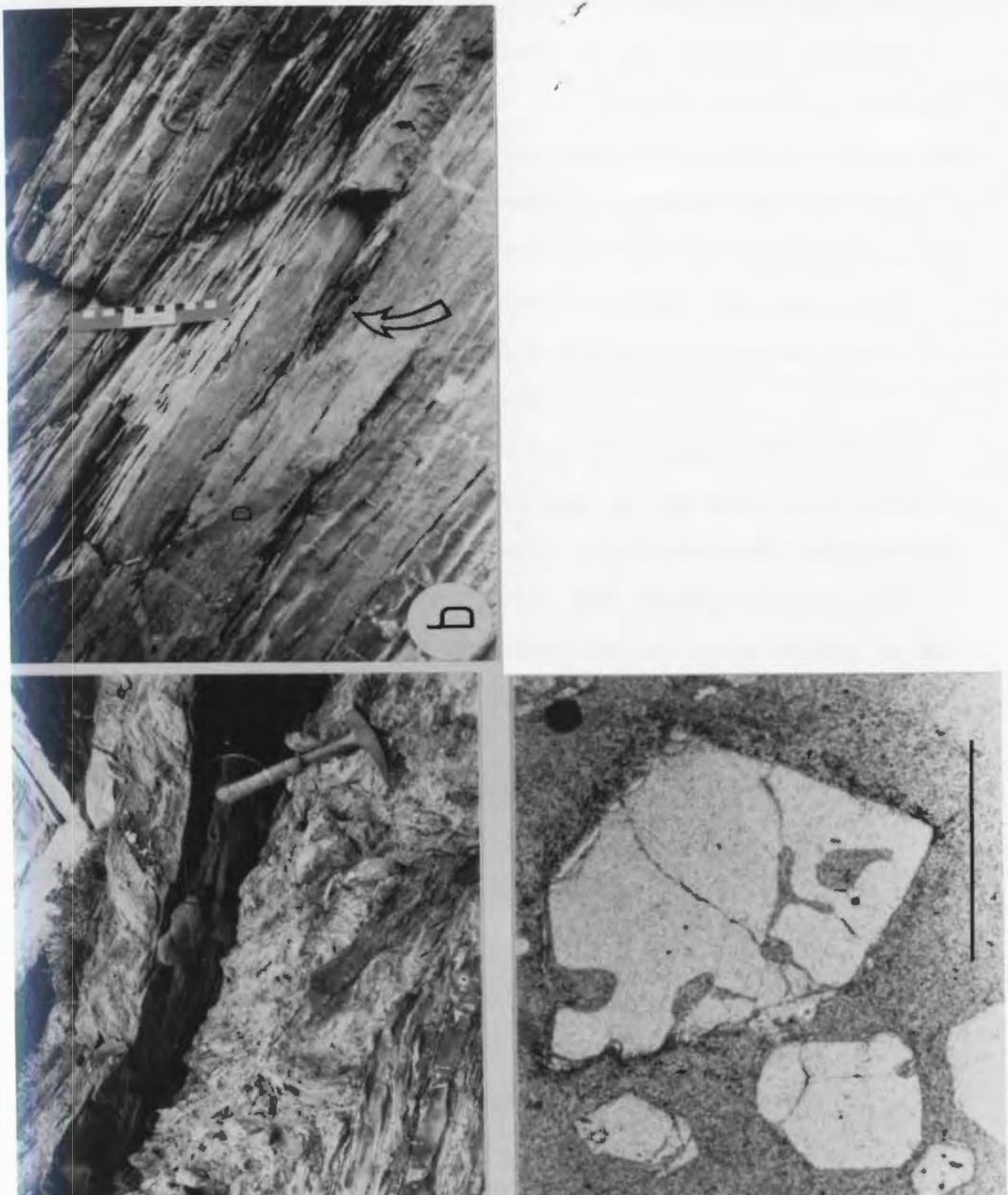
The combination of chaotic deformation and coeval clastic dykes and sills which characterizes the basal Eagle Island Sandstone interval suggests that it originated by processes of slumping and liquified injection of sandstone during the associated phase of rapid loading. The presence of sandstone turbidite beds throughout the interval indicates that "normal" submarine sedimentation of sandstone was ongoing during this episode and it is these beds which

PLATE 4-12: FEATURES OF THE EAGLE ISLAND FORMATION

a: Upper contact of "slump and injection" interval, basal Eagle Island formation, Black Brook North; note chaotically folded interval below contact (lower left) overlain by undeformed sandstone with flute casts.

b: Thin, lensoid channel (arrow) containing ?tuffaceous grains within shale/silty dolostone interval of basal Eagle Island formation; note sandstone dyke (D) on left.

c: Photomicrograph of embayed, euhedral crystalline quartz grains, displaying resorption features, surrounded by chloritic shale; sample from lensoid channel illustrated in preceding photograph; scale bar is 1mm.



may have provided a source of subsequently remobilized sand. The variable thickness (and local absence) of the interval throughout the area suggests that slumping was localized and may have responded to local variations in submarine topography. The Overfall Brook area exposure indicates that slumping predated sandstone deposition locally, where it was responsible for some of the deformation noted within the uppermost Middle Arm Point Formation. The angular discontinuity described above locally defines a sharp top to this basal "slumped and injected" interval.

The same depositional mechanism has been suggesred by Hiscott (1979) for a similar interval at the base of the Ordovician Tourelle Sandstone in Quebec. He suggested that liquefaction was facilitated by loading and compaction under a clay seal during slumping. He further suggests that similar processes did not occur higher in the section due to the absence of an effective permeability seal.

4.7.2 ?Tuffaceous channels within the basal interval

Sparsely scattered throughout shaly portions of this basal interval (at Grassy Cove, Eagle Island North and Middle Arm Point) are thin, highly lensoid scours, generally 1 to 2cm thick and roughly 15cm in lateral extent (Plate 4-12b). These are defined by the subtle contrast of their (medium) sandy mud fill and the surrounding host shale. Shale within the channel is either of the same (commonly green hue) as the host shale or darker green, but is indistinguishable, and commonly chlorite-dominated, in thin section. The distinctive aspect of these units is the nature of the component sand grains. These include feldspar grains, but are otherwise dominated by pristine quartz particles which display beta quartz crystalline outlines, resorption features and inclusians (Plate 4-12c) which are characteristic of volcanic tuffs (Blatt et al., 1980). Evidence of volcanism at this time (middle Arenig) has not previously been reported from the Northern Head group or Cow Head Group.

4.7.3 Overlying bedded sandstone, conglomerate and siltstone

Overlying bedded units of the Eagle Island formation display a wide variety of lithofacies which can be broadly characterized as : 1) thick massive sandstone (including conglomerate), 2) medium-bedded sandstone, 3) siltstone-dominated intervals and 4) shale-dominated interbeds.

4.7.3.1 General aspect

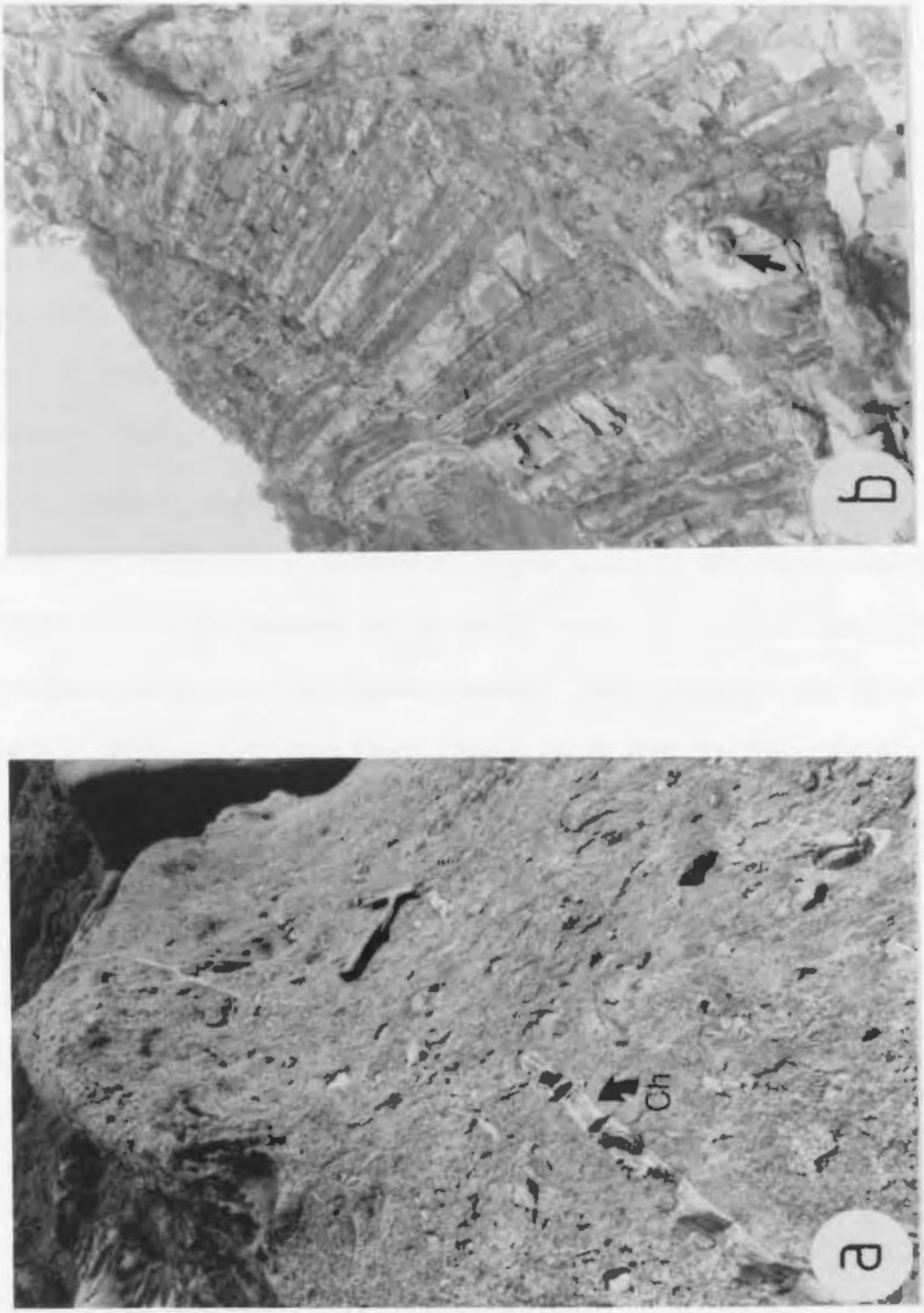
1) Massive sandstones are impressive and appear in units 30m to 70m in thickness, which commonly display amalgamation of individual beds 5m or more in thickness. Other internal structure is rare and even bedding is difficult to identify within the center of these units. They are composed of generally sub-angular, coarse sand to granule, quartz-rich sandstone. The base of each unit is highly irregular, scoured and displays a variety of sole-markings dominated by large flute casts. Scattered conglomeratic intervals occur, frequently near the base, and contain angular clasts of chert, green shale and dolostone (rarely limestone and never red shale) clearly derived from the underlying Middle Arm Point Formation (Plate 4-13a).

Because of the nature of the exposure, the geometry of these

PLATE 4-13: EAGLE ISLAND FORMATION LITHOLOGIES

a: Conglomeratic sandstone with angular clasts of (Middle Arm Point) chert (ch) and silty dolostone; Eagle Island North.

b: Eagle Island Formation: interval dominated by medium-bedded sandstone, interbedded with siltstone and grey shale; Whites Brook; backpack (arrow) for scale.


b
a
Ch

units is not clear, but they appear to thin laterally.

2) Medium- to thick-bedded sandstone appears in intervals 5 to 30m thick and consists of beds of greenish medium sandstone 30cm to 1+m thick, interbedded with siltstone and grey shale (Plate 4-13b). Sandstone beds are normally-graded and the upward transition from massive or parallel-laminated bases to ripple cross-laminated tops suggests partial Bouma cycles.

3) Siltstone-dominated intervals consist of 5 to 10cm beds of siltstone and very fine sandstone, commonly parallel or ripple laminated, interbedded with grey shale and displaying scattered interbeds of medium sandstone as above.

4) Shale-dominated intervals are of 2 kinds. The first is grey shale with scattered siltstone interbeds which occurs in intervals 2 to 5m thick intimately interbedded with sandstone. The clear association with sandstone suggests a linked source. The second type is red and green shale, with scattered thin chert beds and is identical to underlying Middle Arm Point shale. At Rocky Point (West Bay) these intervals reach 30+m in thickness but elsewhere are generally less than 5m thick.

Bedded carbonate is extremely rare within the Eagle Island Formation but occurs in the type section at Middle Arm Point (fig 3-10) within a siltstone interval immediately overlying the basal "slump and injection" interval. Here an 8cm bed of limestone granule conglomerate is capped by a 5cm rippled dolomitic siltstone. Thin-bedded lime mudstone and dolostone packages, like those within shale intervals in the underlying Middle Arm Point Formation, are not present.

4.7.3.2 Composition

A limited petrographic survey of these sandstones (5 thin sections) confirms the abundance of quartz, as noted in the field. Quartz grains are generally rounded to sub-rounded, predominantly monocrystalline, and constitute 40% of the lithology on average. Sedimentary rock fragments are not abundant, but the majority of those identified are quartz sandstone. Volcanic rock fragments, commonly displaying spherulitic or felted to trachytic texture, are generally the next most abundant component and constitute roughly 20%. These are locally epidotized and are apparent in the field as bright green grains in coarse sandstone. The percentage of plagioclase is highly variable, ranging from less than 5% to roughly 20%. Orthoclase is a common minor component. Microcline, constituting 5 to 10% of the rock, is ubiquitous. Detrital mica is an accessory local component.

There are very few sedimentary rock fragments which would suggest appreciable input into the sandstone from erosion of the underlying Northern Head group. In total, sedimentary rock fragments (excluding quartz) constitute 5 to 10% of the lithology and are dominated by semi-opaque, phosphatized shale grains. These (not chromite) probably account for most of the dark grains evident in the field. Fine to medium quartzose sandstone grains are the next most abundant sedimentary rock fragment.

Accessory heavy minerals have been identified with the aid of the SEM and EDAX. These are predominantly zircon with lesser amounts of chrome-spinel.

4.7.3.3 Paleocurrent directions

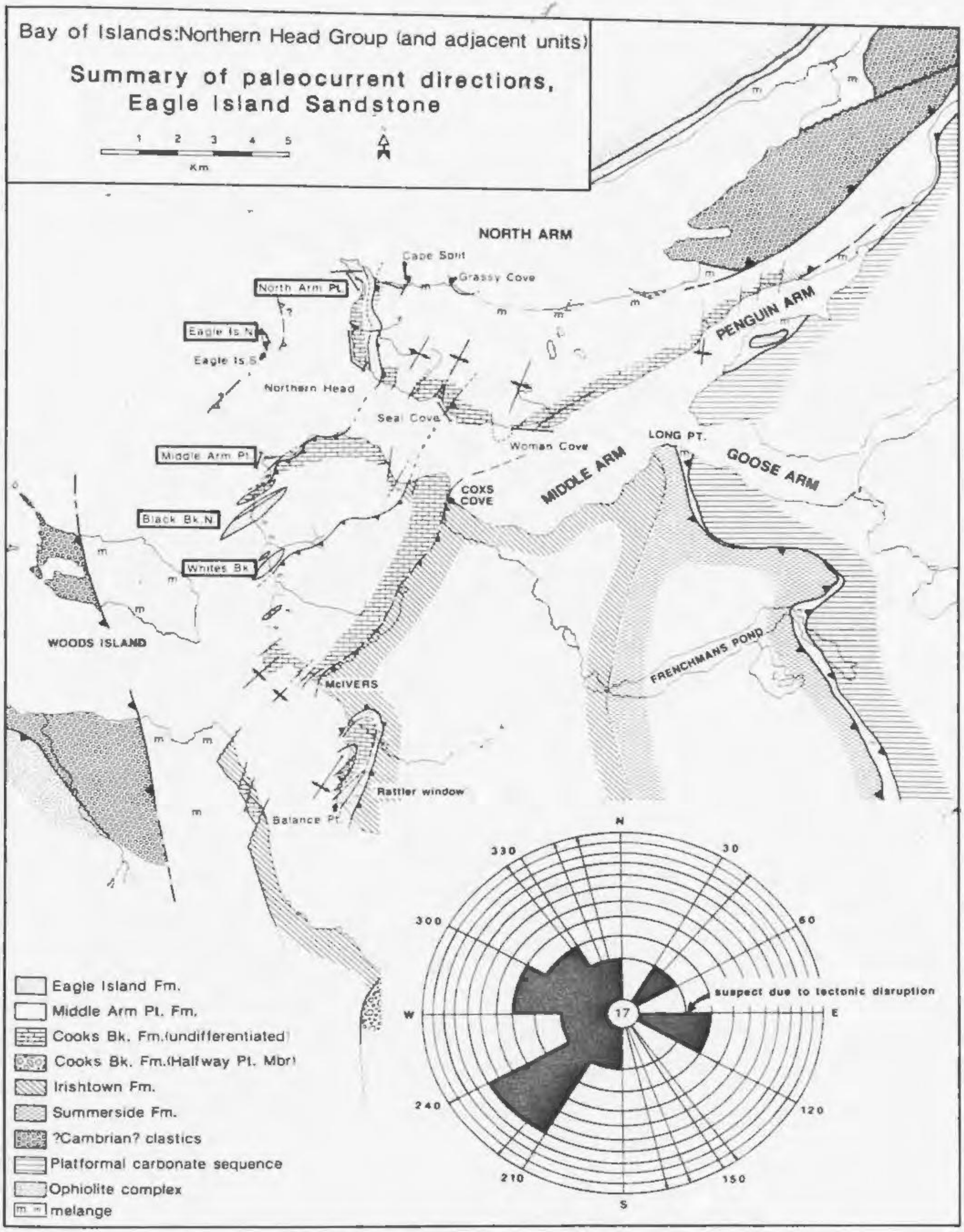
A rigorous examination of paleocurrent directions in the Eagle Island formation was not undertaken 1) because it was considered beyond the scope of this project and 2) because of inherent uncertainty in restoring bedding to the depositional attitude in such a complexly deformed study area. However, a brief survey of paleocurrent directions was undertaken from selected sandstone exposures to provide a broad indication of transport direction and its variability. The orientation of flute casts, and a few current lineations were measured on the base of predominantly medium- to thick-bedded sandstones (total 21 measurements), and bedding was simply rotated to the horizontal. Results are presented in Table 4-3 and Figure 4-5 and indicate a general transport direction toward the west, with a maximum toward the SW.

4.7.4 Summary and Interpretation

At the base of the Eagle Island formation is an interval, up to at least 37m in thickness which is characterized by slumping and clastic injections. This indicates that the end of Middle Arm Point deposition and the beginning of sandstone deposition was a period of tectonic instability. While the facies relationships within the Eagle Island formation have not been examined in detail, the lithologies described above are readily referable to the facies generally recognized in a submarine fan setting (Mutti and Ricci Lucchi, 1978; Walker, 1978, 1984). Sediment transport in the Eagle Island formation was toward the SW and the suggestion of

Figure 4-5

Summary of paleocurrent directions (flute casts and current lineations), Eagle Island formation; equal area rose diagram showing number of readings for flutes, current lineations are shown as thin arrows. Areas of data collection are highlighted by "boxes". Refer also to Table 4-3.



Bay of Islands:Northern Head Group (and adjacent units)
Summary of paleocurrent directions, Eagle Island Sandstone
1 2 3 4 5
Km
NORTH ARM
Cape Spilt
Grassy Cove
North Arm Pt.
Eagle Is.N.
Eagle Is.S.
Northern Head
Seal Cove
Woman Cove
LONG PT.
PENGUIN ARM
GOOSE ARM
MIDDLE ARM
Middle Arm Pt.
COXS COVE
Black Bk.N.
Whites Bk.
WOODS ISLAND
McIVERS
FRENCHMANS POND
Rattler window
Balance Pt.
N
330
30
300
60
W
17
E
suspect due to tectonic disruption
240
120
210
150
S
Eagle Island Fm.
Middle Arm Pt. Fm.
Cooks Bk. Fm.(undifferentiated)
Cooks Bk. Fm.(Halfway Pt. Mbr)
Irishtown Fm.
Summerside Fm.
?Cambrian? clastics
Platformal carbonate sequence
Ophiolite complex
melange

Table 4-3: Eagle Island Sandstone: Paleocurrent directions

Locality	Azimuth	Comments
Middle Arm Pt.	280	
"	210	
"	204	
"	229	
"	030	slump & injection
Black Bk. N.	228	
"	237	
"	166/344	current lineation
"	038/218	"
Whites Bk.	160/340	"
Eagle Is. N.	280	
"	302	
"	235	
"	092	tectonic disruption
North Arm Pt.	100	"
"	260	
"	276	
"	227	
Blk. Pt. (West Bay)	330	
"	355	
"	146/326	current lineation

Stevens (1970) of derivation from a mixed source of silicic intrusives, parts of an ophiolite suite and older, quartz-rich sedimentary lithologies (Summerside or Irishtown Formations?) seems correct.

4.8 SEDIMENTOLOGY: SUMMARY AND INTERPRETATION

4.8.1 Carbonate margin-to-basin transitions: general discussion

The term "platform margin" in this discussion is used to refer to the seaward termination of platformal, shallow-water carbonate sedimentation, bounded oceanward by a slope, which may be of variable declivity, which passes oceanward into a "basin" or "basin plain". This use of "margin" is synonymous with "platform edge" in discussions where "margin" has also been used in a more general way (James, 1982; James and Stevens, 1986) to encompass the entire transition from platform to basin plain.

The transition from platform margin to basin varies with the nature of the margin itself, and the corresponding relief between platform and basin (Wilson, 1975; McIlreath and James, 1979; James, 1982; Read, 1982) Variations in this transition have been broadly classified (James and McIlreath, 1979; James, 1982; Read, 1982) to include both "depositional" and "bypass" margins.

1) "Depositional margins" are characterised by a gently inclined slope connecting platform edge and basin plain, and may witness deposition anywhere on the slope. This style of transition is broadly synonymous with the "non-rimmed homoclinal ramp" (Ahr, 1973; Read, 1982; Cook, 1983), which is generally characterised by broad, gradational facies belts and the relative paucity of mass transport processes. This has also been modified (Read, 1982; Cook, 1983) to include a "non-rimmed distally steepened ramp" which displays a shelf-slope break, focusing mass transport processes, in deep water.

2) Higher relief "bypass margins" are characterised by a steep slope and the accumulation of a wedge of redeposited sediment ("carbonate base-of-slope apron"; Cook, 1983) at its base.

4.8.2 <u>Northern Head Group: General Depositional Setting</u>

The Northern Head group is dominated by redeposited carbonate and shale and was clearly deposited in the transitional zone between a carbonate margin and basinal setting. The contained sediments described in the foregoing chapter cover a spectum of gravity deposits and include debris flows and coarse-grained turbidites (conglomerates), carbonate turbidites (calcarenites and dolostones), muddy turbidites (certain shale intervals) and hemi-pelagites (lime mudstone and certain shale intervals). Evidence of gravity slide-related truncation surfaces (Upper Cambrian calcarenite interval) is also present. Suggestions of localized current reworking have also been noted (dolomitic shale intervals within the lowermost Cooks Brook, selected silty dolostone units within the Middle Arm Point). These lithologies, and their interpreted depositional mechanisms are characteristic of overall deposition of the Northern Head Group in a slope environment. A similar spectrum of lithologies has been described from numerous ancient (summarized or included in Cook and Enos, 1977; McIlreath and James, 1979; Cook et al., 1983; Cook and Mullins, 1983) and modern examples (ibid.; Schlager and Chermak, 1979; Mullins and Neumann, 1979; Crevello and Schlager, 1980; Mullins, 1983) of deep-water carbonate slope environments.

Unlike many of the examples referenced above, the Northern Head group and Cow Head Group, transported sequences within the Humber

Arm Allochthon, are tectonically "isolated", and cannot be directly interpreted in the context of an adjacent platform margin nor basin plain. Based upon present evidence, the Northern Head group may represent part of a "slope sediment apron" deposited on a "depositional margin", or part of a "base of slope sediment apron" as a component of a "by-pass margin" (cf. James and Stevens, 1986). Several lines of evidence suggest that the latter case is more likely:

1) The Irishtown Formation, upon which the Northern Head Group is deposited, is considered to have most likely been deposited in a submarine fan setting (Chapter 3). Such deep-water deposition is most commonly initiated at a region of decreasing slope, i.e. the base-of-slope or continental rise in a transitional oceanic setting (Nelson and Nilsen, 1974; Stanley and Unrug, 1972).

2) Folded rafts of thin-bedded lime mudstone within conglomerates of the Halfway Point member imply the presence of fine-grained sediments upslope, separating these conglomerates from their shallow-water (partial) source (cf. James and Stevens, 1986).

3) Gently inclined depositional margins may vary to some degree with slope declivity but generally display very broad, gradational facies belts and are volumerically dominated by argillaceous lime wackestone and mudstone with few and thin debris flows (Cook, 1983; Read, 1980; 1982). This contrasts with the abrupt vertical facies changes and numerous debris flows within the Cambrian portion, at least, of the Northern Head group. Furthermore, in the case of "distally-steepened homoclinal ramps", the location of the

shelfbreak in deeper water results in the dominance of deep-water-derived slope components (and corresponding paucity of shallow-water-derived components) within mass transport deposits. The clear presence of shallow-water components within the Cambrian (and lowermost Ordovician) debris flows of the Northern Head group also mitigates against deposition in this type of environment.

Modern carbonate wedges (base-of-slope aprons) are commonly 7 to 15 km wide (Crevello et al., 1985). Comparable widths are described in ancient examples (ibid., summarized in Cook, 1983), but isolated channelized debris flows have been noted 50 km from the platform margin in the Devonian of the Yukon (Cook, 1983). Carbonate slope or base-of-slope aprons may be broadly characterized (Cook, 1983a; 1983b) as either: 1) constructed by a number of episodic, single-pulse, thick and laterally extensive debris sheets (cf. McIlreath, 1977), 2) reflecting the complex, non-systematic interplay of mass transport processes, including the punctuated input of debris flow lobes, or 3) submarine fan deposits (cf. Cook and Egbert, 1981). The character of the Northern Head group does not reflect the sheet-like nature of option 1, nor is it consistent with the systematic facies changes demonstrated by submarine fan deposits. Rather, the Northern Head group is best characterized as a carbonate base-of-slope apron which reflects, through its depositional history, temporal changes in the nature of the platform margin.

4.8.3 Temporal changes in depositional setting

Since sediments deposited in a carbonate slope or base-of-slope apron are directly derived from upslope, these deposits reflect the changing nature of the platform margin, which may be in turn controlled by factors such as tectonic setting and history and large-scale sealevel changes (James, 1982; James and Mountjoy, 1983). The interplay of these factors may result in: i) a stationary margin, which may evolve from "ramp" to "rimmed" style with carbonate accretion over time, ii) an offlapping or prograding margin, iii) an onlapping or "backstepping" margin, iv) a drowned margin, or v) an emergent margin (James and Mountjoy, 1983). In the final two cases, sedimentation in a carbonate wedge downslope from the platform margin will be restricted, and aspects of "starved sedimentation" may appear.

Within the Northern Head group, components derived from a shallow-water platformal carbonate setting have been identified and include ooids, calcified algae, bioclastic debris, detrital dolomite and siliciclastic grains. Other components were derived from the slope itself, and include tabular clasts within conglomerate, matrix components within conglomerate, and a variety of intraclasts. Terrigenous mud (shale) and lime mudstone are regarded as hemipelagic deposits, which may have been, in part, redeposited from higher on the slope. Clear changes in depositional setting occur through the Northern Head group, and the salient aspects of these are summarized below.

Cambrian

1) Facies contrasts at the base of the Cooks Brook Formation have been interpreted to represent the localized and punctuated onset of mass transport-dominated carbonate sedimentation. This could have been influenced by the topography of the underlying Irishtown Formation, where a "gullied" setting may have resulted in the initial deposition of isolated debris lobes (cf. Crevello et al., 1985), an example of which is the Halfway Point member. This deposition witnessed the direct input of coarse, shallow-water-derived sediment (boulders of algal boundstone and oolitic carbonate), which diminishes upsection. Meanwhile, cyclic shale sedimentation, as muddy turbidites, commonly organic carbon-rich, and probably derived from the upper slope, commenced elsewhere, to continue sporadically through the depositional history of the Northern Head group.

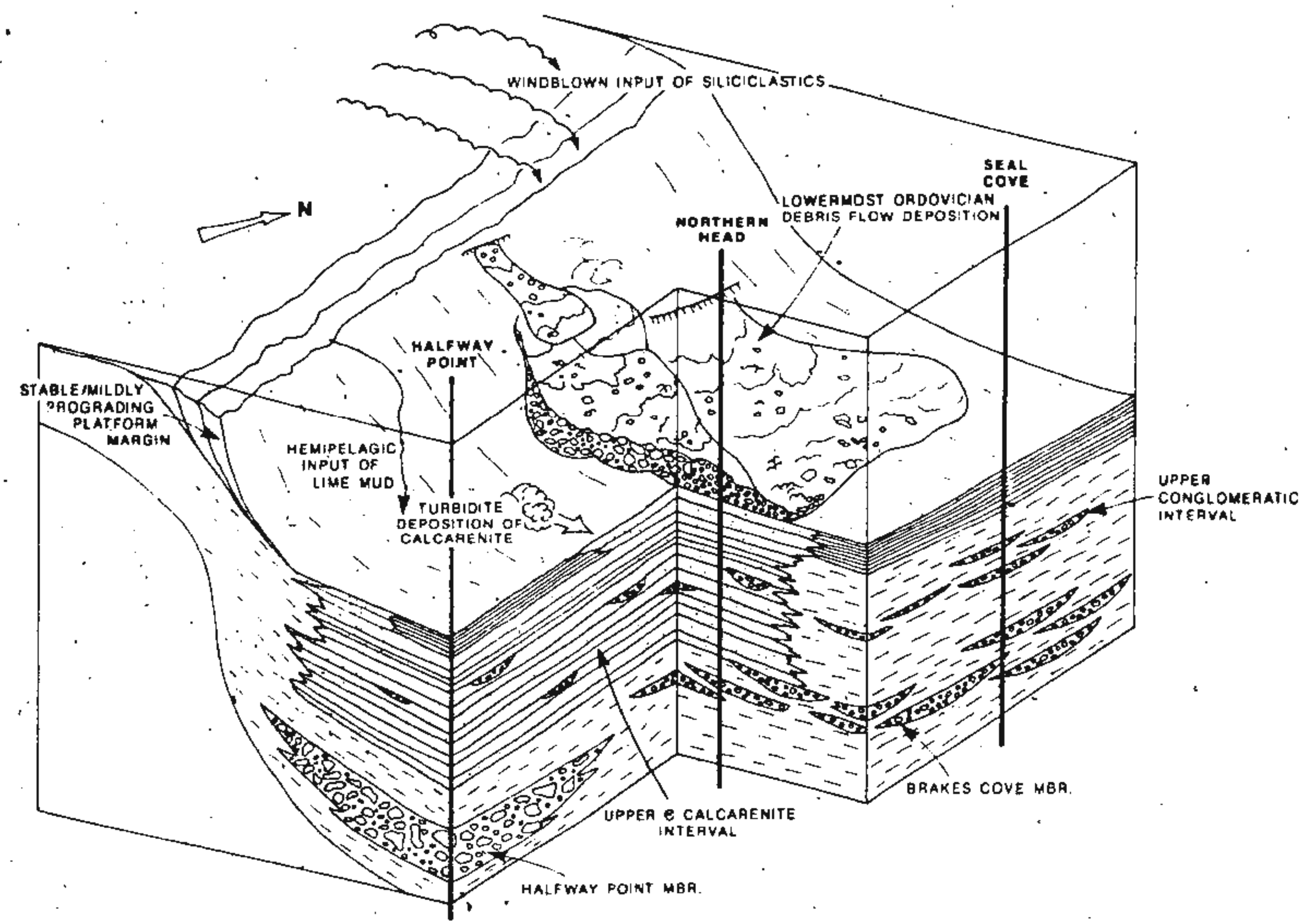
2) Sedimentation in the Late Cambrian began with widespread deposition of relatively thin, lensoid debris flows (Brakes Cove member), against background sedimentation of shale and thin-bedded carbonate. This is regarded as the last episode of debris flow construction of laterally extensive lobes in the Northern Head group and is present in all sections except the farthest southeast (Halfway Point/Giles Point).

3) In the northwest (Northern Head) sedimentation through the rest of the Cambrian is dominated by thin to medium-bedded, relatively coarse calcarenites, interpreted as turbidites, with scattered, thin lensoid conglomerates, regarded as localized debris flows. These

turbidites contain abundant shallow-water-derived components (calcified algae, bioclastic debris, detrital dolomite). Evidence of gravity sliding, consistent with deposition in a slope setting, is present in this interval. To the southeast, in general, shale is more abundant through this interval. This is, however, punctuated by an interval of thin lensoid conglomerates, well-developed at Seal Cove, tentatively correlated to those at Woman Cove, and regarded as a localized lobe constructed of thin debris flows. In the southeast, the uppermost Cambrian is dominated by lime mudstone rhythmites. The Halfway Point section is hybrid, in that it displays a calcarenite/localized conglomerate interval similar to Northern Head, which passes upward into thin lime mudstone rhythmites. This Upper Cambrian interval records diminished input of coarse shallow-water-derived material, but relatively continuous turbidite sedimentation, and is thought to reflect generally low relief but stable conditions on the platform margin upslope. Non-systematic bedding style changes described in the calcarenite interval may represent minor progradational events. A marked increase in the quartzose silt and sand component is noted in the calcarenite interval here, and is particularly coarse in the northwest (Northern Head section). There is not a pronounced across-strike facies contrast through the Cambrian, but the characteristics described above suggest a northwest-to-southeast proximal-to-distal polarity in sedimentation. The above-described aspects of the Cambrian depositional setting of the Northern Head group are summarized in figure 4-6.

Figure 4-6

Northern Head group: Schemaric summary of Cambrian depositional setting. Bold axes represent measured sections whose location is shown in Figure 3-2.



WINDBLOWN INPUT OF SILICICLASTICS
N
SEAL COVE
LOWERMOST ORDOVICIAN DEBRIS FLOW DEPOSITION
NORTHERN HEAD
HALFWAY POINT
STABLE/MILDLY PROGRADING PLATFORM MARGIN
HEMIPELAGIC INPUT OF LIME MUD
TURBIDITE DEPOSITION OF CALCARENITE
UPPER CONGLOMERATIC INTERVAL
BRAKES COVE MBR.
UPPER Є CALCARENITE INTERVAL
HALFWAY POINT MBR.

Ordovician

4) In the Lower Ordovician, the uppermost occurrence of debris flow deposition dominated by shelf-derived components occurs in the northwest (?proximal) section at Northern Head, where oolitic boulders are present within a thick conglomerate, but this cannot be traced southeastward. This conglomerate appears to represent the last evidence of significant progradation of the margin upslope.

5) Elsewhere, the fine-grained sedimentation style noted in the uppermost Cambrian is continuous into a distinctive (Tremadoc) interval dominated by black, organic carbon-rich shale and thin-bedded lime mudstone. This is regarded as the product of a period of predominantly hemipelagic sedimentation virtually cut off from mass transport input from the shelf and deposited under anoxic marine conditions. This event signals a change in sedimentation style and a dramatic change in the proportion of shelf-derived sedimentary components. A marked change in the platform margin is implied and may be related to sealevel change or tectonic controls (?margin collapse).

6) The base of the Middle Arm Point Formation (Woman Cove member) which overlies the above-described interval represents the first episode in a new regime of sedimentation and marine conditions, in the Tremadoc. The detrital dolomite and minor siliciclastic grains which dominate this interval have been noted as minor components throughout the Northern Head group, but now, in the absence of other input from upslope, become dominant. Reworking of sediments in this interval is interpretated to reflect the influence of bottom currents.

7) Localized debris flow deposition overlies the Woman Cove member in the western portion of the Bay of Islands. This conglomerate immediately overlies the silty dolostone unit at North Arm Point, but they are separated by an interval of shale at Eagle Island South, suggesting an irregular submarine topography through this interval. The conglomerate is absent in the east (Woman Cove), where shale and thin-bedded lime mudstone occur.

8) Also confined to the western portion of the Bay of Islands, in a fashion similar to the conglomeratic debris flow described above, is the "dark parted lime grainstone interval" which contains abundant shallow-water-derived components (algal grains). Although interpretation of a depositional méchanism for this lithology is hampered by bioturbation, it is tentatively regarded as a series of thin turbidites which have redeposited shallow-water-derived sediment. Black, organic carbon-rich shale interbeds may represent mudstone redeposited in the same event(s) and preserved by rapid burial.

9) The overlying, broadly correlatable North Arm Point member spans the Tremadoc/Arenig boundary. Faunal evidence suggests condensed sedimentation through this interval (Chapter 3) and the abundance of bioturbation and scattered, extensively cross-laminated silty dolostone also indicates "starved" sedimentation under a regime of bottom current reworking.

10) The uppermost portion of the Middle Arm Point Formation reflects continuous shale sedimentation under mildly oxidizing marine conditions. This is punctuated by the input of 1) thin turbidites

comprising silty dolomite alone, or silty dolomite plus lime mudstone (differentiated into thin beds during deposition) and ii) muddy turbidites comprising black, organic carbon-rich mud, which temporarily affected the delicate Eh balance of the depositional environment. Lime mudstone generally occurs in thin-bedded units, except for an isolated, thick (and highly bioturbated) interval exposed only in the west (Eagle Island North).

The restricted occurrence, in the western portion of the Bay of Islands, of three slope-deposited and, in part, shelf-derived units described above: the i) Middle Arm Point conglomerate, ii) "dark parted lime grainstone interval" and iii) Eagle Island lime mudstone unit suggests that northwest-to-southeast proximality continued through the Ordovician portion of the Northern Head group.

Early sea-floor silicification, with silica derived from a probable biogenic source, is most prominent through this interval. ii) The above described interval represents the most extreme development of "restricted input" of shelf-derived sediment, confined only to shale, silty dolomite, siliciclastic grains and lime mudstone. In this context, the granule conglomerates described from immediately below, and within, the basal portion of the Eagle Island formation are anomalous, since they comprise abundant shallow-water-derived algal and bioclastic grains. They represent a final pulse of mass transport (distal debris flow or turbidite) from the platform and must reflect a platform event, most likely tectonic instability, at the close of Northern Head Group sedimentation. The nature of the Ordovician depositional environment of the Northern Head group is summarized in figure 4-7.

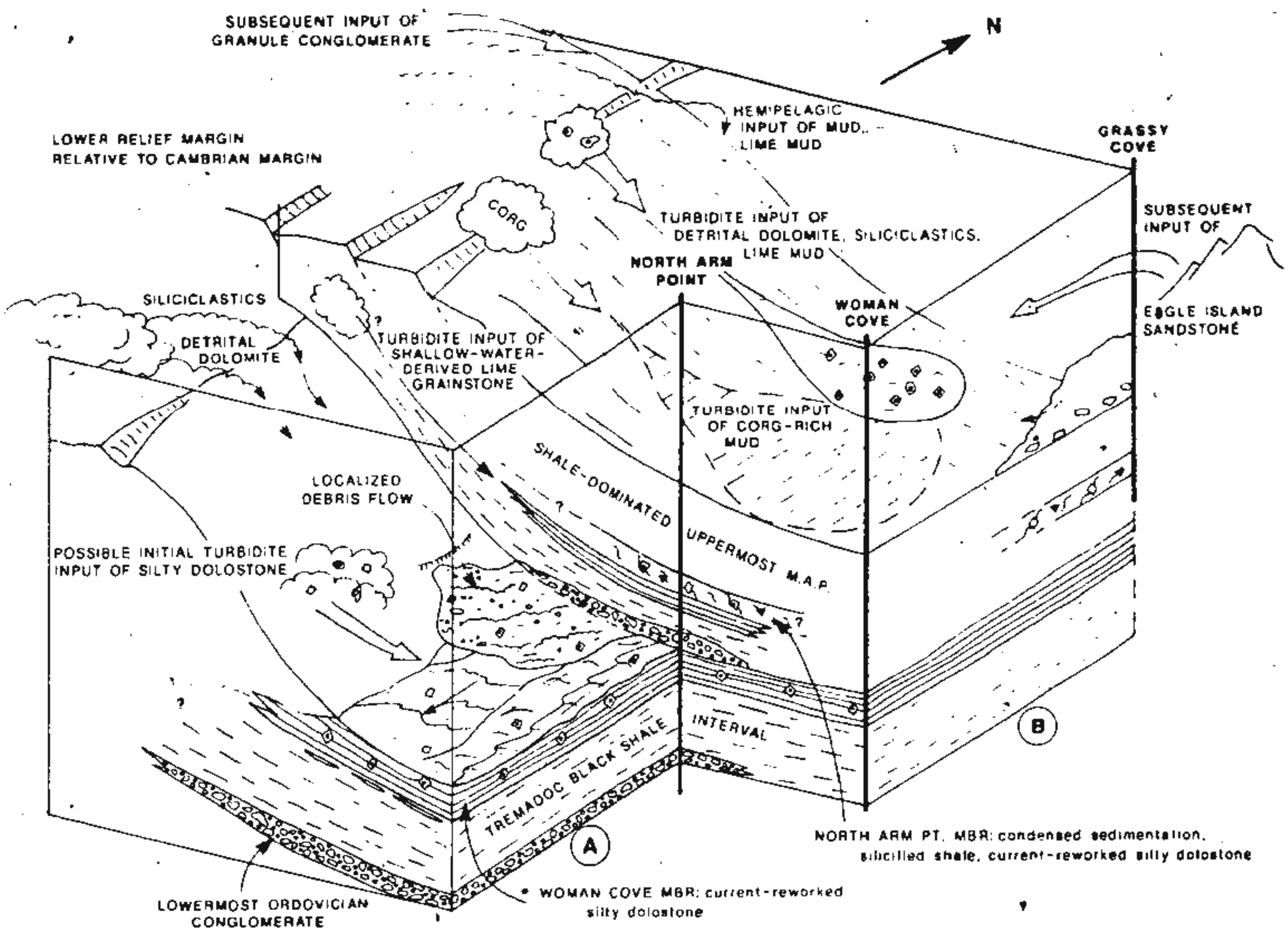
12) Slumping and clastic injection accompanied rapid loading at the onset of deposition of the Eagle Island Sandstone in the middle Arenig (I.v.v. zone). This is followed by sandstone-dominated sedimentation consistent with deposition in a submarine fan setting, with paleocurrent flow probably toward the southwest.

The above summary of the Ordovician documents the slow destruction of a carbonate margin, as reflected in changing deposition within the carbonate slope or base-of-slope sediment apron which the Northern Head group represents. This is indicated by the changing nature and restricted input of shelf-derived sediment in the Ordovician. Deposition through the Cambrian is consistent with a stable or gently prograding platform margin. The first signal of a change in the margin is the episode of hemipelagic-dominated sedimentation in the Early Ordovician (Tremadoc). Subsequent sedimentation appears to reflect a much lower-relief style of platform margin-to-basin transition, demonstrating more affinity with the muddy "ramp" type of margin discussed at the outset of this section. This is accompanied by a change in ambient levels of dissolved oxygen in the depositional environment, reflected in the level of bioturbation (see Chapter 5), nature of shales through the section, and diagenetic processes (see Chapter 6). This may, in turn, be related to the variable input of ?upper slope-derived organic carbon into the depositional environment, as a function of changing slope morphology.

The changing nature of a carbonate margin, and downslope deposits, records the interplay of tectonic effects and sea-level

Figure 4-7

Northern Head group: Schematic summary of Ordovician depositional setting.
Block A, on left, summarizes deposition up to the Middle Arm Point conglomerate.
Block B, on right, summarizes deposition through the remainder of the Middle Arm Point.
Bold axes represent measured sections whose location is shown in Figure 4-1.


N
SUBSEQUENT INPUT OF GRANULE CONGLOMERATE
HEMIPELAGIC INPUT OF MUD, LIME MUD
LOWER RELIEF MARGIN RELATIVE TO CAMBRIAN MARGIN
GRASSY COVE
CORG
TURBIDITE INPUT OF DETRITAL DOLOMITE, SILICICLASTICS, LIME MUD
SUBSEQUENT INPUT OF
NORTH ARM POINT
WOMAN COVE
EAGLE ISLAND SANDSTONE
SILICICLASTICS
DETRITAL DOLOMITE
TURBIDITE INPUT OF SHALLOW-WATER-DERIVED LIME GRAINSTONE
TURBIDITE INPUT OF CORG-RICH MUD
SHALE-DOMINATED UPPERMOST M.A.P.
LOCALIZED DEBRIS FLOW
POSSIBLE INITIAL TURBIDITE INPUT OF SILTY DOLOSTONE
INTERVAL
TREMADOC BLACK SHALE
A
B
NORTH ARM PT. MBR: condensed sedimentation, silicified shale, current-reworked silty dolostone
LOWERMOST ORDOVICIAN CONGLOMERATE
WOMAN COVE MBR: current-reworked silty dolostone

changes (James and Mountjoy, 1983). This will be discussed in light of the above-presented evidence in the final chapter.

CHAPTER 5

TRACE FOSSILS AND THEIR STRATIGRAPHIC DISTRIBUTION

Introduction

The intensity of bioturbation displays an overall increase upward through the Northern Head group, increasing markedly at the Cooks Brook/Middle Arm Point boundary. Where preservation is adequate, traces are assigned to a characteristic genus, and five intervals displaying broadly contrasting trace fossil assemblages are identified through the section (figure 5-1) and described below. The level of bioturbation is not consistent through each interval; particularly within the Cooks Brook Formation where bioturbation is sparse and trace fossils have been noted or collected from scattered individual horizons which are thought to display the maximum bioturbation within a given interval.

5.1 Lower Cooks Brook interval

Trace fossils within this interval were collected from shale interbeds within the Halfway Point member, and the upper part of shale cycles in the lowermost Cooks Brook Formation (see Shale section, Chapter 4). The following trace fossils have been recognized:

Palaeophycus Type A; Halfway point member; Plate 5-1a

Description: Thinly-lined elliptical tubes, 2 to 4mm in diameter, 25mm in exposed length, which are characteristically irregular, indented and partially collapsed. They are generally oriented sub-

Figure 5-1

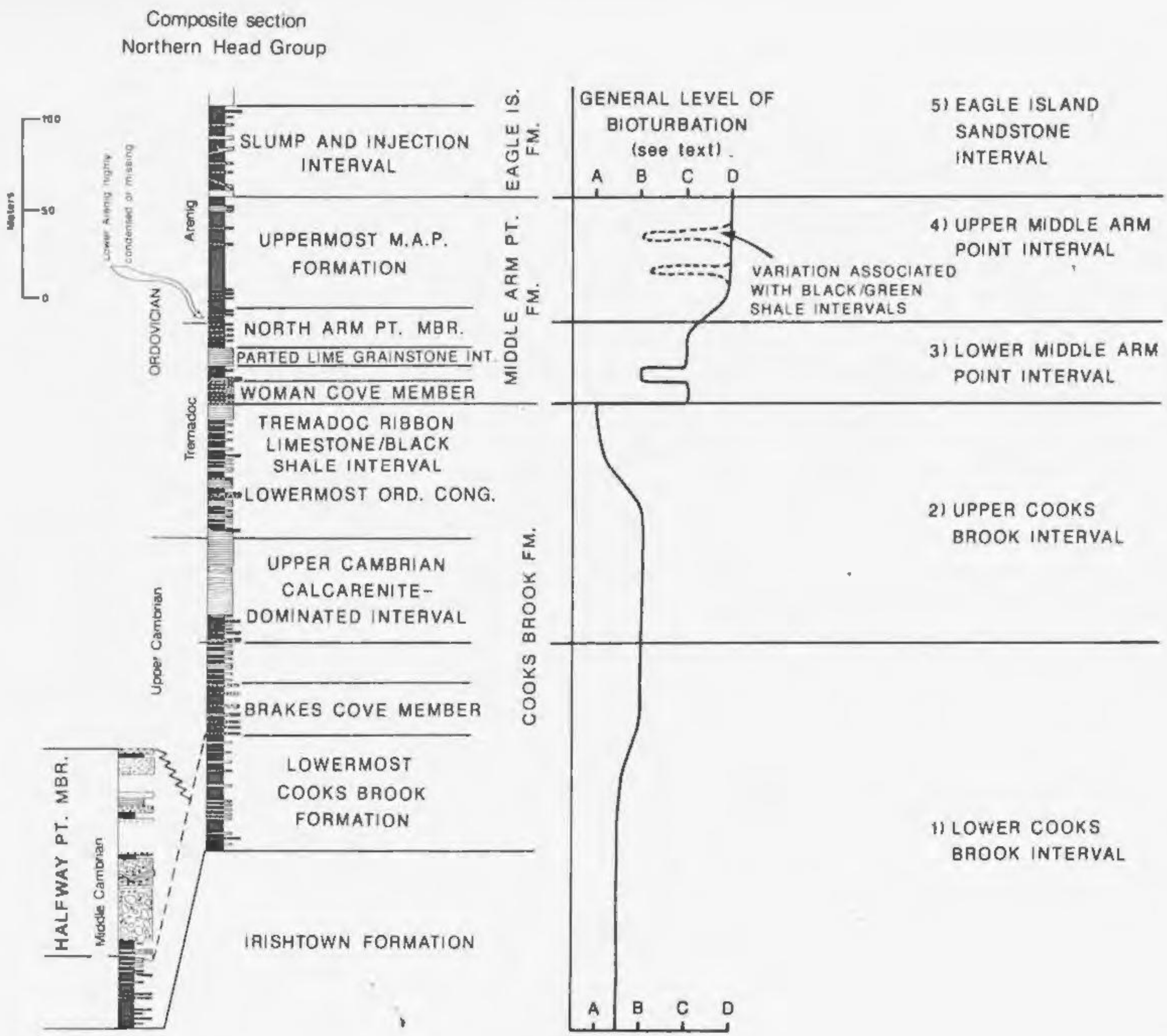
Trace fossil intervals and levels of bioturbation through the Northern Head group. Characteristics of bioturbation levels are as follows:

Class A: Fine laminations well-preserved, no bioturbation

Class B: Laminations well-preserved; isolated traces occurring on scattered bedding planes; traces generally small (< 3mm) and oriented only parallel to bedding.

Class C: Laminations and other small-scale sedimentary structures disrupted but still discernable; abundant traces commonly touching or intersecting; traces commonly larger than above (ranging up to 8mm in diameter) and both parallel to, and crosscutting bedding

Class D: No fine lamination preserved, other sedimentary structures rarely preserved, massive intervals common; traces of comparable size to Class C; traces at a high angle to bedding abundant.


Composite section
Northern Head Group
Meters
100
50
0
Lower Arenig highly condensed or missing
Arenig
ORDOVICIAN
Tremadoc
Upper Cambrian
Middle Cambrian
HALFWAY PT. MBR.
SLUMP AND INJECTION INTERVAL
UPPERMOST M.A.P. FORMATION
NORTH ARM PT. MBR.
PARTED LIME GRAINSTONE INT.
WOMAN COVE MEMBER
TREMADOC RIBBON LIMESTONE/BLACK SHALE INTERVAL
LOWERMOST ORD. CONG.
UPPER CAMBRIAN CALCARENITE-DOMINATED INTERVAL
BRAKES COVE MEMBER
LOWERMOST COOKS BROOK FORMATION
IRISHTOWN FORMATION
EAGLE IS. FM.
MIDDLE ARM PT. FM.
COOKS BROOK FM.
GENERAL LEVEL OF BIOTURBATION (see text)
A B C D
VARIATION ASSOCIATED WITH BLACK/GREEN SHALE INTERVALS
A B C D
5) EAGLE ISLAND SANDSTONE INTERVAL
4) UPPER MIDDLE ARM POINT INTERVAL
3) LOWER MIDDLE ARM POINT INTERVAL
2) UPPER COOKS BROOK INTERVAL
1) LOWER COOKS BROOK INTERVAL

parallel to bedding, but occur highly oblique to bedding in some layers. They occur within thinly interbedded silty lime grainstone and grey shale.

Palaeophycus Type B; Halfway Point member; Plate 5-1b

These are closely related to the above, but have been distinguished because they display a more regular wall structure and are somewhat smaller.

Description: Thinly-lined, partially flattened tubes 1 to 2mm in diameter, ranging up to 30mm in length but commonly 10 to 20mm. These are characteristically bedding parallel only, and occur on the base of fine to medium lime grainstone beds.

Syncoprulus Type A; lowermost Cooks Bk. Fm.; Plate 5-1c
(Northern Head section)

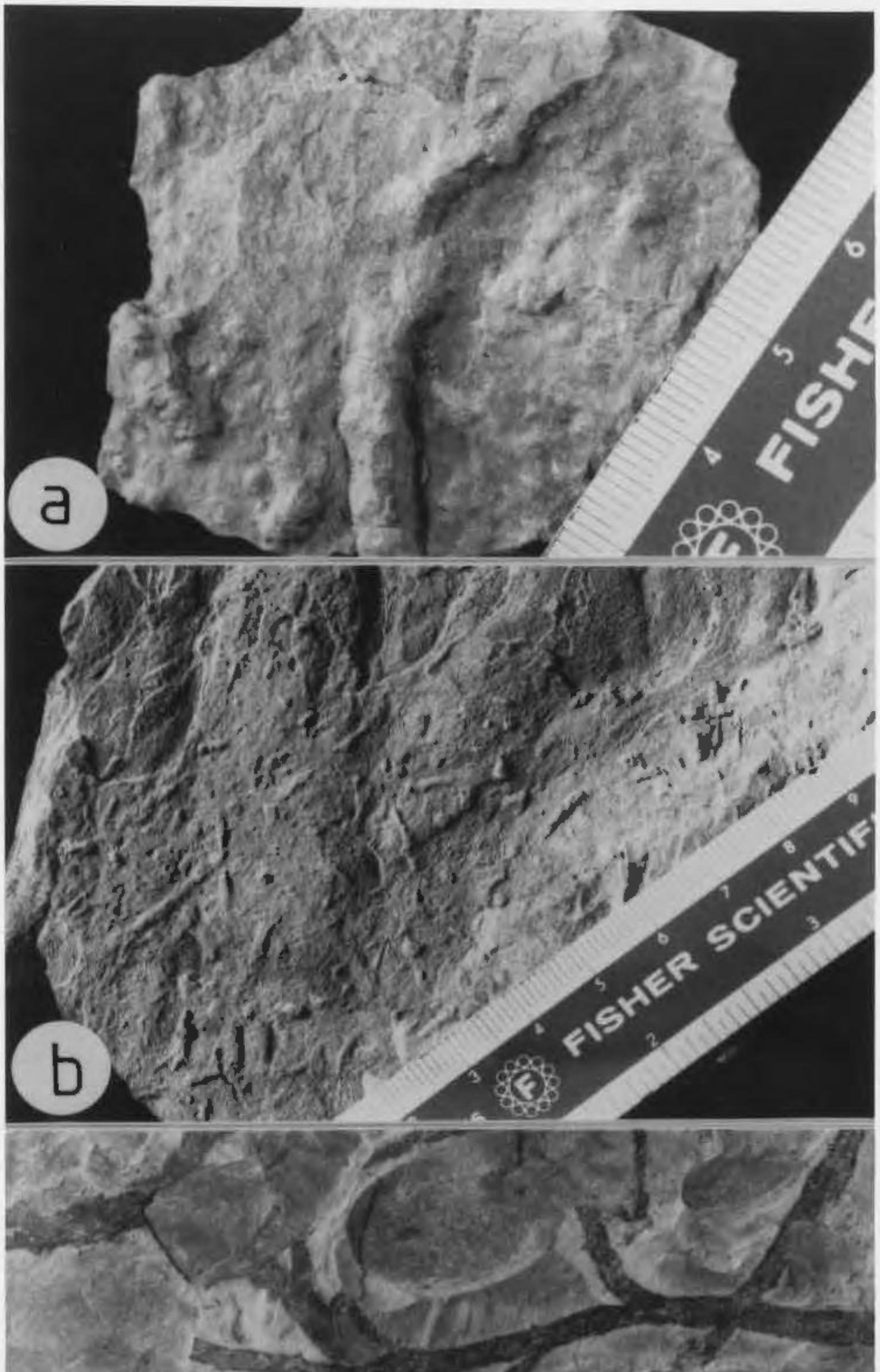
Description: Highly flattened, dark "films", 3 to 5mm in width and 150mm in total length, scattered on bedding planes of dolomitic green shale. These display an irregular dichotomous branching at roughly 15mm intervals, and are locally flattened, one atop another, at a high angle. Internally, they display a faint pelleted texture, comprising elliptical pellets less than 1mm in length.

PLATE 5-1: TRACES OF THE LOWER COOKS BROOK INTERVAL

a: Palaeophycus Type A

b: Palaeophycus Type B

c: Syncoprulus Type A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5.2 Upper Cooks Brook interval

Traces here occur within shale interbeds, and on the base of calcarenite beds, and are scattered through this interval at several localities. The density of traces on individual bedding surfaces is low. The following trace fossils are recognized:

Planolites Type A: Plate 5-2a

Description: Regular, smooth, elliptical tubes, .5 to .75mm in diameter and up to 70mm in exposed length. These occur as isolated, locally intersecting, straight to gently curving traces on individual bedding planes, parallel to bedding only, within grey shale interbeds. These generally occur alone, but locally co-occur with Planolites Type B described below.

Planolites Type B; Plate 5-2b

Description: Cylindrical tubes, .1 to .2mm in diameter, and up to 20mm in total exposed length. These commonly branch dichotomously at 3 to 10mm intervals. They are confined to individual bedding planes within grey, calcareous shale. The burrow-fill is commonly finely pyritized and subject to removal by weathering on exposed surfaces.

Palaeophycus Type C; Plate 5-2c

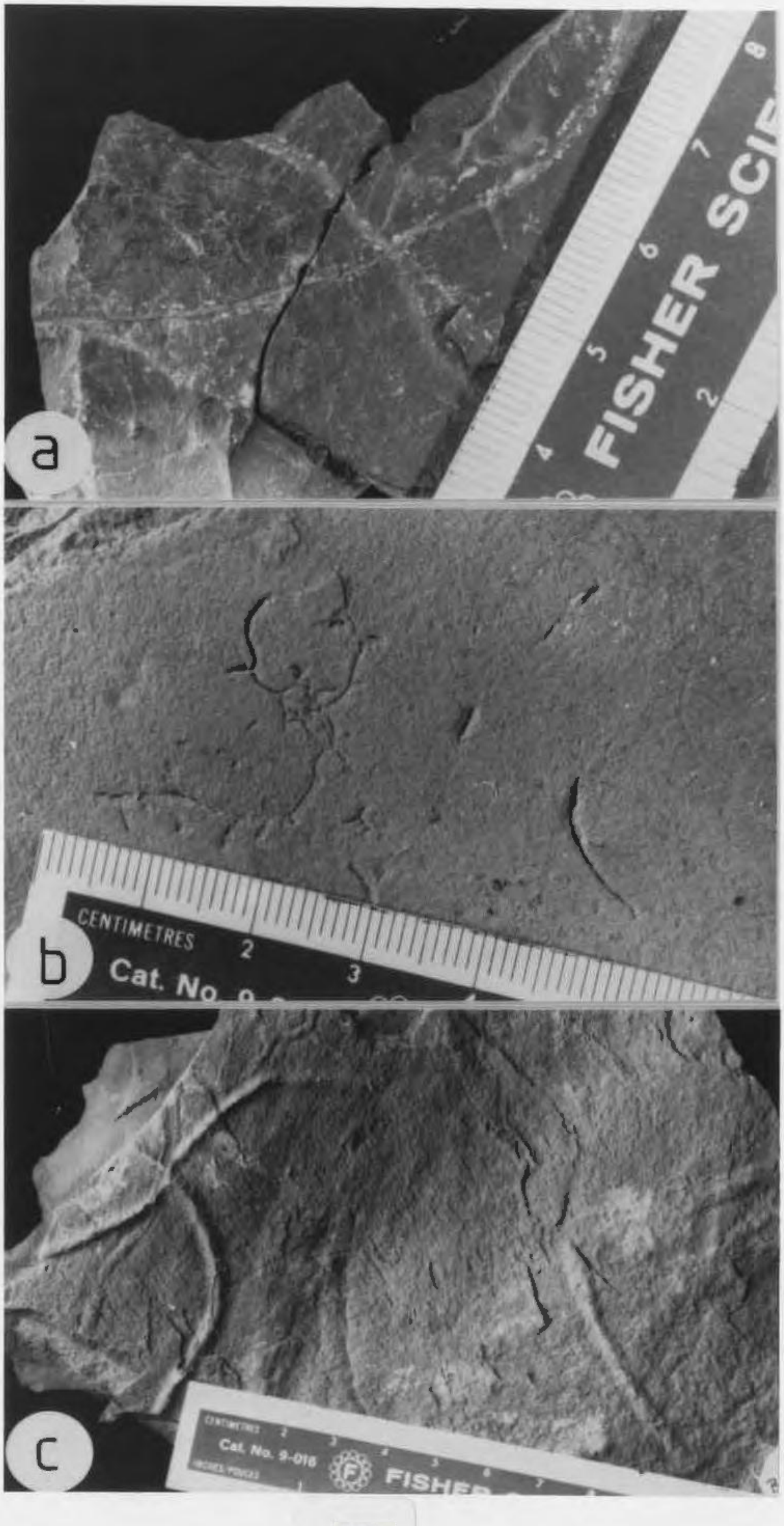
Description: Thinly-lined, partially flattened, elliptical tubes, 2 to 3mm in diameter and up to 100mm in length. These are gently sinuous, rarely branching, but locally intersecting and are confined to individual bedding planes in calcareous grey shale. These traces differ from the Palaeophycus described above in that they display a smoother, more regular wall structure, are generally longer and

PLATE 5-2: TRACES OF THE UPPER COOKS BROOK INTERVAL

a: Planolites Type A

b: Planolites Type B

c: Palaeophycus Type C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straighter, and never crosscut bedding.

Syncoprulus Type A; Plate 5-3a
As described above, occurring within thinly-bedded black and grey shale.

Syncoprulus Type B; Plate 5-3b and c
Description: Cylindrical tubes, 1 to 2mm in diameter and up to 400mm in length, which are generally straight and rarely branching. These are strictly bedding parallel and occur within laminated silty calcarenite. They are generally pyritized and commonly preserve a segmented burrow fill at 2 to 3mm intervals.

5.3 Lower Middle Arm Point Interval

As mentioned above, the intensity of bioturbation increases markedly in the silty dolostones of the Woman Cove member. A similar style of bioturbation, although not as intense, occurs higher in the Middle Arm Point, in the "dark lime grainstone interval" (described in Chapter 3). The following trace fossils have been recognized within the Woman Cove member:

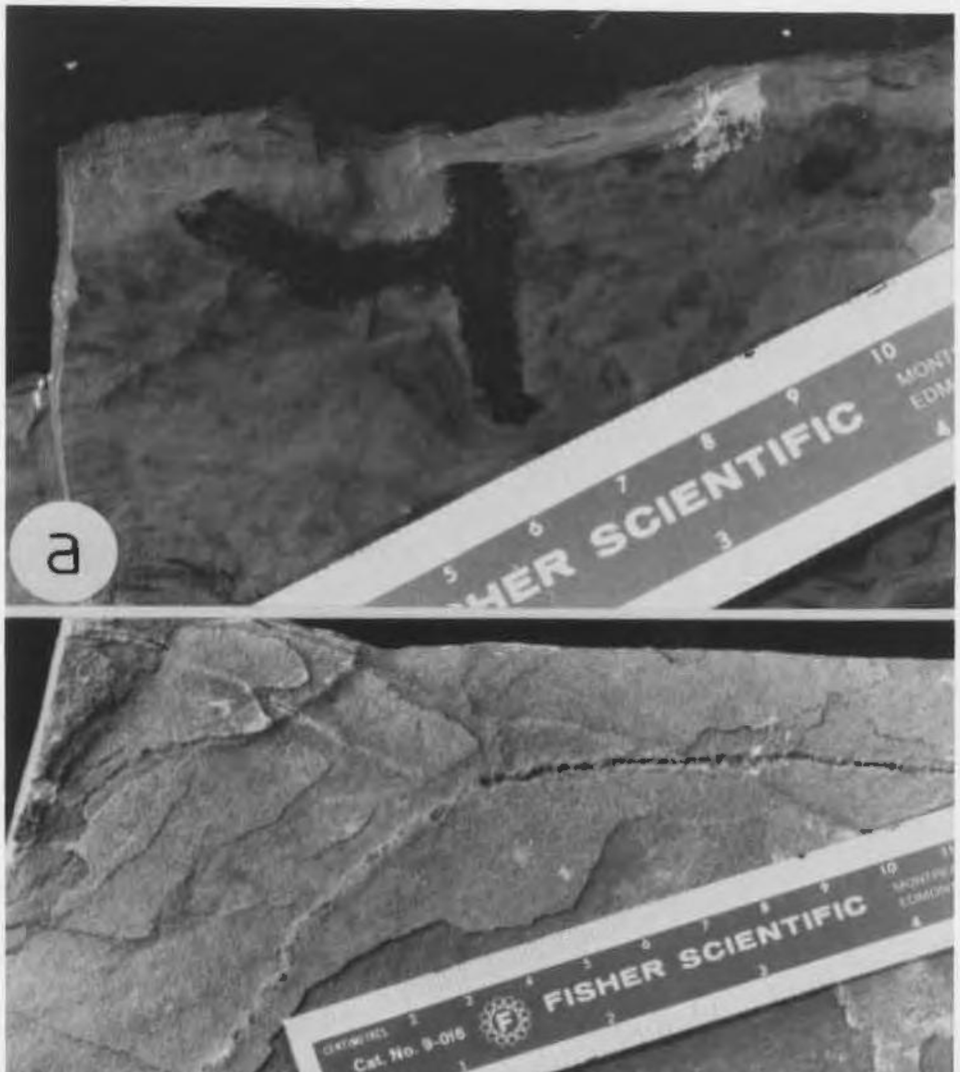
Palaeophycus cf. Type A; refer to Plate 4-7b, Plate 5-4a
Description: Thinly-lined, cylindrical tubes 3 to 8mm in diameter and up to 60mm in length (where parallel to bedding). These tubes are both bedding parallel and transect bedding at a high angle, where they are preserved as rounded "buttons" on bedding planes.

PLATE 5-3: TRACES OF THE UPPER COOKS BROOK INTERVAL (contd)

a: _Syncoprulus_ Type A

b: _Syncoprulus_ Type B

c: _Syncoprulus_ Type B; detail illustrating segmented, pyritized burrow-fill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These traces are most commonly preserved on the base of silty dolostone beds, but also occur on the base of individual cosets _within_ beds, and are always filled with silty dolostone. At least some of the vertical burrows were present during current reworking (or deposition) of the silty dolostone beds, since flute casts have locally been initiated in the lee of individual traces (see _Dolomite_ section, this chapter).

?_Cylindrichnus_ sp. ; Plate 5-4a

Description: Tubes, oriented at a high angle to bedding, cylindrical in cross-section and 4 to 5mm in diameter. Where silicified, these display a core, approximately 1.5mm in diameter surrounded by a concentrically thin-layered internal structure, extending to the burrow wall, which is roughly 1mm in thickness.

The assignment of above-described traces to the genus _Cylindrichnus_ is considered tentative. These traces are intimately associated with the _Palaeophycus_ described above and it is possible that the features described above represent merely variations in the preservation style of _Palaeophycus_. The subconical longitudinal profile described in _Cylindrichnus_ ~~by Chamberlain~~ (1978) has not been noted in vertical sections of these traces.

Planolites Type A; as described above; Plate 5-4a

1mm in diameter, gently sinuous, commonly weathered in relief

Traces within the "dark parted lime grainstone interval" are confined to carbonate beds, while shale interbeds are thinly-laminated, organic carbon-rich and unbioturbated. Both bedding parallel and steeply crosscutting traces are noted, and these range from 5 to 10mm in diameter. Preservation is not good, but these traces are broadly assigned to the genus Palaeophycus since a wall-lining several millimeters in thickness is commonly present and burrows are filled with material similar to the surrounding sediment (i.e. lime grainstone).

5.4 Upper Middle Arm Point Interval

This interval comprises variable levels of bioturbation, ranging from poorly bioturbated, banded black and green shale, through shale displaying regularly-spaced, discrete bioturbated horizons (see Shale section, Chapter 4), to thoroughly bioturbated, massive shale intervals. The only evidence of active bioturbation in carbonate sediment within the Northern Head group occurs within this interval. Traces are commonly difficult to characterize because of poor lithologic contrast or poor preservation within shale and hence are simply termed "bioturbation". The following traces have been recognized in massive, commonly intensely bioturbated shale units:

?Cylindrichnus sp. (?Palaeophycus); Plate 5-4b

Description: Lined, smooth-walled tubes, 2 to 4mm in diameter and generally 20+mm in length. These are generally oriented at a high angle to bedding over most of their length, but commonly bend to

PLATE 5-4: TRACES OF THE MIDDLE ARM POINT FORMATION

a: ?Cylindrichnus sp. (arrows); vertically oriented tubes, with well-developed burrow wall, concentrically-laminated burrow fill, with local preservation of a core

also

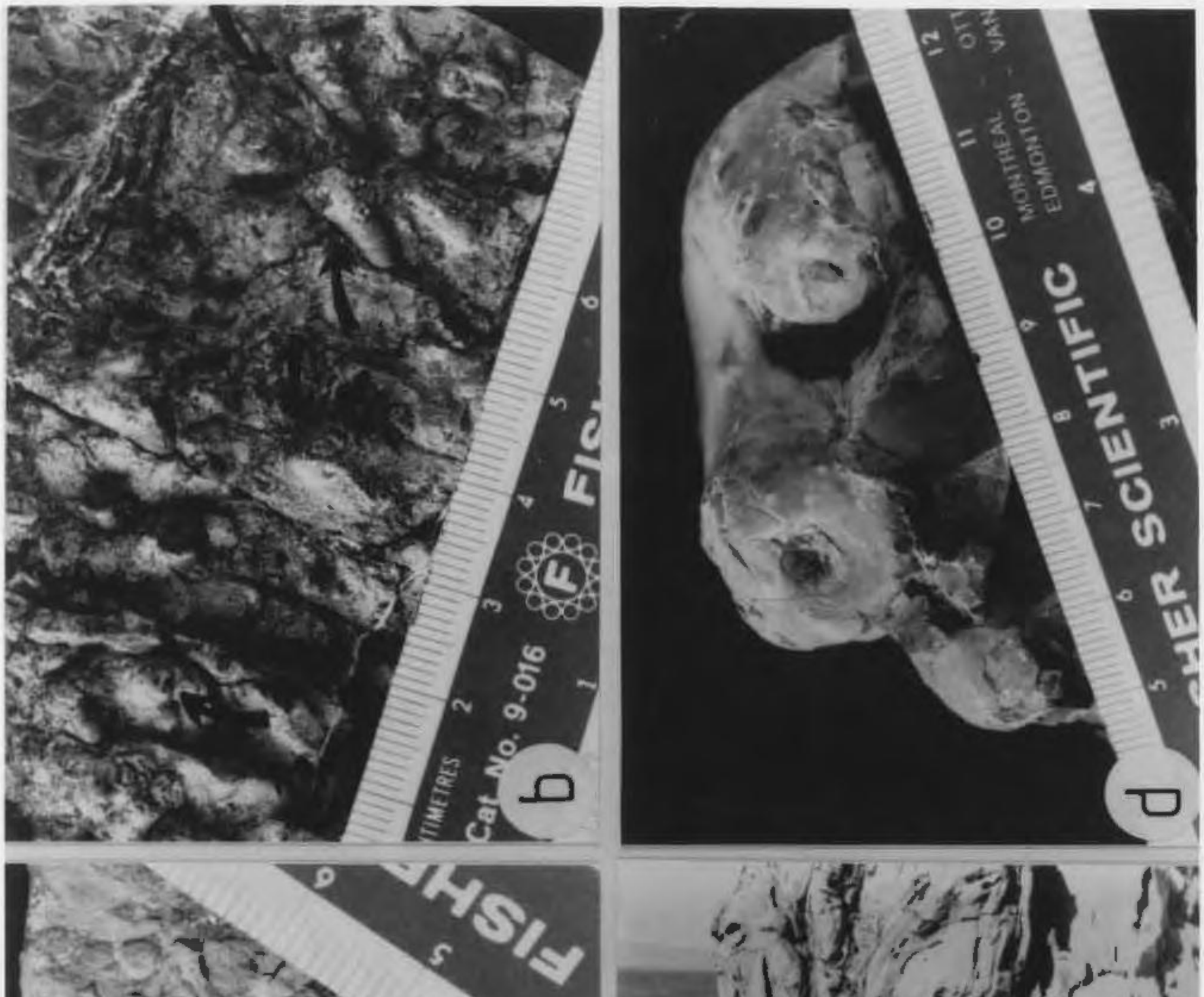
Palaeophycus Type A (P) and

Planolites Type A (Pl.)

b: ?Cylindrichnus (?Planolites) (arrows)

c: Palaeophycus Type D within lime mudstone/shale interval, Eagle Island North

d: Palaeophycus Type D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become gently oblique to bedding near the bottom. Tubes have a wall .5 to 1mm in thickness, a central core up to 1mm in diameter; and a concentrically-lined interior. These traces occur within massive green and red shale and are commonly filled with sediment containing a slightly higher silt component (dolomite and siliciclastic grains) than the host sediment.

It is only where these traces are preferentially silicified that any structure can be seen and bioturbation in massive shale units can be difficult to identify, collect or even recognize. It is, however, these traces, or ones of similar style, which are most widespread through this interval and constitute the most intense bioturbation in the Northern Head group.

Palaeophycus Type D; Plate 5-4c and d

Description: Thick-walled cylindrical tubes 1 to 2cm in diameter and up to roughly 8cm in length, oriented subparallel to bedding. Tube walls are composed of lime mudstone and are 2 to 3mm thick. Cores are either hollow or filled with coarse-crystalline calcite and locally contain a final fill of quartz or pyrite.

These burrows are densely concentrated in a 3m thick unit of lime mudstone within the uppermost Middle Arm Point at Eagle Island North. This unit, and this style of bioturbation occurs only at this locality. The lower 2m of this unit comprises thoroughly bioturbated lime mudstone beds 5 to 15cm thick and these traces also occur within shale interbeds here and in the overlying 1m transition into green shale (Plate 5-4c).

The following traces are commonly associated with thin-bedded shale units and are characteristic of the bioturbated portions of the black/green shale lithologic association discussed in the Shale section, Chapter 4.

Syncoprulus Type A; Plate 5-5a

These are similar to those described above. They are highly flattened, pelleted, straight, generally unbranched, black impressions up to 8mm wide and 100mm long. They occur isolated, and locally crossing, on shale bedding planes, commonly alone or in association with the ?Chondrites described below.

?Chondrites; Plate 5-5b

Description: Highly flattened dark impressions 2mm in width and roughly 20mm in length which branch at roughly 4mm intervals. These occur relatively sparsely, always in association with the above, within thin-bedded shale intervals.

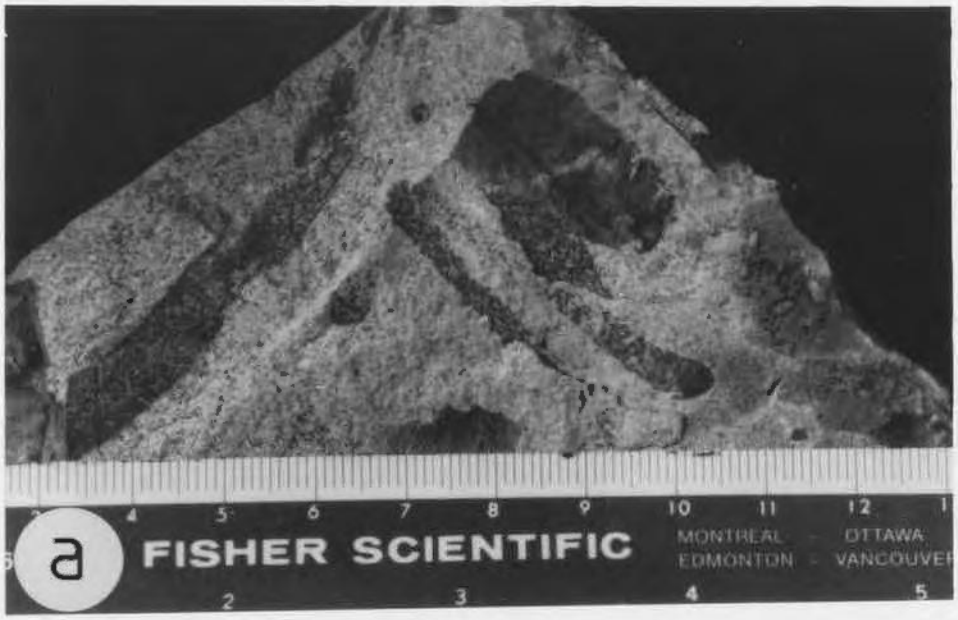
5.5 Eagle Island Formation

A different assemblage of trace fossils accompanies the lithologic change into sandstones of the Eagle Island Formation. Traces most commonly occur on the base of thin to medium-bedded fine sandstone. The following traces have been recognized in this interval:

PLATE 5-5: TRACES OF THE MIDDLE ARM POINT FM. (contd.)

a: Syncoprulus Type A

b: ?Chondrites; generally associated with the Syncoprulus Type A illustrated in the preceding photograph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EDMONTON - VANCOUVER


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Protopaleodictyon sp.; Plate 5-6a

Description: Branching, meandering tubular burrows, roughly 4mm in diameter, which anastomose to produce an imperfect Paleodictyon-type network.

Cosmorhaphe Type A; Plate 5-6b

Description: An unbranched tubular trace 2mm in diameter which displays meanders on two orders. First order meanders are somewhat irregular, forming tight curves with an amplitude of roughly 5cm. Second order meanders are more gently and regularly sinuous, with an amplitude of 1cm.

Cosmorhaphe Type B; Plate 5-6c

Description: Similar to the above, but tubes are generally larger, 5 to 7mm in diameter, and meanders are tighter (i.e. of reduced wavelength relative to amplitude). Amplitude of first order meanders is 10+cm, and of second order meanders: 5cm.

Planolites ?Type B; Plate 5-6b

This is similar to that described above, but slightly larger (diameter .5mm) and not pyritized. Branching style is similar.

5.6 Discussion and Interpretation

5.6.1 Nomenclature

The informal nomenclature scheme used herein is adopted to discriminate recognizably distinctive traces, while avoiding the unnecessary proliferation of species names (especially within

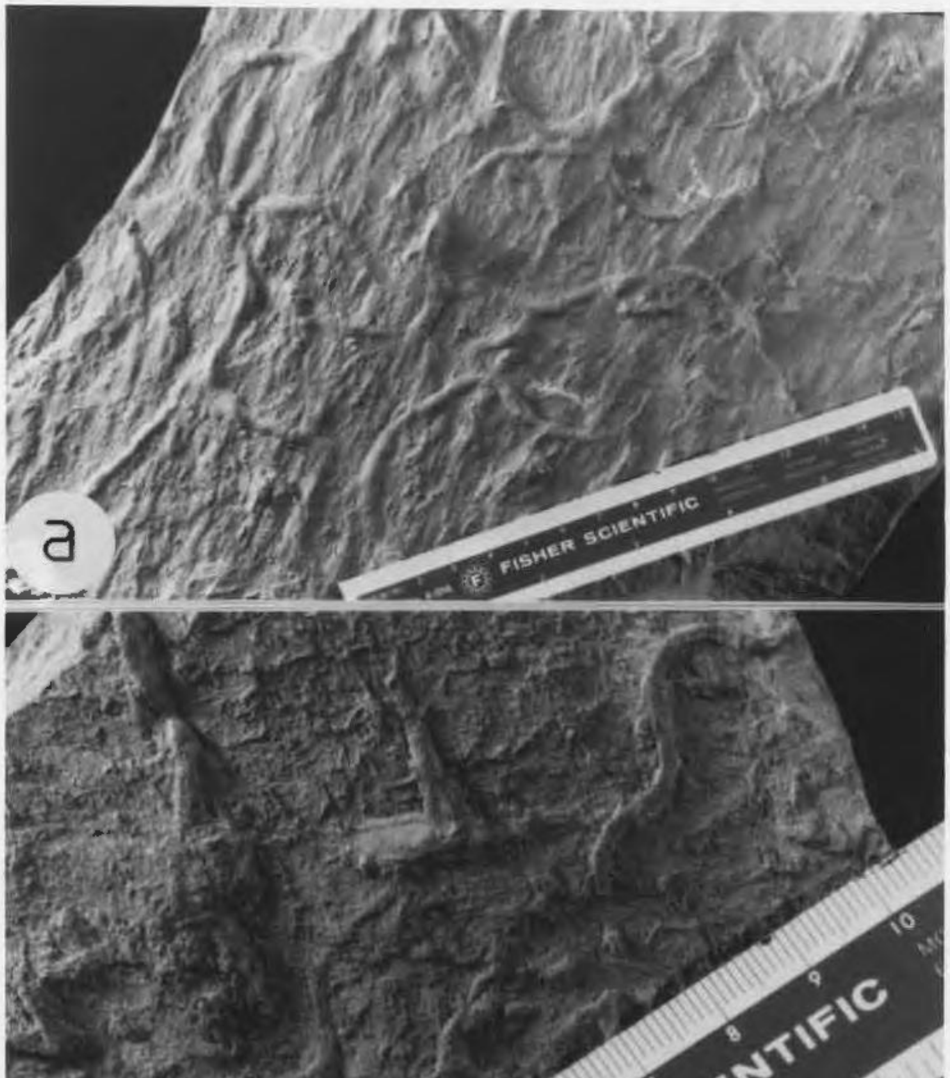
PLATE 5-6: TRACES OF THE EAGLE ISLAND FORMATION

a: Protopaleodictyon; Eagle Island Formation

b: 1) Cosmorhaphe Type A; larger meandering traces

2) Planolites ?Type B; smaller traces

c: Cosmorhaphe Type B; Eagle Island Formation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b
15 cm.
c

Palaeophycus and Planolites; cf. Pemberton and Frey, 1982). The general similarity of Palaeophycus Type A, B, and C with Palaeophycus tubularis (Pemberton and Frey, 1982) and Palaeophycus Type D with P. heberti (ibid.) has been pointed out to the author (G. Narbonne, pers. comm., 1987).

5.6.2 Environmental setting

The assemblages of trace fossils which span the Northern Head group are consistent with a deep-water setting; the recognized genera described above can be readily assigned to the Nereites Ichnofacies of Seilacher (1967) and the relatively low diversity exhibited is typical of such an environment (Seilacher, 1978). Two broadly contrasting trace fossil assemblages appear in discussions of deep-water environments:

1) A (siliciclastic) "flysch-related assemblage" (Crimes, 1977; Seilacher, 1977; Ekdale et al., 1984) with a relatively diverse fauna dominated by horizontal trails and burrows, particularly graphoglyptids (such as Paleodictyon and Cosmorhaphe).

2) An "abyssal assemblage", where principal trace fossils include Chondrites, Planolites, Teichichnus and Zoophycus. Studies of recent deep-ocean sediment (Ekdale, 1977; Ekdale et al., 1984) suggest that traces in the modern pelagic environment are abundant, poorly preserved, and produced mainly by infaunal, deposit-feeding vermiform animals. In clay-dominated environments below the CCD, the trace fossil assemblage is commonly dominated by Planolites (Ekdale et al., 1984).

The contrast of these two loosely-defined assemblages is clear in comparing the Northern Head group (affinities with "abyssal assemblage") and the overlying Eagle Island Formation ("flysch-related assemblage").

5.6.3 Significance of stratigraphic variation in bioturbation levels

It is difficult to quantify levels of bioturbation within a thick sequence such as the Northern Head group, because of the local variability which occurs within any given interval and because of the preservational factors of different lithologies and different types of trace fossils. Factors such as i) the preservation of fine lamination (cf. Bralower and Thierstein, 1984), ii) density of traces per unit volume of rock, iii) types of trace fossils and iv) dominant orientation of traces are considered important. To give the reader an impression of the stratigraphic variation in bioturbation levels through the Northern Head Group the intervals discussed above have been broadly classified according to the following scheme and are displayed in figure 5-1.

Class A: Fine laminations well-preserved, no bioturbation.

Class B: Laminations well-preserved; isolated traces occurring on scattered bedding planes; traces generally small (< 3mm) and oriented only parallel to bedding.

Class C: Laminations and other small-scale sedimentary structures disrupted but still discernable; abundant traces commonly touching or intersecting; traces commonly larger than above (ranging up to 8mm in diameter) and both parallel to, and crosscutting bedding.

Class D: No fine lamination preserved, other sedimentary structures rarely preserved, massive intervals common; traces comparable in size to Class C; traces at a high angle to bedding abundant.

Figure 5-1 is generalized, and the variability of bedding styles and bioturbation in, for example, the uppermost Middle Arm Point interval is not portrayed (see discussion below). Because of the pronounced shift in lithology and depositional environment, the Eagle Island Formation is not included. The feature of note is the marked increase in bioturbation at the base of the Middle Arm Point Formation, in contrast with the paucity of bioturbation through the underlying (lower) Tremadoc interval.

A comparable six-category classification scheme has recently been advanced Droser and Bottjer (1986), but the simpler scheme presented here best reflects the nature of the Northern Head group.

5.6.4 Implied levels of oxygen in the depositional environment

Based upon their levels of dissolved oxygen, marine waters may be broadly characterized as aerobic (> 1 ml/l dissolved O_2), dysaerobic (.1 to 1 ml/l) or anaerobic (< .1 ml/l) (Rhoads and Morse, 1971; Byers, 1977). Faunal communities in marine environments decrease in diversity and size of individuals with decreasing oxygen levels, from commonly rich, diverse communities under aerobic conditions, to a restricted (commonly vermiform) infaunal community under dysaerobic conditions to a complete lack of benthos under anaerobic conditions (ibid.). Moreover, decreasing levels of dissolved oxygen at the sea-floor restrict the depth of penetration and occupation of sediment by infauna (Savdra and Bottjer, 1986), so that at low oxygen levels fauna may be confined to very shallow levels and resultant traces will be predominantly bedding parallel. With increased bottom-water oxygen levels, vertical burrows may be developed as infauna test oxygen levels within the sediment (cf. Jordan, 1985).

Based upon the above discussion, the bioturbation pattern through the Northern Head group suggests that dysaerobic to locally anaerobic depositional conditions persisted through the deposition of the Cooks Brook Formation, with an apparent marked upward increase in levels of dissolved oxygen commencing at the base of the Middle Arm Point Formation (late Tremadoc). An increase in ambient dissolved oxygen from low background levels commonly results in individual-rich, low diversity faunal communities (Seilacher, 1978), and this seems to be the case at the Cooks Brook/Middle Arm Point Boundary. The continued low diversity and persistence of unbioturbated intervals within the Middle Arm Point suggests that despite this relative increase in Eh, depositional conditions probably still fluctuated within the dysaerobic zone.

An inverse relationship between bioturbation intensity (and trace fossil diversity) and the amount of unoxidized organic carbon preserved in the host sediment has been demonstrated in the Cretaceous (Ekdale, 1985) and this pattern is also reflected in the Northern Head group (Shale section, Chapter 4; Chapter 6). The notable exception to this is the "dark parted lime grainstone interval", where an anomalous concentration of organic carbon has been preserved in the presence of elevated bioturbation. It is possible in this case that infauna were brought in with the redeposited carbonate of this interval (cf. Byers, 1977).

The association of Chondrites with Syncoprulus Type A in the upper Middle Arm Point has been noted above. This association, and the similarity in overall form of these traces suggests that they may represent similar environmental conditions. The presence of Chondrites alone is generally regarded as representing very low ambient dissolved oxygen levels (Ekdale, 1985; Bromley and Ekdale, 1984; Ekdale et al., 1984). Within Cretaceous pelagic sediments Chondrites appears alone in zones immediately adjacent to unburrowed horizons (Ekdale, 1985). Within Devonian black shales, Chondrites is regarded as the trace of a "pioneer" burrower within black mud, while Planolites is regarded as the trace of a mobile deposit-feeder, which, where vertical, represents the testing of oxygen levels within sediment overlain by relatively oxygenated bottom waters (Jordan, 1985). The same variation in style of bioturbation appears in the upper Middle Arm Point, where Syncoprulus/Chondrites is noted on the mildly bioturbated margins of black/green shale intervals, developed under temporarily lowered Eh conditions, while Cylindrichnus (?Planolites) is dominant within extensively bioturbated red/green shale intervals, deposited under better oxygenated conditions (see Shale ~~section~~, Chapter 4).

Trace fossil diversity in "neritic" and "flysch" facies remained relatively constant through the Lower Paleozoic (Seilacher, 1978), and it is considered unlikely that the increase in bioturbation level within the Northern Head Group is the result of any marked evolutionary faunal change. It might be argued that the elevated levels of bioturbation within the Middle Arm Point merely reflect a decrease in sedimentation rate; however, the fact that the upward increase in bioturbation occurs in concert with sedimentologic (Chapter 4), diagenetic (Chapter 6), and geochemical (Chapter 7) changes indicates a real upward increase in the Eh of depositional conditions, which began in the Tremadoc.

CHAPTER 6

DIAGENESIS

Introduction

This chapter is divided into two sections; the first provides a general description of the diagenetic processes of calcite cementation, dolomite cementation, replacement and overgrowth, silicification, authigenic growth of barite, and pyritization, and relates these in a diagenetic sequence. The second part puts some of these diagenetic processes in a stratigraphic perspective, focusing on the contrasting nature of early diagenesis in the Northern Head Group. The principles of early burial diagenesis and its control on changing Eh conditions are reviewed in Appendix G.

6.1 OVERALL DIAGENETIC SEQUENCE

6.1.1 Cementation by calcite

Calcite cementation has been examined in a variety of lithologies, including conglomerate (both within clasts and matrix), granule conglomerate, and calcarenite. Calcite diagenesis within finer grained lithologies (lime mudstone) reflects a path of aggrading neomorphism of lime mud. Cementation of the silty dolostones described in Chapter 4 is dominated by dolomite and silica, with calcite occurring only rarely as a late-stage patchy cement and localized replacement.

Notwithstanding plastically-folded lime mudstone rafts, clasts within conglomerates display evidence of early cementation and lithification. Many angular clasts are clearly derived from extension fracturing and may display evidence of matrix injection along cross-cutting fractures (refer to Chapter 4; Plate 4-9b). Rounded clasts display evidence of a uniform abrasion of allochems and interstitial cement at their margins, suggesting that they were thoroughly lithified before tranportation and incorporation in the host conglomerate. The precipitation of calcite cement <u>within</u> these clasts (in coarser conglomerate), and <u>between</u> grains in bedded units of granule conglomerate and calcarenite follows an essentially identical pattern, suggesting that the process of calcite cementation occurred under similar diagenetic conditions, and was early in all cases.

6.1.1.1 <u>Calcite cementation in clasts within conglomerate</u>

A survey of clast lithologies within conglomerates reveals the prominence of sparry calcite cement. The first generation of this cement is commonly an isopachous rim of acicular to bladed non-ferroan calcite crystals. The thickness of this rim is generally approximately 30 micrometers and it is usually composed of a single generation of crystals which display bladed terminations. It is particularly well-developed in oosparite, but overgrows a variety of grains. This is followed by a generation of blocky, equant spar which increases in crystal size toward the centre of pores, ranging from 30 micrometers in size locally up to roughly 400 micrometers (Plate 6-1a). This size increase is commonly accompanied by an increasing ferroan content, as indicated by staining. The sharp planar crystal boundaries, clear enfacial angles and lack of any remnant recrystallization fabrics within this spar confirm its origin as a cement. The final stages of spar precipitation are locally accompanied by the growth of euhedral ferroan dolomite crystals, which range in size up to 200 micrometers and display a subtle Fe-enrichment from core to rim. Locally, the generation of acicular to bladed rimming cement is missing and only blocky, equant spar is present.

6.1.1.2 Cementation within granule conglomerate and calcarenite

The style of cementation between grains in these lithologies is similar to that described above. A geopetal style of pore-filling is noted locally, where the early, rimming acicular to bladed cement is confined to one (upper) margin of pores, with the remainder of the pores filled with either coarse, blocky non-ferroan to ferroan sparry cement, or a generally finer and more irregularly crystalline ferroan sparry material. Based upon the irregular crystal size and shape, and remnant domains of micrite within this material, it is regarded as microspar to pseudospar which has grown under conditions of aggrading neomorphism. In some cases, the early acicular rimming cement is grain-specific, and only overgrows micritic grains. Within calcarenites, it is locally "shelter porosity", created by shell fragments, which is occupied by this style of cement.

The blocky equant spar ranges in crystal size from 20 micrometers at pore margins up to roughly 100 micrometers at pore centres, and generally displays the trend toward late-stage Fe enrichment described above. Within finer-grained calcarenites and lime mudstones, this Fe-enrichment is confined to the fine crystalline cement which occurs at both margins of cm-scale beds, suggesting that "marginal aggradation" (cf. Coniglio, 1985) has taken place in the presence of a more evolved, Fe-enriched pore water.

Many grains within granule conglomerates, in particular, display thin "micrite envelopes" (cf. Bathurst, 1971). Although the relationship cannot be directly demonstrated, the presence of very fine algal boring has been noted here and is thought to be responsible for this thin layer of alteration at grain margins.

Lime mudstone grains, generally peloidal, are most commonly only slightly recrystallized, but locally display a complete spectrum of neomorphic fabrics. They range from pristine micrite through microspar and patchy development of pseudospar. In extreme cases, relic peloids are defined by isopachous rims of blocky, fine-crystalline, generally non-ferroan spar which surround patchily recrystallized domains. Accompanying shell fragments are also recrystallized in such cases.

The syntaxial overgrowth of pelmatozoan grains is present throughout this lithology..

Dolomite is present within these lithologies in three forms, as: i) detrital grains with a generally ferroan overgrowth, ii) interlocking masses ("clumps") of dolomite which appear to represent complete replacement of certain grains (refer to <u>Dolomite</u> section, Chapter 4) and iii) isolated euhedral, generally non-ferroan crystals which occur interstitial to grains, and locally as replacements at grain margins, which appear to have precipitated immediately prior to, or locally coeval with, the equant sparry cement. The nature of dolomite occurrence will be discussed in the Dolomite section to follow.

The final episode of cementation is generally the widespread infilling of remaining pore space with amorphous to fine-crystalline silica.

6.1.2 Dolomite

Dolomite appears within the Northern Head group in three ways: i) as a component of cement, ii) as a replacement of certain allochems, and iii) as allodapic detrital grains, which generally display euhedral overgrowth. As indicated in Chapter 4, detrital dolomite is conspicuously prominent within the Middle Arm Point Formation.

6.1.2.1 Dolomite as a cement

The occurrence of dolomite as a cement component has been mentioned above, and it appears that this precipitation has occurred at various stages during the diagenetic sequence. Euhedral non-ferroan dolomite appears early within calcarenite and granule conglomerate, where it has been precipitated (locally as a replacement) at grain margins, prior to, or coeval with, blocky spar cement. Dolomite is also present within conglomerate cement, where it occurs as large, euhedral ferroan grains (displaying ferroan enrichment outward) which postdate the main phase of blocky spar cementation, and immediately predate the final diagenetic phase of silica cementation (and localized replacement) (Plate 6-1b). Thus it appears that dolomite precipitation spans the phase of calcite cementation described above, and in so doing, reflects the overall trend toward increasing Fe-enrichment through the diagenetic sequence.

6.1.2.2 Dolomite as a replacement of grains and intraclasts

The presence of dolomite as a replacememt of grains and intraclasts has been documented in Chapter 4, and mentioned above. This replacement appears in partial to complete stages of development where it has resulted in interlocking masses of generally euhedral dolomite crystals. The host grains are most commonly micritic peloids and intraclasts.

Based upon petrographic evidence, the timing of this replacement is variable, and ranges from an early process, which occurred prior to transport and redeposition (detrital dolomite), to later, in situ replacement. In the first case, dolomite crystals are sharply truncated by abrasion at grain margins (Plate 6-1c), while in the second case euhedral crystals extend into adjacent areas of cement and matrix, and dolomitization appears to have been in situ and coeval with cementation and neomorphism (Plate 6-1d).

Two principal styles of in situ replacement are noted. In the first case dolomite is characterized by euhedral crystals roughly 30 to 60 micrometers in size. In the second case, dolomite is generally anhedral and of much smaller crystal size (roughly 10 micrometers). This second style of dolomitization commonly appears to be intimately associated with aggrading neomorphism of the surrounding micritic matrix, and locally also partially replaces bioclastic debris (shell fragments).

The stage at which dolomitization occurred broadly reflects the trend toward increasing Fe-enrichment through the diagenetic sequence. The early-dolomitized grains and intraclasts are generally non-ferroan, while later dolomites are commonly ferroan, either within crystals or as a finely crystalline to amorphous ferroan dolomitic "paste" surrounding crystals, or encapsulating the entire cluster of previously-precipitated dolomite. This observation is complicated by the locally observed recrystallization of dolomite, where early, coarse, non-ferroan dolomite crystals (60 to 100 micrometers) have been replaced by finer (30 micrometer) ferroan dolomite crystals (Plate 6-2a).

6.1.2.3 Dolomitic grain overgrowth

The pronounced appearance, within the Middle Arm Point Formation, of dolomite crystals which display abraded, detrital cores and commonly Fe(Mn)-rich overgrowths has been noted in Chapter 4. It is difficult to relate this episode of overgrowth to the timing of calcite cementation described above, since the two processes do not generally co-occur. Diagenesis within the silty dolostones of the Middle Arm Point Formation is dominated by dolomite overgrowth and localized fine-crystalline cementation and silicification. The rare occurrence of calcite within this lithology is noted as a patchy, scattered late replacement at dolomite crystal margins and locally cores, predating final silica cementation.

The ferroan overgrowth of dolomite grains is locally accompanied by a fine-crystalline, anhedral ferroan dolomite cement which occurs interstitially to dolomite rhombs, immediately predating or coeval with silica cementation. This is of identical composition, and is clearly of the same generation, as the ferroan dolomite overgrowth. As discussed previously, the overgrowth was procipitated *in situ*; it is never abraded, is locally excluded at grain contacts, and locally incorporates multiple abraded grains.

6.1.2.4 Dolomite populations within the Middle Arm Point Formation

Petrographic examination, using staining and cathodoluminesence, indicates that there are two principal populations of dolomite within the Northern Head group. The first is most commonly non-ferroan, commonly occurs in interlocking clusters, and is interpreted to be the result of the dolomitization of limestone grains and intraclasts. This dolomitic replacement may have occurred before grain transport (and in this case dolomite is non-ferroan) or may have occurred *in situ*, in which case the resulting dolomite displays ferroan enrichment to a variable degree. The second population consists of dolomite crystals which display irregular, abraded, detrital cores and ferroan rims.

The first population of replacement dolomite dominates the Cooks Brook Formation, while a mixture of the two end-members occurs within silty dolostones of the Middle Arm Point Formation. At the transitional base of the Middle Arm Point (base of the Woman Cove member) silty dolostone is dominated by interlocking clusters of non-ferroan dolomite (dolomitized intraclasts) encapaulated in a ferroan rim. In general the percentage of "replacement dolomite" sharply diminishes upward through the Middle Arm Point and silty dolostones higher in the section are dominated by dolomite which has incorporated variable amounts of Fe and Mn in euhedral overgrowth.

6.1.3 Silicification

The presence of amorphous to microcrystalline silica as a final stage of cementation has been noted above in a variety of lithologies: conglomerate, granule conglomerate, calcarenite, silty dolostone and shale. The particular abundance of pervasive silica cementation (and localized replacement) within the Ordovician, where it has resulted in the formation of cherts, has been demonstrated in Chapter 4. Here the common association of chertification with biogenic debris, and implied derivation of silica through processes of early dissolution and re-precipitation of biogenic silica has also been indicated.

Silica cement (and localized replacement) formed at several stages in the diagenetic history, and silicification appears to have been a protracted process.

The precipitation of silica is very rarely observed to predate carbonate precipitation within the Northern Head group. It occurs as a late final pore-filling cement within granule conglomerate, for example Plate 6-2b, and surrounds overgrown dolomite grains within silty dolostone (Plate 4-7d). Corrosion and replacement of carbonate grains by silica has been noted locally in a variety of lithologies. In this sense, the precipitation of silica, whether as a late-stage pore-filling following extensive carbonate cementation, or as a pervasive microcrystalline cement which has permeated the clay matrix and surrounds a variety of grains, appears to represent a

PLATE 6-1: CALCITE AND DOLOMITE CEMENT, DOLOMITE GRAINS

a: Photomicrograph of oosparite displaying calcite cement fabrics; first generation of bladed cement (b) rims oolites (o) and is postdated by pore-filling blocky spar (s) which increases in crystal size and ferroan content toward pore center; scale bar is .1 mm.

b: Photomicrograph of dolomitic conglomerate cement. Euhedral dolomite grains are ferroan and display ferroan enrichment outward (note dark rim). Final silica cement (Si) contains scattered, anhedral ferroan calcite; scale bar is 1 mm.

c: Photomicrograph of dolomite grain within calcarenite. Dolomite "cluster" (left) represents the early replacement of a calcitic grain, and displays abrasion of dolomite crystal (arrow) at cluster margin; scale bar is .1 mm.

d: Photomicrograph of dolomite within calcarenite. Dolomitic "cluster" ("Dol" center, outlined) displays irregular, intergrown relationship with surrounding, spar-cemented peloidal grainstone; scale bar is .1 mm.

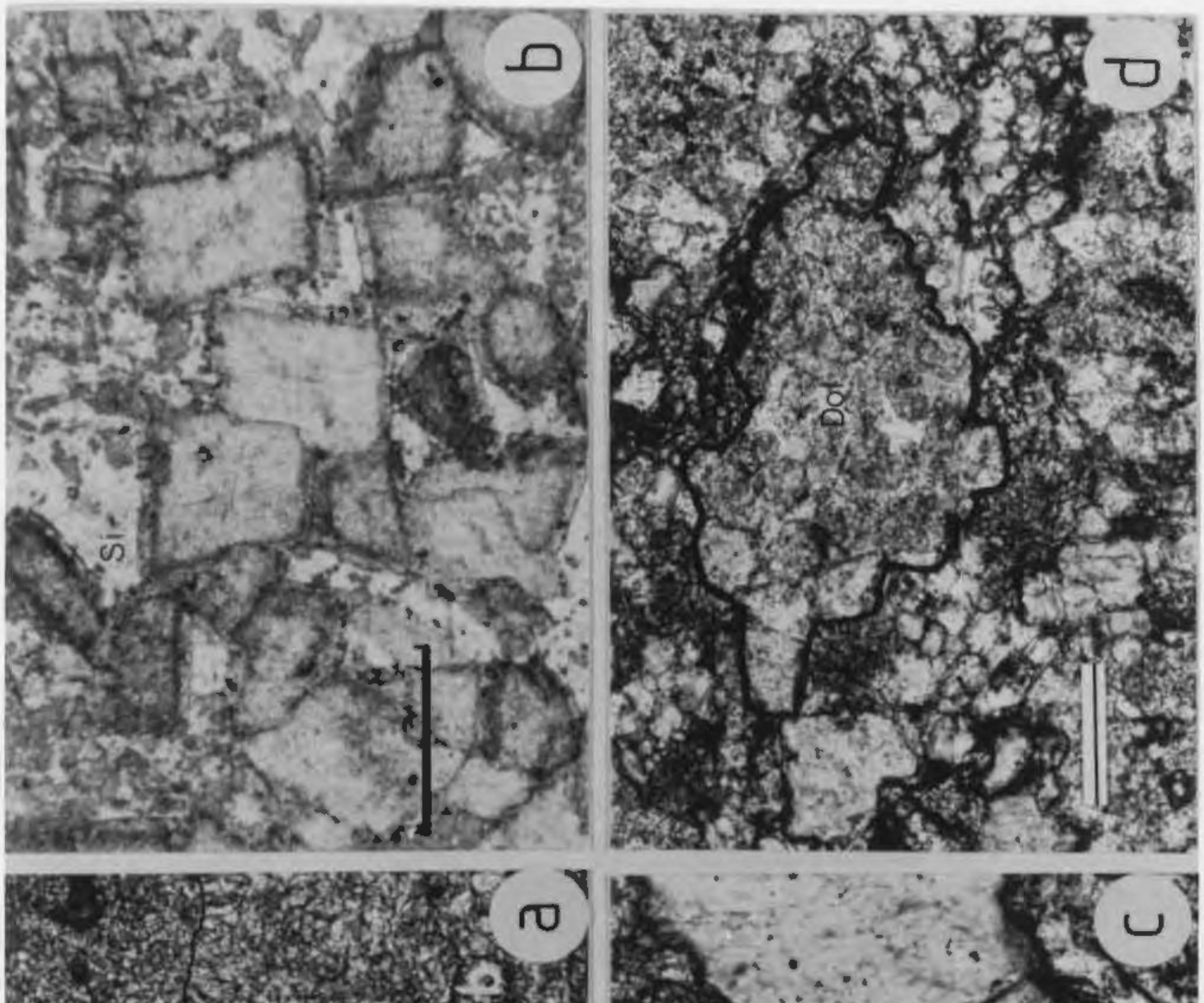

a
b
c
d
Si
Dol

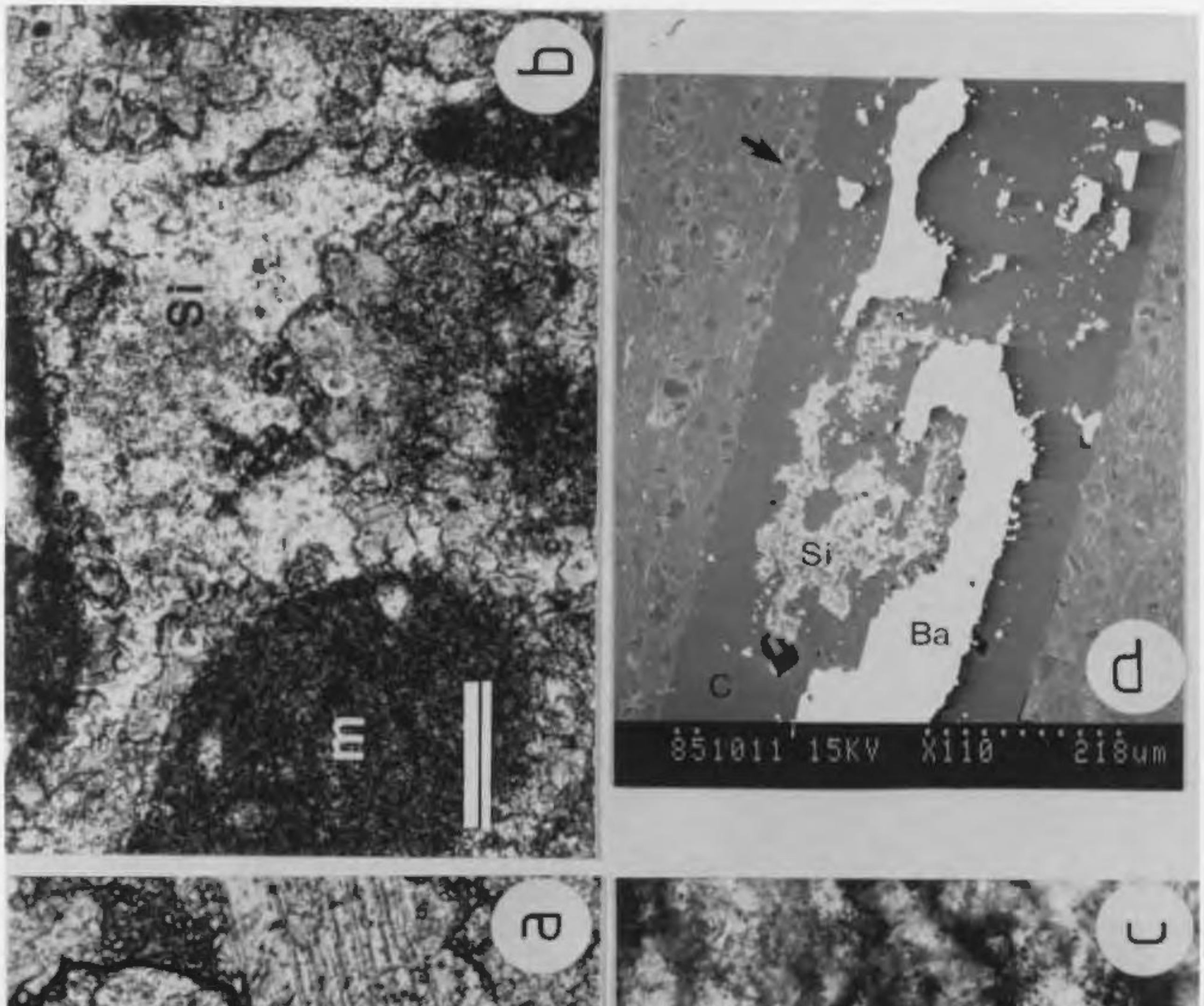
PLATE 6-2: DOLOMITE (contd); SILICA; HEMATITE; BARITE

a: Photomicrograph of dolomite grain within granule conglomerate. Original coarse dolomite crystal (outlined) has been replaced by finer crystalline (ferroan) dolomite; scale bar is .1 mm.

b: Photomicrograph of granule conglomerate illustrating early calcitic cement (c), generally rimming micritic grains (m), and followed by extensive, pore-filling silica cement (Si); scale bar is .1 mm.

c: Photomicrograph of silicified silty dolostone illustrating microcrystalline hematite (dark areas) occurring as flakes, and locally surrounding overgrown dolomite grain (D); scale bar is .1 mm

d: SEM/EDAX photomicrograph (backscatter mode) illustrating barite crystal (Ba), corroded and partially replaced by calcite (C) and silica (Si); note projection of overgrown dolomite grain (arrow) into margin; green shale, uppermost Middle Arm Point Formation.


a
b
c
d
si
m
Si
Ba
C
851011 15KV X110 218um

final closure of the diagenetic system and a barrier to further fluid movement.

Field evidence presented in Chapter 4 indicates that in many cases, especially within shales and silty dolostones of the Middle Arm Point, silicification has occurred early, possibly at or near the seafloor. Hence, within silty dolostones, particularly early silicification, promoted perhaps by porosity or permeability inhomogeneities or localized silica sources, may have excluded stages of dolomite overgrowth which have proceeded to completion nearby. This may be one factor which has contributed to the somewhat variable nature of dolomite overgrowth within these silty dolostones mentioned above.

6.1.4 Preservation of hematite

As noted in Chapter 4, the stability of hematite in the diagenetic system is locally indicated by its presence as a coating on overgrown dolomite (and siliciclastic) grains (Plate 6-2c) or as granular to flaky material distributed within silica cement. The significance of this preservation will be discussed in Section 6.2.

6.1.5 Barite authigenesis

The precipitation of authigenic barite occurs within the Middle Arm Point Formation. Where crystalline barite has not been noted in the field, its presence is implied by shale geochemical data which indicate anomalous Ba concentrations. This, and the implications of the stratigraphic distribution of barite, will be discussed in Section 6.2.

The principal occurrence of barite is as scattered, euhedral, bladed crystals up to 3mm in length in otherwise massive (commonly green) shale of the uppermost Middle Arm Point Formation. The pre-compactional authigenic growth of these crystals is indicated by the compactional bending of microlaminae around them. These crystals commonly display corrosion and partial replacement by an intergrown mixture of calcite and silica. Detailed examination indicates that this replacement predated ferroan overgrowth of dolomite grains within the host shale, based upon the projection of this overgrowth from adjacent dolomite grains into the (replaced) calcite margins of the crystal (Plate 6-2d).

Barite has also been noted as a minor vein-filling and in the complex formation of a chert/carbonate nodule within Middle Arm Point shale. Here the precipitation of anhedral masses of barite postdates silica precipitation and immediately predates the final precipitation of Fe/Mn carbonate.

6.1.6 Precipitation of pyrite

The precipitation of pyrite occurs principally within shales of the Northern Head group. Although pyrite is present within a variety of shale lithologies, it is generally more abundant in black shale than green or red shale, and differs in its manner of occurrence. The greater abundance of pyrite within black shale is apparent even within thinly interbedded black and green shale intervals (e.g. base of the Cooks Brook Formation at Northern Head).

The presence of pyrite within black shale is characterized by its fine-crystalline nature and early precipitation. Pyrite commonly occurs as disseminated delicate framboids, roughly 100 micrometers in diameter (Plate 6-3a). Spherical framboidal nodules are also present locally and range in size up to roughly 7mm. Locally uncompacted burrows are filled with fine-crystalline pyrite. Graptolites are commonly preserved in semi-relief by pyrite.

Pyrite in green shales, particularly within the Middle Arm Point Formation, is more coarsely crystalline than that described above and tends to have been precipitated at a later stage, where it commonly replaces diagenetically-precipitated carbonate (Plate 6-3b). Framboidal nodules of pyrite do occur locally with Middle Arm Point green shale, where they range up to 1cm in diameter and comprise individual crystals up to 1mm in size.

6.1.6.1 Pyrite replacement of carbonate

Pyrite replacement of carbonate grains is generally sparse through the Northern Head group, but is spectacularly developed at the base of the Cooks Brook Formation, particularly at Seal Cove. Here, over a roughly 10m shale-dominated interval, several beds of what was originally carbonate pebble conglomerate, ranging in thickness from 2 to roughly 40cm are partially to completely replaced, pebble by pebble, by pyrite (Plate 6-3c). The only lithology which is never replaced is black, phosphatized shale, which comprises up to 10 % of individual beds. In some instances, where replacement is complete, these beds appear to be composed of pebbles of detrital pyrite, but petrographic examination indicates that this is a relatively fine-crystalline (30 micrometers) pebble

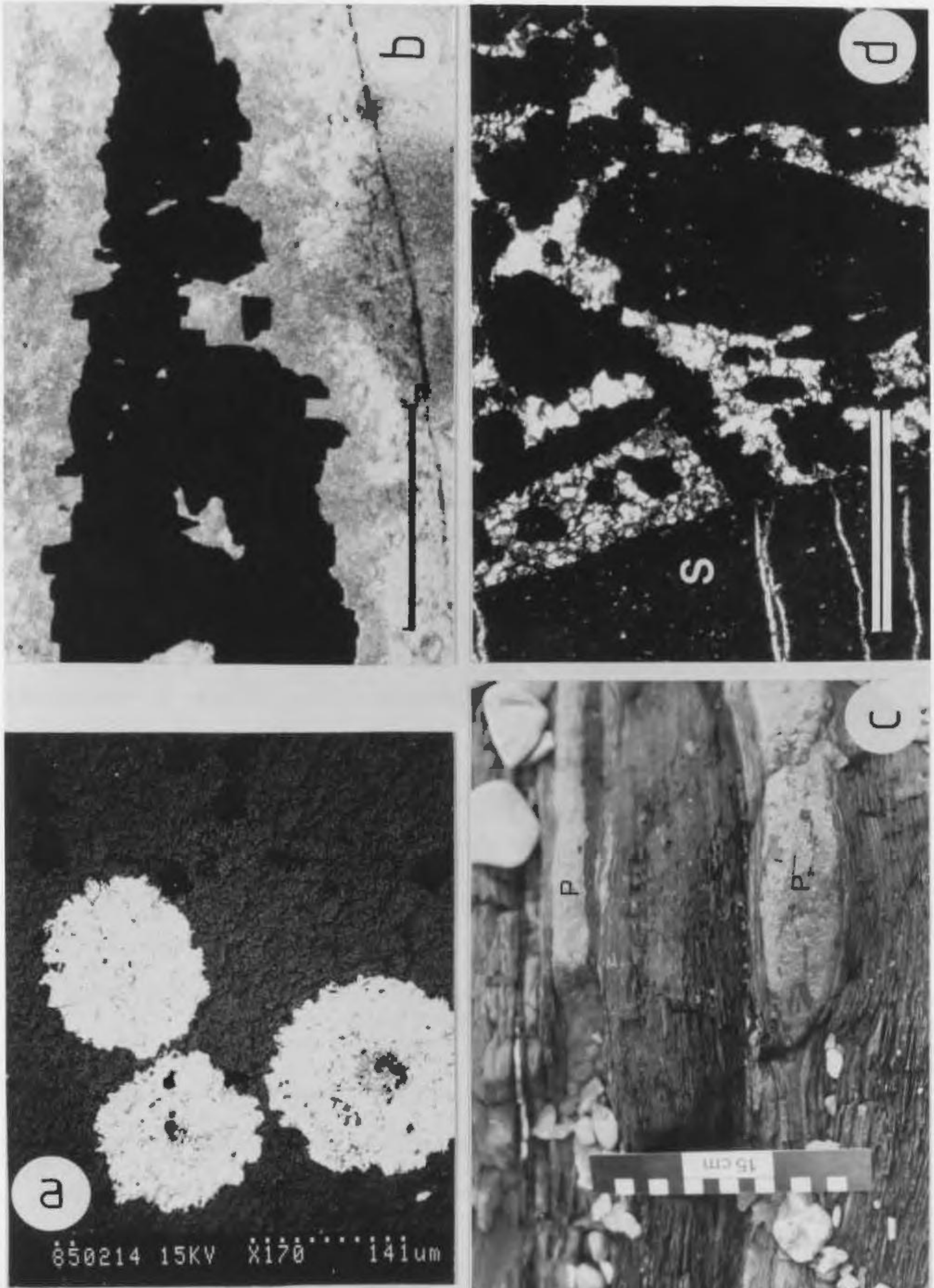
PLATE 6-3: ASPECTS OF PYRITE AUTHIGENESIS

a: SEM/EDAX photomicrograph illustrating framboids of early-precipitated, fine-crystalline pyrite within black shale; Cooks Brook Formation

b: Photomicrograph illustrating coarse, late-stage pyrite replacement of diagenetic carbonate nodule within green shale, Middle Arm Point Formation; scale bar is 1 mm.

c: Granule to pebble conglomerate beds (interbedded with black shale) displaying extensive replacement by pyrite (P). The only pebbles to have escaped this whole-scale style of replacement are phosphatized black shale, visible in the lower unit; lowermost Cooks Brook Formation, Seal Cove.

d: Photomicrograph of pyritized granule conglomerate (illustrated in 6-3c) displaying complete, grain-by-grain replacement. Grains are surrounded by ferroan carbonate cement; grain on extreme left is phosphatized black shale (S) which is not pyritized; scale bar is 1 mm.


a
850214 15KV X170 141um
b
c
P
P'
15 cm
d
S

by pebble replacement of an original carbonate host, with interstitial ferroan carbonate cement (Plate 6-3d).

Similar pyritization, although not as extensively developed as at Seal Cove, is characteristic of the lowermost Cooks Brook Formation, and is noted at Halfway Point, Northern Head, and in Middle Trout River Brook to the north.

6.1.7 Minor authigenic phases: feldspar

Authigenic feldspar occurs commonly as a minor component throughout the Northern Head group, both within bedded carbonate and clasts within conglomerate. It is present most commonly within micritic lithologies, often with a detrital core of feldspar, or sometimes dolomite. This feldspar commonly occurs as pristine, euhedral grains which may display albite twinning, or the polysynthetic twinning of microcline.

Microanalysis indicates that authigenic feldspar is always alkali. The predominant feldspar displays a composition of pure albite, while K-feldspar (?microcline) occurs less commonly.

The timing of feldspar growth is not clear, however it both overgrows, and is overgrown and locally partially replaced by, authigenic dolomite. No consistent crosscutting or replacement relationships with other authigenic phases have been noted, and the precipitation of authigenic feldpar is thought to have occurred throughout the sequence of early diagenesis outlined above.

All of the authigenic feldspar examined in an extensive survey of carbonate occurrences by Kastner (1971) are alkali, and are most common in micritic lithologies. Kastner concludes that, in general, feldspar authigenesis may have proceeded in carbonates under low to moderate temperature and pressure conditions, where clay minerals, free silica and detrital feldspars have provided silica and alumina and alkalies have been derived from seawater. Hence the common occurrence of authigenic feldspar in micritic lithologies, both within the Northern Head group, and in general, may be related to the presence of adequate clay minerals, available for subsequent authigenesis.

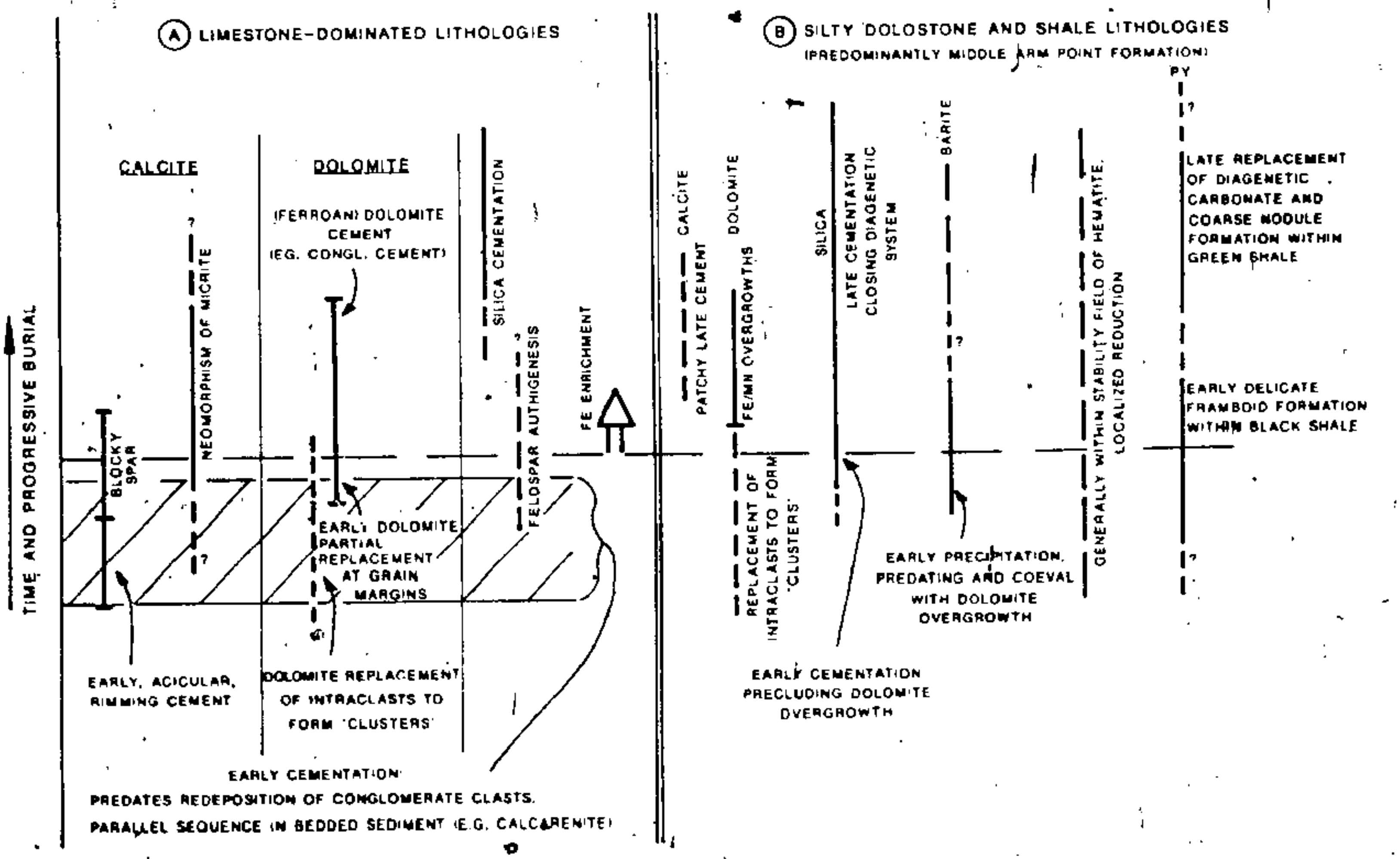
6.1.8 Overall diagenetic sequence: summary

Somewhat different diagenetic sequences are recognized in i) limestone-dominated lithologies and ii) silty dolostones and shales (predominantly Middle Arm Point). These are summarized in figure 6-1.

Cementation in limestone-dominated lithologies is represented by i) the precipitation of fibrous to acicular rimming cement, followed by ii) the precipitation of equant, blocky spar, iii) coeval with, or immediately postdated by the localized precipitation of euhedral dolomite, with iv) the final pore-filling (and localized replacement) by amorphous to fine-crystalline silica. The principal carbonate species, calcite and dolomite, display an overall trend toward Fe-enrichment through this sequence. The neomorphism of lime mudstone, within allochems, intergranular material and lime mudstone beds is represented by the variable growth of microspar and pseudospar, and has occurred in parallel with this sequence and with overall Fe-enrichment. While examples of early neomorphism do occur,

Figure 6-1

Schematic summary of diagenetic sequence(s) recognized within 1) limestone-dominated lithologies and 2) silty dolostone and shale lithologies of the Northern Head group.



TIME AND PROGRESSIVE BURIAL
(A) LIMESTONE-DOMINATED LITHOLOGIES
CALCITE
DOLOMITE
BLOCKY SPAR
NEOMORPHISM OF MICRITE
(FERROAN) DOLOMITE CEMENT (EG. CONGL. CEMENT)
SILICA CEMENTATION
FELDSPAR AUTHIGENESIS
FE ENRICHMENT
EARLY DOLOMITE PARTIAL REPLACEMENT AT GRAIN MARGINS
EARLY, ACICULAR, RIMMING CEMENT
DOLOMITE REPLACEMENT OF INTRACLASTS TO FORM 'CLUSTERS'
EARLY CEMENTATION
PREDATES REDEPOSITION OF CONGLOMERATE CLASTS.
PARALLEL SEQUENCE IN BEDDED SEDIMENT (E.G. CALCARENITE)
(B) SILTY DOLOSTONE AND SHALE LITHOLOGIES
(PREDOMINANTLY MIDDLE ARM POINT FORMATION)
CALCITE
PATCHY LATE CEMENT
DOLOMITE
FE/MN OVERGROWTHS
REPLACEMENT OF INTRACLASTS TO FORM 'CLUSTERS'
SILICA
LATE CEMENTATION CLOSING DIAGENETIC SYSTEM
EARLY CEMENTATION PRECLUDING DOLOMITE OVERGROWTH
BARITE
EARLY PRECIPITATION, PREDATING AND COEVAL WITH DOLOMITE OVERGROWTH
GENERALLY WITHIN STABILITY FIELD OF HEMATITE, LOCALIZED REDUCTION
PY
LATE REPLACEMENT OF DIAGENETIC CARBONATE AND COARSE NODULE FORMATION WITHIN GREEN SHALE
EARLY DELICATE FRAMBOID FORMATION WITHIN BLACK SHALE

much of this recrystallization appears to postdate early cementation.

The replacement of grains and intraclasts (commonly peloidal micrite) by dolomite may have occurred throughout this sequence, but is noted <u>within</u> cemented clasts in conglomerate, and is thought to have generally preceded calcite cementation and hence to have been an early process. As a result, this dolomite is more frequently non-ferroan, but i) replacement or ii) encapsulation of the commonly observed "replacement dolomite cluster" by later ferroan dolomite has been noted.

Within silty dolostones and shales of the Middle Arm Point Formation calcite cement is rare, and only occurs as a patchy late cement or localized replacement. The diagenetic sequence within these lithologies includes: i) ?the continued replacement of calcitic grains by (commonly ferroan) dolomite, ii) the overgrowth of abraded dolomite grains by commonly Fe and/or Mn-rich dolomite, locally followed by iii) the coating of these, and other grains, by a thin rim of hematite, immediately predating and during iv) the protracted process of pervasive cementation and localized replacemement by silica. Hematite (or a metastable precursor) has been distributed as a detrital component within the sediment. It does not appear to have directly participated in the diagenetic sequence.

The precipitation of barite within shale locally occurs within this sequence, either i) relatively early, where it has been replaced, in part, by calcite and silica and predates the overgrowth of neighbouring dolomite grains within shale or ii) during late Mn-carbonate precipitation, which has locally postdated silicification (in late nodule formation).

Precipitation of pyrite has generally occurred early within black shale. Within green shale, particularly within the uppermost Middle Arm Point Formation, pyrite, and locally other sulphides, appears latest in the diagenetic sequence, as a final, very fine pore-filling and localized replacement. Pyrite replacement of carbonate allochems is generally sparse in the Northern Head group, but is developed to a pronounced degree at the base of the Cooks Brook Formation.

Based upon i) the similarity of cementation style between clasts in conglomerate and bedded sediment, ii) the pre-compactional nature of cement in all carbonate and many shale units and iii) the occurrence of most cementation prior to silica precipitation, which can be demonstrated, at least in some lithologies, to be early, the diagenetic cementation sequence outlined above is regarded as the result of early, shallow-burial diagenesis.

6.2 EVIDENCE FOR CONTRASTING DIAGENETIC STYLES WITHIN THE NORTHERN HEAD GROUP

Introduction

This section incorporates pertinent parts of the examination of shale geochemistry through the Northern Head group.

Shale geochemical data provide a key piece of evidence which indicates that early diagenetic processes differed through the Northern Head group. Bulk shale samples were collected through the section (refer to Appendix E) and aspects of their geochemistry indicate fundamental differences in depositional and early diagenetic conditions.

Much of the discussion in this section is based upon general principles of changing Eh, and progressive Fe and Mn mobilisation, during shallow burial. These are reviewed in Appendix G.

6.2.1 Stratigraphic distribution of manganese

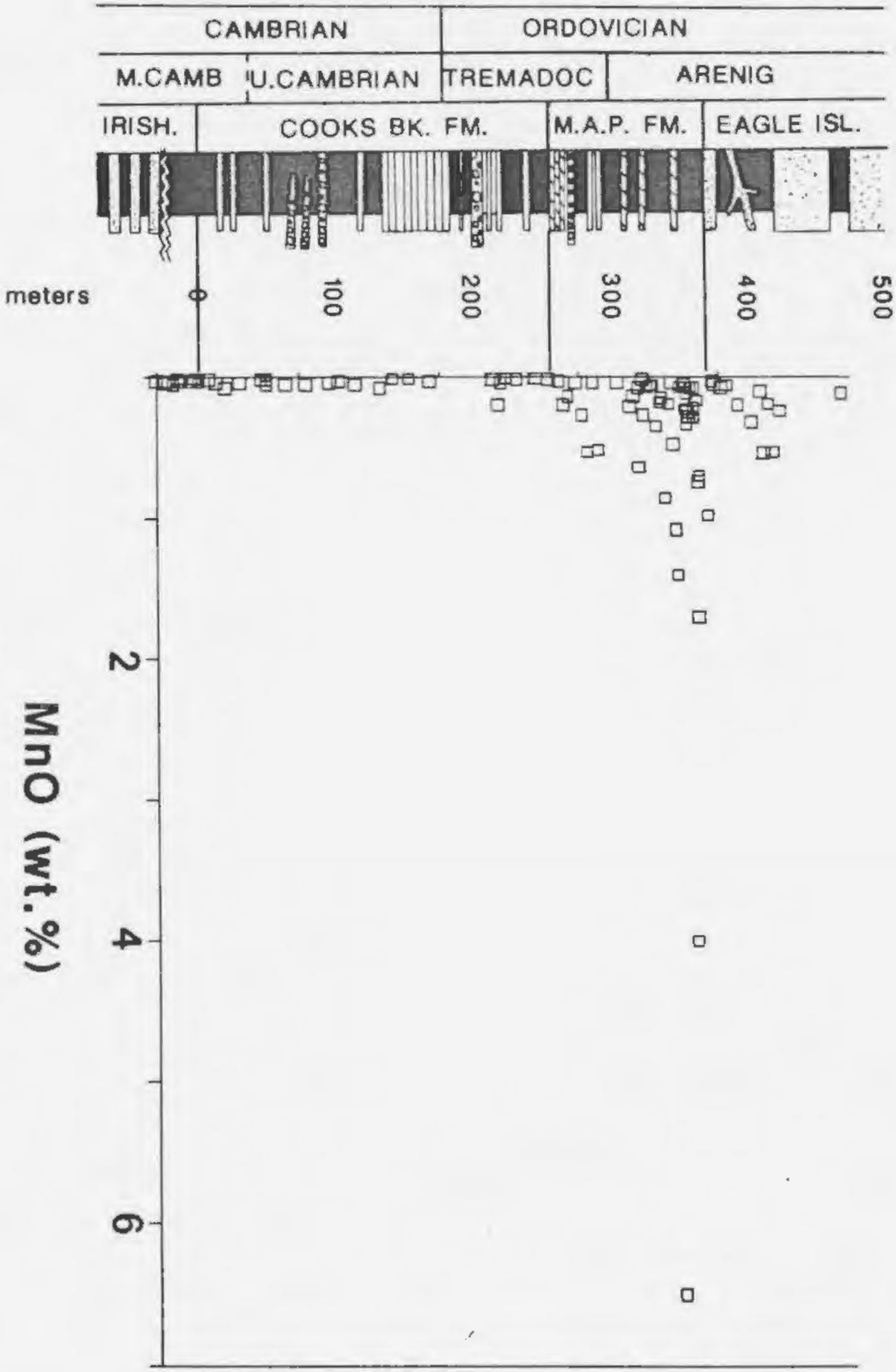
The distribution of manganese in shales of the Northern Head Group is shown in figure 6-2, which displays a marked increase, from low, "background" levels through the Cooks-Brooks Formation to anomolously elevated levels, ranging up to 6.5 wt.% MnO within shales of the Middle Arm Point and lowermost Eagle Island formation.

6.2.2 Nature of Mn occurrence within the Middle Arm Point

A detailed examination of shale and dolomitic siltstone samples within the Middle Arm Point Formation indicates that Mn occurs in three principal ways, as: i) diagenetically-precipitated fine crystals of Mn-carbonate disseminated within intervals of red and

Figure 6-2

Stratigraphic distribution of Mn in shales of the Northern Head group.



CAMBRIAN
ORDOVICIAN
M.CAMB
U.CAMBRIAN
TREMADOC
ARENIG
IRISH.
COOKS BK. FM.
M.A.P. FM.
EAGLE ISL.
meters
0
100
200
300
400
500
2
4
6
MnO (wt.%)

green shale, ii) diagenetically-precipitated horizons, or layers, of Mn-carbonate up to 3cm thick, in red and green shale intervals, and iii) Mn/Fe-carbonate overgrowths which are widely developed on individual grains within dolomitic siltstones. Manganese is always associated with carbonate minerals, and only appears as an oxide because of recent weathering.

6.2.2.1 <u>Disseminated Mn-carbonate within shale</u>

This style of Mn-carbonate appears within both red and green shales of the uppermost Middle Arm Point and lowermost Eagle Island formation as intervals ranging from 10cm up to roughly 1m in thickness. Bulk shale samples from such intervals contain concentrations of MnO ranging from .5 to 1.4 wt.%, and locally display a metallic patina of pyrolusite on weathered surfaces.

The mineral is rhodochrosite which displays the average composition $Mn_{(.81)}Ca_{(.12)}Mg_{(.07)}(CO_3)$, and is relatively consistent in composition through three samples examined in detail. Crystals are isolated, unzoned, and euhedral and range in size up to 1mm (Plate 6-4a). No evidence of replacement of earlier mineral phases is noted.

6.2.2.2 <u>Diagenetic Mn-carbonate horizons within shale</u>

Horizons of diagenetic Mn-carbonate occur within red and green shale intervals within the uppermost Middle Arm Point and lowermost Eagle Island formations. They are bedding-parallel and generally range in thickness from 1 to 3cm. These horizons range from subtle, somewhat diffuse features to clearly-defined, commonly maroon-weathering (5RP 2/2) layers. These features were not immediately apparent during early field work, and their significance was only recognized where they were incorporated in bulk shale samples, where they are partially responsible for the concentrations of MnO displayed in fig. 6-2. Field and petrographic evidence indicates that these horizons originated in three principal ways: i) along burrowed horizons, ii) as a cement within silty or sandy layers and iii) by variable overgrowth of very fine detrital dolomite grains within shale.

The clearest example of diagenetic Mn-carbonate precipitation along burrowed horizons occurs in those illustrated in Chapter 4 (Plate 4-4a). Other examples demonstrate evidence of burrowing, but this is commonly partially obscured by later diagenesis. These horizons occur within otherwise massive green shale, and are an average of .7mm thick. Burrows and "crusts" within featureless chloritic shale contain scattered fine to medium siliciclastic silt grains which are enclosed in domains of poikilitic cement up to 1mm in size (Plate 6-4b). This carbonate is manganiferous ferroan dolomite, with an average composition of $Ca_{(.51)}Mg_{(.33)}Mn_{(.12)}Fe_{(.04)}(CO_3)$. Different domains are somewhat variable in composition. Slightly darker-coloured and maroon-weathering domains, non-systematically distributed through the horizon contain slightly more Mn (16 mole%, at the expense of Mg and Fe).

Zones where Mn-carbonate appears as a cement within silty to sandy horizons range from 1 to 3cm in thickness (Plate 6-4c).

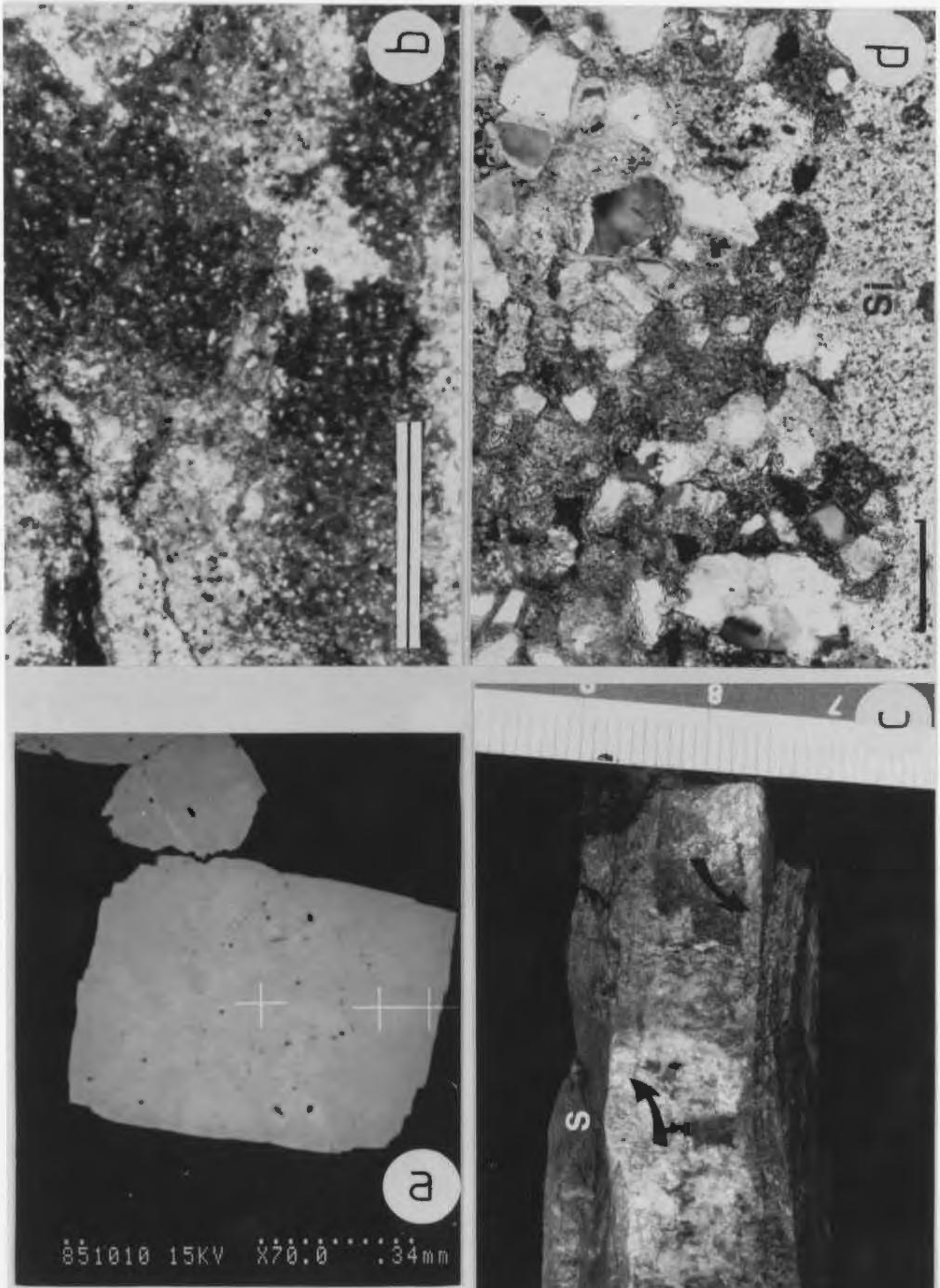
PLATE 6-4: ASPECTS OF DIAGENETIC MN-CARBONATE

a: SEM/EDAX photomicrograph (backscatter mode) illustrating isolated, euhedral rhodochrosite crystals within red shale (surrounding dark area); Middle Arm Point Formation.

b: Photomicrograph of Mn-carbonate crust localized along burrowed horizon within (green) shale. Carbonate occurs as irregular domains, which ~~pot~~kiliticelly enclose scattered siliciclastic silt grains; green shale interval, Middle Arm Point Formation; scale bar is 1 mm.

c: Diagenetic Mn-carbonate horizon collected from shale-dominated interval, uppermost Middle Arm Point Formation; horizon occurs within shale (s); margins (arrows) are pervasively silica-cemented.

d: Photomicrograph of Mn-carbonate horizon illustrated in 6-4c, displaying angular siliciclastic silt grains poikilitically surrounded by carbonate; pervasively silica-cemented margin (Si) appears at base; scale bar is .1 mm.


a
851010 15KV X70.0 .34mm
b
c
7
8
S
d
si

display somewhat irregular but bedding-parallel margins and are laterally continuous over outcrop scale of several meters. Cementation is pervasive within these horizons and poikilitically surrounds rounded to angular siliciclastic grains which commonly range from coarse silt to fine sand. This cement occurs in irregular domains roughly .5mm in size (Plate 6-4d). Faint relics of overgrown silty dolomite grains are locally visible within the cement. No compositional zoning from core to margin has been detected within these horizons, neither petrographically nor by microanalysis. The horizons are, however, locally bounded by thin marginal, symmetrical zones of pervasive microcrystalline silica cementation (several millimeters thick); this cement also appears as scattered domains within the carbonate horizon itself.

Non-systematic compositional variation appears within the carbonate cement. XRD reflections of the carbonate present are uninterpretable, in part because of mutual interference, and also probably because of peak shifts associated with complex substition within the carbonate(s). Two principal populations appear based upon composition established by microprobe. The most abundant is Ca/Mg-rhodocrosite of average composition $Mn_{(.59)}Ca_{(.24)}Mg_{(.17)}CO_3$. The second is Mn/Fe-dolomite of average composition $Ca_{(.50)}Mg_{(.23)}Mn_{(.22)}Fe_{(.05)}(CO_3)$. The complex compositional variation, and presence of the second species, may have resulted from the extensive replacement suggested by the presence of the relic dolomite rhombs.

The presence of more subtle, diffuse horizons of diagenetic Mn-carbonate within shales of the same general stratigraphic interval described above was initially indicated by bulk shale samples which display surprising concentrations of MnO ranging up to 4 wt.%. More detailed examination upon subsequent visits to such localities revealed the presence of horizons ranging from .5 to 3cm thick which comprise variable concentrations of very fine crystalline carbonate hosted within otherwise massive, commonly green shale. Faint relic bioturbation structures locally disrupt such horizons.

More detailed examination of these horizons using the SEM/EDAX reveals the presence of overgrown carbonate grains which commonly range in size from 10 to 30 micrometers as well as siliciclastic grains of comparable size, within a clay matrix (Plate 6-5a). These fine silt grains are commonly concentrated in very thin laminae, and carbonate overgrowths within them form an interlocking mosaic. The irregular, commonly rounded core of these carbonate grains suggests that they have been abraded prior to overgrowth. Microanalysis of one sample using the EDAX (refer to Appendix E) qualitatively indicates the profound enrichment of Mn (and to a lesser degree Fe) within the overgrowths relative to the cores. The average core composition is $Ca_{(.67)}Mg_{(.33)}(CO_3)$ while the composition of the rim is $Ca_{(.46)}Mg_{(.15)}Mn_{(.31)}Fe_{(.08)}(CO_3)$.

Of particular interest in the same sample is the presence of barite, visible using the SEM/EDAX. This barite forms a discontinuous rim around the abraded cores of dolomite grains, and is patchily distributed through the overgrowths (Plate 6-5b). The possible significance of this precipitation of barite, immediately predating and coeval with manganiferous dolomite precipitation is discussed below in terms of the diagenetic model.

Core/rim relationships within dolomite grains could not be as readily resolved in another sample which was analysed using the microprobe, and contains dolomite grains of average composition $Ca_{(.48)}Mg_{(.32)}Mn_{(.14)}Fe_{(.06)}(CO_3)$.

Late, coarse recrystallization of diagenetic carbonate horizons (1 to 3cm thick) has also occurred, in areas of relatively more intense deformation (e.g. vicinity of McIvers, core of Woman Cove syncline), within what is clearly deformed Middle Arm Point shale. Evidence that these horizons were recrystallized during tectonism includes their disposition only in deformed zones, their association with thin fracture-fillings at a high angle to bedding, and their coarse-crystalline fibrous nature, which is commonly noted, in thin section, to be associated with tension-gash formation.

These horizons contain a complex mixture of Mn-carbonate. Coarser crystals, which locally display a rosette, or "button-like" habit (Plate 6-5c), have been identified as rhodocrosite by XRD examination. Microprobe analysis of coarse crystals within more massive horizons indicates a composition of $Mn_{(.82)}Ca_{(.14)}Mg_{(.04)}CO_3$. Finer-crystalline carbonate contains variable concentrations of Ca and Mn and but commonly displays an average composition of kutnohorite: $Ca_{(.79)}Mn_{(.19)}Mg_{(.02)}CO_3$.

6.2.2.3 <u>Carbonate overgrowth within silty dolostones</u>

The general aspect of silty dolostones has been described previously, in Chapter 4 and in the first section of this chapter. These units comprise an interlocking mosaic of dolomite grains which

PLATE 6-5: ASPECTS OF DIAGENETIC CARBONATE OVERGROWTH

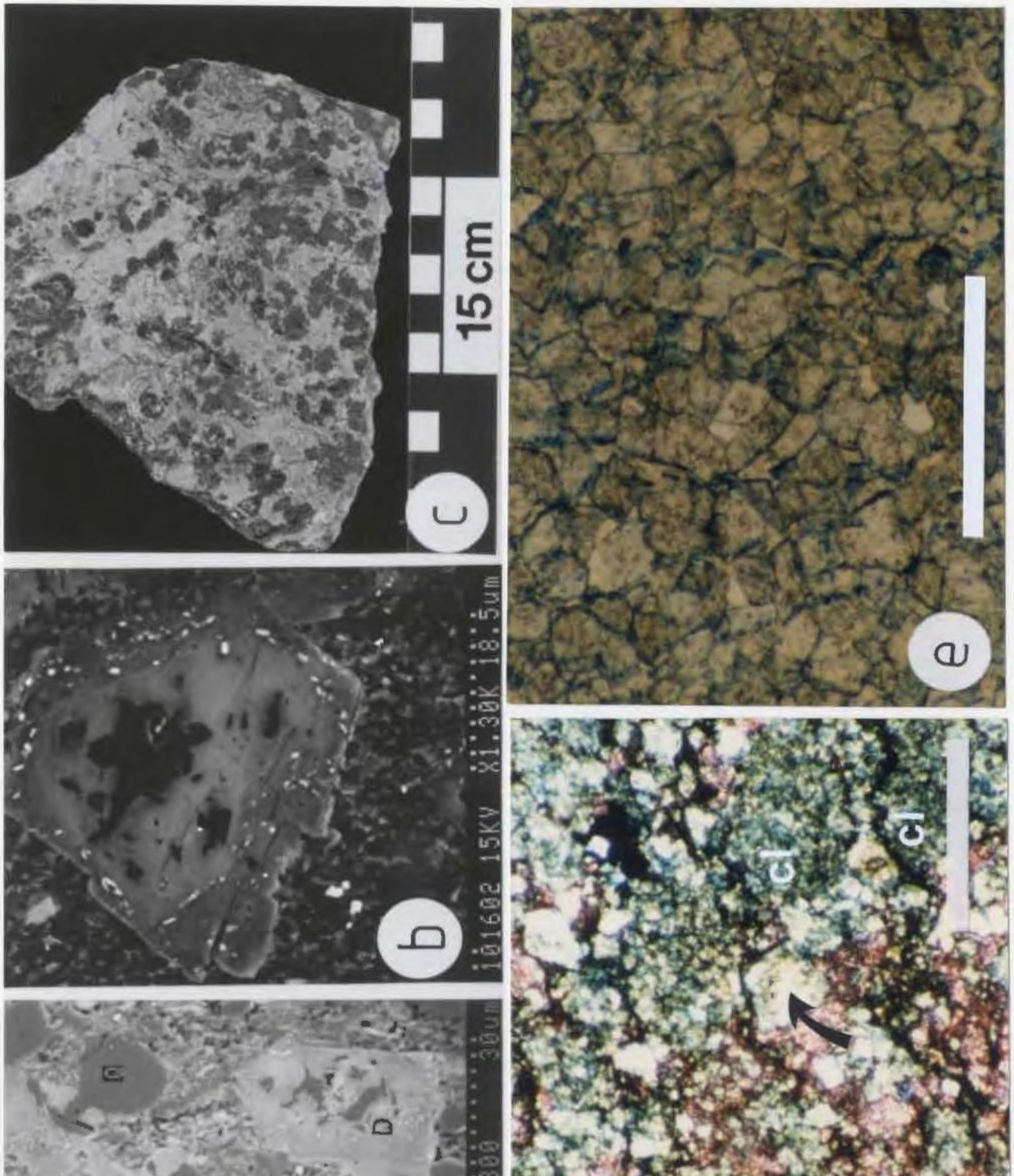
a: SEM/EDAX photomicrograph. Interlocking mosaic of (overgrown) dolomitic grains (D), locally replaced by silica, and accompanied by detrital grains of quartz (Q) and feldspar (fsp); diagenetic Mn-carbonate horizon, uppermost Middle Arm Point Formation.

b: SEM/EDAX photomicrograph (backscatter mode). Dolomite grain displaying irregular, abraded core and Mn, Fe-dolomite overgrowth; bright material rimming core and scattered throughout overgrowth is barite; diagenetic horizon, uppermost Middle Arm Point Formation.

c: Recrystallized rhodochrosite displaying rosette or "button-like" habit (darkened by weathering) within green shale matrix; Middle Arm Point Formation.

d: Photomicrograph of silty dolostone from transitional base of the Woman Cove member. Dolomite component is dominated by clusters of fine-crystalline dolomite (cl), but also contains individual abraded and overgrown dolomite grains (arrows), which dominate stratigraphically higher silty dolostones; scale bar is 1 mm.

e: Photomicrograph of silty dolostone displaying interlocking mosaic of overgrown dolomite grains; note late ferroan overgrowth localized along thin vertical planes, and vertical margins of individual grains; scale bar is 1 mm.


a
D
FSP
101603 15KV X800 30um
b
101602 15KV X1.30K 18.5um
c
15cm
d
cl
cl
e

have been pervasively surrounded, and locally partially replaced, by fine-crystalline silica. Dolomite grains are thought to have been derived through two principal mechanisms: the generally early replacement of calcitic grains and intraclasts, and the in situ overgrowth of detrital dolomite grains. A survey of this lithology, using stained thin sections, cathodoluminescence, SEM/EDAX and microprobing indicates that dolomite overgrowth is highly variable, both in degree and in composition, between and within individual samples.

Staining and cathodoluminescence indicates that, in general, 50 to 75% of the dolomite grains within these silty dolostones display a ferroan, generally euhedral style of overgrowth. The remainder of the dolomite includes i) irregular, abraded grains, similar to the cores of nearby overgrown grains, and ii) euhedral to subhedral grains, which do not contain a detrital core, but which may locally display internal zoning.

A comparable mixed population is apparent under cathodoluminescence. This includes i) grains with a generally small non-luminescent core, displaying a moderately to brightly luminescent overgrowth, which is commonly surrounded by a thin non-luminescent rim, ii) irregularly-shaped, non-luminescent grains which locally display a thin luminescent rim, and iii) grains which are faintly luminescent to non-luminescent throughout, locally displaying internal zoning. The first group corresponds to the abraded-core, Mn-to-Fe-rimmed dolomite which dominates the Middle Arm Point, and changing Fe and Mn concentration is clearly responsible for the luminescence pattern observed (Fairchild, 1983;

cf. Coniglio, 1985). The second group can be correlated with detrital grains which have undergone very limited overgrowth, while the third group is thought to include both the "replacement" dolomites described above, and directly-precipitated dolomite, without a detrital core.

Compositional variation within dolomite overgrowth

The broad spectrum of compositional variation in dolomite overgrowth which is suggested by staining and cathodoluminescence, has been examined using the SEM/EDAX and microprobe, and examples indicative of this variation are discussed here (data summarized in Table 6-1). Dolomite cement from the Cooks Brook Formation is included as a basis for comparison with the dolomitic siltstones of the Middle Arm Point.

Ferroan enrichment within dolomite cement of the Cooks Brook

As noted in earlier discussion of the diagenetic sequence, ferroan enrichment occurs within calcite and dolomite cements through the Northern Head group. The compositional zoning in such dolomite cements constitutes an outward enrichment in Fe, commonly most pronounced along a thin rim, with no asssociated increase in Mn. A Cooks Brook (Upper Cambrian) example is included in Table 6-1, and displays generally high Fe values throughout, which range from 2.98 wt.% FeO (4 mole % $FeCO_3$) at the core, to 7.6 wt.% FeO (10.6 mole % $FeCO_3$) at the rim.

Table 6-1 Dolomite: Summary of microprobe data
(each entry is an average of five analyses)

1) P.A.2: Cooks Brook dolomite cement

Core	Mg	Ca	Mn	Fe
Wt.% oxide	16.65	31.19	.765	2.98
Mole fraction	.403	.545	.0096	.0405

Rim				
Wt.% oxide	16.11	27.53	.26	7.56
Mole fraction	.401	.488	.003	.106

2) NAP85-4: "replacement" dolomite, base of Woman Cove Mbr.

	Mg	Ca	Mn	Fe
Wt.% oxide	19.61	32.35	.06	1.00
Mole fraction	.451	.535	.000	.012

3) WCW-7: detrital dolomite, upper portion of Woman Cove Mbr.

Core	Mg	Ca	Mn	Fe
Wt.% oxide	20.36	30.78	.083	.095
Mole fraction	.49	.51	---	---

Rim				
Wt.% oxide	17.02	28.68	3.54	1.51
Mole fraction	.415	.509	.051	.023

4) MAP-1: thin bed of silty dolostone, uppermost M.A.P.

Top of bed

Core	Mg	Ca	Mn	Fe
Wt.% oxide	18.86	31.87	.395	.633
Mole fraction	.445	.540	.005	.008

Rim				
Wt.% oxide	17.53	32.90	.402	.958
Mole fraction	.417	.560	.006	.012

Base of bed

Core	Mg	Ca	Mn	Fe
Wt.% oxide	18.96	33.52	.320	.405
Mole fraction	.450	.550	---	---

Table 6-1 (continued)

Rim

Wt.% oxide	17.65	33.10	.650	2.53
Mole fraction	.410	.551	.007	.032

5) NA12: thin bed of silty dolostone, uppermost M.A.P.

Top of bed

Core	Mg	Ca	Mn	Fe
Wt.% oxide	16.28	30.36	2.27	1.75
Mole fraction	.403	.542	.031	.024

Rim

Wt.% oxide	12.63	28.52	6.16	5.37
Mole fraction	.318	.518	.088	.075

Base of bed

Core	Mg	Ca	Mn	Fe
Wt.% oxide	15.46	30.19	3.50	4.76
Mole fraction	.449	.545	---	.004

Rim

Wt.% oxide	15.46	30.19	3.50	4.76
Mole fraction	.366	.518	.048	.065

Middle Arm Point dolomitic siltstones

Silty dolostones at the transitional base of the Woman Cove member are dominated by "clusters" of fine-crystalline dolomite which are interpreted to represent thoroughly dolomitized grains and intraclasts (Plate 6-5d). These locally display a faint, scattered ferroan alteration, or encapsulation in a thin ferroan rim, with no associated Mn-enrichment. Microprobe analysis indicates an average composition of $Ca_{(.54)}Mg_{(.45)}Fe_{(.01)}(CO_3)$.

Grains displaying irregular, non-ferroan cores with ferroan overgrowths are scattered throughout this basal interval (Plate 6-5d), and dominate the silty dolomites immediately upsection, within the Woman Cove member proper. The core/rim relationship in these grains is apparent using the SEM/EDAX (backscatter mode) and a traverse of microanalyses (SEM/EDAX) indicates pronounced Fe-enrichment with little associated Mn-enrichment (fig 6-3), displaying an affinity in style with the Cooks Brook cement dolomite described above.

A sample chosen from the uppermost part of the Woman Cove member (WCW 7) illustrates the common occurrence of both Mn and Fe-enrichment in the rim. The irregular cores in this sample display a relatively uniform composition consistent with an average of $Ca_{(.52)}Mg_{(.48)}(CO_3)$. The rims in this sample display an average composition of $Ca_{(.51)}Mg_{(.42)}Mn_{(.05)}Fe_{(.02)}CO_3$.

Mn/Fe ratios, as indicated by microanalysis, are commonly highly variable within and between individual samples, as suggested by petrographic examination and the highly variable style of cathodoluminescence. One sample, for example, contains grains where

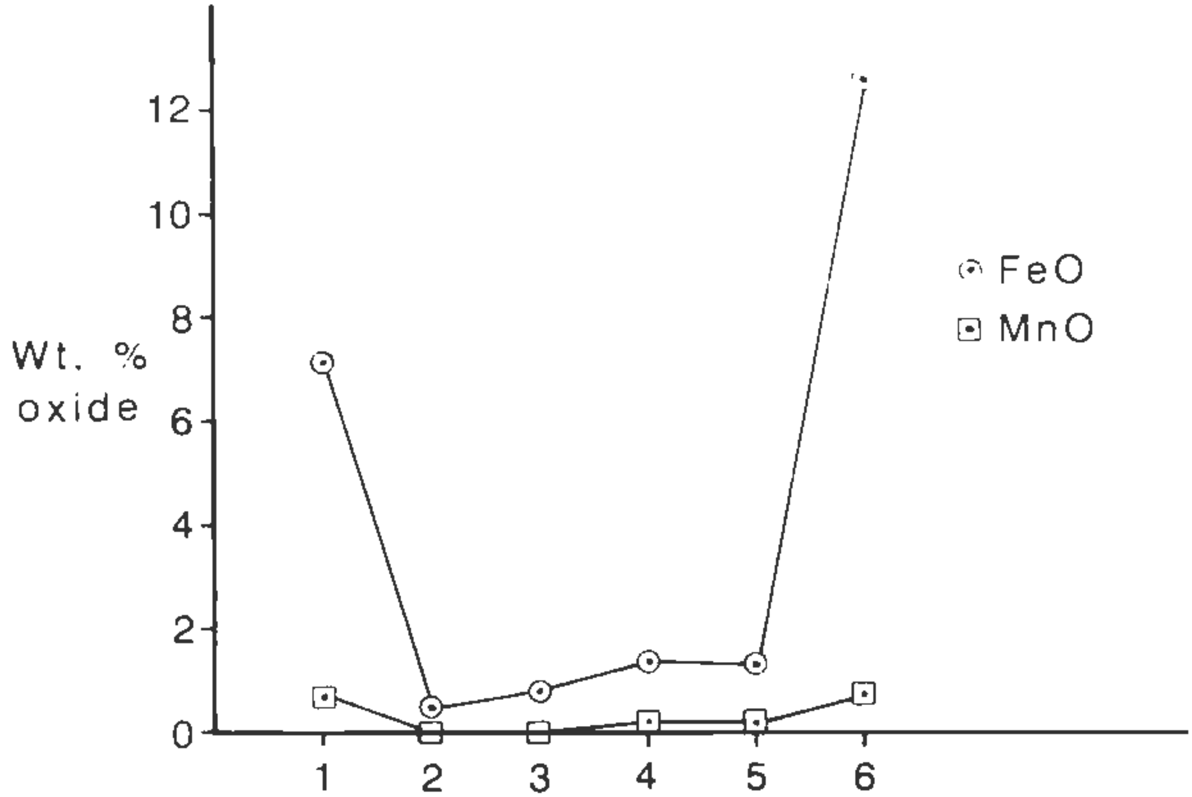
i) there is no compositional difference between core and rim, ii) there is an outward decrease in Mn, or iii) there is an increase from zero concentration in the core to levels, in the rim, of FeO ranging from 2 to 7 wt.% and MnO ranging from 1.3 to 4.3 wt.%. In general, individual overgrowths display a transition, detectable using the SEM/EDAX and consistent with cathodoluminescence patterns, of increasing Fe/Mn ratio outward.

Moreover, some thin sections examined span individual thin beds of silty dolostone, and indicate transitional differences in the style of overgrowth through the bed. In some cases (e.g. Sample MAP 1), ferroan overgrowth and "granular" ferroan cement appears to be much more pronounced at the base of beds, as indicated by staining and confirmed by microprobe analysis (summarized in fig. 6-4, Table 6-1). Mn-enrichment is much more subtle in this case.

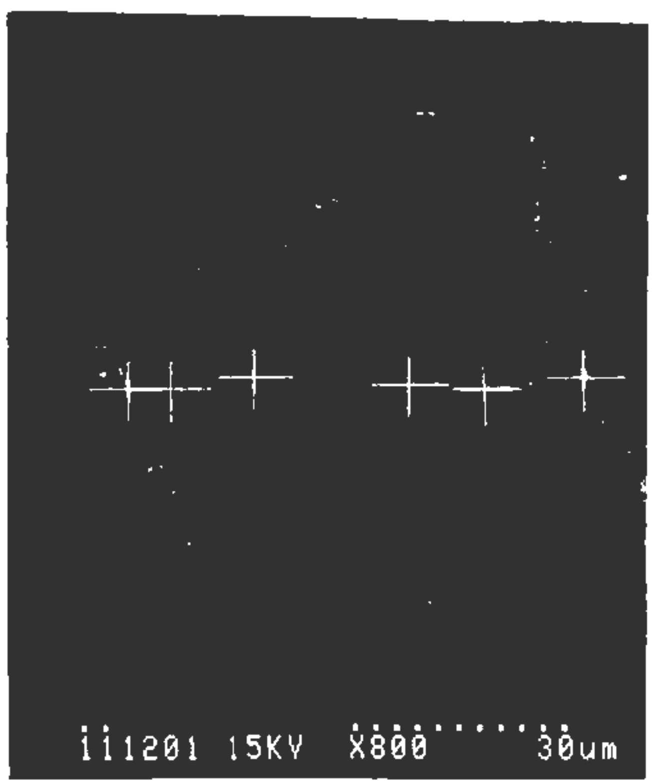
In other cases, normal grading is evident within a thin bed, and very fine sand grains at the base display unaltered cores of average composition $Ca_{(.55)}Mg_{(.45)}(CO_3)$, with thin Mn/Fe-rich rims, while fine silt grains at the bed-top display relatively much broader rims with more pronounced Mn/Fe-enrichment (summmarized in fig 6-5). In some grains here no cores are visible (see fig 6-5) and either total core-replacement or direct precipitation of Mn,Fe-enriched dolomite has occurred. This may be one mechanism which contributes to the variability in dolomite grains mentioned above.

Figure 6-3

Compositional variation within dolomite grain in the lower portion of the Woman Cove member (Sample NAP85-3). Traverse of microanalyses using the SEM/EDAX qualitatively indicates Fe-enrichment at the rim, with only subtle Mn-enrichment.



12
10
8
6
4
2
0
Wt. %
oxide
FeO
MnO
1
2
3
4
5
6



111201 15KV X800 30um

Figure 6-4

Schematic illustration of more pronounced Fe-enrichment, within overgrowths and late dolomitic "granular" cement, at the base of a thin (approx. 2 cm) silty dolostone bed, uppermost Middle Arm Point Formation.

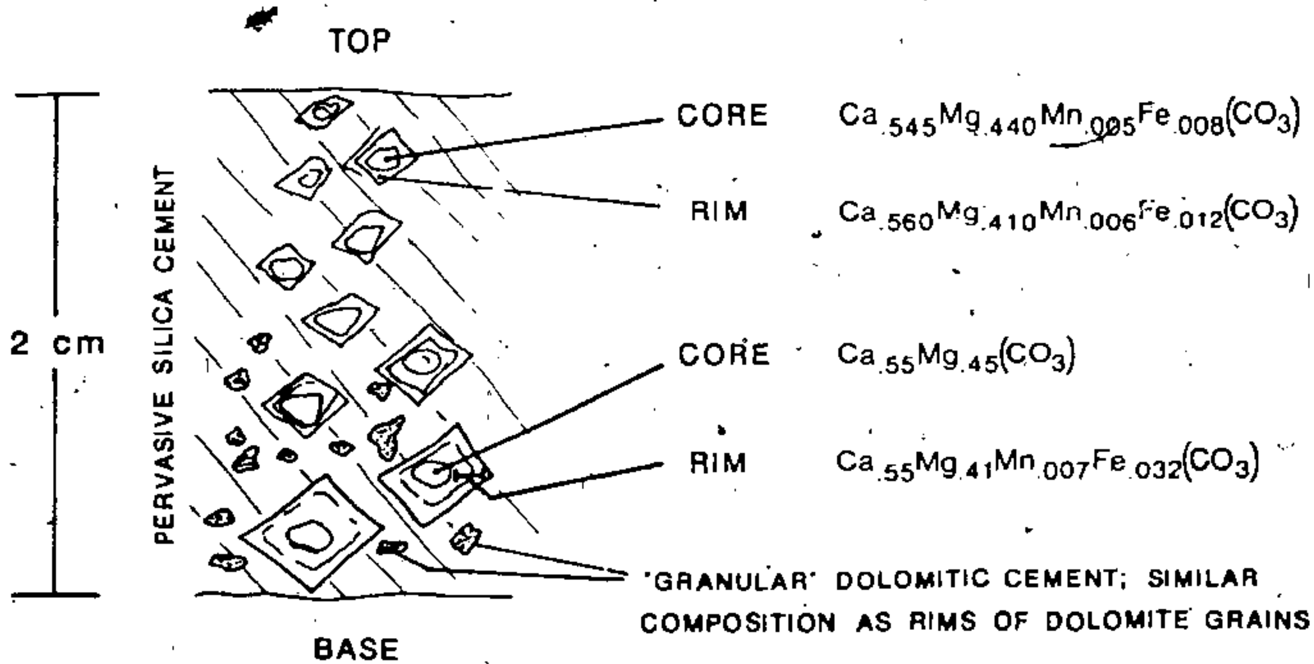
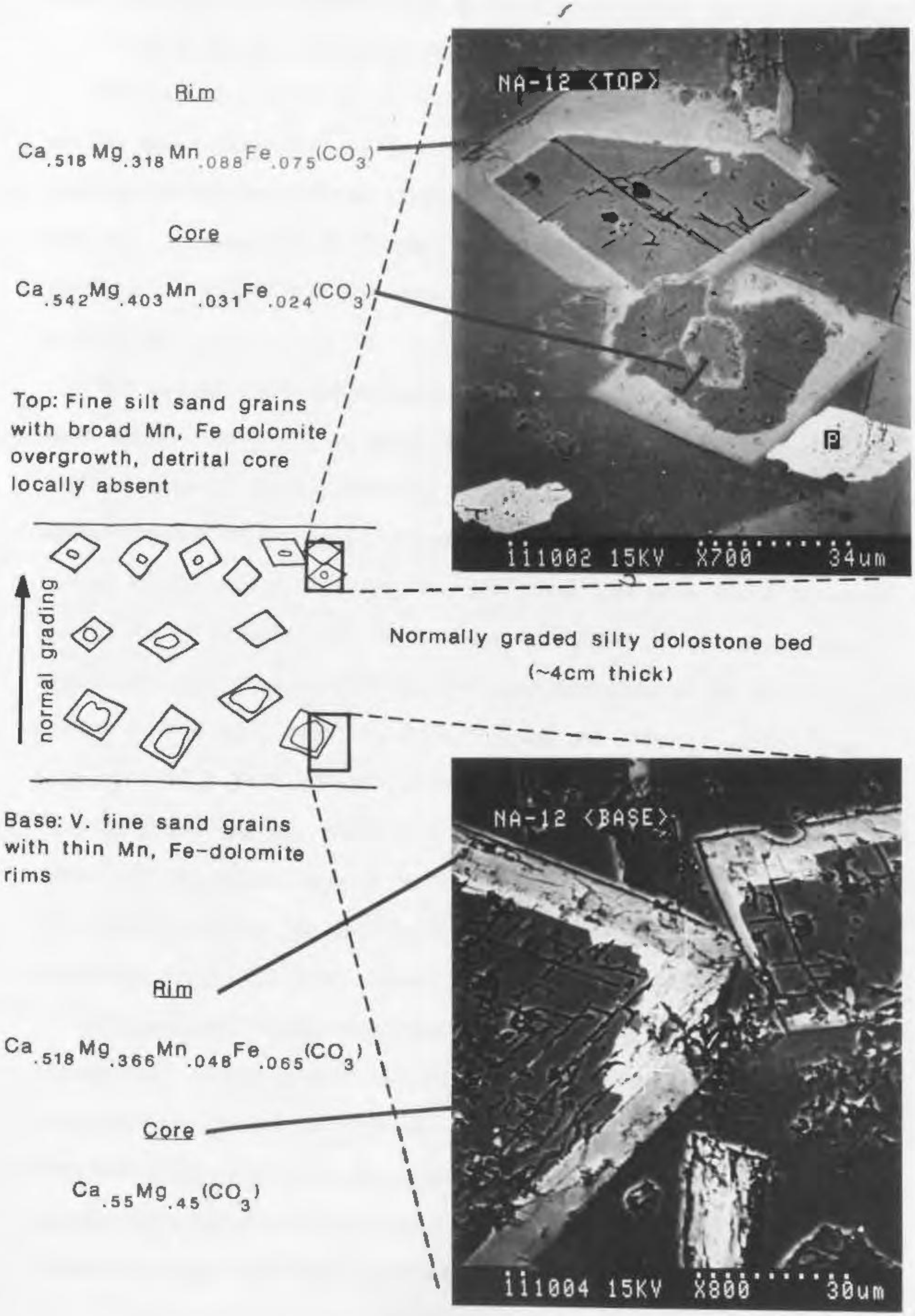

TOP
CORE $Ca_{.545}Mg_{.440}Mn_{.005}Fe_{.008}(CO_3)$
RIM $Ca_{.560}Mg_{.410}Mn_{.006}Fe_{.012}(CO_3)$
2 cm
PERVASIVE SILICA CEMENT
CORE $Ca_{.55}Mg_{.45}(CO_3)$
RIM $Ca_{.55}Mg_{.41}Mn_{.007}Fe_{.032}(CO_3)$
'GRANULAR' DOLOMITIC CEMENT; SIMILAR COMPOSITION AS RIMS OF DOLOMITE GRAINS
BASE

Figure 6-5

Variation in style and ~~c~~omposition of overgrowth through graded dolostone bed, uppermost Middle Arm Point Formation. Compositional zoning is apparent in SEM/EDAX photomicrographs (backscatter mode), and is confirmed by microprobe analyses shown (each an average of five analyses).



Rim
$Ca_{.518}Mg_{.318}Mn_{.088}Fe_{.075}(CO_3)$
Core
$Ca_{.542}Mg_{.403}Mn_{.031}Fe_{.024}(CO_3)$
Top: Fine silt sand grains with broad Mn, Fe dolomite overgrowth, detrital core locally absent
normal grading
Base: V. fine sand grains with thin Mn, Fe-dolomite rims
Rim
$Ca_{.518}Mg_{.366}Mn_{.048}Fe_{.065}(CO_3)$
Core
$Ca_{.55}Mg_{.45}(CO_3)$
NA-12 <TOP>
P
111002 15KV X700 34um
Normally graded silty dolostone bed
(~4cm thick)
NA-12 <BASE>
111004 15KV X800 30um

6.2.3 Diagenetic precipitation of Mn/Fe-carbonates in the Northern Head group: Interpretation

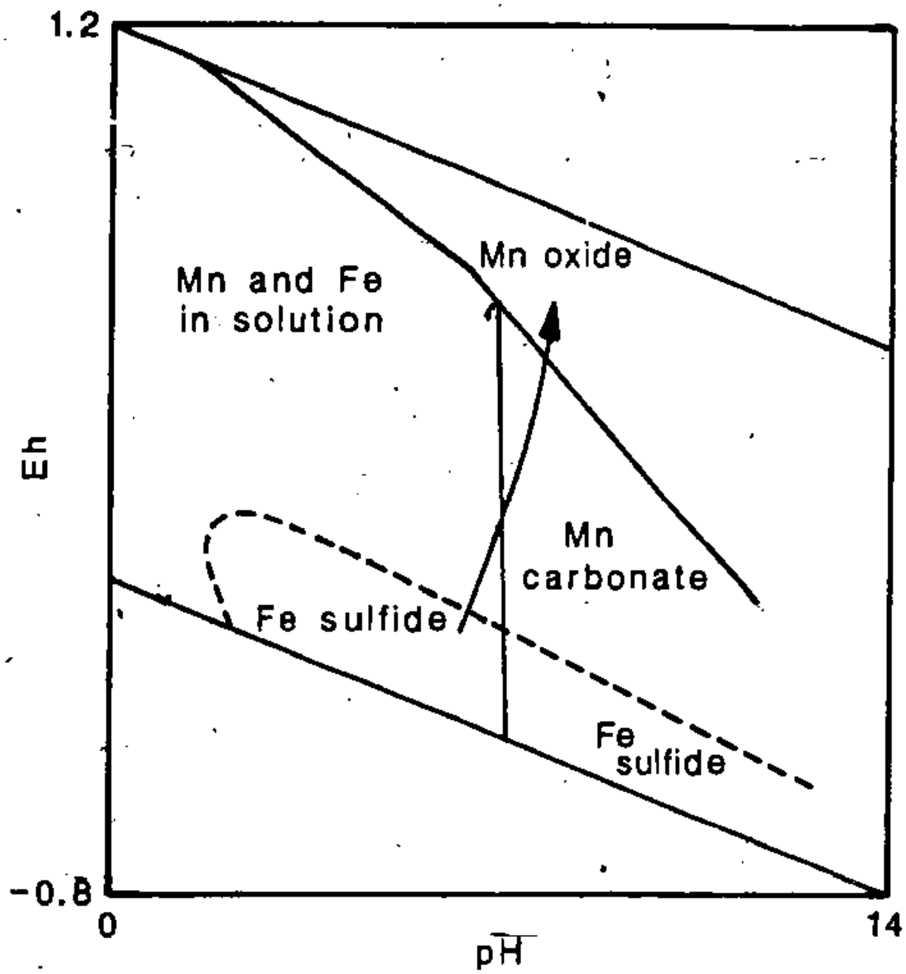
The general model of the progressive reduction of sediment, during the bacterially-modiated oxidation of organic carbon under shallow-burial conditions (Appendix G) provides a clear mechanism for the introduction of reduced Mn and Fe into pore waters and their resultant availability for incorporation into early-precipitated carbonates.

The widely accepted mechanism of concentration of Mn and Fe in deep-marine sediments is most simply expressed in an example with well-oxygenated bottom waters. In this setting, Mn and Fe, mobilized under shallow-burial early diagenetic conditions, are transported upward by processes of molecular diffusion and pore-water movement during early de-watering. When these dissolved metals encounter overlying oxidizing conditions the precipitation of Mn and Fe oxides occurs across an "oxidative front" (Lynn and Bonatti, 1965; e.g. Wilson et al., 1986). Under conditions of slightly lower Eh and elevated bicarbonate concentration, however, this precipitation will occur not as oxides, but as carbonates (fig 6-6). The buffering action of hydrogen ion uptake during Mn oxide reduction may be important in such a case (Suess, 1979; Hesse, 1986).

An analogous relationship between Mn oxides and carbonates is illustrated in Cretaceous and Tertiary shallow-water-deposited Mn ore deposits (Frakes and Bolton, 1984; Bolton and Frakes, 1985). Here Mn-oxides have been precipitated in the shallowest, best-oxygenated portions of the basin, while laterally equivalent Mn-carbonates have been precipitated at greater water depths, under

Figure 6-6

Schematic Eh-pH diagram illustrating the relationship of Mn-carbonate and oxide stability fields, and the typical oxidation path of an anoxic water mass (redrawn from Force et al., 1983).


1.2
Eh
-0.8
0
14
pH
Mn oxide
Mn and Fe
in solution
Mn
carbonate
Fe sulfide
Fe
sulfide

apparently lower Eh conditions.

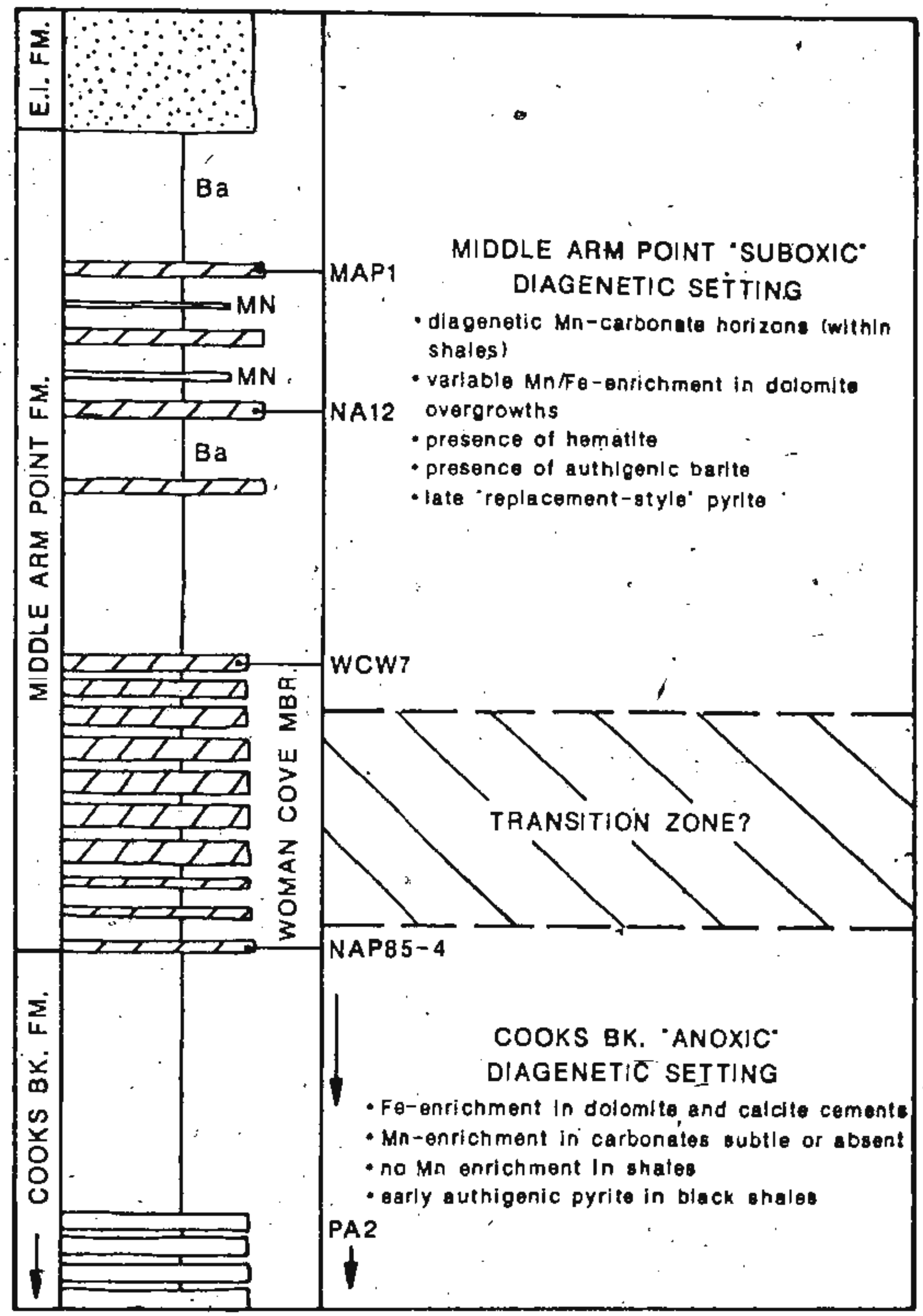
The contrasting solubility of Mn and Fe under decreasing Eh conditions (fig G-2) provides a theoretical basis for expecting that under progressive burial end resultant progressive reduction, Mn will become enriched in pore waters, and available for incorporation in carbonates first, followed by Fe under continued lowering of Eh conditions. One implication of this diagenetic separation of Fe and Mn is compositional zoning within co-precipitated carbonate cements and overgrowths (cf. Frank et al., 1982). Within the silty dolostones described above, the general pattern of i) the absence of Mn in cores, followed by ii) Mn-enriched overgrowth and iii) subsequent Fe-enriched rim is thought to reflect this mechanism. The ferroan nature of the subhedral, "granular" dolomite cement which was precipitated coeval with final silica cementation is consistent with its derivation from more highly evolved, Fe-enriched pore water. The same overall pattern has been well-documented in the carbonate cements of the Cow Head Group by Coniglio (1985) through the use of cathodoluminescence and microprobing.

6.2.4 Contrasting diagenetic settings in the Northern Head Group

The conspicuous appearance of Mn-carbonates within the Middle Arm Point Formation, in the variety of occurrences detailed above, contrasts with the "Fe-only" enrichment noted within calcite and dolomite cements of the underlying Cooks Brook Formation. It is clear that processes of early diagenesis differ in these two formations, in concert with the contrasting depositional settings

Figure 6-7

Schematic summary of the contrasting diagenetic settings of the Northern Head group. The location of individual samples (e.g. NAP85-4) referred to in the text and Table 6-1 are also shown.


E.I. FM.
MIDDLE ARM POINT FM.
COOKS BK. FM.
WOMAN COVE MBR.
Ba
MN
MN
Ba
MAP1
NA12
WCW7
NAP85-4
PA2
MIDDLE ARM POINT "SUBOXIC" DIAGENETIC SETTING
• diagenetic Mn-carbonate horizons (within shales)
• variable Mn/Fe-enrichment in dolomite overgrowths
• presence of hematite
• presence of authigenic barite
• late "replacement-style" pyrite
TRANSITION ZONE?
COOKS BK. "ANOXIC" DIAGENETIC SETTING
• Fe-enrichment in dolomite and calcite cements
• Mn-enrichment in carbonates subtle or absent
• no Mn enrichment in shales
• early authigenic pyrite in black shales

outlined in previous chapters.

These contrasting depositional settings are schematically illustrated in fig,6-7 and are broadly distinguished as i) the Cooks Brook "anoxic" diagenetic setting and ii) the Middle Arm Point "suboxic" diagenetic setting.

6.2.4.1 Cooks Brook "anoxic" diagenetic setting

The extensive preservation of organic carbon and paucity of bioturbation through the Cooks Brook Formation suggests that levels of dissolved oxygen were very low in the depositional setting overall, and that anoxic conditions at the sea-floor were probably common. In such a setting, the absence of the zones of i) oxidation and ii) nitrate reduction may be expected, resulting in the presence of the sulphate reduction zone at the sea-floor. Under the early onset of such reducing conditions, the very early mobilization of Mn, either in the water column, on the sea-floor or at very shallow burial depths (where upward diffusion would occur) may be expected. The net result is the loss of Mn to the water column, and its probable removal by water movement. This type of Mn mobilization is widely noted in modern examples of reduced bottom-water conditions (Grill, 1978; Klinkhammer and Bender, 1980).

The mobilization of Fe, on the other hand, may be expected through the zone of sulphate reduction and into the zone of methanogenesis. This reduced Fe will first be incorporated in sulphides, and upon the depletion of reduced sulphur, may be incorporated in the precipitation of carbonate (Hein et al., 1979; Hesse, 1986)

This style of early diagenesis is consistent with the progressive enrichment of Fe in calcite and dolomite cements of the Northern Head group. Samples discussed above from the lower part of the Woman Cove member also demonstrate an affinity with this style of diagenesis, in the Fe-enrichment noted in dolomite overgrowths with little associated Mn-enrichment. This suggests that the transition into the overlying diagenetic setting may have occured through the lower part of the Middle Arm Point.

Petrographic evidence from the silty dolostones of the Middle Arm Point suggests that some late precipitation of ferroan dolomite as overgrowths may have occurred during vertical fluid movement. Within several samples ferroan overgrowth is pronounced along thin vertical "lines" which transect the sample, within an otherwise subtly overgrown dolomite mosaic (Plate 6-5e). These subtle features are not late fractures or veins, and are revealed only by staining. This suggests the possibility that reduced Fe may have been derived at one level in the diagenetic zonation, transported upward and precipitated later.

6.2.4.2 Middle Arm Point "suboxic" diagenetic setting

The elevated levels of bioturbation, paucity of organic carbon and widespread occurrence of hematite through much of the Middle Arm Point Formation indicate elevated levels of dissolved oxygen in the depositional setting relative to the underlying Cooks Brook Formation. The implied levels of dissolved oxygen need not be particularly high in this case, since oxygen levels as low as .5ml/L

O_2 may have supported bioturbation at the levels noted (refer to Chapter 5) and remained within the stability field of hematite. This change in depositional setting is accompanied by an apparent change in the style of early diagenesis, manifested by the diversa occurrences of Mn-carbonate discussed above, and the precipitation of barite, which has been mentioned in the discussion of diagenetic sequence above and is discussed in greater detail below.

6.2.4.3 Recent analogues of Mn-carbonate precipitation

The presence of diagenetically-precipitated Mn-carbonate formed under shallow-burial conditions in modern deep-marine settings has been documented in numerous examples. In general, Mn-enrichment appears in the upper 10 to 20cm of cored intervals, as horizons, crusts or cement dominated by Mn-carbonate, commonly in association with Mn-oxides (Calvert and Price, 1970; 1972) and locally with associated Mn-sulphides (Suess, 1979). Concentrations of 1.5 to 5% Mn are present in bulk samples of such horizons (Calvert and Price, 1970; Pederson and Price, 1982). Carbonate compositions of $Mn_{(.85)}Ca_{(.10)}Mg_{(.05)}CO_3$ (Suess, 1979) and $Mn_{(47.7)}Ca_{(45.1)}Mg_{(7.2)}CO_3$ (Calvert and Price, 1970) have been reported. These Mn-carbonate horizons are associated with elevated levels of dissolved Mn in pore water, ranging up to approximately 15 ppm (Calvert and Price, 1972).

The mechanism of this precipitation of Mn-carbonate within sediment appears to be somewhat variable, but is basically consistent with the general model outlined above, i.e. the mobilization of Mn under reducing conditions associated with progressive burial; the upward movement of this dissolved Mn, and subsequent precipitation at shallower levels in the sediment. Several examples indicate the clear association of Mn-carbonate with coarser horizons within the sediment, where grain-size is thought to have had a catalytic effect on carbonate nucleation (Hein et al., 1979; Pedersen and Price, 1982 and other examples cited therein). This effect is evident in the diagenetic horizons described above.

This style of precipitation appears to have occurred at different levels within the sediment, relative to the diagenetic zonation described above. Evidence of relatively shallow precipitation is reported in one example from the Panama Basin (Pedersen and Price, 1982). There is no evidence, in this case, of variation in pore-water alkalinity through cores of 160cm. There is no significant difference in organic carbon content of sediment through this interval, nor is there any evidence of sulphate reduction. The carbon isotopic signature of Mn-carbonate here is the same as that of co-deposited benthic forams suggesting the supply of bicarbonate and Ca by local dissolution. Sufficient organic carbon is needed in such a setting only to act as as electron donor in the reduction of Mn oxides, which may commence at Eh levels as high as +330 mV (ibid.). Carbon isotopic evidence in other examples indicates either i) mixed derivation of carbon from organic matter and local dissolution sources (Suess, 1979), to ii) organic-derived carbon from the zone of methanogenesis (Hein et al., 1979).

Evidence from pore water sampling and theoretical considerations suggest a general pattern of Mn distribution in sediments overlain by relatively oxidizing marine waters, illustrated in fig 6-8. This indicates the mobilization of Mn in the lower part of the interval, an upward concentration gradient to a layer (at variable depth depending upon local conditions) which is saturated to supersaturated with respect to $MnCO_3$ and where precipitation of Mn-carbonate occurs. Loss by diffusion accounts for the upward decrease in dissolved Mn above this layer (Li et al., 1969; Calvert and Price, 1972; Robbins and Callender, 1975).

6.2.5 Precipitation of Mn-carbonate in the Middle Arm Point Formation

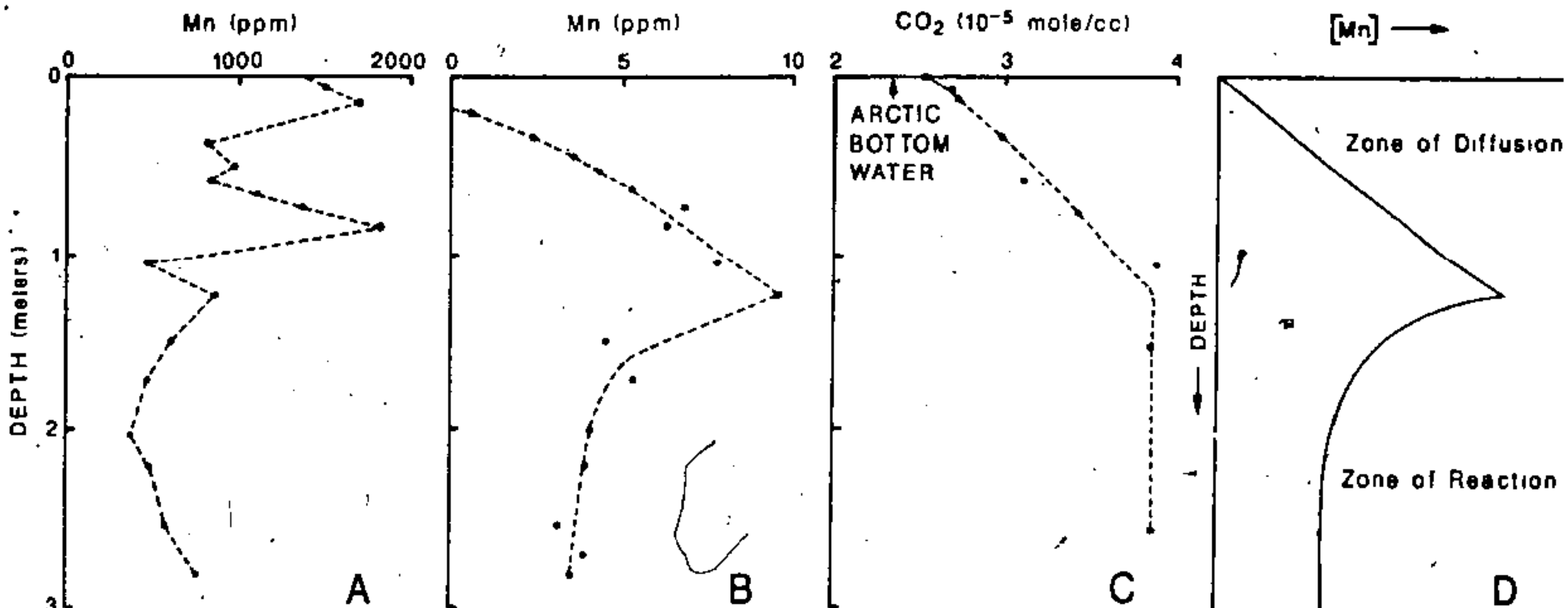
The foregoing discussion suggests that three principal mechanisms may have controlled the locus of Mn(Fe)-carbonate precipitation within the Middle Arm Point Formation. These are:

1) porosity and/or permeability variations through a given interval, which probably accounts for i) the style of diagenetic horizon which originated through poikilitic cementation of silty or sandy layers and ii) the variable overgrowth within dolomitic siltstone units. Solubility factors would also clearly have been modified, in the second case, by the presence of detrital dolomite grains which have acted as templates for subsequent overgrowth from Mn/Fe-enriched pore waters.

2) Precipitation of Mn-carbonate within otherwise relatively homogeneous intervals may have been localized purely by reaction/diffusion-controlled gradients in Mn and bicarbonate concentration as schematically illustrated in figure 6-8. This may account for the occurrence of intervals of scattered rhodocrosite

Figure 6-8

Variation, with depth, of A) Mn content in sediment, B) dissolved Mn concentration within pore waters, and C) total inorganic carbonate content within modern pelagic sediments. These data (redrawn from Li et al., 1969) are correlated, in D) with the governing mechanisms of 1) reaction (i.e. solution and precipitation of Mn-carbonate phases) and 2) diffusion of dissolved species to overlying bottom-waters (redrawn from Calvert and Price, 1972).


Mn (ppm)
0
1000
2000
DEPTH (meters)
0
1
2
3
A
Mn (ppm)
0
5
10
B
CO2 (10^-5 mole/cc)
2
3
4
ARCTIC
BOTTOM
WATER
C
[Mn]
Zone of Diffusion
DEPTH
Zone of Reaction
D

crystals, and for the "diffuse"-style of diagenetic horizon, both described above. In the second case, the presence of very fine detrital dolomite grains may again have further acted to localize Mn-carbonate precipitation.

The presence of "detrital" hematite disseminated through silty dolostone units and locally coating overgrown dolomite grains, prior to silica cementation, provides an important clue which suggests that precipitation of Mn/Fe-carbonate (as overgrowths) in these units occurred, at least locally, under relatively elevated Eh conditions. It is clear that under more reducing conditions, ferric Fe would be reduced, and would be either removed in solution or precipitated as Fe-sulphide.

The variable style of overgrowth described from the silty dolostones of the Middle Arm Point is thought to record the complex interplay of several factors, which include i) the local availability, in pore-waters, of Mn or Fe for incorporation in overgrowths, and ii) the "access" which these pore waters have to precipitating dolomite, which may be governed by local permeability or porosity variations, in turn affected by the timing and degree of silica cementation. Hence abraded grains which are not overgrown may have been isolated by early cementation or other permeability barriers, while the variable Mn/Fe ratio of surrounding overgrowths may reflect the punctuated onset of overgrowth from pore-water at different stages of evolution. Gradients in the nature and composition of overgrowths through individual beds may possibly reflect i) progressive, basally-aggraded precipitation of carbonate through the bed during burial, or ii) sharp concentration gradients of Fe and Mn reflecting locally pronounced redox gradients.

6.2.6 Potential preservation of early-precipitated diagenetic horizons

Clearly continuing burial will result in the migration of sediment through progressively more reducing conditions and will result in the continual dissolution and upward recycling of Mn near the top of the sedimentary column (Robbins and Callender, 1975; Grill, 1978; Wilson et al., 1986). Under these circumstances it is difficult to imagine the ultimate preservation of horizons of diagenetic Mn-carbonate such as those described above. Two possible preservation mechanisms are suggested by the Middle Arm Point occurrences:

1) It is unclear how much organic carbon may originally have been deposited through the Middle Arm Point Formation, and subsequently lost through bacterial metabolism, however the green and red shales which host diagenetic Mn-carbonate now contain essentially no organic carbon. The bacterially-driven oxidation of organic carbon is essentially the "engine" which drives the continuing reduction of sediment through progressive burial. Contained organic carbon may be totally consumed early (i.e. at shallow levels) in the diagenetic system, through a combination of diminished initial supply and/or extensive consumption in the oxidation zone. It is possible that under these conditions Eh may stabilise during continued burial, until lithification is essentially complete.

2) The possible role of early pervasive, silica cementation as a

locally early closure of the diagenetic system has been suggested in preceding sections, and this may have acted to preserve early-precipitated diagenetic features under continued burial. The presence of fine crystalline chert, co-precipitated with recent diagenetic Mn-carbonate, has been noted by Suess (1979). He regarded this as remobilized biogenic silica and suggested that the dissolution and reprecipitation of silica and oxidation of organic matter proceeded simultaneously.

6 2.7 Distribution and significance of barite

The occurrence of authigenic barite crystals within uppermost Middle Arm Point shale has been outlined previously. Similar occurrences of barite throughout this interval are implied by the geochemical signature of shales, which indicates prominent barium anomalies, ranging up to .5% Ba (fig 6-9). It is not considered likely that barium is present in this abundance in any form but barium sulphate. Incorporation of barium within diagenetically-precipitated feldspars has been reported in Ordovician sediments (Bjorlykke and Griffin, 1973), but similar occurrences have not been noted in reconnaissance microanalysis of authigenic feldspar within the Northern Head Group.

The only other sulphate occurrence is fine-crystalline celestite, present in four barium-rich samples (fig 6-9). This is indicated by anomalous Sr concentrations (400 to 600 ppm) against an otherwise uniformly low (100 ppm) Sr distribution through the Northern Head group.

6.2.7.1 Origin of barite

Authigenic barite is a common minor component of modern pelagic sediment, where concentrations of 1 to 3 % have been noted (Dean and Schreiber, 1978; Church, 1979). Concentrations of barite are generally associated with accumulations of pelagic biogenic debris (siliceous and calcareous plankton), and barite is rich in pelleted suspended particulate matter within the Pacific Ocean (Church, 1979). Notwithstanding specific and localized examples of hydrothermal input, the "degradation and alteration of barium-enriched biological remains in restricted, sulphate-excess microenvironments" is regarded as the principal source of barite in modern deep-marine sediments (Church, 1979). This cannot be directly demonstrated, but is considered consistent with barite occurrence in the Middle Arm Point Formation.

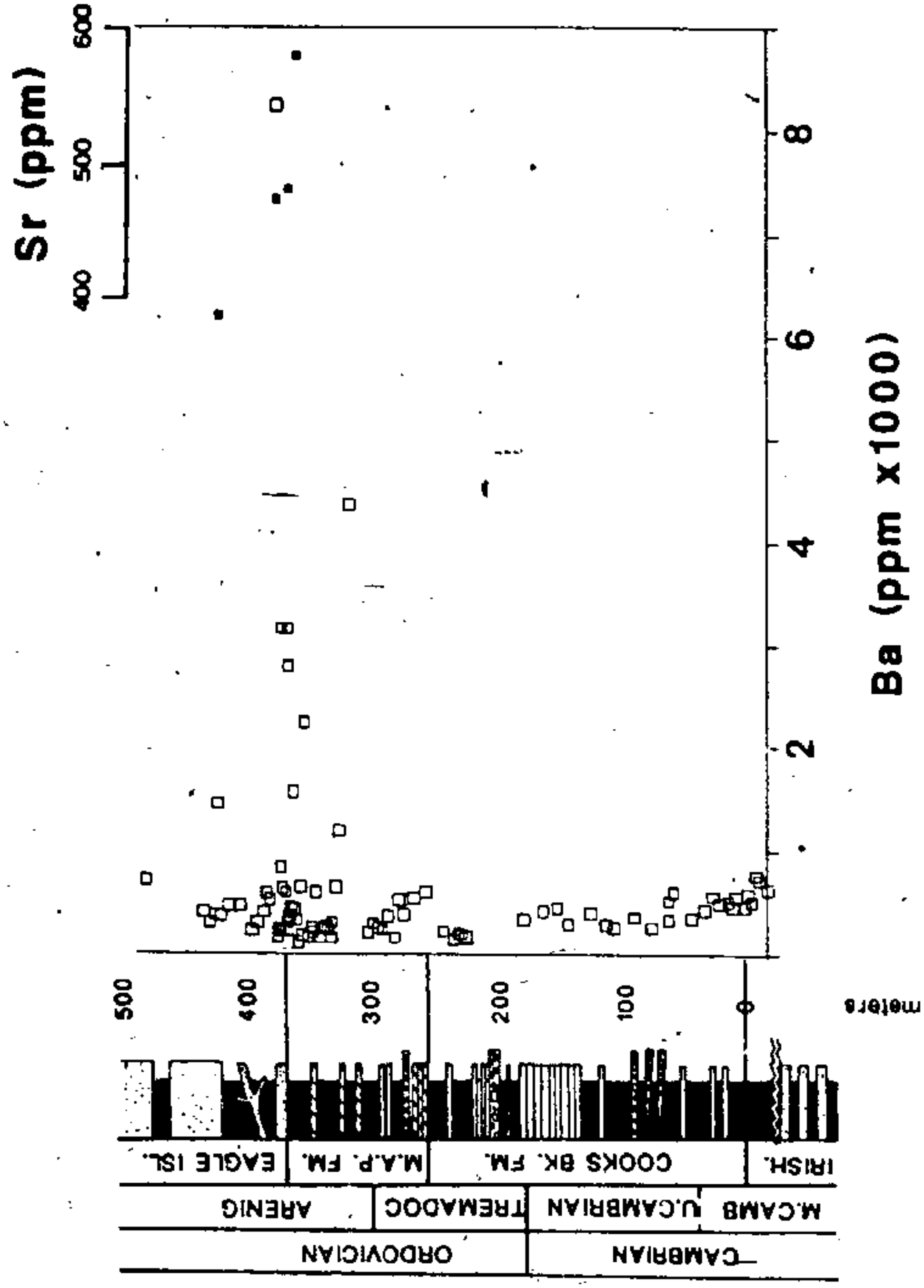
6.2.7.2 Postulated significance of barite distribution in the Northern Head group

The localization of authigenic barite within the uppermost Middle Arm Point and lowermost Eagle Island formations offers confirming evidence of the contrasting early diagenetic settings, outlined above, within the Northern Head group.

Barite has been noted as i) early precipitated, euhedral crystals, locally replaced by calcite, which appear to predate adjacent detrital dolomite overgrowth, ii) thin rims coating detrital dolomite grains and patchy domains within subsequent overgrowths, and iii) irregular domains precipitated during complex

Figure 6-9

Stratigraphic distribution of Ba within shales of the Northern Head group. Anomalous concentrations of Sr within four Ba-rich samples are also indicated, and range from approximately 400 to 600 ppm.


Sr (ppm)
400
500
600
Ba (ppm x1000)
2
4
6
8
metres
0
100
200
300
400
500
IRISH.
COOKS BK. FM.
M.A.P. FM.
EAGLE ISL.
M.CAMB
U.CAMBRIAN
TREMADOC
ARENIG
CAMBRIAN
ORDOVICIAN

chert/Mn-carbonate nodule formation.

As outlined above, active sulphate reduction will occur at, or near, the sediment-water interface under anoxic conditions, and the early diagenetic precipitation and/or preservation of sulphate minerals in such a setting is highly unlikely. This is consistent with the apparent absence of barite through the Cooks Brook "anoxic" diagenetic setting outlined in the preceding section.

This bacterially-driven sulphate reduction proceeds only in the complete absence of oxygen (Berner, 1980) and under more oxidizing depositional conditions, an oxidizing zone of variable thickness will exist at the top of the sediment column, where sulphate is stable. The principal sources of sulphate in pore waters of this zone will be i) diffusion from overlying seawater and ii) upward diffusion of reduced sulphur from the underlying zone of sulphate reduction, which has been subsequently re-oxidized (Tissot and Welte, 1978; Berner, 1980). Such a diagenetic environment clearly represents suitable conditions for the precipitation of sulphate minerals (i.e. barite) and the distribution of barite described above is considered further evidence of a "suboxic" style of early diagenetic setting within the Middle Arm Point Formation, as outlined in the preceding section. The preservation of such early-precipitated barite, upon continued burial, would depend upon factors of subsequent early cementation and the overall reducing capacity of more evolved pore-waters, as discussed previously. The corrosion and replacement by calcite, noted previously, may possibly record localized diagenetic events in the sulphate reduction zone.

6.2.8 Evidence from pyrite precipitation

The occurrence of pyrite as i) an early, commonly fine-crystalline authigenic phase within black shales and ii) a late-stage replacement, commonly of authigenic carbonate, within green shales (especially in the Middle Arm Point Formation) has been described in Section 1.

Under the early onset of anoxic conditions represented by black shales, the coeval processes of sulphate reduction and reduction and mobilization of Fe provide a ready mechanism for the early precipitation of Fe sulphide. This commonly proceeds through an intermediate metastable Fe monosulphide to pyrite (Berner, 1980; Curtis, 1980). This may occur within diagenetic microenvironments, such as thin black (i.e. organic carbon-rich) shale beds, accounting for the observed localization of pyrite within them. The same principle applies to the Cooks Brook "anoxic" diagenetic setting as a whole, and suggests that the "early" style of authigenic pyrite is consistent with the interpreted overall pattern of early diagenesis.

On the other hand, the generally coarser, "replacement-style" of pyrite noted within green shales generally, particularly within the Middle Arm Point, is consistent with the localized precipitation of Fe sulphide late in the diagenetic sequence, under reducing conditions associated with continued burial.

The widespread pyritization of carbonate pebbles, stratigraphically localized at the base of the Cooks Brook Formation, overlies a roughly 40m interval dominated by black shale (refer to Chapter 3). Such an interval is unique in the stratigraphic section here and must have represented an extensive reservoir of organic carbon to act as a substrate for sulphate reduction. A net increase in acidity associated with such pronounced sulphate reduction (Curtis, 1980) may have resulted in carbonate dissolution and immediate widespread replacement by Fe sulphide to the anomalous degree noted.

6.2.9 Early diagenesis of the Northern Head group: Summary

Aspects of the changing geochemistry of shales through the section, the style and composition of early- precipitated carbonates, the presence and distribution of barite, and the nature of pyrite authigenesis all suggest that early diagenetic conditions in the Northern Head group changed in concert with changing depositional conditions.

Two principal modes of early diagenesis are noted. The first is accompanied by the overall abundance of organic carbon, and is characterized by late-stage ferroan enrichment in calcite and dolomite cement with little or no accompanying Mn-enrichment, ii) the absence of Mn in shales, iii) the absence of barite, and iv) the presence of early-precipitated pyrite, and the apparent absence of ferric Fe compounds. These characteristics are consistent with the early onset of anoxic diagenetic conditions, at, or very close to the seafloor. This "Cooks Brook anoxic early diagenetic setting" prevailed from at least the uppermost Irishtown Formation, through the Cooks Brook, and appears to be transitional through the basal Middle Arm Point Formation into the overlying "Middle Arm Point suboxic early diagenetic setting". This overlying setting is characterized by i) the widespread occurrence of Mn-carbonates within a variety of diagenetically-precipitated horizons in shale-dominated intervals, ii) the incorporation of Mn in euhedral overgrowths within silty dolostone units, which have iii) been precipitated within the stability field of hematite, iv) the presence of authigenic barite and v) an overall late-stage, "replacement" style of pyrite precipitation. These features are thought to reflect early diagenesis under redox gradients at shallow depths in the sediment, which existed as a result of increased oxygen levels in the depositional environment.

CHAPTER 7

SHALE GEOCHEMISTRY

7.1 Introduction

Deposition of the Northern Head group spans establishment of a long-lived shallow-water carbonate platform and its subsequent burial. With this history in mind, shale samples were collected to provide possible additional evidence of changing depositional and diagenetic conditions or source areas.

Geochemistry of an individual shale is the complex sum of many factors, which include i) the original mineralogy, reflecting the composition and weathering history of the source area(s), ii) the effect of depositional conditions, such as hydraulic sorting or sediment oxidation and iii) the diagenetic history. For example, the distribution of SiO_2 through shales of the Northern Head group is the net result of both the original input of detrital grains of quartz and silicates such as feldspar and clay minerals, and diagenetic processes of silicification discussed in Chapters 4 and 6.

Given these diverse controls on the final composition of a shale, aspects of shale geochemistry must be carefully separated, and selected to address specific questions of geological significance. Aspects of shale geochemistry clearly indicate changes in depositional and early diagenetic conditions through the Northern Head group as discussed in Chapters 4 and 6. The purpose of this chapter is to address one principal question: is there a change in aspects of the major and trace element geochemistry of shales through the section, which may be related to changing provenance through the deposition of the Northern Head Group?

7.2 Approach

A total of 96 shale samples were collected through the Northern Head group, and the underlying Irishtown Formation and overlying Eagle Island formation.

The position of samples within individual sections was noted, and translated into the overall stratigraphic position in a composite section, based upon the correlations presented in Chapter 3. The greater sampling density apparent through the Middle Arm Point and lowermost Eagle Island formations reflects the lithologic variability of shales through this interval.

In depositional settings receiving mixed carbonate/siliciclastic input, such as the Northern Head Group, these two principal components have a "dilution effect", one upon the other, so that the concentration of elements principally associated with detrital siliciclastic input, will be diminished, or diluted, within carbonate-rich samples. Moreover, the grain-size distribution of a given sample may govern the mineralogical composition, and hence exert a control on the elemental composition. To facilitate comparison, given these effects, a deliberate effort was made to collect representative samples of non-calcareous shales with a modal grain size in the clay to fine silt range (based upon field examination).

All samples were analysed for major elements, and the following trace elements: Pb, U, Th, Rb, Sr, Y, Zr, Nb, Ga, Zn, Cu, Ni, La, Ti, Ba, V, Ce and Cr. Determination of total organic carbon content was performed on 66 representative samples. Clay mineralogy of the <2 micrometer fraction was determined for a representative 30 samples. All analytical procedures are summarized in Appendix E.

7.3 Major and trace element variation in the Northern Head group

Three different suites of elements are apparent in the shale samples studied, and are distinguishable by the internal similarity of their distribution, governed by different geological factors. The first is a group of selected major elements (and related traces) which are associated with the detrital input of silicate minerals, particularly clay minerals, which volumetrically dominate. Evidence of this relationship with clay mineralogy is discussed in this section. Distribution of the second suite of (trace) elements displays stratigraphically localized anomalous concentrations, demonstrated through SEM/EDAX examination to be associated with the presence of detrital heavy mineral silt grains. The third suite of elements also displays localized anomalous concentrations, found, through SEM/EDAX examination to be governed by the presence of sulphide minerals.

The distribution of Mn, Fe, Ba and Sr has already been discussed in Chapter 6 and demonstrated to be governed by early diagenetic processes. Concentrations of U, Th and Nb were found to be consistently low in the shales examined, and these elements are not used in the discussion and interpretation presented here.

7.4 Elements associated with detrital silicate minerals and clay mineralogy: K, Al, Na, Ti, Rb, Ga, and La

Based upon the similarity of their stratigraphic distribution, and principles outlined in the foregoing discussion, several major elements are grouped together, and regarded as reflecting basic changes in the detrital input of silicate minerals into shales of the Northern Head Group (fig 7-1). These elements are potassium, aluminum, sodium and titanium, plus the trace elements rubidium, gallium and lanthanum.

7.4:1 Common mineralogical occurrence of these elements

The distribution of potassium is principally related to the presence of illite and K-feldspar. Aluminum is a ubiquitous "detrital" element, present in varying proportions within alumino-silicates; it is a major component of illite, for example (38.5 wt.% Al_2O_3). Titanium is contained in a number of common, detrital heavy minerals including rutile, sphene, ilmenite, and anatase, which appear commonly in multi-cycle clastic sediments. Sodium may substitute within clay mineral structure, but is principally contributed by the presence of plagioclase. The well-established substitution of rubidium for potassium and gallium for aluminum (Krauskopf, 1967; Fairbridge, 1972) results in the clear parallelism in distribution of these respective elements (fig 7-1). Likewise, the substitution of lanthanum in "detrital" silicates, e.g. monazite (Fairbridge, 1972), results in a similar parallelism.

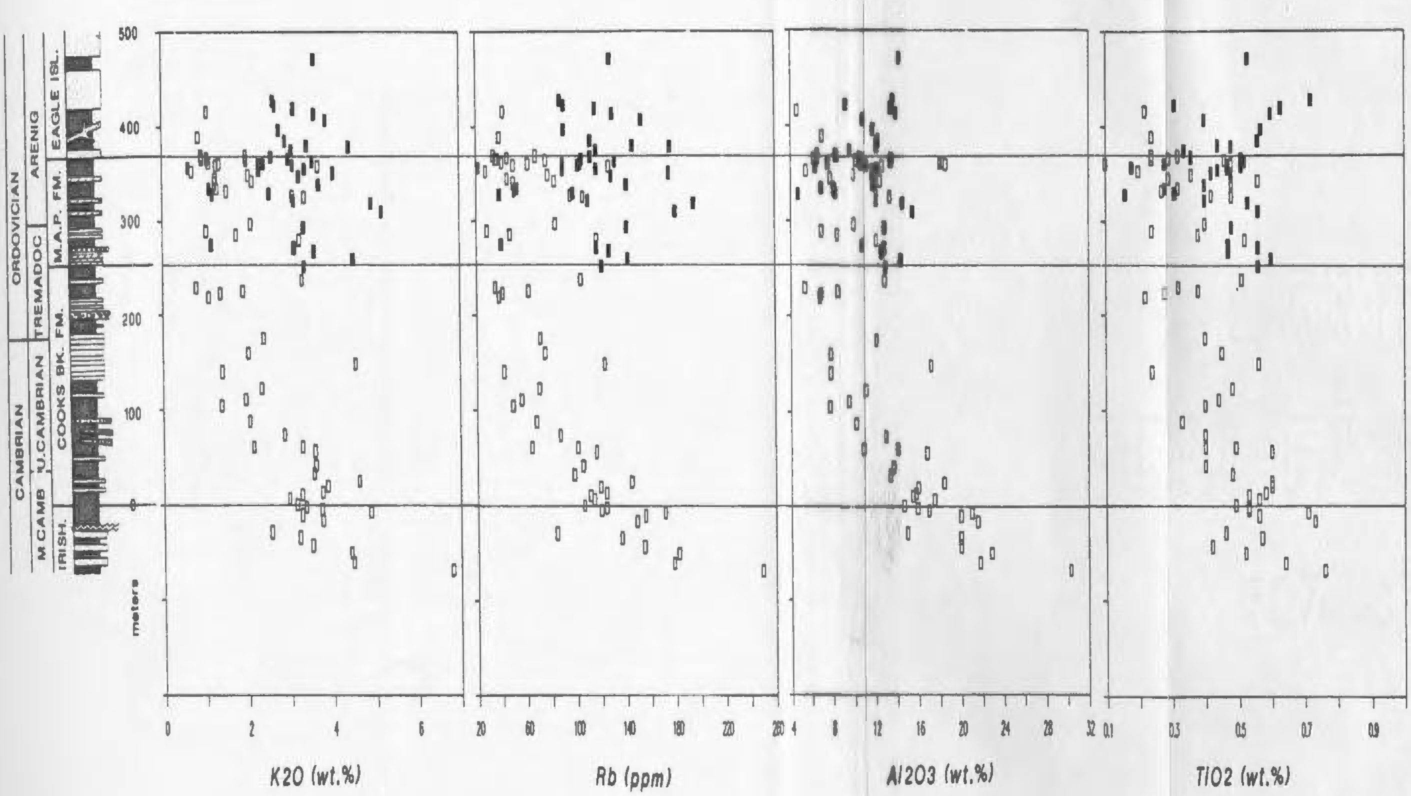
Figure 7-1

Stratigraphic distribution of representative elements associated with detrital silicate minerals and clay mineralogy, in shales of the Northern Head group and adjacent units.

Open squares represent shales of the Irishtown Formation, plus "Group A" shales (i.e. black plus black/green) of the Northern Head group and Eagle Island formation.

Filled squares represent "Group B" shales of the Northern Head group and Eagle Island formation (i.e. green plus red/green shales, commonly associated with detrital dolomite, and displaying evidence of bottom current activity).

The contrast in major element composition of these two groups is summarized in Table 7-1.


ORDOVICIAN
CAMBRIAN
ARENIG
TREMADOC
U.CAMBRIAN
M CAMB
EAGLE ISL.
M.A.P. FM.
COOKS BK. FM.
IRISH.
meters
K2O (wt.%)
Rb (ppm)
Al2O3 (wt.%)
TiO2 (wt.%)

7.4.2 <u>Maturity indices</u>

Additional perspective, in examining relative changes in the concentration of these elements, is gained through the use of ratios, that is "maturity indices", chosen to reflect mineralogical changes. The most useful of these are i) $Al_2O_3+K_2O/MgO+Na_2O$ (Bjorlykke, 1974) (referred to herein as "M1") and ii) K/Rb ("M2") (cf. Dypvik, 1977; 1984). M1 is chosen to broadly reflect a general weathering sequence (cf. Krauskopf, 1967) and may respond principally to changes in clay mineralogy *viz* illite/chlorite ratio, plus relative proportions of K-feldspar vs. plagioclase. MgO is included in the denominator of the ratio to reflect the presence of chlorite. Hence "mature", intensely weathered source terrains may be expected to yield high ratios, while relatively "immature", or more mafic-rich source terrains may be expected to yield lower ratios. Given the elements used, it is clear that this index may be affected by the presence of i) dolomite or ii) authigenic feldspar within individual samples. However, the number of samples with appreciable amounts of dolomite, based upon the original sampling criteria, are considered too few to significantly alter the distribution, and the growth of authigenic feldspar appears to be confined principally to carbonate lithologies.

M2 is chosen to reflect the stronger chemical bond of rubidium relative to potassium, in both mineralogical substitution and adsorption. Hence deeply-leached source terrains commonly suffer preferential removal of K, and display low K/Rb ratios (30 to 80) while more immature terrains display K/Rb ratios closer to that of seawater (240) (Fairbridge, 1972).

Stratigraphic distribution of these indices is illustrated in figure 7-2.

7.4.3 Clay mineralogy

Given the volumetric importance of clay minerals within the shales examined, the clay mineralogy of 30 representative samples was determined, using the methods described in Appendix E. These samples span the Summerside and Irishtown Formations, Northern Head group and lowermost Eagle Island formation. Untreated, glycolated and heated preparations indicate that the only clay minerals present are illite and chlorite. No evidence of mixed-layer clays nor kaolinite has been detected.

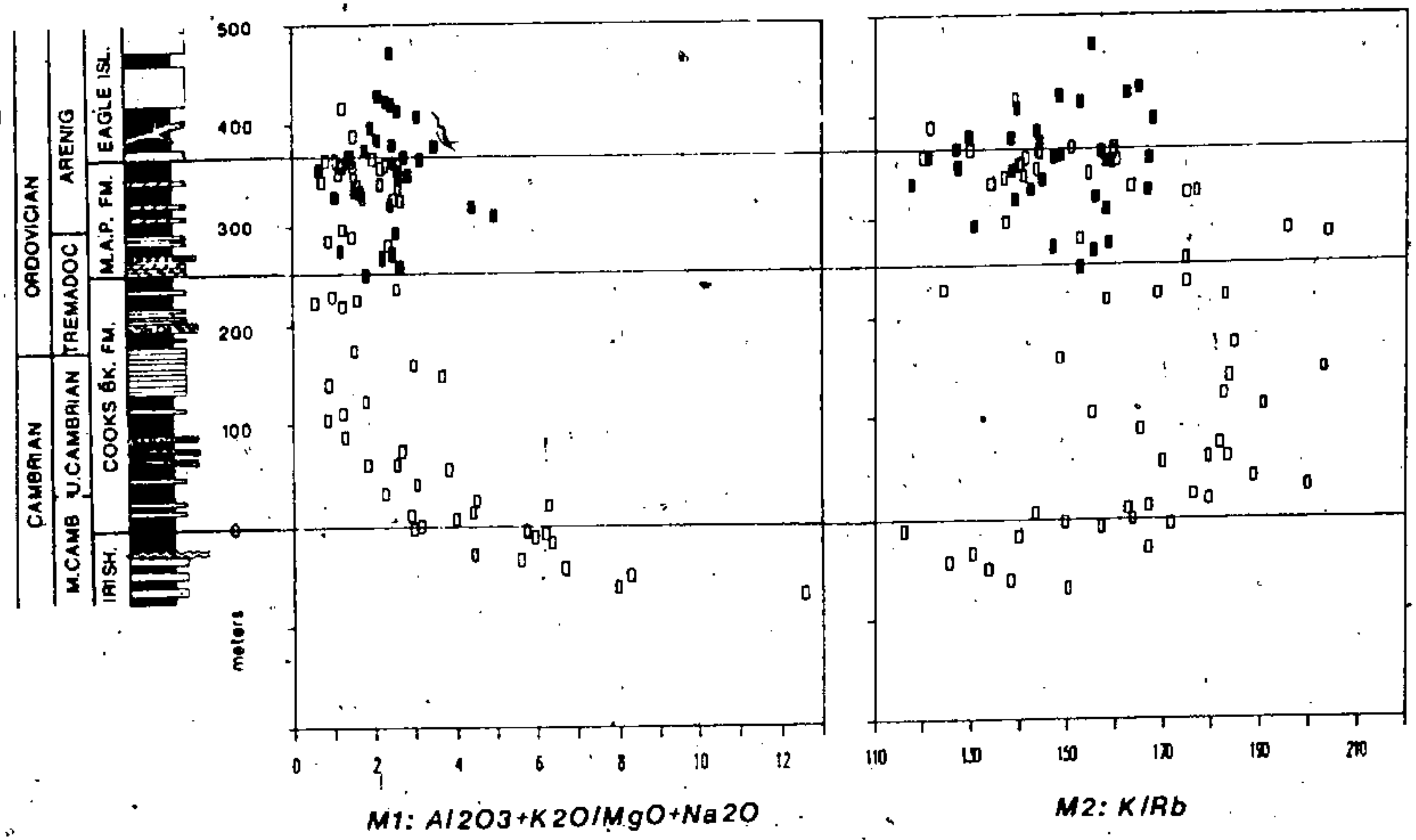
The relative proportions of illite and chlorite have been estimated by comparing the area of the chlorite 7A reflection [002] with the illite 10A [001] reflection (approximated as peak height x width at half height, after Norrish and Taylor (1962), Dypvik (1977) and Bjorlykke and Englund (1979). The changing nature of the chlorite/illite ratio through the stratigraphic section is illustrated in figure 7-3.

7.4.4 Stratigraphic variation

Based upon the stratigraphic variation in concentrations of the "detrital" elements (fig 7-1), maturity indices M1 and M2, and chlorite/illite ratio (fig 7-2), three groups of shale, with distinctive signatures are distinguished. Shales of the Irishtown Formation represent the first group.

Figure 7-2

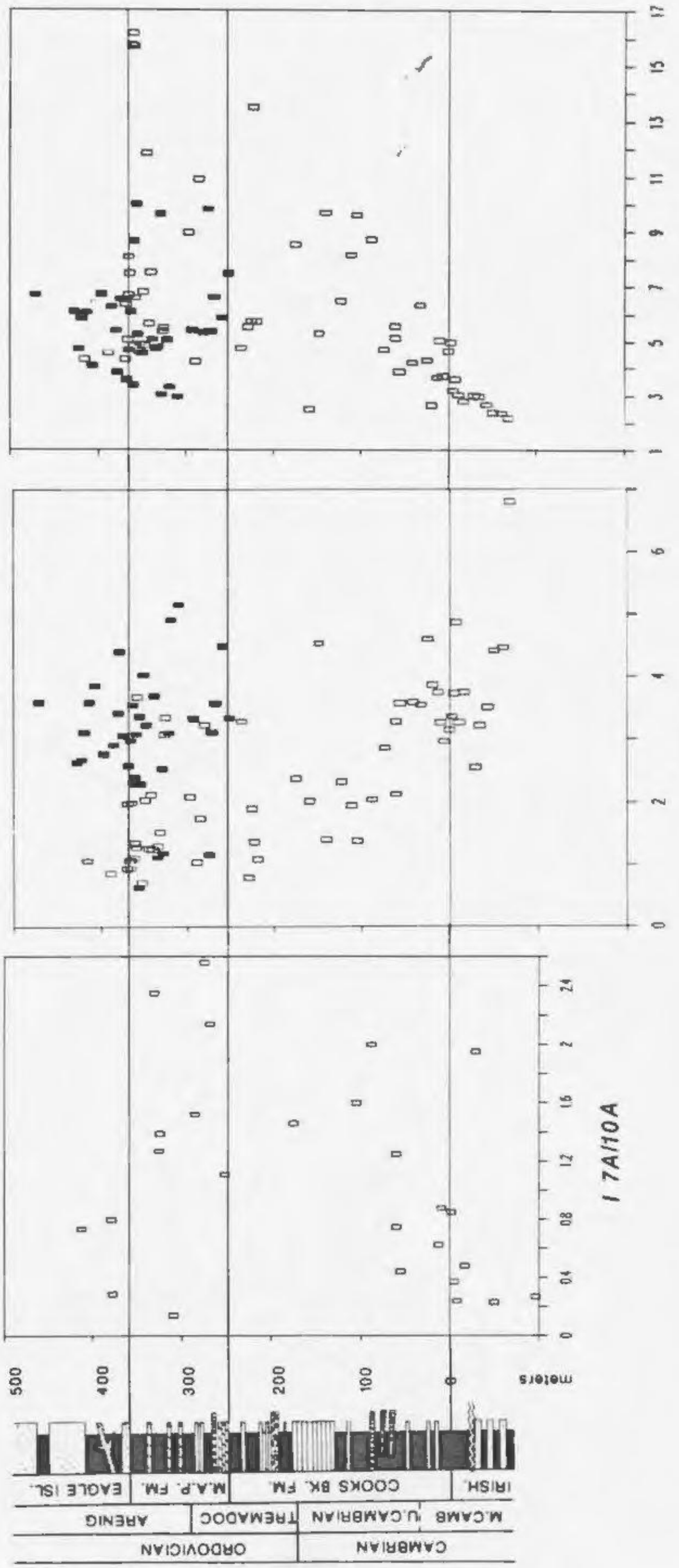
Stratigraphic variation in the maturity indices, "M1" and "M2", for shales of the Irishtown Formation, Northern Head group and Eagle Island formation. The symbols used are the same as in Figure 7-1.



ORDOVICIAN
CAMBRIAN
ARENIG
TREMADOC
U.CAMBRIAN
M.CAMB
EAGLE ISL.
M.A.P. FM.
COOKS BK. FM.
IRISH.
500
400
300
200
100
0
meters
0
2
4
6
8
10
12
M1: Al2O3+K2O/MgO+Na2O
110
130
150
170
190
210
M2: K/Rb

Figure 7-3

Stratigraphic variation in clay mineralogy within the Irishtown Formation, Northern Head group and Eagle Island formation (refer to text for details). Irishtown shales are relatively illite-rich, displaying high K2O and low MgO values. The relative increase in chlorite upward is accompanied by a decrease in K2O and increase in MgO. Group "B" shales (filled squares) of the Middle Arm Point and Eagle Island formations are commonly anomalously rich in illite (refer to discussion in text; Table 7-1).


CAMBRIAN
ORDOVICIAN
M.CAMB
U.CAMBRIAN
TREMADOC
ARENIG
IRISH.
COOKS BK. FM.
M.A.P. FM.
EAGLE ISL.
meters
I 7A/10A
K2O (wt.%)
MgO (wt.%)

Two groups of shale are discriminated within the Northern Head group, based principally upon the sedimentologic associations delineated in Chapter 4. These are:

A) Black and green shales, commonly associated with limestones, which occur within sequences interpreted (in Chapter 4) to represent gravity transport deposits (principally turbidites and debris flow deposits).

B) Red and green shales which appear within the Middle Arm Point Formation, and are commonly associated with (detrital) dolomite, including the green shale interbeds within the Woman Cove Member. These shales commonly occur within intervals which display evidence of i) elevated levels of dissolved oxygen (Chapters 4, 5 and 6) and ii) bottom-current deposition or reworking (Chapter 4).

7.4.4.1 Irishtown shales

Shales of the Irishtown Formation are characterized by relatively high concentrations of detrital elements, high values of M1 and low values of M2, and relative abundance of illite (figs. 7-1, 2, 3; Table 7-1). This signature suggests derivation of this group of shales from a "mature", weathered source terrain, likely continental basement. This is consistent with the derivation of these shales from the same type of mature source area which yielded the dominantly quartzitic sandstones of the Irishtown and with the relative abundance of detrital mica noted in petrographic examination (Chapter 4).

7.4.4.2 Group A shales of the Northern Head group

The transition from Irishtown upward into the Cooks Brook Formation is accompanied by a sharp, systematic decrease in the concentrations of the "detrital" element suite, and corresponding decrease in M1 and increase in M2, and significantly increased proportion of chlorite upward through the remainder of the Northern Head group (figs. 7-1, 2, 3; Table 7-1). This is indicative of markedly reduced input from the mature type of source area which dominated shales of the Irishtown. This change appears in concert with, and is likely directly related to, the establishment of the shallow-water carbonate platform upslope. In this sense, the platform may have acted as a barrier, diminishing direct continental input to predominantly eolian-transported material, and increasing the relative importance of marine-transported mud.

7.4.4.3 Group B shales of the Northern Head group

This group of Middle Arm Point shales is geochemically distinct from group A in i) the elevated concentration of potassium commensurate with increased proportions of illite, ii) elevated values of M1, and iii) lower values of M2 (figs. 7-1, 2, 3; Table 7-1). The fact that this sedimentologically distinctive group of shales also displays a distinctive geochemical signature suggests that it denotes input of clay-sized material from a different source area, beginning at the base of the Middle Arm Point Formation.

TABLE 7-1: COMPARISON OF MAJOR ELEMENT COMPOSITION OF GROUP "A" AND "B" SHALES OF THE MIDDLE ARM POINT AND EAGLE ISLAND FORMATIONS

Group "A" are black plus black and green shales
Group "B" are green plus red and green shales, commonly associated with detrital dolomite, and displaying evidence of bottom current activity. Note, in particular, the elevated K20 content of group "B", associated with more abundant illite.

	Group "A" (Average of 25 samples)	Group "B" (Average of 36 samples)
SiO2	55.08	62.45
TiO2	0.35	0.46
Al2O3	10.21	11.53
MnO	0.51	0.42
MgO	7.50	5.62
CaO	5.53	1.99
Na2O	0.72	0.83
K2O	1.68	3.07
P2O5	0.20	0.11
LOI	10.64	7.01
FeTot	7.18	6.25
Corg	0.16	0.06
M1	1.54	2.41
M2	150.53	147.67
Rb	60.96	115.11

The dispersion of elemental concentrations within the Middle Arm Point Formation is considered to be the result of two principal factors. The first and most important is the presence of the two genetically different groups of shales outlined above. The average chemical composition of these two groups is compared in Table 7-1. The contrast in these groups is most evident in the elevated potassium content of Group B, which is interpreted to reflect the relative abundance of illite (fig 7-3).

This distinction may have been "smeared" somewhat in the dispersion of elemental concentrations during diagenesis. Silicification and localized carbonate precipitation, extant in the Middle Arm Point Formation (Chapters 4, 6), may have served to disperse elemental concentrations, in the localized partial replacement of clay matrix inherent in these diagenetic processes. Diagenetic redistribution of titanium, as amorphous oxides, (cf. Bjorlykke and Englund, 1979; Morad and AlDahan, 1986) may also have occurred at this time.

7.4.4.4 Discussion

A similar approach has been employed in studies of Lower Paleozoic sequences in the Scandinavian Caledonides (Bjorlykke, 1974; Dypvik, 1977; Bjorlykke and Englund, 1979). Here Cambrian and Lower Ordovician shales are illite-dominated and regarded as derived from a deeply-weathered continental source area. A marked change to chlorite-dominated shale in the Middle Ordovician has been ascribed by these authors to derivation from oceanic volcanics to the west during Taconic orogenesis. This is accompanied by increased Ni and

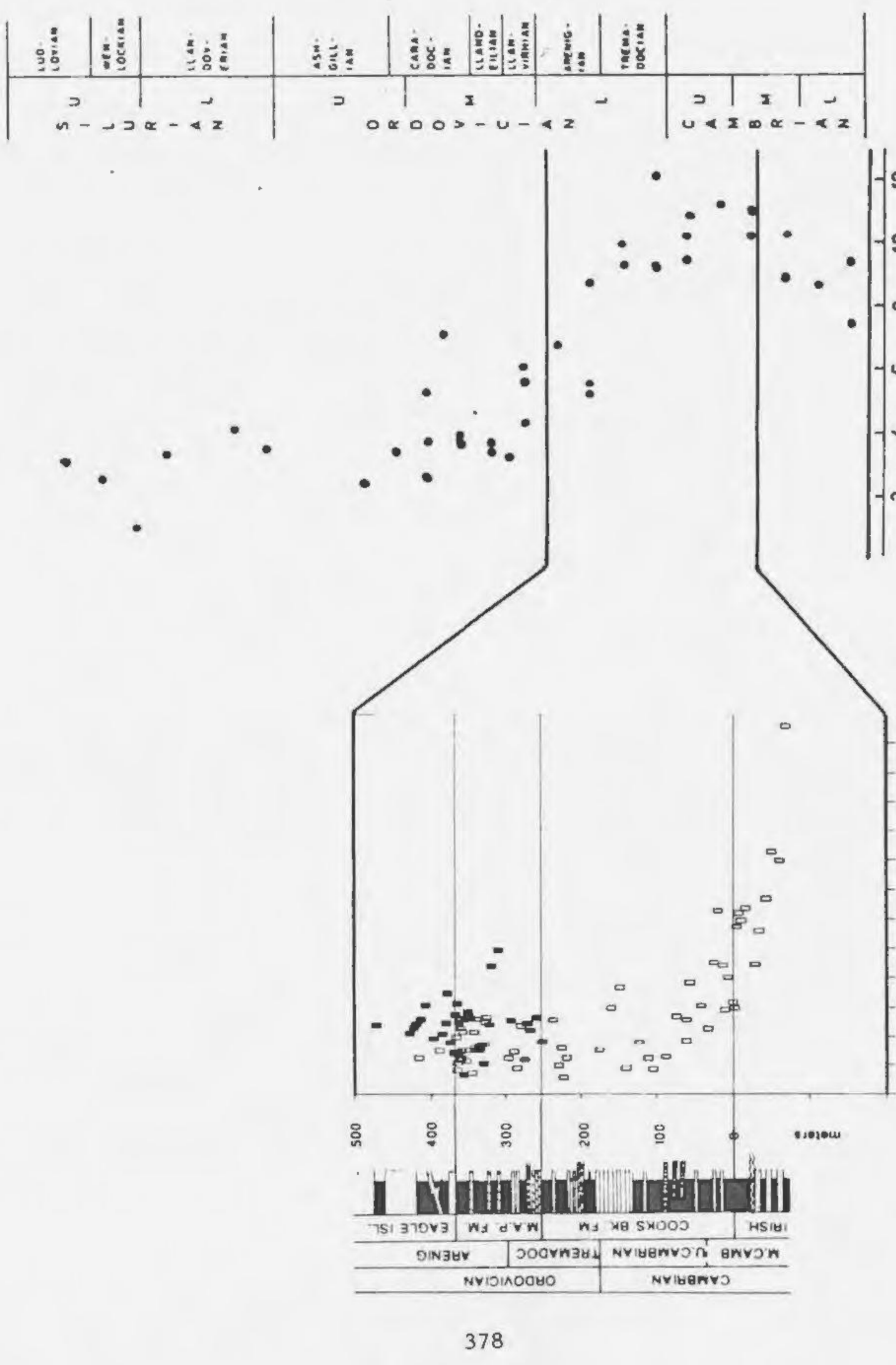
Cr concentrations suggestive of an ultrabasic input.

The maturity index (=MI) of Bjorlykke (1974) is broadly similar to that derived in this study for Irishtown plus "Group A" shales (fig 7-4). The presence of "Group B" shales is an additional factor not encountered in the Scandinavian studies, fundamentally related to the difference in depositional setting of the two areas (epicontinental vs. deep marine). The temporal and geographic relationship of this clay mineralogic change with the arrival of a volcanic source has been convincingly demonstrated in the Lower Paleozoic of Scandinavia (ibid.). However there is no compelling evidence in the regional geology of western Newfoundland to suggest the direct input of volcanic-dominated source terrains to account for this progressive change in MI (and associated factors), which begins at the end of the Middle Cambrian. Rather, this change appears to be associated with the evolution of the margin upslope and represents the marked reduction of an illite-dominated mud component, which is probably continent-derived and the commensurate increase in a chlorite-dominated component. This might have been accomodated, for example, by the "shut-off" of direct fluvial input of mud into the marine system due to the establishment of the shallow-water carbonate platform, and relative increase in delivery of mud to the depositional site by a possible combination of eolian transport or geostrophic marine currents.

Stratigraphically distinct clay mineral suites have been identified in the Cow Head Group, and this change in clay mineralogy has been ascribed to the influx of volcanogenic material in the late

Figure 7-4

Comparison of stratigraphic variation in "maturity index" (MI: $Al_2O_3+K_2O/MgO+Na_2O$) for 1) shales of the Northern Head group and adjacent units and 2) the Lower Paleozoic epicontinental sequence of the Oslo region (Bjorlykke, 1974). A pronounced reduction occurs through the upper Middle Cambrian to Lower Ordovician interval in both cases. This is thought, in this study, to reflect the onset of platformal carbonate sedimentation, while in the Scandinavian study is interpreted to reflect mud input from a volcanic-dominated, "immature" source area during Taconic orogenesis.



(1)
CAMBRIAN
ORDOVICIAN
M.CAMB
U.CAMBRIAN
TREMADOC
ARENIG
IRISH
COOKS BK. FM
M.A.P. FM
EAGLE ISL.
meters
M1: Al2O3+K2O/MgO+Na2O
(2)
M
SILURIAN
ORDOVICIAN
CAMBRIAN

Early and Middle Ordovician (Suchecki et al., 1977). These assemblages are: i) an upper Middle Cambrian to lower Lower Ordovician illite-chlorite suite, ii) a Lower Ordovician illite-expandable chlorite suite and iii) an upper Lower to Middle Ordovician corrensite-illite-smectite suite. Corrensite is regarded by these authors as the diagenetic product of Mg-rich volcanogenic detritus. The presence of corrensite in Lower Ordovician Cow Head shales was confirmed by Coniglio (1985), however no smectite nor expandable chlorite were identified by Coniglio.

Based upon the examination of 30 representative samples, the clay mineralogy of the Northern Head group contrasts with that reported from the Cow Head Group, in the absence of mixed-layer clays, including corrensite and expandable chlorite. This may be due to i) the deep diagenetic transformation of mixed-layer clays to illite or chlorite in the Northern Head group or ii) contrasting local source area influence in the Ordovician. Systematic investigation of this problem is considered beyond the scope of this study. However a comparable deep diagenetic history for the two groups is suggested by i) comparably low conodont C.A.I. (approximately 1.5 for Middle Arm Point specimens; C.R. Barnes, pers. comm., 1985) and ii) roughly equivalent illite crystallinity, based upon a brief survey of Cow Head Group shales. Hence a factor of contrasting source area contribution is considered more likely responsible for this apparent difference in clay mineralogy in the Ordovician.

7.5 Trace elements associated with detrital heavy minerals: Cr, Zr, Y, V, and P

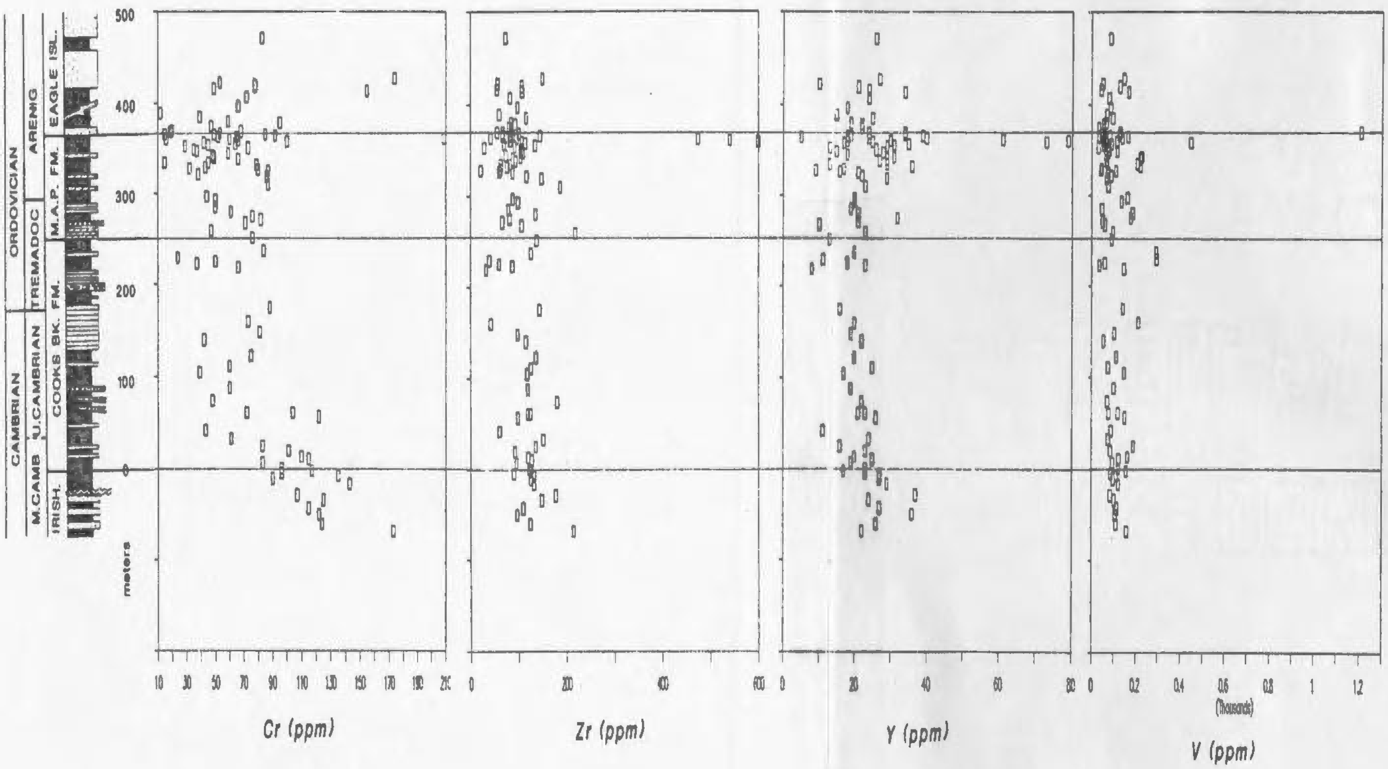
Other selected elements display a different style of distribution through the section. The concentrations of chromium, zirconium, yttrium, vanadium and phosphorus are relatively consistent through the section, up to a point immediately below the base of the Eagle Island formation, where a few anomalously high values occur (fig 7-5).

Of particular interest at the outset of this study were chromium and nickel, since these elements are commonly enriched in ultrabasic rocks and their enrichment in shales has been used in similar studies to infer the contribution of an ophiolitic source terrain (Bjorlykke, 1974; Bjorlykke and Englund, 1979). Within such a setting, chromium occurs principally within chromite, a common "detrital heavy mineral", but may substitute to a minor degree within mafic minerals or chlorite. Nickel may occur within sulphide minerals, and commonly substitutes within olivine and pyroxene. Both elements may also conceivably be transported through adsorption on clay mineral surfaces, or through association with organic material.

At the base of the section, the upward transition from Irishtown into Cooks Brook Formation is accompanied by a reduction in chromium and nickel values consistent with change from terriginous clastic to carbonate-dominated source area and depositional setting. Anomalous nickel concentrations at the top of the section are controlled by sulphide occurrences which will be discussed in the next section. The anomalous concentrations of chromium, zirconium, yttrium,

Figure 7-5

Stratigraphic variation in trace elements controlled by the localized presence of detrital heavy mineral silt grains (note anomalous values at the base of the Eagle Island formation).


ORDOVICIAN
CAMBRIAN
ARENIG
TREMADOC
U.CAMBRIAN
M.CAMB
EAGLE ISL.
M.A.P. FM.
COOKS BK. FM.
IRISH.
meters
Cr (ppm)
Zr (ppm)
Y (ppm)
V (ppm)
(Thousands)

vanadium and phosphorus at the base of the Eagle Island formation are all controlled by the presence of subrounded detrital "heavy mineral" silt grains. Detrital chromite, zircon, xenotime, Y-bearing monazite, and vanadium-bearing ilmenite grains have all been identified within these shales using the SEM/EDAX. Particularly anomalous values (fig 7-5) are associated with six individual samples which appear to contain particularly abundant concentrations of detrital heavy mineral silt grains. A SEM/EDAX survey of shales at this general stratigraphic interval reveals the presence of similar detrital grains in other samples, but apparently not in concentrations sufficient to result in pronounced geochemical anomalies. The most abundant of these are monazite ($(Ce,La,Y,Th)PO_4$) and xenotime (YPO_4) which probably account for the subtle increase in yttrium concentration in many samples at this stratigraphic level. Only uniform, background levels of Ce and La have been noted here, suggesting that these detrital phosphates are Y-rich.

Apart from its anomalous enrichment at this stratigraphic horizon, the concentration of vanadium is uniformly low throughout the Northern Head group. It displays no correlation with organic carbon, but is strictly controlled by the occurrence within these detrital grains. Similarly, this is the only enrichment of phosphorus within Northern Head group shales.

7.5.1 Discussion

Microanalysis of many clay mineral grains and the common interstitial silica (refer to Chapters 4, 6) was conducted in the SEM/EDAX survey of these shales and the above-discussed elements were found to be confined only to detrital grains. No evidence of substitution within clays, nor diagenetic precipitation or redistribution involving these elements was detected. Thus it appears that the principal control on the concentation of these elements was the input of detrital silt grains, and their localized concentration during deposition.

Elevated concentrations of Cr occur in the uppermost Irishtown and lowermost Cooks Brook Formations (fig 7-5). This suggests the contribution of ultrabasic source terrain(s) in the Middle Cambrian. One such source may have been ultrabasic intrusives within the crystalline basement. Determination of source terrains of the Irishtown Formation would require a detailed petrographic examination, beyond the scope of this project; this problem awaits further study.

The localized presence of detrital chromite grains is suggestive of some input from an ultrabasic source, beginning at the base of the Eagle Island formation. Elevated concentrations of chromium, consistent with contribution from an ophiolitic source terrain, have been reported from sandstone samples of this unit (referred to as Blow Me Down Brook Formation) and presumed equivalents in western Newfoundland (including the autochthonous Mainland Sandstone) and Quebec (Tourelle Formation) by Hiscott (1984).

Monazite, xenotime and zircon, on the other other hand, are common accessory minerals in granite, syenite and gneissic rocks, and are commonly concentrated in detrital sediments derived from these (Berry and Mason, 1959).

7.5.2 Summary

The stratigraphic distribution of chromium, yttrium and zirconium indicates a scattered change in shale geochemistry at the base of the Eagle Island formation associated with the localized concentration of detrital heavy mineral silt grains derived from a mixed source area, including an original acidic igneous component (or sedimentary rocks derived from such a lithology) plus ophiolitic input.

7.6 Elements controlled by sulphide occurrence: Zn, Pb, Cu and Ni

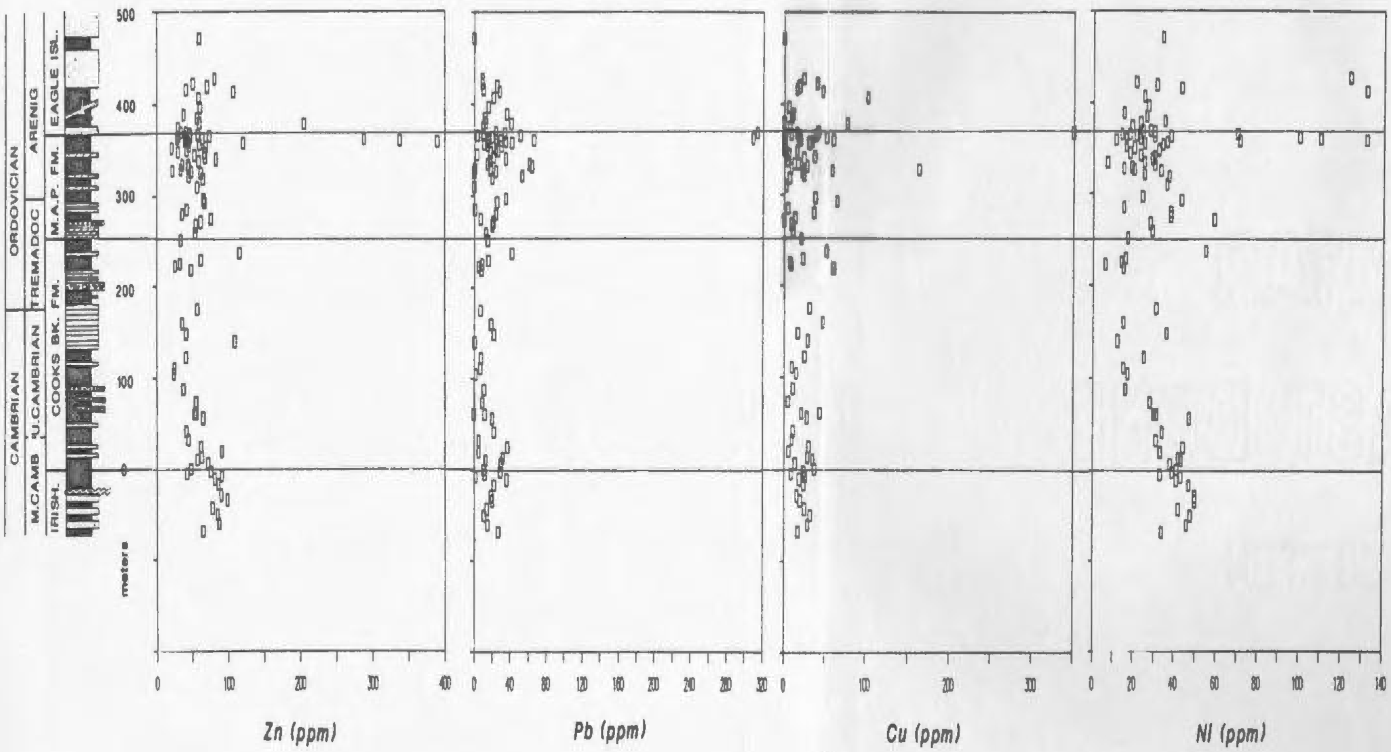
The stratigraphic distribution of zinc, lead, copper and nickel indicates anomalously elevated concentrations of these metals in shales at the base of, and within, the Eagle Island formation (fig 7-6). Detailed SEM/EDAX examination of individual shale samples here, indicates the presence of finely disseminated blebs of galena and sphalerite (commonly intergrown) and locally chalcopyrite and pentlandite. These are roughly 10 micrometers in size, and commonly demonstrate irregular, intergrown and locally replacive boundaries with the surrounding clay matrix.

Discussion

The mobility of transition metals such as copper, lead and zinc generally increases under oxidizing conditions, while reducing conditions generally result in precipitation as sulphides in the presence of reduced sulphur (Jacobs and Emerson, 1982; Maynard, 1983). Transport mechanisms may include the formation of complexes involving chloride or organic matter. Concentration of metals in

Figure 7-6

Stratigraphic distribution of Zn, Pb, Cu, and Zn within shales of the Northern Head group and adjacent units. This displays the anomalous concentration of these elements in sulphides localized at the base of the Eagle Island formation.



ORDOVICIAN
CAMBRIAN
M.CAMB
U.CAMBRIAN
TREMADOC
ARENIG
IRISH.
COOKS BK. FM.
M.A.P. FM.
EAGLE ISL.
meters
500
400
300
200
100
0
Zn (ppm)
Pb (ppm)
Cu (ppm)
Ni (ppm)

organic material may commence during the life-cycle of organisms, and combined with the behaviour of these metals outlined above, is thought to account for the common association of sulphide mineralization with (organic-rich) black shale (Vine and Tourtelot, 1970; Calvert and Price, 1970; Maynard, 1983).

These processes of metal-enrichment in black shales do not, however, appear to be the principal factors controlling the anomalous occurrence of Pb, Zn, Cu and Ni in the Northern Head group, since this enrichment appears in an interval which has undergone the relatively most oxidizing depositional and early diagenetic conditions (refer to Chapters 4, 5 and 6).

Thus it is considered likely that the pronounced enrichment of these metals is associated with the arrival of the Eagle Island formation. Clear candidates for the source of these metals are the numerous sulphide occurrences within the basic volcanics of the North Arm and Blow-Me-Down ophiolitic massifs (e.g York Harbour, Gregory River deposits). The irregular and intergrown morphology of individual grains, however, is more suggestive of post-depositional precipitation as opposed to simple detrital transport and deposition. This suggests the possibility that these metals suffered solution under oxidizing conditions of transport and deposition (cf. Klinkhammer et al., 1982) to be later reprecipitated as sulphides during burial diagenesis.

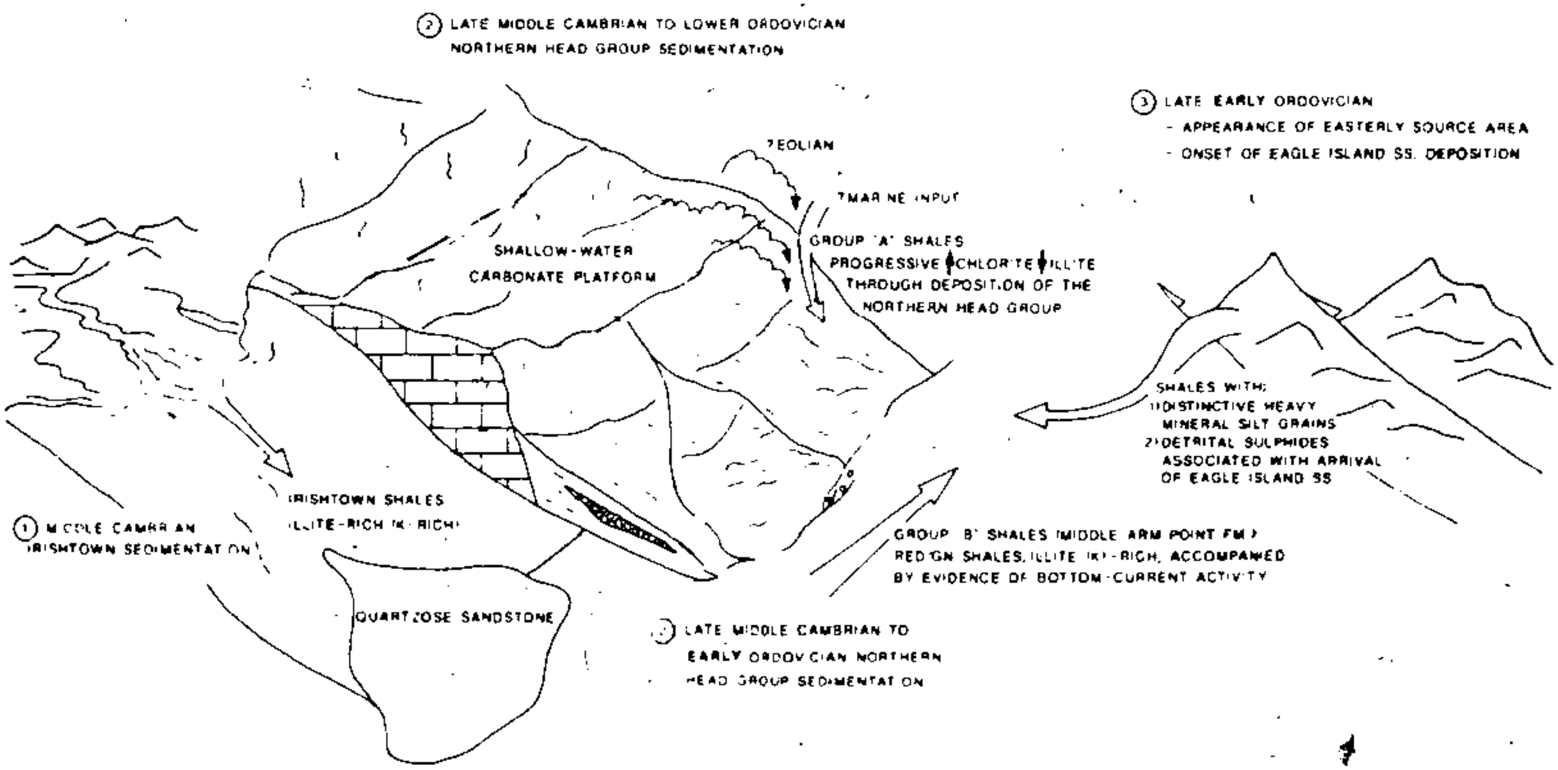
7.7 Overall summary and interpretation

Groups of shale with different geochemical signatures indicate changing source area input during the deposition of the Northern Head group (and related units). Based upon signatures defined by a suite of elements (and derived indices) thought to be controlled by detrital input of silicate minerals (principally clay minerals), three fundamental groups of shale are discriminated. Superimposed upon the distribution of these groups, suites of elements controlled by the presence of i) detrital heavy mineral silt grains, and ii) sulphides, display anomalous concentrations which are stratigraphically related to the arrival of the Eagle Island formation, and are interpreted as the first evidence of input from an allochthonous source terrain (fig 7-7).

Shales of the Irishtown and lowermost Cooks Brook constitute the first group. These contain abundant illite (plus TiO_2) and are interpreted to have been directly derived from a deeply-weathered (K/Rb ratio) continental source area. Based upon sedimenrologic associations, shales of the Northern Head group are distinguished as i) black and green shales, commonly associated with limestones which appear within intervals interpreted as gravity transported plus hemipelagic deposits, and ii) red and green shales, commonly with associated siliciclastic grains and detrital dolomite, which commonly display evidence of bottom current deposition or reworking. The first of these groups displays elevated proportions of chlorite, and commensurate decrease in illite (plus associated silicate-related elements) suggestive of derivation from a different source

Figure 7-7

Schematic diagram summarizing the provenance of distinctive shale groups during deposition of the Northern Head group and adjacent units.


(2) LATE MIDDLE CAMBRIAN TO LOWER ORDOVICIAN
NORTHERN HEAD GROUP SEDIMENTATION
?EOLIAN
?MARINE INPUT
GROUP 'A' SHALES
PROGRESSIVE CHLORITE ILLITE
THROUGH DEPOSITION OF THE
NORTHERN HEAD GROUP
SHALLOW-WATER
CARBONATE PLATFORM
(3) LATE EARLY ORDOVICIAN
- APPEARANCE OF EASTERLY SOURCE AREA
- ONSET OF EAGLE ISLAND SS. DEPOSITION
SHALES WITH;
1) DISTINCTIVE HEAVY
MINERAL SILT GRAINS
2) DETRITAL SULPHIDES
ASSOCIATED WITH ARRIVAL
OF EAGLE ISLAND SS
IRISHTOWN SHALES
(ILLITE-RICH (K)-RICH)
(1) MIDDLE CAMBRIAN
IRISHTOWN SEDIMENTATION
QUARTZOSE SANDSTONE
GROUP 'B' SHALES (MIDDLE ARM POINT FM.)
RED-GN SHALES, ILLITE (K)-RICH, ACCOMPANIED
BY EVIDENCE OF BOTTOM-CURRENT ACTIVITY
(2) LATE MIDDLE CAMBRIAN TO
EARLY ORDOVICIAN NORTHERN
HEAD GROUP SEDIMENTATION

area than shales of the Irishtown. This contrast appears at the Irishtown/Cooks Brook boundary, is progressive through the Northern Head group, and is interpreted as a change in the input of the mud component which resulted from the development of the shallow-water carbonate platform upslope.

The second group of shales appears at the base of the Middle Arm Point Formation, and is geochemically characterized by elevated proportions of illite (clay mineralogy and M1) and diminished K/Rb ratio. This suggests that the bottom currents which were postulated in Chapter 4 to have been periodically operative during the deposition of the Middle Arm Point Formation were delivering a distinctive mud component to the depositional site. It is interesting to note that this group of shales displays a geochemical affinity with those of the Irishtown Formation, in terms of the first suite of elements (and derived indices). Possibly somewhere along the continental margin, mud was being supplied (and laterally transported) from a source which was either i) similar to that which yielded Irishtown shale (i.e. probably weathered contineotal basement) or ii) exposed and eroded Irishtown lithologies themselves (or lateral equivalents).

Superimposed on these trends are coincident Cr, Zr, Y, V and P anomalies traced to concentrations of detrital heavy mineral grains and clearly directly related to the arrival of the Eagle Island formation. The heavy minerals detected, chromite plus monazite, xenotime, zircon and ilmenite suggest a geologically diverse source area, consistent with Stevens' (1970) suggestion of derivation of the "transgressive flysch" from a mixed source of silicic intrusives, parts of an ophiolite suite; plus sedimentary lithologies.

The appearance of Pb, Zn, Cu and Ni sulphides at essentially the same stratigraphic level is interpreted to reflect a mechanism involving derivation of existing sulphides from basic volcanics of the ophiolite suite, and possible remobilisation of these metals during early diagenesis and subsequent reprecipitation.

CHAPTER 8

SUMMARY AND DISCUSSION

Introduction

This chapter begins with a synthesis of stratigraphic, sedimentologic, diagenetic and geochemical observations and interpretations, indicative of the changing depositional setting of the Northern Head group. The depositional history of i) the Cow Head Group and ii) the coeval carbonate platform is briefly summarized to facilitate a comparison with the Northern Head group. This comparison is presented to evaluate two working hypotheses: that the Northern Head group was deposited as i) a basinward, distal equivalent of the Cow Head Group, or ii) as a lateral equivalent along an irregular continental margin. Tectonic and paleoceanographic implications of the depositional model are discussed in a final section.

8.1 Depositional history of the Northern Head group

The Northern Head group is a base of slope sediment apron deposit which ranges in age from late Middle Cambrian to Early Ordovician. Systematic changes appear through the deposition of the Northern Head group. Changes in aspects of sedimentology, ichnology, diagenesis and shale geochemistry appear in concert and are suggestive of evolutionary changes in the margin, which may have been driven by a combination of global (eustatic) or localized (tectonic) mechanisms.

8.1.1 Cooks Brook Formation (late Middle Cambrian to late Tremadoc)

Deposition of the Northern Head group began upon a substrate of the siliciclastic Irishtown Formation, which was volumetrically dominated by quartzitic sandstone and regarded as most likely deposited in a deep-water submarine fan setting. Onset of carbonate debris flow deposition at the base of the Northern Head group is characterised by lateral variations in timing and style. The conglomeratic Halfway Point member incorporates late Middle Cambrian (Bathyuriscus-Elrathina and Bolaspidella Zone) fossils and is interpreted as a submarine canyon deposit, which may have been localized by inherited submarine topography. Shale-dominated sedimentation occurred elsewhere until deposition of the laterally extensive debris flow lobes of the Brakes Cove member in the Late Cambrian (Dresbachian). Turbidite deposition of (quartzose) shallow-water-derived calcarenite was extensive through the remainder of the Cambrian, with a shale-dominated sedimentation, punctuated by a (Franconian) interval of debris flow deposition occurring in more distal sections. Deposition of an interval of lime mudstone rhythmites occurred at the end of the Cambrian in more distal (easterly) sections.

The nature of shales changed with the onset of carbonate sedimentation. Illite-dominated, (hence K-rich) shale occurs in the Irishtown and is consistent with derivation of this mud directly from a weathered continental source. The change to a more chlorite-rich shale commences at the formation boundary and is progressive upward through the remainder of the Northern Head Group, notwithstanding the introduction of a different suite of shales discussed below. Interbedded black and green shale (plus thin-bedded carbonate) are interpreted to reflect the turbiditic input of organic carbon-rich (black) mud from upslope, alternating with (green) hemipelagic intervals. Organic carbon is relatively abundant in the shales of the Cooks Brook Formation, which are very sparsely bioturbated, suggestive of low levels of dissolved oxygen in the depositional environment. This is consistent with an "anoxic" early diagenetic setting, characterised by i) the early and extensive precipitation of Fe-sulphides, ii) ferroan enrichment of early-precipitated carbonate cements and overgrowths, with iii) no associated Mn-carbonate nor barite authigenic phases.

A thick boulder conglomerate containing trilobite and brachiopod fauna characteristic of the Missisquoia and Symphisurina Zones occurs in the proximal (westerly) exposure in the Bay of Islands, overlying coarse, quartzose calcarenites of the uppermost Cambrian. This appears to represent the last significant progradation of the margin upslope, and the last major debris flow deposition dominated by shelf-derived components.

Deposition in the lower part of the Tremadoc (La1 to La2) is represented by a distinctive interval of black, organic carbon-rich shale and thin-bedded lime mudstone, which is regarded as an episode of predominantly hemipelagic sedimentation virtually cut off from mass transport input from the shelf, and deposited under anoxic conditions. This event signals a change in the proportion of shelf-derived sedimentary components, and is followed by wholesale changes in the depositional setting at the base of the overlying Middle Arm Point Formation.

8.1.2 Middle Arm Point Formation (late Tremadoc to Arenig)

Several lines of evidence indicate the contrasting nature of the Middle Arm Point depositional setting:

1) A marked overall increase in the level of bioturbation (Chapter 5) and a commensurate decrease in organic carbon content in shales (Chapters 4, 6) are indicative of increased levels of dissolved oxygen in the depositional environment.

2) A new early diagenetic setting appears commensurate with this environmental change (Chapter 6) and is characterized by i) the precipitation of authigenic Mn-carbonate, as overgrowths on detrital dolomite grains, and as diagenetic horizons precipitated along "redox fronts" in shale, ii) precipitation of authigenic barite (and locally celestite) and iii) a change in Fe-sulphide precipitation to a late "replacive" style. This diagenetic character is most pronounced in the uppermost Middle Arm Point, and is transitional with the underlying "Cooks Brook anoxic setting" through the base of the Middle Arm Point.

3) This change in marine conditions is synchronous with a change in dominant lithologies and sedimentologic style. Shelf-derived, gravity-transported carbonates are markedly diminished in the Middle Arm Point, where shale is much more abundant than below. Conglomeratic debris flows are more localized in nature and contain a higher proportion of locally-derived components (Chapter 4). In the absence of other input from upslope, detrital dolomite appears

as a conspicuous lithologic component throughout the Middle Arm Point, particularly prominent at the base, in the (upper Tremadoc) Woman Cove member (Chapters 3, 4).

4) Evidence of bottom current deposition or reworking is common within the Middle Arm Point. This is well-developed, for example, in the basal Woman Cove member, and in cross-laminated silty dolostones higher in the section. This is true of the North Arm Point member, a broadly correlatable interval of silicified green shale and silty dolostone which spans the Tremadoc/Arenig boundary. Strongly condensed lower Arenig sedimentation through this interval is implied by the apparent absence of three graptolite zones (cf. Williams and Stevens, in press), and may be related to a regime of intense bottom current activity.

5) The suite of predominantly red and green Middle Arm Point shales which occur above the North Arm Point member were deposited in the middle Arenig (I.v. lunatus and I.v. victoriae Zones; cf. Williams and Stevens, in press). These are commonly extensively bioturbated and locally display evidence of bottom current activity. These shales are compositionally and geochemically distinctive in their abundance of illite, relative to green and black shales through the same interval. This suggests that a further aspect of bottom current activity was the lateral transport and introduction of a new mud component into the depositional system.

6) Shale deposition in this uppermost Middle Arm Point interval alternated between two principal modes: i) turbiditic input of organic carbon-rich mud, and accompanying hemipelagic sedimentation,

with associated relatively low Eh conditions in the depositional environment, and ii) deposition of red/green mud with relatively elevated Eh conditions. The contrasting geochemical signature and depositional style of these two suites of shale suggests that the uppermost Middle Arm Point records the interplay of two fundamentally different depositional processes, which, in turn, controlled marine conditions in the depositional environment.

7) Chert is also a conspicuous component of the uppermost Middle Arm Point Formation, where it appears principally as silicified shale and dolostone. The original source of this diagenetically redistributed silica is interpreted to be siliceous biogenic debris, principally radiolaria.

8) In the context of diminished shelf-derived input in the Middle Arm Point Formation, two units are anomalous. The first is an interval of parted lime grainstone, comprising abundant algal grains and accessory phosphatized limestone, with interbeds of organic carbon-rich shale. This occurs above the Woman Cove member (Chapters 3, 4) and is regarded as late Tremadoc. Isolated thin beds of granule conglomerate have been described from the uppermost Middle Arm Point and lowermost Eagle Island formations (I.v. victoriae Zone), and are of similar composition. Both of these lithologies are regarded as platform-derived gravity-transport deposits, and appear to record anomalous events upslope, in the context of the "starved" style of sedimentation which characterizes this stratigraphic interval.

9) Deposition of the overlying Eagle Island formation began in the middle Arenig (I.v. victoriae Zone) in a regime of tectonic

instability which is characterized by slumping and associated clastic injection. The first geochemical evidence of sediment input from a new source terrain appears in shales immediately below the formation boundary, in the form of anomalous concentrations of detrital heavy mineral silt grains and disseminated sulphide mineralization (Chapter 7). The sandstone appears to have been derived from a mixed source terrain which included silicic intrusives, portions of an ophiolite suite and sedimentary lithologies, and was transported in a southwesterly direction (Chapter 4).

8.2 Comparison with the Cow Head Group

As outlined in the introduction, the Cooks Brook and Middle Arm Point Formations have previously been regarded as the "distal equivalent" of the Cow Head Group. Evidence presented in this study suggests an alternative model, based upon some similarities and important differences in depositional style, and response to events recorded on the platform. In the model presented here, the Northern Head is regarded as a lateral equivalent of the Cow Head Group which recorded contrasting margin and slope morphology in the Ordovician. This will be discussed following a brief summary of pertinent aspects of the Cow Head Group, and the relationship to events recorded in the depositional history of the platform.

8.2.1 Summary of the Cow Head Group

The Cow Head Group is interpreted as a toe-of-slope deposit (James and Stevens, 1986) and comprises extensive sediment gravity flows, including numerous coarse carbonate conglomerates of debris flow origin, and hemipelagites, principally shales, siltstones and limestone rhythmites. The strata are disposed in a series of stacked thrust sheets, and retain a distinct NW-proximal, SE-distal polarity. Proximal sections (Shallow Bay Formation) are dominated by conglomeratic intervals, many extremely coarse. The relative proportion of shale increases markedly into distal sections (Green Point Formation). Nevertheless, individual megaconglomerate beds have been demonstrated to be essentially isochronous, and so laterally extensive as to be traceable from proximal to distal sections.

This is possible because the Cow Head Group is richly fossiliferous, in graptolites, shelly fossils and conodonts, and this has facilitated detailed internal correlation.

The depositional history of the Cow Head Group has been summarized as follows (James and Stevens, 1986):

1) During the late Middle Cambrian to early Late Cambrian "basal debris sheets" comprising extensive conglomerates were deposited on a wide, deep-water sediment apron, under generally anoxic conditions.

2) During the Late Cambrian a thick interval comprising (quartzose) calcarenite grain flows and turbidites was deposited in a "calcarenite sediment apron" during overall margin progradation. Narrowing of the apron, beginning in the Trempealeauan, is indicated

by the upward increase in fine-grained carbonate hemipelagites, and the westward upslope onlap of distal shales and siltstones. Massive, welded conglomerates appear in proximal facies at the Cambro-Ordovician boundary, and suggest a short period of oversteepening and erosion.

3) The lower Tremadoc represents deposition of a "wide muddy carbonate apron", represented by massive, welded conglomerates and calcarenites in proximal facies and parted lime mudstone in distal facies. Synsedimentary deformation and intraformational truncation surfaces (within lime mudstone intervals) suggest continued deposition on an unstable slope, during a prolonged period of accretion and basinward progradation of the margin.

4) Deposition during the late Tremadoc and Arenig was complex and represents a narrowing and westward shift of the proximal conglomeratic facies, and upslope onlap of distal shale facies. It is important to note that extensive red shale deposition commenced here, in the upper half of the Tremadoc (upper half of Zone La2) in distal sections, and advanced to its farthest westward encroachment, immediately east of Cow Head proper, by the Tremadoc/Arenig boundary. Condensed sedimentation in the Arenig, through the Australian graptolite Zones Be2, Be3 and Be4 (i.e. most of the T. akzarensis and P. fruticosus Zones of Williams and Stevens, in press) is represented by a thin sequence containing sparse carbonate, abundant phosphate clasts and abundant chert, and brief cessation of conglomerate deposition in the most proximal sections. Following this episode (which is correlated with a major

transgression and temporary platform drowning) sedimentation of carbonate conglomerates and grainstone resumed in proximal sections, suggesting renewed accretion of the platform through the Australian Chewtonian, Castlemainian and Yapeen graptolite zones (i.e. the D. bifidus, I.v. lunatus, I.v. victoriae, and I.v. maximus Zones of Williams and Stevens). This is accompanied by the resumed deposition of black and green shales, which extended basinward, so that only the most distal sections witnessed the continued red shale sedimentation.

Sedimentation in this upper portion of the Cow Head is punctuated by the deposition of three laterally extensive debris sheets (Beds 10, 12 and 14). These are very coarse in proximal settings, can be traced into distal-most sections, and are interpreted to represent episodes of margin collapse.

5) The Cow Head Group is overlain by sandstones of the Lower Head Formation, and deposition of this sandstone is immediately preceded by renewed westward onlap of the red shale facies, in all areas except the most proximal, and an overall reduction in carbonate delivery from the platform, notwithstanding debris sheet deposition (Bed 14) mentioned above. In proximal and distal sections, sandstone deposition occurred in the Australian Da1 or Da2 Zones (U. austrodentatus Zone of Williams and Stevens) close to the Arenig/Llanvirn boundary. In intermediate sections, however, sandstone immediately overlies Australian Zone Ca2 (I.v. victoriae Zone of Williams and Stevens), implying early deposition of the Lower Head Formation (and possible associated basal erosion) along a NE-SW trough transecting the Cow Head sediment apron.

8.2.2 Depositional history of the platform and eustatic events

The nature of the west Newfoundland carbonate platform has been summarized by James and Stevens (1982, 1986), and James et al. (in press), and a generalized account, summarizing events postulated to have affected deep-water sedimentation, is presented here.

Prior to the establisment of an active carbonate platform a siliciclastic-dominated offlap sequence was deposited on the shelf and overlies rifted crystalline basement. This culminated in deposition of the Hawke Bay Sandstone, a thick sequence of shallow-water quartz arenites spanning the Early Cambrian to the early Middle Cambrian. The Irishtown Formation is regarded as a deep-water equivalent of this sequence.

Deposition of the carbonate platform sequence commenced in the late Middle Cambrian (Bathyuriscus-Elrathina Zone), and constitutes interbedded limestones, dolostones, siltstones and shales of the Port au Port Group (Knight and James, in press). Three major shoaling-upward grand cycles are recognized through this upper Middle to Upper Cambrian interval (Chow and James, 1984; in press; James and Stevens, 1986). The lower two are represented as conglomerate-dominated sedimentation in the deep-water debris apron and are representative of continuous margin progradation. The final, Upper Cambrian grand cycle is interpreted to represent vertical rather than lateral margin accretion and is represented by the interval of carbonate sand turbidites, with inferred bypass deposition of quartz sand, in the deep-water sediment apron (James and Stevens, 1986; James et al., in press).

A change in the style of platform sedimentation is roughly coincident with the Cambro-Ordovician boundary and is represented by deposition of the Ordovician St. George Group. This represents a transition to widespread muddy carbonate deposition, with the development of calcified algal buildups at the platform margin, and records an episode of extensive eustatic inundation of the craton.

Two major unconformity-bounded megacycles are present within the St. George Group. The lower megacycle corresponds to roughly the Tremadoc (lower Canadian stage) and comprises subtidal carbonates of the Watts Bight Formation and peritidal, shallowing-upward sequences of the Boat Harbour Formation, and records carbonate production on the platform keeping pace with relative sea level rise (James et al., in press; cf. Barnes, 1984; Fortey, 1984; Vail et al., 1977). An erosional unconformity, indicative of subaerial exposure occurs near the top of the Boat Harbour Formation, coincident with debris flow deposition localized in proximal sections in the Cow Head Group.

The upper megacycle spans the Arenig (upper Canadian and lower Whiterock stages) and comprises subtidal limestones of the Catoche Formation overlain by peritidal carbonates of the Aguathuna Formation. The lower part of this megacycle corresponds to the highest stand of sea level in the Early Paleozoic (ibid.) and is accompanied by arrested deep water sedimentation associated with "backstepping" of the margin.

The peritidal sediments of the Aguathuna Formation are dominated by buff dolostones and contain abundant horizons of silicified evaporites. This interval reflects the slowing of sea level rise and the onset of Taconic orogenesis. Local thickness variations and intraformational breccias within the Aguathuna are indicative of the faulting, uplift and erosion which occurred on the platform at this time (T. Lane, pers. comm., 1986; Knight and James, 1987). This regime of extensional tectonics is postulated to reflect the presence of a peripheral bulge, in advance of the westward-travelling allochthon (James et al., in press). Cow Head Group conglomerates related to margin collapse through this episode (Beds 12, 14) have sampled Upper Cambrian lithologies, suggestive of considerable fault-related relief on the platform.

Dolostones of the St. George Group are overlain by the (Whiterockian) Table Head Group, which appears as grey subtidal limestones at the base (Table Point Formation), and is transitional through parted and ribbon limestones of the Table Cove Formation into laminated black shales of the Black Cove Formation (Klappa et al., 1980). Variability in the thickness and depositional style through the Table Head Group indicates the foundering of the platform as separate blocks prior to the final cut-off of carbonate sedimentation and burial by flysch sedimentation of the Mainland Sandstone (Stenzel and James, 1987).

8.3 Contrast between the Northern Head and Cow Head Groups

Comparison of the Northern Head and Cow Head groups indicate some fundamental similarities in depositional style, and response to platform events outlined above. Distinct differences are apparent in the Ordovician, suggestive of irregularity in the platform margin upslope from the two areas.

1) The depositional history of the Northern Head group and Cow Head Group is very similar through the Cambrian and earliest Ordovician. Deposition of shelf-derived gravity deposits (debris flows and turbidites) was common in both areas, and these were emplaced into an predominantly anoxic depositional environment. The Halfway Point and Brakes Cove members appear within the episode of "basal debris sheet" deposition at Cow Head, and the style of sedimentation in the Northern Head group may be indicative of a more localized onset of shallow-water carbonate sedimentation upslope. Clast size in the Halfway Point member is comparable to that in the conglomerates of the proximal Shallow Bay Formation. Conglomerates higher in the Cooks Brook, however, are generally finer than their Cow Head counterparts.

2) Deposition of the "quartzose calcarenite sediment apron" during margin progradation in the Late Cambrian is common to both groups. Ooids are a prominent component of these calcarenites in the Cow Head Group, suggestive of stacked ooid sand shoals on the margin upslope, while Cooks Brook calcarenites are dominated by peloidal algal grains and ooids are sparse.

The appearance, in the Cooks Brook, of the lime mudstone interval at the top of this sequence parallels that described from the Cow Head Group and interpreted to represent a narrowing of the apron.

3) The Cooks Brook lowermost Ordovician conglomerate contains a mixed trilobite and brachiopod fauna representative of Zones A and B, plus Cow Head trilobite Zone 8 (refer to Chapter 3), suggesting

that it is essentially coeval with the welded conglomerates (Bed 8) which appear in proximal facies in the Cow Head Group. The Cooks Brook conglomerate is likewise restricted to proximal (westerly) exposure, and may represent the same style of oversteepening and erosion at the margin, interpreted for its Cow Head counterpart. Intraformational truncation surfaces, suggestive of deposition on an unstable slope, are common to both groups through this interval.

4) The close of Cooks Brook sedimentation (within the Tremadoc La2 Zone) is represented by a distinctive interval of organic carbon-rich shale and thin-bedded lime mudstone regarded as an episode of predominantly hemipelagic sedimentation, cut off from mass transport input from the shelf. This corresponds with deposition of the "wide muddy carbonate apron" in the Cow Head Group, represented by massive, welded conglomerates and calcarenites in proximal sections and parted lime mudstone in distal sections. The overall depositional regime appears similar in the Northern Head and Cow Head Group, however the reduced carbonate input in the Northern Head is the first suggestion of the transition to a "lower relief" style of margin, which becomes pronounced in the late Tremadoc and Arenig deposition of the overlying Middle Arm Point Formation.

5) In the Northern Head group, deposition of the Woman Cove member records i) the markedly increased presence of detrital dolomite, input by eolian plus gravity-transport processes, commensurate with the diminished input of other allodapic carbonate components, ii) the transition to relatively more oxidizing depositional conditions accompanied by ii) the onset of increased bottom current activity.

This is synchronous with the narrowing of the carbonate sediment apron in the Cow Head Group and the onset of red shale deposition in distal-most sections. The progressive westward onlap of this deposition resulted in a a thick wedge of red shale-dominated facies which characterizes the distal sections. Deposition of red shale does not appear in the Northern Head group, on the other hand until the middle Arenig (D. bifidus Zone of Williams and Stevens).

The fact that these changes, the dominance of detrital dolomite in the Northern Head group and the appearance of bioturbated red shale in distal Cow Head sections appear simultaneously, suggests that they are different responses to the same change in sedimentary regime. This appears be to characterized by diminished overall input from the shelf edge, both in the form of carbonate debris, and organic carbon-rich mud, commensurate with the regime of platform inundation described above. Carbonate gravity flow deposition continued in proximal sections at Cow Head.

6) Although shelf-derived sedimentation becomes markedly diminished in the Northern Head group at this point, some input in proximal sections is indicated by i) localized debris flow deposition overlying the Woman Cove member and ii) the calcarenite and black shale interval which overlies this, both deposited within the late Tremadoc.

7) Evidence of condensed sedimentation in the Northern Head Group appears in the North Arm Point member, spanning the latest Tremadoc to middle Arenig (D. bifidus Zone). An apparently briefer episode of condensed sedimentation appears in the Cow Head Group (see above), where it has been correlated with a major transgression and

temporary platform drowning. If this mechanism is correct, then it appears that platform drowning was more prolonged, and more profound, upslope from the Northern Head group.

8) Contrasting sedimentation in the two groups through the remainder of the Arenig is suggestive of a much lower relief style of margin upslope from the Northern Head Group. Renewed deposition of carbonate conglomerates and grainstones in proximal sections in the Cow Head Group was accompanied by the resumed deposition of black and green shales extending basinward. Sedimentation in the uppermost Middle Arm Point, on the other hand, is shale-dominated, with the sporadic turbiditic input of i) lime mudstone and detrital dolomite, and ii) organic carbon-rich mud (black/green shale intervals) into an overall relatively oxidizing environment with relatively active bottom current activity.

It was an active carbonate margin which supplied the extensive debris sheets (Beds 10, 12 and 14) which span the Cow Head Group in tha Arenig. This style of platform input is very sparsely represented in the Northern Head group. The pebble conglomerate described from the uppermost Middle Arm Point at Black Point (Port au Port Bay) (Chapters 3, 4) contains gneissic pebbles. It is possible that these were introduced through localized unroofing of basement during the same episode of tectonism on the margin which introduced Upper Cambrian lithologies into the Cow Head conglomerates mentioned above.

The final input from the margin is represented by the thin granule conglomerates deposited within the uppermost Middle Arm

Point and lowermost Eagle Island Formation, within the I.v. victoriae Zone (Australian Ca2 Zone). These are anomalous within an otherwise shale-dominated part of the section, and are regarded as representing a final episode of margin collapse. The distinctive chert/dolomite grains which occur within these granule conglomerates, and silty dolostones within this stratigraphic interval, are interpreted to have been directly derived from the coeval Aguathuna Formation (Chapter 4). Their presence within these deep-water sediments is consistent with the regime of faulting, uplift and erosion extant on the margin at this time.

Renewed deposition of red shale in all but the most proximal sections preceeded deposition of the Lower Head Formation, under conditions of final margin collapse. The variable stratigraphic position of the Lower Head Formation has been described above, and clearly postdates deposition of the Eagle Island formation (within the I.v. victoriae Zone, or Australian Zone Ca2). The simplest interpretation of this stratigraphic contrast would suggest that the Northern Head group was situated basinward of the Cow Head Group and hence received the transgressive flysch earlier. On the other hand, lateral transport of the transgressive flysch, along an axis parallel to the continental slope, has been suggested for the Cow Head area, and this lateral style of transgression, from isolated, individal depocenters, may have resulted in the magnitude of stratigraphic variation described.

8.4 Discussion and conclusions

In the Cow Head Group, the transition from a proximal to distal setting is accompanied by a pronounced and systematic increase in shale throughout the entire stratigraphic interval (fig 8-1). Furthermore, distal sections are characterized by a thick wedge of red shale, which first appears in the late Tremadoc. A comparison of the Northern Head group with these fundamental patterns (fig 8-1) indicates that it is very unlikely that the Northern Head group was deposited basinward of the Cow Head Group. Rather than displaying a proximal/distal relationship, the two groups are interpreted as lateral equivalents.

The strong parallelism in the depositional history of the Cooks Brook portion of the Northern Head group and the comparable upper Middle Cambrian to upper Tremadoc portion of the Cow Head Group indicates that these units were deposited along a similar slope, and responded in the same way to regional events controlling the nature of the carbonate platform upslope. The onset of shallow-water carbonate sedimentation may have been more tentative upslope from the Northern Head group, considering the localized nature of debris flow deposition there, and may presage overall less vigorous platform sedimentation in this area relative to that upslope from the Cow Head Group (fig 8-2a).

The depositional history of these units diverged in the late Tremadoc, when carbonate sedimentation appears to have been become markedly less active upslope from the Northern Head Group, throughout the deposition of the Middle Arm Point Formation.

Figure 8-1

Comparison of the Cow Head and Northern Head groups. Cow Head sections from a proximal (Cow Head), intermediate (St. Pauls Tickle) and distal (Martin Point) setting are compared with a composite stratigraphic section of the Northern Head group. Cow Head sections are redrawn from James and Stevens, 1986. Lithologic symbols as per fig 3-1a.

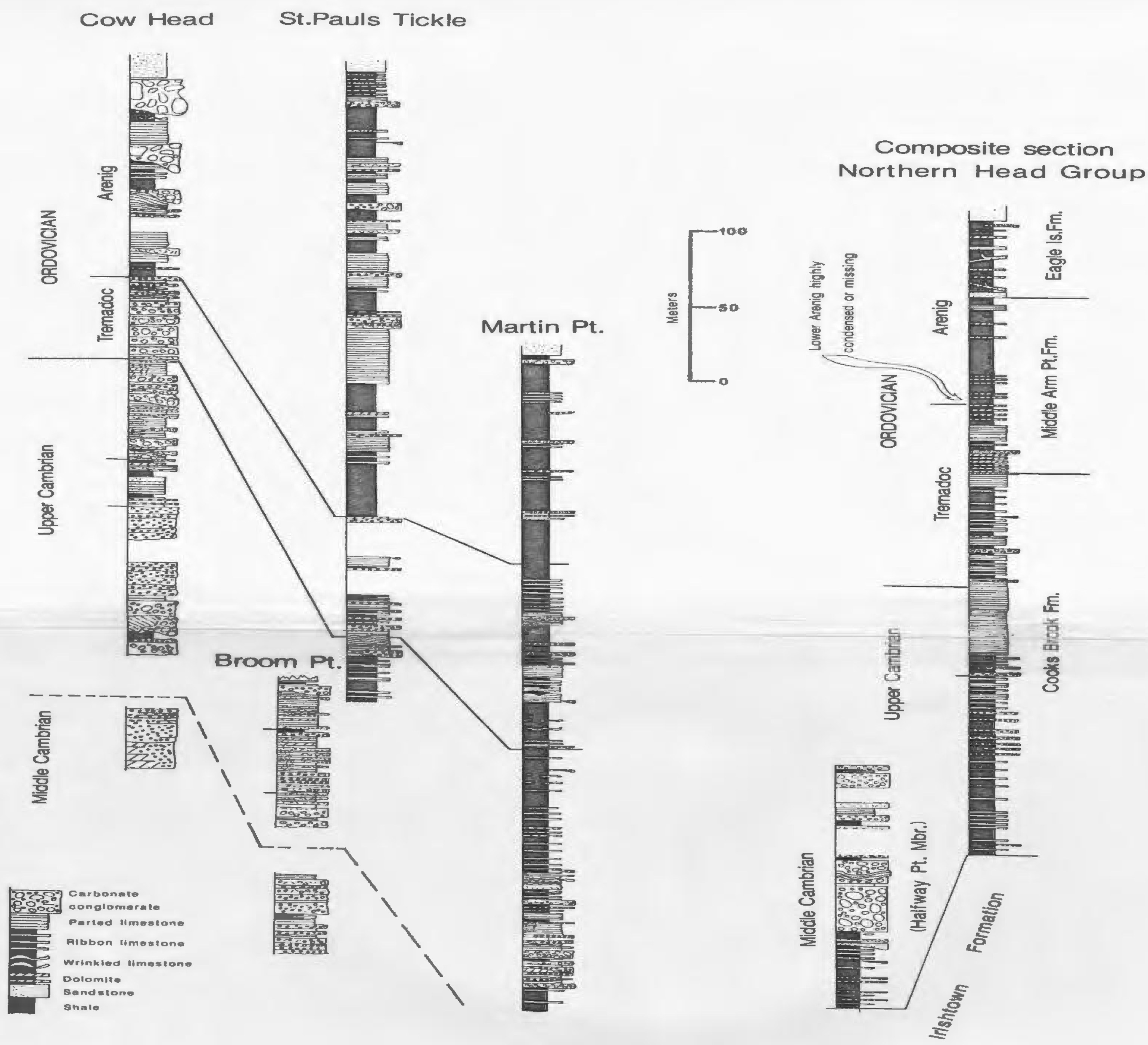
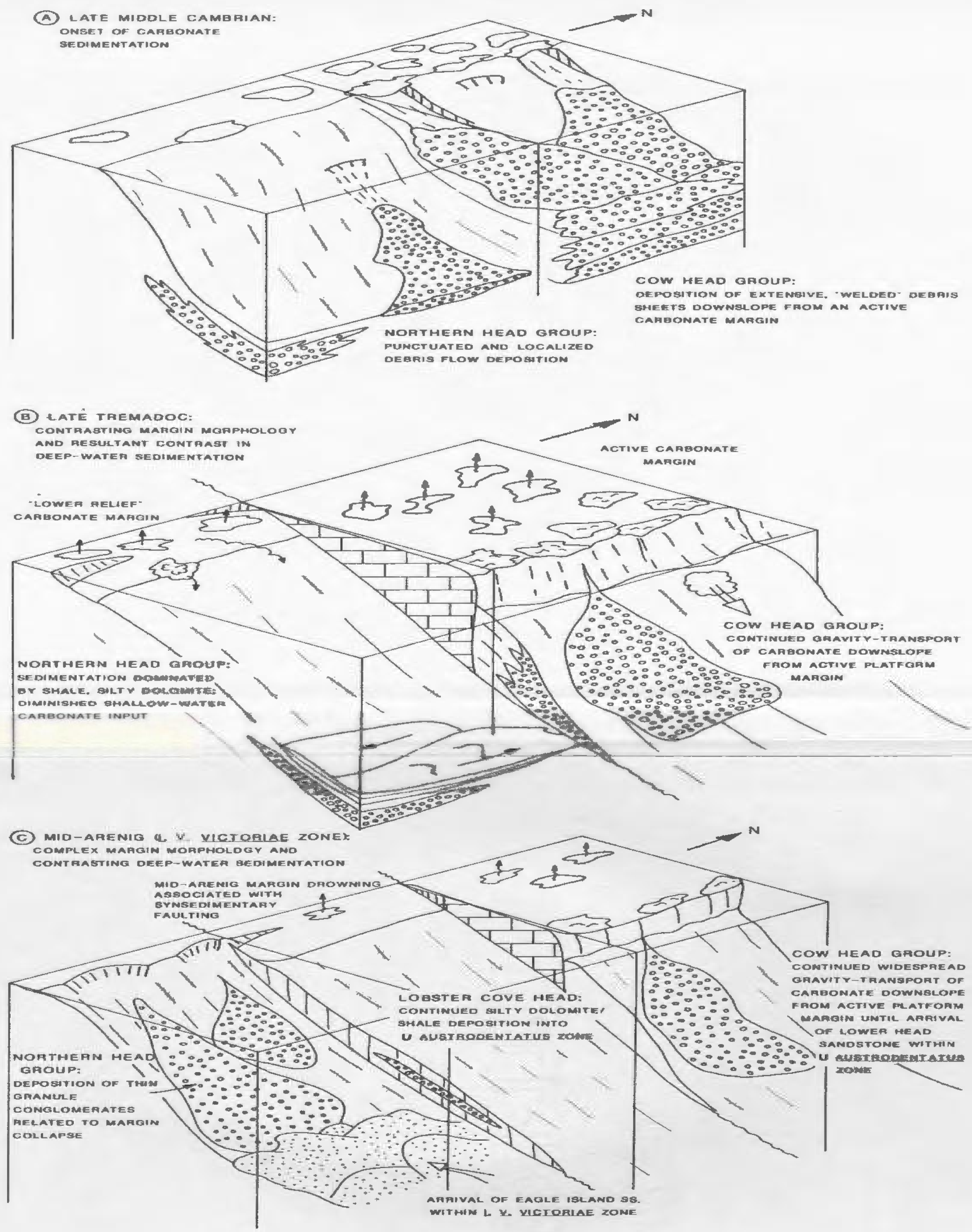

Cow Head
St.Pauls Tickle
Martin Pt.
Broom Pt.
Composite section
Northern Head Group
ORDOVICIAN
Arenig
Tremadoc
Upper Cambrian
Middle Cambrian
Meters
0
50
100
Lower Arenig highly
condensed or missing
Eagle Is.Fm.
Middle Arm Pt.Fm.
Cooks Brook Fm.
(Halfway Pt. Mbr.)
Irishtown
Formation
Carbonate
conglomerate
Parted limestone
Ribbon limestone
Wrinkled limestone
Dolomite
Sandstone
Shale

Figure 8-2

Postulated evolution of the carbonate margin and slope, illustrating the contrasting depositional settings of the Northern Head and Cow Head groups.
Diagram A represents the onset of carbonate sedimentation in the late Middle Cambrian
Diagram B illustrates the contrasting margin morphology developed in the late Tremadoc
Diagram C illustrates the complex margin morphology which existed in the mid-Arenig



(A) LATE MIDDLE CAMBRIAN:
ONSET OF CARBONATE SEDIMENTATION
N
COW HEAD GROUP:
DEPOSITION OF EXTENSIVE, 'WELDED' DEBRIS SHEETS DOWNSLOPE FROM AN ACTIVE CARBONATE MARGIN
NORTHERN HEAD GROUP:
PUNCTUATED AND LOCALIZED DEBRIS FLOW DEPOSITION
(B) LATE TREMADOC:
CONTRASTING MARGIN MORPHOLOGY AND RESULTANT CONTRAST IN DEEP-WATER SEDIMENTATION
N
ACTIVE CARBONATE MARGIN
'LOWER RELIEF' CARBONATE MARGIN
NORTHERN HEAD GROUP:
SEDIMENTATION DOMINATED BY SHALE, SILTY DOLOMITE; DIMINISHED SHALLOW-WATER CARBONATE INPUT
COW HEAD GROUP:
CONTINUED GRAVITY-TRANSPORT OF CARBONATE DOWNSLOPE FROM ACTIVE PLATFORM MARGIN
(C) MID-ARENIG (L V. VICTORIAE ZONE):
COMPLEX MARGIN MORPHOLOGY AND CONTRASTING DEEP-WATER SEDIMENTATION
N
MID-ARENIG MARGIN DROWNING ASSOCIATED WITH SYNSEDIMENTARY FAULTING
LOBSTER COVE HEAD:
CONTINUED SILTY DOLOMITE/ SHALE DEPOSITION INTO U AUSTRODENTATUS ZONE
COW HEAD GROUP:
CONTINUED WIDESPREAD GRAVITY-TRANSPORT OF CARBONATE DOWNSLOPE FROM ACTIVE PLATFORM MARGIN UNTIL ARRIVAL OF LOWER HEAD SANDSTONE WITHIN U AUSTRODENTATUS ZONE
NORTHERN HEAD GROUP:
DEPOSITION OF THIN GRANULE CONGLOMERATES RELATED TO MARGIN COLLAPSE
ARRIVAL OF EAGLE ISLAND SS. WITHIN L V. VICTORIAE ZONE

Condensed sedimentation associated with platform drowning in the early Arenig appears to have been much more prolonged in the Middle Arm Point. Following this episode, the Cow Head Group records renewed accretion of the platform, while the shale-dominated sedimentation of Middle Arm Point Formation indicates a relatively inactive platform immediately upslope (fig 8-2b).

This evidence indicates a different history for portions of the continental margin upslope from the Northern Head group and the Cow Head Group, and suggests that subsidence, and the transition to a low-relief margin began upslope from the Northern Head group in the late Tremadoc, while active carbonate sedimentation continued upslope from the Cow Head Group, right up until deposition of the Lower Head Formation near the close of the Arenig.

8.5 Additional evidence

Examination of the Lobster Cove Head area, geographically intermediate between the Cow Head Group and Northern Head group (fig 8-3), provides additional evidence of a complex platform margin configuration. Here a large raft of Arenig sediments is situated within the Rocky Harbour Melange (Williams et al., 1985), at a structural nexus, with the Cow Head Group terrane to the north, platformal sediments to the east and a terrane comprising Curling Group, Northern Head group equivalents and ophiolite to the south. A discrete break in depositional style is embodied within this sedimentary package (James et al., 1987). The lower part of the sequence, deposited through the _T. approximatus_ to _D. bifidus_ Zone, are similar to proximal facies of the Cow Head Group. The upper part of the sequence (Lobster Cove Head member) is separated by a hiatus corresponding to deposition of the conglomeratic Bed 12 in the Cow Head Group, spans the I.v. victoriae and I.v. maximus Zones and is overlain by the Lower Head Formation, deposited within the U. austrodentatus Zone. The Lobster Cove Head member comprises thick beds of silty dolostone and black and green shale, deposited by weak turbidity currents under dysaerobic conditions. The change in deposition is accounted for here by (mid-Arenig) synsedimentary faulting along the margin which resulted in the drowning of the carbonate platform upslope from Lobster Cove Head, while the area upslope from Cow Head remained one of active carbonate accretion (fig 8-2c).

The style of irregularity in the continental margin implied in the Lobster Cove Head area is considered to be of greater scope and more profound effect in the contrast between the Northern Head group and Cow Head Group.

8.6 Speculation on implications of the model

8.6.1 Tectonic implications

The contrast in Ordovician margin and slope morphology postulated above to account for depositional differences in between the Northern Head and Cow Head Groups implies the presence, along the margin, of subtly different tectonic elements whose sealevel history diverged in the late Tremadoc. This suggests that some form of structural discontinuity separated the margin upslope from the Northern Head group and that upslope from the Cow Head Group.

Evidence of faulting on the margin first appears stratigraphically in the Aguathuna Formation (within the Arenig _I.v. victoriae_ Zone; James et al., 1987; T. Lane, S.H. Williams, pers. comm., 1987) and fault-controlled sedimentation is evident in thickness variations within the overlying Table Head Group (Klappa et al., 1980). Indirect evidence of mid-Arenig (_I.v. lunatus_ Zone) synsedimentary faulting from the Lobster Cove area has been discussed above. No direct evidence of earlier margin faulting (i.e. late Tremadoc) is presently available. This may be obscured, however, by i) the overlying Humber Arm Allochthon and ii) deformation and metamorphism of platformal elements to the east of the Bay of Islands. While an erosional unconformity appears within the (upper Tremadoc) upper Boat Harbour Formation, it is of regional extent and is regarded as a eustatically-controlled feature.

It is not unreasonable to expect structural variation along the margin, however, since the platformal sequence accreted upon a rifted and fragmented crystalline basement which gave rise to initial horst and graben-controlled clastic sedimentation in the Early Cambrian (Williams and Stevens, ~~1969~~, 1974; Williams, 1979). The irregular nature of such a margin is reflected in large scale promontories and re-entrants (Thomas, 1977), and it is likely that this irregularity also occurred on a smaller scale. Fault-block readjustment in such a setting may readily account for the postulated lateral contrast in margin morphology.

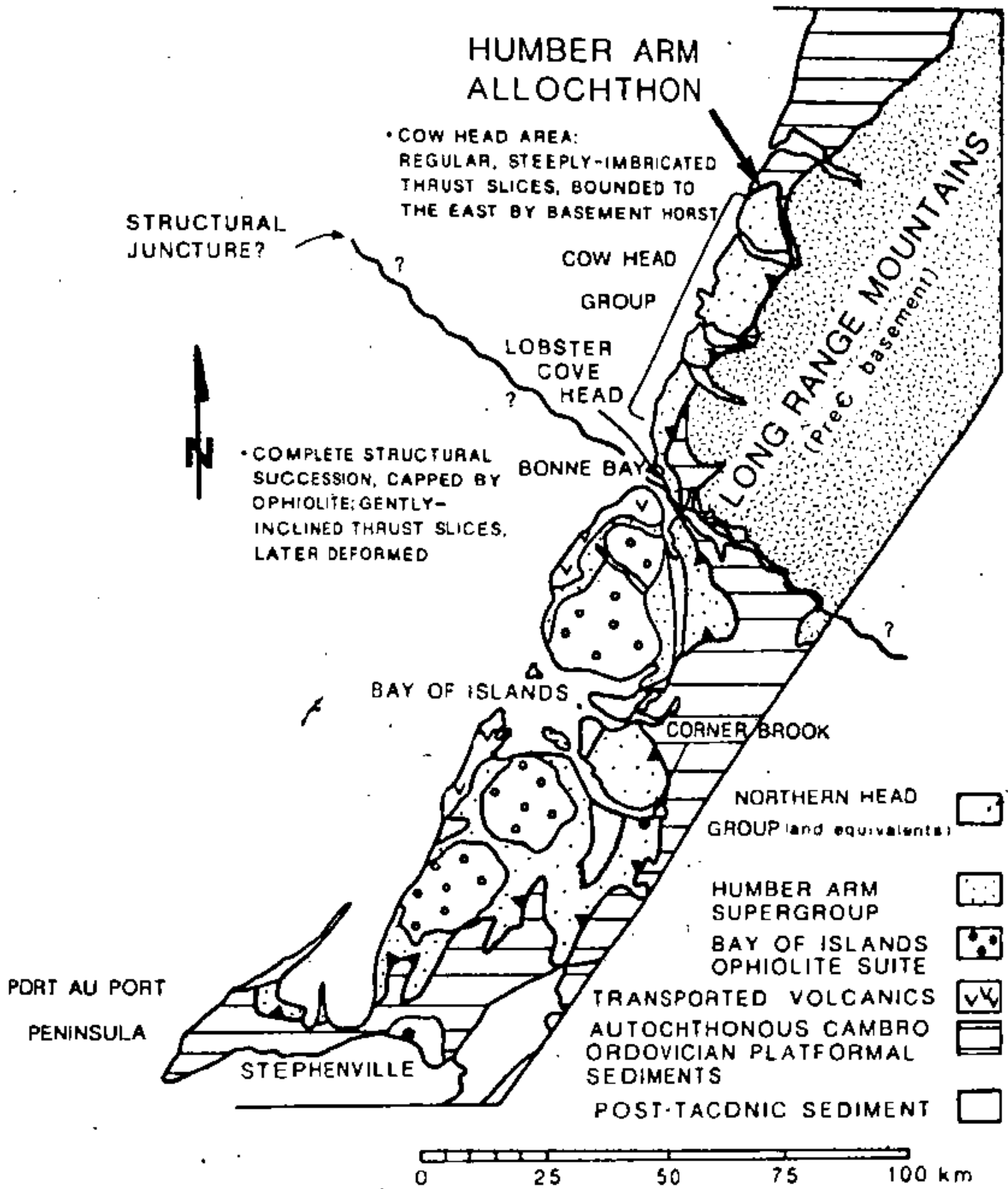
Response to later tectonism

Since a detailed emplacement history of the Humber Arm Allochthon is presently unknown, it is not clear whether emplacement may have been orthogonal to the margin, and hence whether the Northern Head and Cow Head groups overlie portions of the margin which were originally upslope and genetically related. It is interesting to note, however, that the juncture separating the depositionally different Cow Head Group and Northern Head groups, which occurs in the vicinity of Bonne Bay, also represents a structural boundary of some kind (fig. 8-3). North of Bonne Bay the allochthon consists of regularly imbricated thrust slices of Cow Head Group (plus Lower Head Formation). Underlying Summerside and Irishtown equivalents are absent, as is the overlying ophiolite. Here the allochthon is bounded to the east by a high angle reverse fault which has uplifted Grenvillian basement during post-Taconic orogenesis. The sharp southern boundary of this crystalline inlier is a NW-SE trending line which extends through the Bonne Bay area. The Lobster Cove Head area, intermediate in depositional style between the Northern Head and Cow Head groups, is situated immediately north of, but close to, this juncture. South of this line the allochthon comprises lower siliciclastic slices (Summerside and Irishtown Formations and equivalents) and is capped by the Humber Arm Ophiolite Complex. The eastern boundary of the allochthon here is characterized by east-directed thrusting over deformed platformal equivalents.

Hence a contrast in structural response to continued (late Taconic or Acadian) compressional tectonics, both in the allochthon and autochthon, is superimposed upon the contrast in morphology postulated for the margin upslope from the Northern Head and Cow

Figure 8-3

Aspects of the contrasting regional structural style of the Northern Head and Cow Head groups.



HUMBER ARM
ALLOCHTHON
• COW HEAD AREA:
REGULAR, STEEPLY-IMBRICATED
THRUST SLICES, BOUNDED TO
THE EAST BY BASEMENT HORST
STRUCTURAL
JUNCTURE?
COW HEAD
GROUP
LOBSTER
COVE
HEAD
LONG RANGE MOUNTAINS
(PreЄ basement)
N
• COMPLETE STRUCTURAL
SUCCESSION, CAPPED BY
OPHIOLITE; GENTLY-
INCLINED THRUST SLICES,
LATER DEFORMED
BONNE BAY
BAY OF ISLANDS
CORNER BROOK
NORTHERN HEAD
GROUP (and equivalents)
HUMBER ARM
SUPERGROUP
BAY OF ISLANDS
OPHIOLITE SUITE
TRANSPORTED VOLCANICS
AUTOCHTHONOUS CAMBRO
ORDOVICIAN PLATFORMAL
SEDIMENTS
POST-TACONIC SEDIMENT
PORT AU PORT
PENINSULA
STEPHENVILLE
0
25
50
75
100 km

Head groups. Speculatively, then, a basement-related margin discontinuity, which may have controlled the depositional history of the Northern Head and Cow Head Groups, may have persisted to affect later orogenesis, and hence be reflected in regional geologic differences.

8.6.2 Paleoceanographic implications

8.6.2.1 Further contrasting aspects of the Northern Head and Cow Head groups

Discussion in Chapters 3 and 4 indicates that paleoceanographic differences accompanied the contrast in depositional setting between the Northern Head and Cow Head groups. First, based upon present evidence, shales of the Cow Head Group appear to be much richer in graptolites than those of the Northern Head group. Secondly, chert, prominent in the Ordovician, is interpreted in both groups to have been derived from the initial accumulation of planktonic biogenic debris (this study; Coniglio, 1985). This chert is much more abundant in the Cow Head Group, by volume and in variety of occurrence. Thirdly, phosphate appears in both groups principally as phosphatized limestone clasts in conglomerates, and is more abundant in the Cow Head Group. All of these observations suggest a more productive oceanographic regime in water masses overlying, and upslope from, the Cow Head Group. This may be related to the contrasting configuration of the continental slope and margin in the two areas postulated above.

It is also interesting to note that proximal facies in the Cow Head Group record black and green shale sedimentation, i.e.

extensive input of organic carbon-rich mud, which is continuous throughout the deposition of the Cow Head Group. On the other hand, distal sections record deposition of bioturbated red shale associated with diminished overall input from upslope. Basinward incursion of black/green shale sedimentation in the Arenig is associated with renewed accretion of the platform.

8.6.2.2 Discussion

Factors governing the accumulation of organic carbon in marine depositional settings include i) primary biologic activity in overlying or associated water masses, ii) sedimentation rate and iii) the oxygen content of bottom waters. All of these factors may reflect both local conditions, and global marine conditions. The accumulation of organic carbon in the modern ocean, and throughout the Phanerozoic occurs in two principal settings: i) stratified basins, e.g. the modern Black Sea (Degens and Ross, 1974), where stagnation implies the lack of aeration of bottom waters, and ii) the zone of impingement of the oceanic "oxygen minimum layer" upon continental margins (Demaison and Moore, 1980; Jones, 1983). Variation in global marine conditions may occur in response to climatic and eustatic changes which govern such processes as oceanic circulation (influencing, in turn, both nutrient recycling and the aeration of bottom waters). Cyclic changes in global climatic and eustatic conditions have been modelled as a controlling factor in the accumulation of organic carbon throughout the Phanerozoic (Fischer and Arthur, 1979), in the Paleozoic (Berry and Wilde, 1978;

Leggett, 1978, 1980; Leggett et al., 1981) and in the Mesozoic (Jenkyns, 1980; Schlanger and Cita, 1982, and references therein).

In this regard, the relative abundance of organic carbon within the Cambrian to Lower Ordovician Cooks Brook Formation is consistent with an episode of abundant black shale deposition, suggestive of poorly-aerated deep marine bottom-water, worldwide (cf. Leggett et al., 1981). Likewise, the appearance of more oxidizing conditions in the upper Tremadoc of the Northern Head and Cow Head Groups is roughly coincident with a Lower Ordovician interval sparse in black shale worldwide, suggesting that it may reflect global oceanic conditions, in part.

On the other hand, local oceanographic factors may also exert a strong control on organic productivity, and the disposition and width of an "oxygen minimum zone" within the water column. Increased organic productivity results in the increased surface demand for oxygen, the increased sedimentation of organic carbon and the widening of such an oxygen minimum zone. Diminished input of organic carbon would have the opposite effect. In the modern ocean, sedimentation of organic carbon-rich mud generally occurs on the upper slope (Jones, 1983), where it is available for periodic resedimentation by gravity transport (cf. Dean et al., 1977; Rollkotter et al., 1983; Meyers et al., 1984) (fig 8-4).

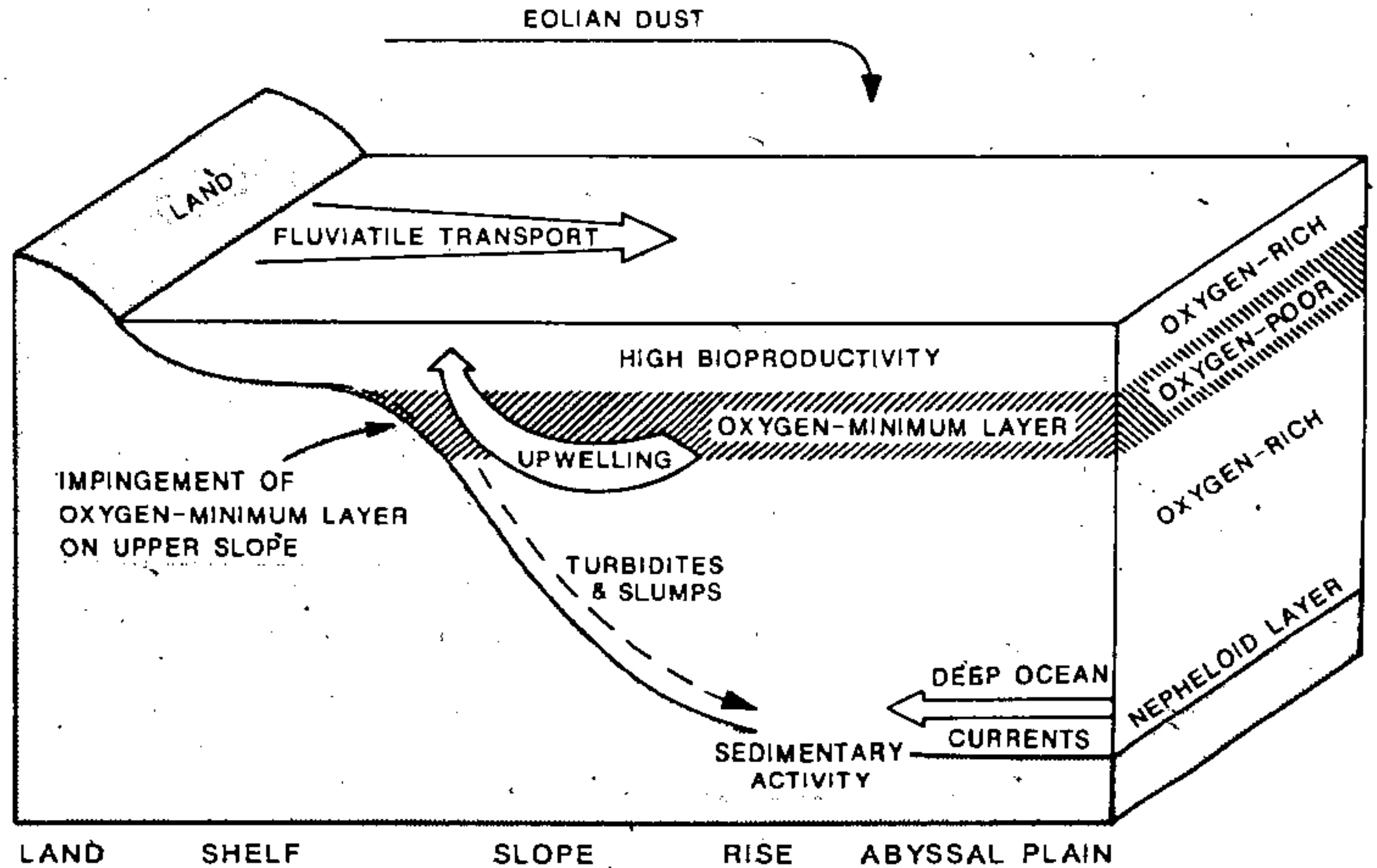
Zones of intense organic productivity in the world oceans are generally associated with areas of upwelling, where deep, nutrient-rich water is circulated upward along continental margins (Thiede and Suess, 1983, and numerous references therein). Modern examples include the west coast of Africa and North and South America, notably Peru (ibid.). Sedimentation characteristic of such areas of upwelling and productivity appears throughout the geologic record and is typified by the abundance of organic carbon, biogenically-derived chert, and phosphate (Lindstrom and Vortisch, 1983; Parrish and Ziegler, 1983, Schopf, 1983).

Oceanic upwelling is a complex process involving the dynamic interaction of atmospheric and oceanic circulation and is controlled in part by continental shelf and slope morphology. While these processes are imperfectly understood, in general it appears that steep continental margins promote more vigorous upwelling, while more gentle slopes result in a regime of weaker upwelling and more vigorous bottom current activity on the shelf and upper slope (Suess and Thiede, 1983; Smith, 1983).

This variation in upwelling, and resultant localized organic productivity, with slope morphology may be a factor in the observed differences between the Cow Head Group and Northern Head group. If the margin upslope from the Cow Head Group remained a prominent, continuously accreting element throughout the Early Ordovician then relatively continuous upwelling and associated organic productivity might be expected. This would provide a ready supply of organic carbon in proximal sections, accounting for the extensive deposition of black shale and the overall abundance, in the Cow Head Group, of graptolites and biogenically-derived chert. Distal sections may have been situated beyond the reach of this extensive supply of organic carbon, and with diminished organic carbon input recorded a relative increase in Eh levels in the depositional environment.

Figure 8-4

Schematic illustration of the deposition and resedimentation of organic carbon-rich mud in the modern slope setting (modified after Rollkotter et al., 1983).


EOLIAN DUST
LAND
FLUVIATILE TRANSPORT
HIGH BIOPRODUCTIVITY
OXYGEN-MINIMUM LAYER
UPWELLING
IMPINGEMENT OF
OXYGEN-MINIMUM LAYER
ON UPPER SLOPE
TURBIDITES
& SLUMPS
OXYGEN-RICH
OXYGEN-POOR
OXYGEN-RICH
NEPHELOID LAYER
DEEP OCEAN
CURRENTS
SEDIMENTARY
ACTIVITY
LAND
SHELF
SLOPE
RISE
ABYSSAL PLAIN

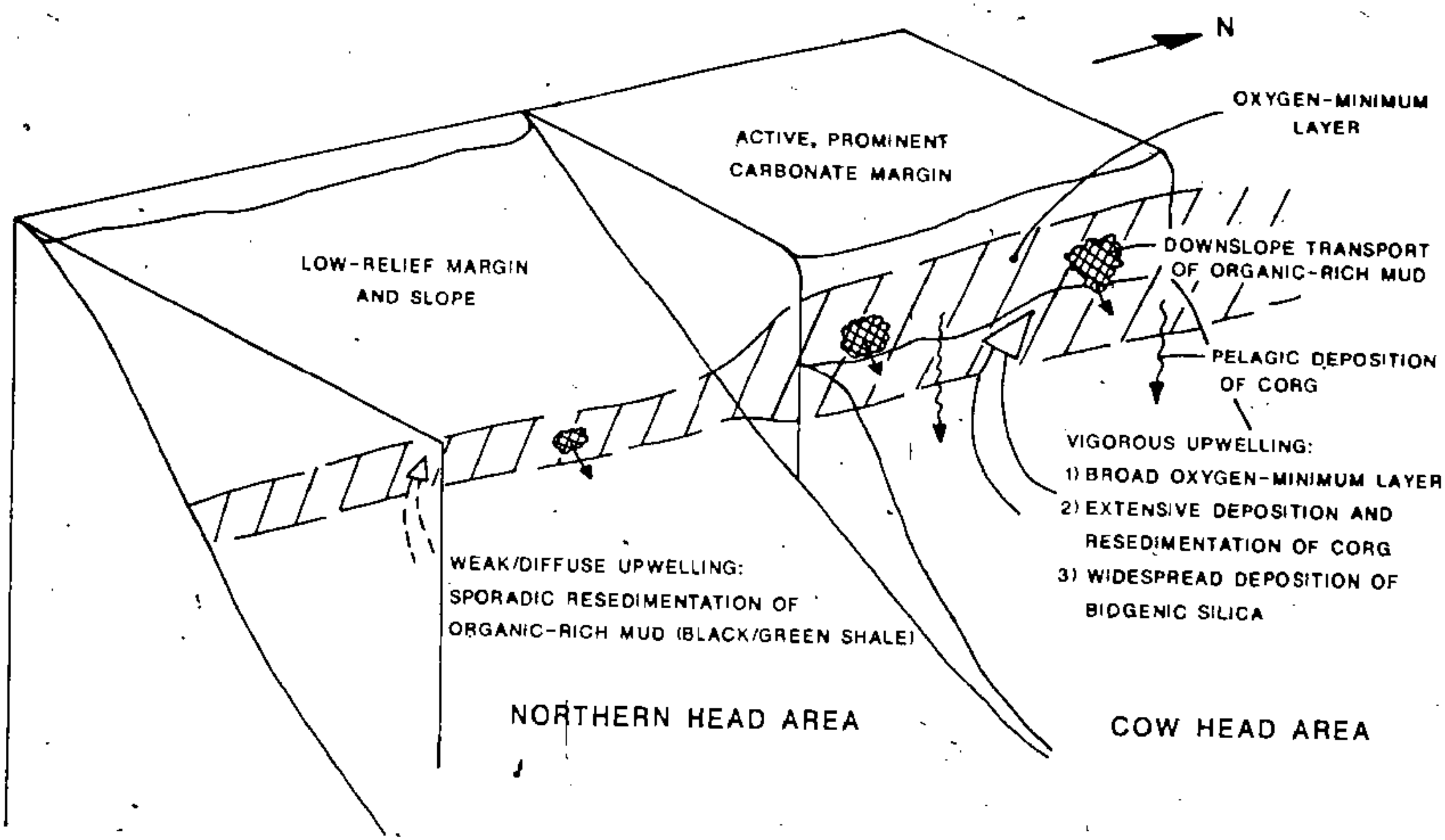
The Northern Head group, on the other hand, is postulated to have been deposited below a lower-relief margin throughout most of the Early Ordovician. Such a margin might be expected to foster less vigorous upwelling, hence a less fecund water mass overlying the shelf break, and diminished overall biogenic input relative to the Cow Head Group (fig 8-5). Hence the postulated late Tremadoc change in margin morphology not only controlled the input of allodapic carbonate but also the volume of resedimented organic carbon, which in turn exerted an influence on the depositional and early diagenetic environment. This model would account for i) the synchroneity of changes in the sedimentologic, ichnologic and early diagenetic aspects of the Northern Head group which are focused at the (upper Tremadoc) Cooks Brook/Middle Arm Point boundary and ii) the contrast in paleoceanographic conditions apparent between the Northern Head group and Cow Head Group.

A possible modern analogue, off the southwest coast of Africa, has been documented by Calvert and Price (1972). Here intense upwelling associated with the Bengela Current is localized in the vicinity of Walvis Bay. The resultant enrichment of organic carbon and biogenic silica in sediments is profoundly localized in an elongate area which spans roughly .5 degrees of latitude, of a comparable scale to the model presented here.

Recent studies of Lower and Middle Ordovician deep-water (slope) sediments within the Northern Appalachians (Lash, 1986; Landing et al., in press) describe shale-dominated plus carbonate intervals, similar in many aspects to the Middle Arm Point Formation. Principal facies are i) a bioturbated red shale faciea indicative of

Figure 8-5

Possible paleoceanographic implications of the contrasting margin configuration represented by the Northern Head and Cow Head groups (schematic diagram).


N
OXYGEN-MINIMUM LAYER
ACTIVE, PROMINENT CARBONATE MARGIN
LOW-RELIEF MARGIN AND SLOPE
DOWNSLOPE TRANSPORT OF ORGANIC-RICH MUD
PELAGIC DEPOSITION OF CORG
VIGOROUS UPWELLING:
1) BROAD OXYGEN-MINIMUM LAYER
2) EXTENSIVE DEPOSITION AND RESEDIMENTATION OF CORG
3) WIDESPREAD DEPOSITION OF BIOGENIC SILICA
WEAK/DIFFUSE UPWELLING:
SPORADIC RESEDIMENTATION OF ORGANIC-RICH MUD (BLACK/GREEN SHALE)
NORTHERN HEAD AREA
COW HEAD AREA

relatively oxidizing depositional conditions and ii) a black shale plus carbonate facies. These authors ascribe the contrasting deposition of these facies to cyclic, global climatic-eustatic controls which resulted in widespread variation in oceanic circulation and the resultant variable preservation of organic carbon in the deep-water depositional environment. Considerable variability in the timing and nature of paleoceanographic changes have been indicated in this study in the relatively localized comparison of the the Northern Head group and Cow Head Group, and similar overall variability is apparent along the margin as a whole. Deposition of the red shale facies is extant in the upper Tremadoc of the Hamburg Klippe of Pennsylvannia (Lash, 1986) for example, but does not appear in the New York Taconic and Quebec Reentrant sections, summarized by Landing et al. (in press), until the Llanvirn.

Global climatic/eustatic controls may have been important in fostering the overall paleoceanographic changes reflected in the Lower Ordovician. However the local and regional variations discussed above suggest that irregularity in the margin configuration and slope morphology may represent an important factor in controlling the input of redeposited organic carbon-rich mud, and hence controlling the nature of the depositional and early diagenetic environment, in settings such as the Middle Arm Point Formation.

REFERENCES CITED

Ahr, W. M., 1973: The carbonate ramp: an alternative to the shelf model: Gulf Coast Assoc. Geol. Socs. Trans., v. 23, p. 221-225.

Amsbury, D. L., 1962: Detrital dolomites in Central Texas: Journal of Sedimentary Petrology, v. 32, p. 5-14.

Barnes, C. R., 1984: Early Ordovician eustatic changes in Canada: in D. L. Bruton (ed), Aspects of the Ordovician System, Paleontological contributions from the University of Oslo, no. 295, p. 51-65.

Barrett, T. J., 1982: Jurassic bedded cherts from the North Apennines, Italy: Dyscyclic sedimentation in the deep pelagic realm: in Cyclic and Event Stratification, edited by G. Einsele and A. Seilacher, Springer Verlag, New York, p. 389-403.

Bathurst, R. G. C., 1971: Carbonate sediments and their diagenesis: Elsevier, New York, 658 pp.

Berner, R. A., 1969: Geothite stability and the origin of red beds: Geochimica et Cosmichimica Acta, v. 33, p. 267-273.

Berner, R. A., 1980: Early diagenesis: a theoretical approach: Princeton Series in Geochemistry, Princeton University Press, 241 pp.

Berry, L. G., and Mason, B., 1959: Mineralogy: Concepts, Descriptions, Determinations: W. H. Freeman and Co., San Francisco, 630 pp.

Berry, W. B. N. and Wilde, P., 1978: Progressive ventilation of the oceans - an explanation for the distribution of the Lower Paleozoic black shales: American Journal of Science, v. 278, p. 257-275.

Bjorlykke, K. and Englund, J. O., 1979: Geochemical response to Upper Precambrian rift basin sedimentation and Lower Paleozoic epicontinental sedimentation in South Norway: Chemical Geology, v. 27, p. 271-295.

Bjorlykke, K., 1974: Geochemical and mineralogic influence of Ordovician Island arcs on epicontinental clastic sedimentation. A study of Lower Paleozoic sedimentation in the Oslo region, Norway: Sedimentology, v. 21, p. 251-272.

Bjorlykke, K. and Griffin, L., 1973: Barium feldspars in Ordovician sediments, Oslo region, Norway: Journal of Sedimentary Petrology, v. 43, p. 461-465.

Blatt, H., Middleton, G., and Murray, R., 1980: Origin of sedimentary rocks: Prentice-Hall, Englewood Cliffs, New Jersey, 782 pp.

Bolton, B. R. and Frakes, L. A., 1985: Geology and genesis of manganese oolite, Chiatara, Georgia, U. S. S. R.: Geological Society of America Bulletin, v. 96, p. 1398-1406.

Bosworth, W., 1985: East-directed imbrication and oblique-slip faulting in the Humber Arm Allochthon of Western Newfoundland; structural and tectonic significance; Canadian Journal of Earth Sciences, v. 22, p. 1351-1360.

Bralower, T. J. and Thierstein, H. R., 1984: Low productivity and slow deep-water circulation in mid-Cretacious oceans: Geology, v. 12, p. 614-618.

Bromley, R. G. and Ekdale, A. A., 1984: Chondrites: a trace fossil indicator of anoxia in sediments: Science, v. 224, p. 872-874.

Bruckner, W. D., 1966: Stratigraphy and structure of west-central Newfoundland: in Poole, W. H. (editor), Guidebook - Geology of parts of Atlantic Provinces: Annual Meeting; Geological Association of Canada and Mining Association of Canada, p. 137-151.

Byers, C. W., 1977: Biofacies patterns in euxinic basins; a general model: in H. E. Cook and P. Enos (editors), Deep-water carbonate environments; Society of Economic Paleontologists and Mineralogists, Special Publication 25, p. 5-18.

Calvert, S. E., 1974: Deposition and diagenesis of silica in marine sediments: in K. J. Hsu and H. C. Jenkyns (editors), Pelagic sediments: on land and under the sea; International Association of Sedimentologists, Special Publication 1, p. 273-299.

Calvert, S. E. and Price, N. B., 1970: Minor metal contents of recent organic-rich sediments off southwest Africa: Nature, v. 227, p 593-595.

Calvert, S. E. and Price, N. B., 1970: Composition of manganese nodules and manganese carbonates from Loch Fyre, Scotland: Contributions to Mineralogy and Petrology, v. 29, p 215-233.

Calvert, S. E. and Price, N. B., 1972: Diffusion and reaction profiles of dissolved manganese in the pore waters of marine sediments: Earth and Planetary Science Letters, v. 16, p. 245-249.

Cawood, P. A. and Williams, H., in press: Acadian basement thrusting, crustal delamination, and structural styles in and around the Humber Arm Allochthon: Geology

Chamberlain, C. K., 1978: Recognition of trace fossils in cores: in Trace fossil concepts ed. P. B. Basan; Society of Economic Paleontologists and Mineralogists, Short Course No. 5, Oklahoma City, p. 119-166.

Chandler, F. W., 1980: Proterozoic redbed sequences of Canada: Geological Society of Canada Bulletin No. 311, 49 pp.

Chow, N., 1986: Sedimentology and diagenesis of Middle and Upper Cambrian platform carbonates and siliciclastics, Port au Port Peninsula, western Newfoundland: unpublished PhD. thesis, Memorial University of Newfoundland, 458 p.

Chow, N. and James, N. P., 1984: Evolution of a carbonate-siliciclastic platform: Middle to Upper Cambrian of Western Newfoundland (abs.): American Association of Petroleum Geologists Bulletin, v. 68, p. 462.

Chow, N. and James, N. P., in press: Cambrian Grand Cycles: a northern Appalachian perspective: Geological Society of America Bulletin.

Church, T. M., 1979: Marine barite: in G. Burns (ed.), Marine Minerals; Mineralogical Society of America, Short Course Notes, v. 6, p. 175-209.

Claypool, G. E. and Kaplan, I. R., 1974: The origin and distribution of methane in marine sediments: in I. R. Kaplan (ed.), Natural gases in marine sediments; Plenum Press, New York, p. 99-139.

Coniglio, M., 1985: Origin and diagenesis of fine-grained slope sediments: Cow Head Group (Cambro-Ordovician), western Newfoundland: unpublished PhD. thesis, Memorial University of Newfoundland, 684 p.

Coniglio, M. and James, N. P., 1985: Calcified algae as sediment contributors to early Paleozoic limestone: evidence from deep-water sediments of the Cow Head Group, Western Newfoundland: Journal of Sedimentary Petrology, v. 55 (5), p 746-754.

Cook, H. E., 1983: Ancient carbonate platform margins, slopes, and basins: in Platform Margin and Deep Water Carbonates, H. E. Cook, A. C. Hine, and H. T. Mullins (editors); Society of Economic Paleontologists and Mineralogists, Short Course No. 12, p. 5-1 to 5-189.

Cook, H. E. (b), 1983: Sedimentology of some allochthonous deep-water carbonate reservoirs, Lower Permian, West Texas: carbonate debris sheets, aprons, or submarine fans? (abs.): Geological Society of America Bulletin, v. 63, P. 442.

Cook, H. E. and Enos, P., 1977: Deep-water carbonate environments: Society of Economic Paleontologists and Mineralogists, Special Publication No. 25, 336 p.

Cook, H. E. and Egbert, R. M., 1981: Late Cambrian - Early Ordovician continental margin sedimentation: in M. E. Taylor (editor), Short papers for the Second International Symposium on the Cambrian System; United States Geological Survey Open-file Report 81-743, p. 50-56.

Cook, H.E., Hine, A.C. and Mullins, H.T., 1983: Platform margin and deep water carbonates: Society of Economic Paleontologists and Mineralogists, Short Course No. 12, 573 p.

Cook, H. E. and Mullins, H. T., 1983: Basin margin environment: in P. A. Scholle, D. G. Bebout, and C. H. Moore (editors), Carbonate Depositional Environments; American Association of Petroleum Geologists Memoir 33, p. 540-617.

Cook, H. E. and Taylor, M. E., 1977: Comparison of continental slope and shelf environments in the Upper Cambrian and Lowest Ordovician of Nevada: in H. E. Cook and P. Enos (editors), Deep-water carbonate environments; Society of Economic Paleontologists and Mineralogists, v. 25, p. 51-81.

Cooper, R. A., 1979: Sequence and correlation of Tremadoc graptolite assemblages: Alcheringa, v. 3, p. 7-19.

Cooper, R. A. and Stewart, I., 1979: The Tremadoc graptolite sequence of Lancefield, Victoria: Paleontology, v. 22, p. 767-797.

Crevello, P. D., Clymer, P. L., and Brinton, L., 1985: Pennsylvanian carbonate slope and basin deposition, Palo Caro basin: in P. D. Crevello and P. M. Harris (editors), Deep-water carbonates -- a core workshop; Society of Economic Paleontologists and Mineralogists Core Workshop No. 6, New Orleans, p. 27-55.

Crevello, P. D. and Schlager, W., 1980: Carbonate debris sheets and turbidites, Exuma Sound, Bahamas: Journal of Sedimentary Petrology, v. 50, p. 2212-2248.

Crimes, T. P., 1977: Trace fossils of an Eocene deep-sea fan, Northern Spain: in T. P. Crimes and J. C. Harper (editors), Trace fossils 2; Geological Journal Special Issue No. 9, p. 71-90.

Curtis, C. D., 1980: Diagenetic alteration in black shales: Journal of the Geological Society of London, v. 137, p. 189-194.

D'Alessandro, A., Ekdale, A. A., and Sonnino, M., 1986: Sedimentologic significance of turbidite ichnofacies in the Saraceno Formation (Eocene), Southern Italy: Journal of Sedimentary Petrology, v. 56(2), p. 294-306.

Dean, W. E., Gardner, J. W., Jansa, L. F., Cepek, P., and Seibold, E., 1977: Cyclic sedimentation along the continental margin of Northwest Africa: Initial Reports of the Deep-Sea Drilling Project, v. 41, p. 965-990.

Dean, W. E. and Gardner, J. V., 1982: Origin and geochemistry of redox cycles of Jurassic to Eocene age, Cape Verde Basin (DSOP site 367), continental margin of Northwest Africa: in S. O., Schlanger and M. B. Cita (editors), Nature and Origin of Cretaceous and carbon-rich facies; Academic Press, New York, p. 55-78.

Dean, W. E. and Schreiber, B. C., 1978: Authigenic barite, Leg 41, Deep-Sea Drilling Project: Initial reports of the Deep-Sea Drilling Project, v. 41, p. 915-932.

Degens, E. T. and Ross, D. A. (eds.): 1974: The Black Sea-geology, chemistry and biology: American Association of Petroleum Geologists Memoir 20, 633 p.

Demaison, G. J. and Moore, G. T., 1980: Anoxic environments and oil source bed genesis: American Association of Petroleum Geologists Bulletin, v. 64(8), p. 1179-1209.

Droser, M. L. and Bottjer, D. J., 1986: A semiquantitative field classification of ichno fabric: Journal of Sedimentary Petrology, v. 56 (4), p. 558-559.

Dypvik, H., 1977: Mineralogical and geochemical studies of Lower Paleozoic rocks from the Trondheim and Oslo regions, Norway: Norsk Geologisk Tidsskrift, v. 57, p. 205-241.

Dypvik, H., 1984: Geochemical compositions and depositional conditions of Upper Jurassic and Lower Cretaceous Yorkshire clays, England: Geological Magazine, v. 121, p. 489-504.

Edwards, B. D., 1985: Bioturbation in a dysaerobic, bathyal basin: California borderland: in H. A. Curran (Editor), Biogenic Structures: Their Use in Interpreting Depositional Environments; Society of Economic Paleontologists and Mineralogists, Special Publication #35, p. 309-331.

Ekdale, A. A. 1985: Trace fossils and mid-Cretaceous anoxic events in the Atlantic Ocean: in H. A. Curran (Editor), Biogenic Structures: Their Use in Interpreting Depositional Environments; Society of Economic Paleontologists and Mineralogists, Special Publication #35, p. 333-342.

Ekdale, A. A., Bromley, R. G., and Pemberton, S. G., 1984: Ichnology: The Use of Trace Fossils in Sedimentology and Stratigraphy: Society of Economic Paleontologists and Mineralogists, Short Course No. 15, 317 pp.

Erdtmann, B. D. and Botsford, J. W., 1986: A new early Tremadoc (La 1) graptolite faunule from Western Newfoundland: its Australian affinities and biofacies relations: Canadian Journal of Earth Sciences, v. 23, p. 766-773.

Fairbridge, R. W. ed., 1972: The Encyclopedia of Geochemistry and Environmental Sciences: Van Nostrand Reinhold Co., New York, 1321 pp.

Fairchild, I. J., 1983: Chemical controls of cathodolo-luminescence of natural dolomites and calcites: new data and review: Sedimentology, v. 30, p. 579-583.

Fischer, A. G. and Arthur, M. A., 1979: Secular variations in the pelagic realm: in H. E. Cook and P. Enos (editors), Deep-water carbonate environments; Society of Economic Paleontologists and Mineralogists Special Publication #25, p. 19-50.

Force, E. R., Cannon, W. F., Koski, R. A., Passmore, K. T., and Doe, B. R., 1983: Influences of ocean anoxic events on manganese deposition and ophiolite-hosted sulphide preservation: in T. M. Cronin, W. F. Cannon, and R. Z. Poore (editors), Paleoclimate and Mineral Deposits; United States Geological Survey, Circular #822, p. 26-29.

Fortey, R. A., 1984: Global earlier Ordovician transgressions and regressions and their biological implications, p. 37-50: in D. L. Bruton (editor), Aspects of the Ordovician System, Paleontological Contributions from the University of Oslo, No. 295, p. 37-51.

Fortey, R. A., Landing, E., and Skevington, D., 1982: Cambro-Ordovician boundary sections in the Cow Head Group, Western Newfoundland: in M. G. Bassett and W. T. Dean (editors), The Cambrian-Ordovician boundary: sections, fossil distributions and correlations; National Museum of Wales, Geological Series No. 3, Cardiff, p. 95-129.

Frakes, L. A. and Bolton, B. R., 1984: Origin of manganese giants: sea-level change and anoxic-oxic history: Geology, v. 12, p. 83-86.

Frank, J. R., Carpenter, A. B., Oglesby, T. W., 1982: Cathodoluminescence and composition of calcite cement in the Taum Sauk Limestone (Upper Cambrian), Southeast Missouri: Journal of Sedimentary Petrology, v. 52 (2), p. 631-638.

Friend, P. F., 1966: Clay fractions and colours of some Devonian red beds in the Catskill Mountains, U. S. A.: Journal of the Geological Society of London, v. 122, p. 273-292.

Froelich, P. N., Klinkhammer, G. P., Bender, M. L., Leudtke, N. A. Heath, G. R., Cullen, D., and Dauphin, P., 1979: Early oxidation of organic matter in pelagic sediments of the eastern equatorial Atlantic: suboxic diagenesis: Geochemica et Cosmochimica Acta, v. 43, p. 1075-1090.

Garrels, R. M. and Christ, C. L., 1965: Solutions, Minerals and Equilibria: Harper, New York, 450 pp.

Geological Society of America Rock Color Chart, 1981: Boulder, Colorado.

Gortner, C. W., and Larue, D. K., 1986: Hemipelagic rocks at Bissex Hill, Barbados; Sedimentology, Geochemistry and depositional environment: Journal of Sedimentary Petrology; v. 56(2), p. 307-316.

Grill, E. V., 1978: The effect of sediment-water exchange on manganese distribution and nodule growth in Jervis Inlet, British Columbia: Geochimica et Cosmichimica Acta, v. 42, p. 485-494.

Graham, H. R., 1965: Radiolarian charts and associated rocks in space and time: Eclog. geol. Helv., v. 58, p. 157-208.

Heir, J. R., O'Neil, J. R., and Jones, M. G., 1979: Origin of authigenic carbonates in sediment from the deep Bering Sea: Sedimentology, v. 26, p. 681-705.

Hesse, R., 1986: Early diagenetic pore water/sediment interaction: Modern offshore basins: Geoscience Canada, v. 13, p. 165-196.

Hibbard, J., 1984: Geology of the Baie Verte Peninsula, Newfoundland: Newfoundland Department of Mines and Energy, Mineral Development Division, Memoir No. 2, 279 p.

Hiscott, R. N., 1978: Provenance of Ordovician deep-water sandstones, Tourelle Formation, Quebec, and implications for initiation of the Taconic orogeny: Canadian Journal of Earth Sciences, v. 15, p. 1579-1597.

Hiscott, R. N., 1979: Clastic sills and dikes associated with deep-water sandstones, Tourelle Formation, Ordovician, Quebec: Journal of Sedimentary Petrology, v. 49, p. 1-10.

Hiscott, R. N., 1980: Depositional framework of sandy mid-fan complexes of the Tourelle Formation, Ordovician, Quebec: American Association of Petroleum Geologists Bulletin, v. 64, p. 1052-1077.

Hiscott, R. N., 1984: Ophiolitic source rocks for Taconic-age flysch: Trace-element evidence: Geological Society of America Bulletin, v. 95, p. 1261-67.

Hiscott, R. N. and James, N. P., 1985: Carbonate debris flows, Cow Head Group, Western Newfoundland: Journal of Sedimentary Petrology, v. 55, p. 735-745.

Howell, B. F., Bridge, J., Deiss, C. F., Edwards, I., Lochman, C., Raasch, G. O., and Resser, C. E., 1944: Correlation of the Cambrian Formations of North America: Geological Society of America Bulletin, v. 55, p. 993-1003.

Hubert, J. K., et al, 1977: The Cow Head Breccia: sedimentology of the Cambro-Ordovician Margin, Newfoundland: in H. E. Cook and P. Enos (editors), Deep-water Carbonate Environments; Society of Economic Paleontologists and Mineralogists, v. 25, p. 125-154.

Ingram, R. L., 1954: Terminology for the thickness of stratification and parting units in sedimentary rocks: Geological Society of America Bulletin, v. 65, p. 937-938.

Irwin, H, Coleman, M., and Curtis, C., 1977: Isotopic evidence for source of diagenetic carbonates formed during burial of organic-rich sediments: Nature, v. 269, p. 209-213.

Irwin, H., 1980: Early diagenetic carbonate precipitation and pore fluid migration in the Kimmeridge Clay of Dorset, England: Sedimentology, v. 27, p. 577-591.

Jacobs, L. and Emerson, S., 1982: Trace metal solubility in an anoxic fjord: Earth and Planetary Science Letters, v. 60, p. 237-252.

James, N. P., 1981: Megablocks of calcified algae in the Cow Head Breccia, Western Newfoundland: vestiges of a Cambro-Ordovician platform margin: Geological Society of America Bulletin, v. 92, p. 799-811.

James, N. P., 1982: Depositional models for carbonate rocks: in A. Parker and B. W. Sellwood (editors), Sediment Diagenesis; NATO ASI Series C: Mathematics and Physical Sciences, Vol. 115, D. Ruedel Publishing Co., Boston, p. 289-348.

James, N. P., Knight, I. and Chow, N., 1983: Middle and Upper Cambrian platform carbonates, western Newfoundland: anatomy of a high-energy shelf: Newfoundland Section, Geological Association of Canada, Program with Abstracts, p. 1.

James, N. P., Stevens, R. K., and Fortey, R. A., 1979: Correlation and timing of platform margin megabreccia deposition, Cow Head and related groups, Western Newfoundland (abstract): American Association of Petroleum Geologists Bulletin, v. 63, p. 474.

James, N. P. and Stevens, R. K., 1982: Anatomy and evolution of a Lower Paleozoic continental margin: International Association of Sedimentologists Guidebook, No. 2B; 75 pp.

James, N. P. and Stevens, R. K., 1986: Stratigraphy and correlation of the Cambro-Ordovician Cow Head Group, western Newfoundland: Geological Survey of Canada Bulletin 366, 143 p.

James, N. P. and Mountjoy, E. W., 1983: Shelf-slope break in fossil carbonate platforms: an overview: in D. J. Stanley and G. T. Moore (editors), The shelfbreak: critical interface on continental margins; Society of Economic Paleontologists and Mineralogists, Special Publication No. 13, p. 189-206.

James, N. P., Botsford, J. W., and Williams, S. H., 1987: Allochthonous slope sequence at Lobster Cove Head: evidence for a complex Middle Ordovician platform margin in western Newfoundland; Canadian Journal of Earth Sciences, v. 24, p. 1199-1211.

James, N. P., Stevens, R. K., Barnes, C. R., and Knight, I. (in press): Evolution of a Lower Paleozoic continental margin carbonate platform, Northern Canadian Appalachians.

Jansa, L. F., 1974: Trace fossils from the Cambro-Ordovician Cow Head Group, Newfoundland, and their paleobathymetric implication: Paleogeography, Paleoclimatology, Paleoecology, v. 15, p. 233-244.

Jenkyns, 1980: Cretaceous anoxic events from continents to oceans: Journal of the Geological Society of London, v. 137, p. 171-188.

Jones, R. W., 1983: Organic matter characteristics near the shelf-slope boundary: in D. J. Stanley and G. T. Moore (editors), The Shelfbreak: Critical Interface on Continental Margins; Society of Economic Paleontologists and Mineralogists, Special Publication No. 33, p. 391-408.

Jordan, D. W., 1985: Trace fossils and depositional environments of Upper Devonian Black shales, East-Central Kentucky, U. S. A.: in H. A. Curran (editor), Biogenic structures: their use in interpreting depositional environments: Society of Economic Paleontologists and Mineralogists, Special Publication No. 35, p. 279-298.

Kastner, M., 1971: Authigenic feldspars in carbonate rocks: American Mineralogist, v. 56, p. 1403-1442.

Keith, B. D. and Friedman, G. M., 1977: A slope-fan-basin plain model, Taconic sequence, New York and Vermont: Journal of Sedimentary Petrology, v. 47, p. 1220-1241.

Kelts, K. and Arthur, M. A., 1981: Turbidites after ten years of deep-sea drilling - wringing out the mop?: in J. E. Warme, R. G. Douglas, and E. L. Winterer (editors), The Deep-Sea Drilling Project: A decade of progress; Society of Economic Paleontologists and Mineralogists, Special Publication No. 32, p. 91-127.

Kindle, C. H., 1981: Cambrian faunas in the limestone conglomerates of Western Newfoundland: in Short Papers for the Second International Symposium on the Cambrian System; United States Geological Survey, Open-file Report 81-743, p. 106-110.

Kindle, C. H., 1982: The C. H. Kindle Collection: Middle Cambrian to Lower Ordovician trilobites from the Cow Head Group, Western Newfoundland: in Current Research, Part C, Geological Survey of Canada, Paper 82 - LC, p. 1-17.

Klappa, C. F., Opalinski, P. R., and James, N. P., 1980: Middle Ordovician Table Head Group of Western Newfoundland: a revised stratigraphy: Canadian Journal of Earth Sciences, v. 17, p. 1007-1019.

Klinkhammer, G. P. and Bender, M. L., 1980: The distribution of manganese in the Pacific Ocean: Earth and Planetary Science Letters, v. 46, p. 361-384.

Klinkhammer, G., Heggie, D. T., and Graham, D. W., 1982: Metal diagenesis in oxic marine sediments: Earth and Planetary Science Letters, v. 61, p. 211-219.

Knight, I. and James, N. P. (in press): Stratigraphy of the St. George Group, Lower Ordovician, Western Newfoundland: Canadian Journal of Earth Sciences.

Krause, F. F. and Oldershaw, A. E., 1979: Submarine carbonate breccia beds -- a depositional model for two-layer, sediment gravity flows from the Sekwi Formation (Lower Cambrian), Mackenzie Mountains, Northwest Territories, Canada: Canadian Journal of Earth Sciences, v. 16, p. 189-199.

Krauskopf, K. B., 1967: Introduction to Geochemistry: McGraw-Hill, New York, 721 pp.

Lajoie, J. and Chagnon, A., 1973: Origin of red beds in a Cambrian flysch sequence, Canadian Appalachians, Quebec: Sedimentology, v. 20, p. 91-103.

Lancelot, Y., 1973: Chert and silica diagenesis in sediments from the Central Pacific: in E. L. Winterer, et al; Initial Reports of the Deep-Sea Drilling project, v. 17, p. 377-405.

Landing, E., Benus, A. P., and Whitney, P. R. (in press): Early and early Middle Ordovician continental slope deposition: Shale cycles and sandstones in the Quebec reentrant and New York Promontory region: Canadian Journal of Earth Sciences.

Lash, G. G., 1986: Possible significance of early Paleozoic fluctuations in bottom current intensity, Northwest Iapetus Ocean: Paleooceanography, v. 1, p. 119-135.

Leggett, J. K., 1978: Eustacy and pelagic realms in the Iapetus Ocean during the Ordovician and Silurian: Earth and Planetary Science Letters, v. 41, p. 163-169.

Leggett, J. K., 1980: British Lower Paleozoic black shales and their palaeo-oceanographic significance: Journal of the Geological Society of London, v. 137, p. 139-156.

Leggett, J. K., McKerrow, W. S., Cocks, L. R. M., and Richards, R. B., 1981: Periodicity in the early Palaeozoic marine realm: Journal of the Geological Society of London, v. 138, p. 167-176.

Levesque, R. J., 1977: Stratigraphy and sedimentology of Middle Cambrian to Lower Ordovician shallow water carbonate rocks, Western Newfoundland: Unpublished M.Sc. thesis, Memorial University of Newfoundland, 276 pp.

Li, Y., Bischoff, J., and Mathieu, G., 1969: The migration of manganese in the Arctic Basin sediment: Earth and Planetary Science Letters, v. 7, p. 265-270.

Lilly, H. D., 1963: Geology of the Hughes Brook - Goose Arm Area, Western Newfoundland: Memorial University of Newfoundland, Department of Geology, Report No. 2, 123 pp.

Lilly, H. D., 1967: Some notes on stratigraphy and structural styles in Central - Western Newfoundland; Geological Association of Canada: Geological Association of Canada, Special Paper No. 4, p. 201-212.

Lindstrom, M., and Vortisch, W., 1983: Indications of upwelling in the Lower Ordovician of Scandinavia: in J. Thiede and E. Suess (editors), Coastal upwelling, its sediment record, Part B: Sedimentary records of ancient coastal upwelling; NATO Conference series, v. iv:10b, p. 535-552.

Lochman-Balk, C. and Wilson, J. L., 1958: Cambrian biostratigraphy in North America: Journal of Paleontology, v. 32, p. 312-350.

Lynn, D. C., and Bonatti, E., 1965: Mobility of manganese in diagenesis of deep-sea sediments: Marine Geology, v. 3, p. 457-474.

Macdonald, D.I.M., 1986: Proximal to distal sedimentological variation in a linear turbidite trough: implications for the fan model: Sedimentology, v. 33, p. 243-259.

Malpas, J. and Stevens, R. K., 1977: The origin and emplacement of the ophiolite suite with examples from Western Newfoundland: Geotectonics, v. 11, p. 453-466.

Markello, J. R. and Read, J. F., 1981: Carbonate ramp-to-deeper shale shelf transitions of an Upper Cambrian intrashelf basin, Nolichucky Formation, S. W. Virginia Appalachians: Sedimentology, v. 81, p. 573-597.

Maynard, J. B., 1983: Geochemistry of sedimentary ore deposits: Springer-Verlag, New York, 305 pp.

McIlreath, I. A., 1977: Accumulation of a Middle Cambrian deep-water limestone debris apron adjacent to a vertical submarine escarpment, southern Rocky Mountains, Canada: in H. E. Cook and P. Enos (editors), Deep-water carbonate environments; Society of Economic Paleontologists and Mineralogists, Special Publication No. 25, p. 113-124.

McIlreath, I. A. and James, N. P., 1979: Carbonates slopes: in R. G. Walker (editor): Geoscience Canada Reprint Series 1, p. 133-143.

McKillop, J. H., 1963: Geology of the Corner Brook Area, Newfoundland, with emphasis on the carbonate deposits: Memorial University of Newfoundland, Department of Geology, Report No. 1, 102 pp.

McPherson, J. G., 1980: Genesis of variegated redbeds in the fluvial Aztec Sittshore (Lake Devonian), southern Victoria Land, Antarctica: Sedimentary Geology, v. 27, p. 119-142.

Meyers, P. A., Leenheer, M. J., Kawka, O. E., and Trull, T. W., 1984: Enhanced preservation of marine derived organic matter in Cenomanian black shales from the southern Angola Basin: Nature, v. 312, p. 356-359.

Middleton, G. V. and Hampton, M. A., 1976: Subaqueous sediment transport and deposition by sediment gravity flows: in D. J. Stanley and D. J. P. Swift (editors), Marine Sediment Transport and Environmental Management; New York, Wiley Interscience, p. 197-218.

Morad, S. and AlDahan, A. A., 1986: Alteration of detrital Fe-Ti oxides in sedimentary rocks: Geological Society of America Bulletin No. 97, p. 567-578.

Mullins, H. T., 1983: Base of slope carbonate aprons: an alternative to submarine fan model (abstract): American Association of Petroleum Geologists Bulletin No. 67, p. 442.

Mullins, H. T. and Neumann, A. C., 1979: Deep carbonate bank margin structure and sedimentation in the Northern Bahamas: in L. J. Doyle and O. H. Pilkey (editors), Geology of continental slopes; Society of Economic Paleontologists and Mineralogists, Special Publication No. 27, p. 165-192.

Mutti, E. and Ricci Lucchi, F., 1978: Turbidites of the Northern Appenines: Introduction to facies analysis (translated by Tor H. Nielson): International Geology Review, v. 20, p. 125-166.

Nelson, C. H. and Nilsen, T. H., 1974: Depositional trends of modern and ancient deep-sea fans: in R. H. Dott Jr. and R. H. Shaver (editors), Modern and Ancient Geosynclinal Sedimentation; Society of Economic Paleontologists and Mineralogists, Special Publication No. 19, p. 69-91.

Normark, W. R., 1974: Submarine canyons and fan valleys: factors affecting growth patterns in deep-sea fans: in R. H. Dott Jr. and R. H. Shaver (editors), Modern and Ancient Geosynclinal sedimentation; Society of Economic Paleontologists and Mineralogists, Special Publication No. 19, p. 56-68.

Norrish, K. and Taylor, R. M., 1962: Quantitative analyses by X-ray diffraction: Clay Mineralogical Bulletin, v. 5, p. 98-104.

North American Commission on Stratigraphic Nomenclature, 1983: North American Stratigraphic Code: American Association of Petroleum Geologists Bulletin No. 67, p. 841-875.

Nriagu, J. O., 1984: Phosphate minerals: their properties and general modes of occurrence: in Phosphate Minerals, J. O. Nriagu and P. B. Moore (eds.); Springer-Verlag, New York, p. 1-136.

Nyman, M., Quinn, L., Reusch, D. N., and Williams, H., 1984: Geology of Lomond map area, Newfoundland: in Current Research, Part A, Geological Survey of Canada Paper, 84-1A, p. 157-164.

Palmer, A. R., 1965: Biomere - a new kind of stratigraphic unit: Journal of Paleontology, v. 39, p. 149-153.

Palmer, A. R., 1977: Biostratigraphy of the Cambrian System - a progress report: Annual Review of Earth and Planetary Sciences, v. 5, p. 13-33.

Parrish, J. T., Ziegler, A. M., and Humphreville, R. G., 1983: Upwelling in the Paleozoic era: in J. Thiedé and E. Suess (editors), Coastal upwelling, its sediment record, Part B: Sedimentary records of ancient coastal upwelling: NATO Conference series, v. iv:10b, p. 553-578.

Pedersen, T. F. and Price, N. B., 1982: The geochemistry of manganese carbonate in Panama Basin Sediments: Geochimica et Cosmichimica Acta, v. 46, p. 59-68.

Pemberton, S. G. and Frey, R. W., 1982: Trace fossil nomenclature and the Planolites - Palaeophycus dilemma: Journal of Paleontology, v. 56(4), p 843-881.

Pickering, K., Stow, D., Watson, M., and Hiscott, R.: Deep-water facies, processes and models: a review and classification scheme for modern and ancient sediments: Earth-Science Reviews, v. 23, p. 75-174.

Pratt, B. R., 1979: The St. George Group (Lower Ordovician), Western Newfoundland: sedimentology, diagenesis and cryptalgal structures: unpublished M.Sc. thesis, Memorial University of Newfoundland, 254 pp.

Quinn, L., 1985: Geology of the Humber Arm Allochthon at South Arm, Bonne Bay, West Newfoundland, with extensions in the Lomond area; unpublished M.Sc. thesis, Memorial University of Newfoundland, 188 pp.

Quinn, L. and Williams, H., 1983: Humber Arm Allochthon at South Arm, Bonne Bay, West Newfoundland: in Current Research, Part A, Geological Survey of Canada Paper, No. 83-1A, p. 179-182.

Read, J. F., 1980: Carbonate ramp to basin transitions and foreland basin evolution, Middle Ordovician, Virginia Appalachians: American Association of Petroleum Geologists Bulletin, v. 64, p. 1575-1612.

Read, J. F., 1982: Carbonate platforms of passive (extensional) continental margins: types, characteristics and evolution: Tectonophysics, v. 81, p. 195-212.

Rhoads, D. C. and Morse, J. W., 1971: Evolution and ecologic significance of oxygen-deficient marine basins: Lethaia, v. 4, p. 413-428.

Robbins, J. A. and Callender, E., 1975: Diagenesis of manganese in Lake Michigan sediments: American Journal of Science, v. 275, p. 512-533.

Rodgers, J. and Neale, E. R. W., 1963: Possible "Taconic" klippen in Western Newfoundland: American Journal of Science, v. 261, p. 713-730.

Rollkotter, J., et al, 1983: Potential deep-sea petroleum source beds related to coastal upwelling: in J. Thiede and E. Suess (editors), Coastal Upwelling, its sediment record, Part B: Sedimentary records of ancient coastal upwelling; NATO Conference Series, v. iv: 10b, p. 467-484.

Ross, R. J. Jr., et al, 1982: The Ordovician System in the United States: International Union of Geological Sciences, Publication No. 12, 73 pp.

Sabins, F. F. Jr., 1962: Grains of detrital, secondary and primary dolomite from Cretaceous strata of the western interior: Geological Society of America Bulletin No. 73, p. 1183-1196.

Savdra, C. E. and Bottjer, D. J., 1986: Trace-fossil model for reconstruction of paleo-oxygenation in bottom waters: Geology, v. 14, p. 3-6.

Schillereff, S. and Williams, H., 1979: Geology of Stephenville Map Area, Newfoundland: in Current Research, Part A: Geological Survey of Canada, Paper 79-1A, p. 327-332.

Schlager, W. and Chermak, A., 1979: Sediment facies of platform-basin transition, Tongue of the Ocean, Bahamas: in L. J. Doyle and O. H. Pilkey (editors), Geology of continental slopes; Society of Economic Paleontologists and Mineralogists, Special Publication No. 27, p. 193-208.

Schlanger, S. O. and Cita, M. B., 1982: Nature and origin of Cretaceous carbon-rich facies: Academic Press, London, 229 pp.

Scholle, P. A., 1971: Diagenesis of deep-water carbonate turbidites, Upper Cretaceous Monte Antola Flysch, North Appenines, Italy: Journal of Sedimentary Petrology, v. 41, p. 233-250.

Schopf, T. J. M., 1983: Paleozoic black shales in relation to continental margin upwelling: in J. Thiede and E. Suess (editors), Coastal upwelling, its sediment record, Part B: Sedimentary records of ancient coastal upwelling; NATO Conference Series, v. iv:10b, p. 579-596.

Schuchert, C. and Dunbar, C. O., 1934: Stratigraphy of Western Newfoundland: Geological Society of America Memoir 1, 123 pp.

Schultz, A. W., 1984: Subaerial debris-flow deposition in the Upper Paleozoic Cutler Formation, western Colorado: Journal of Sedimentary Petrology, v. 54, p. 759-772.

Seilacher, A., 1967: Bathymetry of trace fossils: Marine Geology, v. 5, p. 413-428.

Seilacher, A, 1977: Pattern analysis of Paleodictyon and related trace fossils: in T. P. Crimes and J. C. Harper (editors), Trace Fossils 2; Geological Journal Special Issue No. 9, p. 289-334.

Seilacher, A., 1978: Use of trace fossils for recognizing depositional environments: in P. B. Basan (editor), Trace Fossil Concepts; Society of Economic Paleontologists and Mineralogists, Short Course No. 5, p. 167-181.

Shanmugam, G. and Benedict, G. L., 1978: Fine-grained carbonate debris flow, Ordovician basin margin, Southern Appalachians, Journal of Sedimentary Petrology, v. 48, p. 1233-1240.

Shanmugam, G. and Walker, K. R., 1978: Tectonic significance of distal turbidites in the Middle Ordovician Blockhouse and Lower Sevier Formations in East Tennessee: American Journal of Science, v. 278, p. 551-578.

Silver, E. A. and Beutner, E. C., 1980: Penrose Conference Report: melanges: Geology, v. 8, p. 32-34.

Smith, R. L., 1983: Circularion patterns in upwelling regimes: in J. Thiede and E. Suess (editors), Coastal upwelling, its sediment record, Part A: Responses of the sedimentary regime to present coastal upwelling; NATO Conference Series, v. iv:10a, p. 13-36.

Stanley, D. J. and Unrug, R., 1972: Submarine channel deposits, fluxoturbidites and other indicators of slope and base-of-slope environments in modern and ancient marine basins: in J. K. Rigby and W. K. Hamblin (editors); Recognition of ancient sedimentary environments, Society of Economic Paleontologists and Mineralogists, Special Publication No. 16, p. 287-340.

Stenzel, S. R. and James, N. P., 1987: Death and destruction of an early Paleozoic carbonate platform, western Newfoundland: Society of Economic Paleontologists and Mineralogists Mid-Year Meeting, Austin.

Stevens, R. K., 1965: Geology of the Humber Arm area, west Newfoundland: Unpublished M. Sc. thesis, Memorial University of Newfoundland, 121 pp.

Stevens, R. K., 1970: Cambro-Ordovician flysch sedimentation and tectonics in west Newfoundland and their possible bearing on a proto-Atlantic Ocean: Geological Association of Canada, Special Paper No. 7, p. 165-177.

Stevens, R. K., 1976: Lower Paleozoic evolution of Western Newfoundland: Unpublished Ph.D. thesis, University of Western Ontario.

Stevens, R. K., 1983: The transported sedimentary rocks of Western Newfoundland. Evolution of the ancient continental margin of Western Newfoundland: Geological Association of Canada, Newfoundland section, Program with abstracts.

Stitt, J. H., 1971: Late Cambrian and earliest Ordovician trilobites, Timbered Hills and Lower Arbuckle Groups, Western Arbuckle Mountain, Murray County, Oklahoma: Oklahoma Geological Survey, Bulletin V110, 83 pp.

Stow, D. A. V. and Lowell, J. P. B., 1979: Contourites: their recognition in modern and ancient sediments: Earth-Science Review, v. 14, p. 251-291.

Stow, D. A. V. and Shanmugan, G., 1980: Sequence of structures in fine-grained turbidites, comparison of recent deep-sea and ancient flysch sediments: Sedimentary Geology, v. 25, p. 23-42.

Stow, D. A. V. and Piper, D. J. W., 1984: Deep-water, fine-grained sediments: deep-water processes and facies: in D. A. V. Stow and D. J. W. Piper (editors); Fine-grained sediments: processes and facies, Geological Society of London Special Publication No. 15, p. 611-645.

Suchecki, R. K., Perry, E. A., Hubert, J. F., 1977: Clay petrology of Cambro-Ordivician continental margin, Cow Head Klippe, Western Newfoundland: Clays and Clay Minerals, v. 26, p. 163-170.

Suess, E., 1979: Mineral phases formed in anoxic sediments by microbial decomposition of organic matter: Geochimica et Cosmichimica Acta, v. 43, p. 339-352.

Suess, E. and Thiede, J., 1983: Introduction in J. Thiede and E. Suess (editors); Coastal upwelling, its sediment record: NATO Conference Series, v. iv: 10 a and b, pp. 1-12.

Taylor, M. E., 1977: Late Cambrian of western North America: trilobite biofacies, environmental significance and biostratigraphic implications in Concepts and Methods of Biostratigraphy, E. G. Kaufmann and J. E. Hazel (eds.): Dowden, Hutchison and Ross, Stroudburg, Pa., p. 397-427.

Taylor, M. E. and Cook, H. E., 1976: Continental shelf and slope facies in the Upper Cambrian and lowest Ordovician of Nevada: in R. A. Robison and A. J. Rowell (editors); Cambrian paleontology and environments and western North America, Brigham Young University Geology Studies, v. 23, p. 181-214.

Thiede, J. and Suess, E., (eds.), 1983: Coastal upwelling, its sediment record: NATO Conference Series, v. iv: 10 a and b, 512 p.

Thomas, D. E., 1960: The zonal distribution of Australian graptolites: Royal Society of New South Wales, Journal and Proceedings, v. 94, p. 1 - 58.

Thomas, W. A., 1977: Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin: American Journal of Science, v. 277, p. 1233-1278.

Tissot, B. P. and Welte, D. H., 1978: Petroleum formation and occurrence - a new approach to oil and gas exploration: Springer Verlag, Berlin, 538 pp.

Vail, P. R., Mitchum, R. M., and Thompson, S., III, 1977: Global cycles of relative changes in sea level: in C. E. Payton (editor); Seismic stratigraphy - applications to hydrocarbon exploration, American Association of Petroleum Geologists Memoir No. 26, p. 83-92.

Van der Weijden, C. H., Schuiling, R. D. and Das, H. A., 1970: Some geochemical characteristics of sediments from the North Atlantic Ocean: Marine Geology, v. 9, p. 81-99.

Van Houten, F. B., 1968: Iron oxides in red beds: Geological Society of America Bulletin, v. 79, p. 399-416.

Van Houten, F. B., 1973: The origin of red beds, a review-1961-1972: in F. A. Donath, F. G. Stehli and G. W. Wetherill (editors); Annual Review of Earth and Planetary Science Letters, v. 1, p. 39-61.

Vine, J. D. and Tourtelot, E. B., 1970: Geochemistry of black shale deposits -- a summary report: Economic Geology, v. 85, p. 253-272.

Walker, R. G., 1967: Turbidite sedimentary structures and their relationship to proximal and distal depositional environments: Journal of Sedimentary Petrology, v. 37, p. 25-43.

Walker, R. G., 1978: Deep water sandstone facies and ancient submarine fans; models for exploration for stratigraphic traps: American Association of Petroleum Geologists Bulletin, v. 62, p. 932-966.

Walker, R. G., 1984: Turbidites and associated coarse clastic deposits: in R. G. Walker (editor); Facies Models, 2nd edition, Geoscience Canada Reprint Series, v. 1, p. 171-188.

Weitz, J. L., 1953: Geology of the Bay of Islands area, western Newfoundland: Unpublished Ph.D. thesis, Yale University.

Waldron, J. W. F., 1985: Structural history of continental margin sediments beneath the Bay of Islands Ophiolite, Newfoundland: Canadian Journal of Earth Sciences, v. 22, p. 1618-1632.

Walthier, T. N., 1949: Geology and mineral deposits of the area between Corner Brook and Stephenville, western Newfoundland: Newfoundland Geological Survey, Bulletin No. 35, Part I, 54 pp.

Welton, J. E., 1984: SEM Petrology Atlas, The American Association of Petroleum Geologists methods in exploration series No. 4: American Association of Petroleum Geologists, Tulsa, 237, pp.

Wentworth, C. K., 1922: A scale of grade and class terms for clastic sediments: Journal of Geology, v. 30, p. 377-392.

Westergard, A. H., 1946: Agnostidea of the Middle Cambrian of Sweden: Sveriges Geologiska Undersokning, Series C., No. 177, Arbok 40, No. 1, 140 pp.

Westergard, A. H., 1947: Supplementary notes on the Upper Cambrian trilobites of Sweden: Sveriges Geologiska Undersokning, Series C, No. 489, Arsbok 41, No. 8, 34 pp.

Whittington, H. B. and Kindle, C. H., 1969: Cambrian and Ordovician stratigraphy of western Newfoundland: in M. Kay (editor); North Atlantic Geology and Continental Drift; American Association of Petroleum Geologists Memoir No. 12, p. 655-664.

Williams, H., 1973: Bay of Islands Map Area, Newfoundland: Geological Survey of Canada Paper 72-34.

Williams, H., 1975: Structural succession, nomenclature, and interpretation of transported rocks in western Newfoundland: Canadian Journal of Earth Sciences, v. 12, p. 1874-1894.

Williams, H., 1979: Appalachian Orogen in Canada: Canadian Journal of Earth Sciences, v. 16, p. 792-807.

Williams, H., 1981: Geology, Stephenville map area, Newfoundland (12BN 1/2): Geological Survey of Canada, Open File 276.

Williams, H. and Stevens, R. K., 1969: Geology of Belle Isle - northern extrimity of the deformed Appalachian miogeosynclinal belt: Canadian Journal of Earth Sciences, p. 1145-1157.

Williams, H. and Stevens, R. K., 1974: The ancient continental margin of eastern North America: in The geology of continental margins; edited by C. A. Burk and C. L. Drake; Springer Verlag, New York, p. 781-796.

Williams, H., James, N. P., and Stevens, R. K., 1985: Humber Arm Allochthon and nearby groups between Bonne Bay and Portland Creek, western Newfoundland: in Current Research, Part A, Geological Survey of Canada, Paper 85-1A, p. 399-406.

Williams, H., Cawood, P. A., James, N. P., and Botsford, J. W., 1986: Geology of the St. Paul's Inlet area (12H/13), western Newfoundland: Geological Survey of Canada, Open File No. 1238.

Williams, H. and Cawood, P. A. (compilers), 1987: Geology, Humber Arm Allocthon, Newfoundland: Geological Survey of Canada, Map, scale 1:250,000.

Wilson, J. L., 1975: Carbonate facies in geological history: Springer Verlag, New York, 471 pp.

Wilson, T. R. S., Thomson, J., Hydes, D. J., Colley, S., Calkin, F., and Sorensen, J., 1986: Oxidation fronts in pelagic sediments: diagenetic formation of metal-rich layers: Science, v. 232, p. 972-975.

Wise, S. W., and Weaver, F. M., 1974: Chertification of oceanic sediments: in Pelagic sediments on land and under the sea; edited by K. J. Hsu and H. C. Jenkyns: International Association of Sedimentologists Special Publication No. 1, p. 301-326.

Young, H. R. and Doig, D. J., 1986: Petrology and provenance of the Glauconitic Sandstone, south-central Alberta, with comments on the occurrence of detrital dolomite: Canadian Society of Petroleum Geologists Bulletin, v. 34(4), p. 408-425.

Ziegler, A. M. and Mckerrow, W. S., 1975: Silurian marine red beds: American Journal of Science, v. 275, p. 31-56.

APPENDIX B

DISCUSSION OF MEASURED SECTIONS

A total of 12 sections have been used to assemble the stratigraphy presented in this study. This has been augmented with observations from other areas (e.g. Giles Point, Brakes Cove, the Rattler window) where the degree of deformation does not facilitate the measurement of sections.

This appendix is intended as a guide to the location and structural interpretation of sections discussed in the text, and illustrated in Appendix A.

1) HALFWAY POINT

Location and setting

This section is located on the south shore of the Humber Arm, near the community of Halfway Point. The lowermost part of the section (21U/195274) is exposed in rocky headlands along the shoreline. The middle part of the section is covered at the shore by pebble beach and talus, but is exposed along the road.

The section spans the western limb of the Cooks Brook Syncline and exposes the lower part of the Cooks Brook Formation. The contact with the underlying Irishtown Formation and the Halfway Point member are well exposed at the base, and the section is measured eastward to the broad hinge zone of the syncline west of Cooks Brook (21U/212253). The same interval, more highly deformed (faulted and folded), is exposed on the steeper eastern limb of the syncline in the vicinity of Giles Point.

Structural aspects

The section is deformed by numerous folds, with steeply-inclined axial planes, which range in wavelength from less than 1 m to over 50 m and appear to be parasitic on the limb of the major Cooks Brook syncline. Hence stratigraphic intervals are frequently repeated along the shoreline and the section is assembled with careful attention to younging indicators. Covered intervals occur in the upper part of the Halfway Point member, but nearby bedding attitudes give no indication of major dislocations of the section in these areas.

2) NORTHERN HEAD

Location and access

This section spans Northern Head proper, extending from immediately south of the unnamed brook north of Northern Head (21U/186464) to immediately east of Northern Head (21U/188455).

The section exposes almost the entire Cooks Brook Formation. Shales of the uppermost Irishtown Formation occur at the base (north end) where the contact with the lowermost Cooks Brook Formation is disrupted by minor faults.

Structural aspects

The principal structural complexity is dominantly EW-trending normal faulting, with offsets of from 1 to 30 m. This faulting has been accounted for through the use of recognizable marker horizons, which include nodular lime mudstone horizons in the lower part, conglomerates of the Brakes Cove member above these, and individual i) thin conglomerates or ii) amalgamated beds in the overlying, thick, calcarenite-dominated interval. The Brakes Cove member is also exposed in isolated fault blocks to the north.

A series of subtle east-dipping shear planes results in the localized repetition of section in the upper (southeast) part. This deformation increases eastward, and the combination of this early shearing and intense normal faulting obscures the contact with the overlying Middle Arm Point Formation.

3) SEAL COVE

Location, setting and structural aspects

The Seal Cove section occurs on the eastern limb of a major anticline which trends roughly NS through Seal Cove proper. Shales of the uppermost Irishtown Formation are exposed in the centre of the cove (21U/210444), and the section extends eastward from this point. The western limb of the anticline (western shore of the cove) is too intensely faulted to be incorporated in any detail.

The entire section is repeated by a thrust; detachment has occurred at the base of the Cooks Brook Formation. Stratigraphy is identical in both structural sheets, however the lower (westerly) sheet is the most intact. The section is bounded to the east by a zone of intense deformation which has rendered stratigraphy unrecognizable.

4) WOMAN COVE

Location and setting

The Woman Cove section is situated on the eastern limb of a major, roughly NS-trending syncline, the core of which occurs west of Woman Cove proper. Elements of the stratigraphy are recognizable on the western limb of the syncline, but are juxtaposed by shearing.

Structural aspects

The section is separated into two parts by a NE-trending fault (visible on airphotos) which occurs in the centre of Woman Cove (21U/236436). The offset on this fault cannot be measured, but based upon i) the similarity with other sections spanning the same stratigraphic interval and ii) the relatively small offset (less than 30 m) displayed by similar faults elsewhere. the section is regarded as continuous.

The base of the lower part of the section (Woman Cove East) is east of Woman Point (21U/247441). Farther east, stratigraphy is obscured by folding and faulting, and the contact with the underlying Irishtown Formation is only poorly exposed, in isolated fault blocks, on the north shore of Penguin Arm. The section is measured, through several syncline/anticline pairs, to the tip of Woman Point (21U/236435) where the Brakes Cove member is exposed.

The section continues on the west side of the fault, and is disrupted by another fault zone, which appears within a calcarenite-dominated interval, and is again thought to be of negligible offset. The Woman Cove member is well-exposed above this. The shale-dominated upper Middle Arm Point interval occupies the broad hinge of the Woman Cove syncline, where it is thrown into numerous folds, of 20 to 100m wavelength.

5) NORTH ARM POINT

Location and setting

This section is disposed along the western side of North Arm Point. It exposes the uppermost part of the Cooks Brook Formation (southern end: 21U/189478), the entire Middle Arm Point Formation, and the overlying Eagle Island formation, at the tip of North Arm Point.

Stuctural aspects

Strata at the base of the section (Tremadoc black shale and ribbon limestone interval) are steeply inclined but upright, and are bounded to the south(east) by a vertical fault zone, which separates them from highly deformed Cooks Brook lithologies.

The section is measured northward, where strata are progressively overturned, and the upper part of the section is situated on the western, lower limb of a major recumbent fold, with a NE-dipping axial plane. ~~The~~ basal contact of the Middle Arm Point Formation is exposed twice ~~through~~ broad (late) warping about an EW-trending axis. The contact with the overlying Eagle Island formation is disrupted by minor shearing, but stratigraphic relationships have been preserved.

6) EAGLE ISLAND NORTH

Location,setting and structural aspects

This section is situated on the north(west) shore of Eagle Island and exposes part of the North Arm Point member, the uppermost Middle Arm Point Formation, and the contact with the overlying Eagle Island formation.

The base of the section is bounded to the east by a vertical fault, juxtaposing the North Arm Point member with the (uplifted) Eagle Island formation which is exposed on the eastern half of the island. The section is measured westward from this point (21U/163463), through near-vertical strata, to the northwest tip of the island, which exposes basal conglomerates of the Eagle Island formation. Minor faulting occurs at a low angle to bedding in the upper part of the section, but has resulted in horizontal displacements of less than 3 m.

7) EAGLE ISLAND SOUTH

Location, setting and structural aspects

This section is located on the southwestern shore of Eagle Island. The base is situated at the southwestern tip of the island (21U/164457) in the core of a NW-trending, NW-plunging, tightly folded anticline. The lower part of the section, which exposes Tremadoc black shale overlain by the Woman Cove member, is disrupted by folding. Deformation decreases upsection, through the uppermost Middle Arm Point interval. The contact with the "slump and injection interval" of the Eagle Island formation occurs on the southernmost headland on the western side of the island. Complex folding in this interval precludes thickness measurement.

8) MIDDLE ARM POINT

Location, access and structural aspects

This section is located immediately north of Middle Arm Point proper (21U/165427) and is bounded by zones of intense deformation, essentially melange, to the north(east) and south. The measured section provided in Appendix B illustrates the uppermost part of the Middle Arm Point Formation and the overlying "slump and injection interval": the basal part of the Eagle Island formation. Southward, upsection, a thick (170 m) interval of the Eagle Island formation is exposed in the promontories of Middle Arm Point (summarized in fig 3-10).

9) BLACK BROOK NORTH

Location, setting and structural aspects

This section is situated on the prominent headland north of Black Brook (21U/159410). This headland exposes a huge raft, approximately 500 m in thickness, which occurs within shaly melange. The raft is, itself, internally-deformed, but still preserves stratigraphic relationships which are totally obscured in the melange. Thick intervals of the Eagle Island formation dominate the raft, and the contact with the underlying Middle Arm Point Formation is repeated three times by faulting or folding. The Black Brook North section is the least-deformed exposure of this contact. It is bounded to the north by a (now steeply-inclined) thrust which juxtaposes the uppermost part of the Middle Arm Point Formation with sandstone. This is overlain, to the south, by the basal "slump and injection interval" of the Eagle Island formation, which is, in turn, overlain by sandstones and conglomerates of the Eagle Island formation. In exposing the same stratigraphic interval, the section is similar to the Middle Arm Point section.

10) and 11) <u>CAPE SPLIT and GRASSY COVE</u>

<u>Location and setting</u>

The Cape Split (21U/203477) and Grassy Cove (21U/214477) sections are situated on the southern shore of North Arm. This shoreline is dominated by melange which contains predominantly Middle Arm Point and Eagle Island Formation lithologies. The most intact blocks within this melange are composed of Eagle Island formation, which may include thin intervals of the underlying Middle Arm Point Formation at their base. Both of these sections expose the top of the Middle Arm Point Formation, basal "slump and injection interval" and overlying sandstone of the Eagle Island formation. The Grassy Cove section is unique in that the North Arm Point member is directly overlain by sandstone, and the shale-dominated uppermost Middle Arm Point interval is absent.

12) <u>BLACK POINT (THE GRAVELS)</u> (Port au Port Bay)

<u>Location and setting</u>

This section is situated in the southern half of Black Point (21U/755844) in Port au Port Bay, roughly 5 km north of the Port au Port isthmus. This promontory exposes a large raft within shaly melange, close to the structural base of the Humber Arm Allochthon. Sandstones of the Eagle Island formation occupy the northern portion of the raft, and the upper part of the Middle Arm Point Formation is exposed in the south.

Structural aspects

The entire raft is thrown into a series of tight EW-trending folds, of roughly 50 m wavelength. Middle Arm Point lithologies are exposed in an anticline at the southern boundary of the raft. The southern limb of this anticline passes transitionally into shaly melange, and the section through the Middle Arm Point interval is measured on the northern limb, from the core of the fold northward. The upper (northern) boundary of the section is a fault, situated near the hinge of the adjacent syncline, which juxtaposes Middle Arm Point lithologies with (overturned) siltstones and sandstones of the overlying Eagle Island formation.

APPENDIX C

FOSSIL LOCALITIES AND FAUNAL ASSEMBLAGES

This list constitutes principally new localities, discovered in the course of this study. Previously-described localities are also incorporated, and so indicated.

Fossil identifications and advice regarding interpretation of biostratigraphic zones was provided by several experts, whose contribution is indicated for each locality. Trilobites were identified by W.D. Boyce (WDB); graptolites were identified by S.H. Williams (SHW), R.K. Stevens (RKS); and B.D. Erdtmann (BDE).

Individual trilobite-bearing boulders are assigned identification numbers (e.g. 85F91), employed by W.D. Boyce, at the Newfoundland Department of Mines and Energy, where the specimens are presently stored.

IRISHTOWN FORMATION

1) McIvers; Irishtown conglomerate; G.S.C. 66026 (W.H. Fritz to R.K. Stevens, 1967)

?*Austinvillia* sp.
Pagetides sp.

"Lower Cambrian, probably lower Lower Cambrian"

COOKS BROOK FORMATION

HALFWAY POINT MEMBER

2) Halfway Point; boulders in conglomerate
a) (A.R. Palmer to R.K. Stevens, 1979)

Trilobites
Bathyuriscus sp.
Kootenia sp.
Peronopsis gaspensis?
Semisphaerocephalus sp.
undet. ptychopariid (n. gen.?)
Brachiopods
Acrothele subsidua
Linnarssonia ophirensis
Prototrata? sp.
Mollusca
Hyolithes sp.

"*Bathyuriscus*-*Elrathina* Zone/ *Ptychagnostus gibbus* Zone"

b) G.S.C. 74853 (W.H. Fritz to R.K. Stevens, 1967)

?Phoidagnostus sp.
Lingulella sp. "late Middle Cambrian"

3) Halfway Point section; thin-bedded (nodular) lime mudstone; WDB

Bathyuriscus elegans (numerous individuals)

Bolaspidella Zone

4) Bound Head (Rattler block); boulders within conglomerate; (W.H. Fritz to R.K. Stevens, 1968)

a) G.S.C. 82089
?Bathyuriscus sp.
Hypagnostus parvifrons
Utaspsis sp.
unidentified pygidium

b) G.S.C. 82090
Hypagnostus parvifrons
Utaspis sp.
unidentified pygidium

c) G.S.C. 82091
?Utaspis sp.
undet. agnostid

"Bolaspidella Zone"

5) Bound Head (Rattler block); thin-bedded (nodular) lime mudstone; WDB

Bathyuriscus elegans
Modocia nuchaspina

Bolaspidella Zone

BRAKES COVE MEMBER

6) Conglomeratic interval north of, and projected into Northern Head section; boulders within conglomerate; WDB

Bolaspidella Zone

85F91
?Elrathia sp. cf. ?E. limbata Rasetti, 1963
Hypagnostus parvifrons Linnarson

Ptychagnostus sp. cf. P. hybridus Robison, 1964

Dresbachian Stage Cedaria Zone

85F92
    Cedaria sp. (cranidia)
    Kingstonia sp. (cranidia, pygidia)
    Terranovella sp. (cranidia)

85F94
Trilobites
    Kormagnostus sp.
    ?Bonneterina sp. (cranidium)
    Cedaria sp.
Brachiopods
    undet. inarticulata

85F95
Trilobites
    Cedaria sp. (pygidia)
Brachiopods
    undet. inarticulata

85F101
    Cedaria sp. (abundant cranidia)
    Kingstonia sp. (cranidium)

85F102
    Cedaria sp. (pygidium)
    Kingstonia sp. (pygidium)
    Kormagnostus sp. (pygidium)
    Terranovella sp. (cranidium)

85F103
Trilobites
    Cedaria sp. (cranidia)
    Kormagnostus (cranidium)
Brachiopods
    undet. inarticulata

Dresbachian Stage Cedaria-Crepicephalus Zone

85F96
    Cedaria sp. (cranidium)
    Crepicephalus sp. (pygidium)
    Kingstonia sp. (pygidium)
    Terranovella sp. (cranidia)

85F97
    Tricrepicephalus sp.

85F98

Kingstonia sp.
Terranovella sp. (cranidia)
Tricrepicephalus sp.

85F100
Crepicephalus sp. (pygidium)
Hypagnostus sp. (cranidium)
Kormagnostus sp. (cranidium)

Dresbachian Stage *Crepicephalus* Zone

85F90
Trilobites
Crepicephalus sp. (pygidium)
Eldoradia sp. (cranidium)
Tricrepicephalus sp.
Brachiopods
undet. inarticulata

85F93
Crepicaphalus sp. (cranidium)
Tricrepicephalus sp. (cranidium, pygidium)

Problematic collections, Zone uncertain

85F89
Trilobites: gen. and sp. undet.
Brachiopods: undet. inarticulata

85F99
Trilobites (fragments): gen. and sp. undet.
Brachiopods: undet. inaticulata

85F104
?*Blainiopsis* sp. cf. *B. holtedahli* Poulsen, 1946 (pygidium)
?*Ehmania*/*Ehmaniella*/*Modocia* sp.
?*Onchonotopsis* sp. cf. *O. occidentalis* Palmer, 1968 (cranidia)
?*Welleraspis* sp. (cranidia)

85F105
Trilobite: gen. and sp. undet. (cranidium)

7) Northern Head section; boulders within conglomerates; WDB

Dresbachian Stage Cedaria to Crepicephalus Zone

85F227
?Cedaria sp. (cranidia, pygidia)
Crepicephalus sp. (cranidium, pygidia)
Eldoradia sp. (cranidia)
?Hypagnostus sp. (cranidium)
Kormagnostus sp. (cranidium, pygidium)
Terranovella sp. (cranidia)
Tricrepicephalus sp. (cranidium, pygidia)
Trilobagnostus/ Triplagnostus (cranidium)

85F228
Kingstonia sp. (cranidium)
gen. and sp. undet. (cranidium)

Dresbachian Stage Crepicephalus Zone

85F226
Crepicephalus sp.
?Coosella sp. (pygidium)
Kormagnostus sp.
Terranovella sp. (cranidia)
Tricrepicephalus sp. (cranidium)
gen. and sp. undet.

Problematic collections, Zone uncertain

85F224
?Acadagnostus/Hastagnostus sp. (cranidium)
gen. and sp. undet. (librigena, pygidium)

85F225
Trilobites: gen. and sp. undet. (cranidia, pygidium)

85F229
?Blountia/Cedaria sp. (pygidium)
?Coosella/Meteoraspis sp. (pygidium)

8) Lower conglomerate within Seal Cove section; boulder within conglomerate; WDB

85F230
~~Bynumina~~ (Aphelotoxon) sp. cf. B. (A.) marginata Palmer, 1965
Deirocephalus sp. (cranidium)
Kingstonia sp.
?Sigmocheilus sp. cf. S. pogonipensis Resser
gen. and sp. undet.

Dresbachian Stage Cedaria to Crepicephalus Zone

9) Western conglomerate at Brakes Cove; boulders within conglomerate; WDB

Dresbachian Stage Cedaria Zone

86F89
Trilobite
    Cedaria
Brachiopods
    undet. inarticulata

Dresbachian Stage Cedaria-Crepicephalus Zone

86F88
    ?Crepicephalus sp. (pygidia)
    ?Prehousia/Prosaukia sp.

86F90
    Crepicephalus sp. (pygidium)
    Meteoraspis sp. (cranidium)
    Tricrepicephalus sp. (pygidium)

86F91
    Holcacephalus sp. (cranidia)
    Tricrepicephalus sp. (cranidium)
    gen. and sp. undet.

86F92
Trilobites
    Meteoraspis sp. (cranidia, librigena)
    Holcacephalus sp. (cranidium)
Brachiopods
    undet. inarticulata

Problematic collections

86F87
Trilobites: gen. and sp. undet.

10) Eastern conglomerate at Brakes Cove; boulders within conglomerate; WDB

Bolaspidella Zone

84F139
    Marjumia sp. cf. M. callas (Walcott, 1916) (cranidium)
    gen. and sp. undet.

Dresbachian Stage Cedaria-Crepicephalus Zone

86F93

Deiracephalus sp. (cranidium)
Kormagnostus sp. (cephalon)

86F94
Kormagnostus sp. (cephalon)
Tricrepicephalus sp. (cranidium)

86F95
Crepicephalus sp. (cranidium, pygidium)
Kormagnostus sp. (cephalon)
Tricrepicephalus sp. (pygidium)

86F96
Densonella sp. (cranidium)
Tricrepicephalus sp. (cranidium)
gen. and sp. undet.

86F97
Kingstonia sp. (cranidium)
Kormagnostus sp. (pygidium)

11) Woman Cove Head (conglomerate within Woman Cove section); boulders within conglomerate; WDB

Dresbachian Stage Cedaria Zone

85F106
?Bolaspidella sp. of Kindle, 1983 (plate 1.2, fig 14)
Cedaria sp. (cranidia)
Kormagnostus sp. cf. K. simplex Resser (cranidium)

85F107
?Cedaria sp. (cranidium)
Hypagnostus sp. (pygidium)

Problematic collections, Zone uncertain

85F108
Hypagnostus sp. (cranidium, pygidium)

85F109
Olenaspella sp. cf. O. evansi Kobayashi (cranidium)
Proceratopyge sp. cf. P. rectispinatus Troessson (cranidia)
or possibly
Pterocephalia sp. cf. P. constricta Palmer, 1968

85F110
?Ptychaspis sp. (cranidia, pygidium)

85F111

?Ptychaspis sp. (pygidium)

85F112
Trilobites: (fragment) gen. and spec. undet.
Brachipods: undet. inarticulata

85F113
Hypagnostus sp. cf. H. correctus Opik, 1967 (pygidium)
or possibly
Hypagnostus sp. cf. H. clipeus Whitehouse (Opik, 1979)
or possibly
Hypagnostus sp. cf. H. inaequalis Opik, 1979

85F114
?Onchonotopsis sp. (cranidium)

85F115
?Bynumina/Ithycephalus sp. (cranidium)

12) Penguin Arm (Allans Brook); boulders within conglomerate; WDB

86F82
Kingstonia sp. (cranidium)

86F83
?Chariocephalus sp. (cranidium)

86F84
?Kingstonia (cranidium)

"?Dresbachian Stage Cedaria Zone"

13) Penguin Arm; boulders within conglomerate; WDB

86F85
Bolaspidella sp. (cranidium)
Kormagnostus sp. (cephalon)

86F86
Trilobites: gen. and sp. undet.

"?Dresbachian Stage Cedaria Zone

"UPPER CONGLOMERATE": SEAL COVE

14) Upper conglomerate at Seal Cove; boulder within conglomerate; WDB

85F231

?Dellea sp. (cranidium)
Parabolinoides hebe Frederickson (cranidium)

Franconian Stage *Taenicephalus* Zone

UPPER CAMBRIAN CALCARENITE-DOMINATED INTERVAL

15) Northern Head section; shale interbeds in uppermost portion of calcarenite-dominated interval; BDE

Graptolites
undet. gen. and sp. cf. *Callograptus*

LOWER ORDOVICIAN CONGLOMERATE

16) Northern Head section, prominent conglomerate in upper part of section; boulders in conglomerate; WDB

Trempealeauan Stage *Saukia* Zone

85F120

Platydiamesus depressus Rassetti, 1963b)

Early Ordovician *Missisquoia* Zone to Ross-Hintze Zone B

85F118
Trilobites
Ptychopleurites brevifrons Kobayashi (cranidium)
Symphisurina bubops Winston and Nicholls, 1967
Brachiopods
Apheorthis sp.

85F119
Symphisurina bubops Winston and Nicholls, 1967

85F121
Symphisurina bubops Winston and Nicholls, 1967

85F122
Trilobites
Symphisurina bubops Winston and Nicholls, 1967
Brachiopods
?Nanorthis sp.

Problematic collections

85F117
Trilobite fragments: gen. and sp. undet.

LOWER ORDOVICIAN BLACK SHALE/RIBBON LIMESTONE INTERVAL

17) lowermost Eagle Island South section; black shale; Erdtmann and Botsford, 1986

Rhabdinopora enigma
Anisograptus compactus
Rhabdinopora scitulum

equivalent to Australian La1 Zone (Assemblage 2; Cooper, 1979)

18) Black Head, Middle Arm; "deformed Cooks Brook Formation"; black shale; Stevens, 1965

Dictyonema sp. cf. *D. cyathiforme*
Dictyonema sp. cf. *D. rusticus*
Dictyonema sp. cf. *D. lapworthi*
Anisograptus mataensis

Assemblage 2 (Cooper, 1979)

19) "deformed Cooks Brook Formation, immediately SE Black Head; interbedded black and green shale; RKS

Staurograptus sp.

20) lowermost North Arm Point section; siliceous black shale with minor lime mudstone; RKS

Dictyonema sp. s.l.
Adelograptus (*Bryograptus*) *victoriae*
Kaierograptus antiquus

equivalent to Australian La2 Zone (Assemblage 4; Cooper, 1979).

21) uppermost portion of Northern Head section; black shale

interbeds within ribbon limestone; BDE

Araneograptus murrayi
undet. graptoloid siculae

equivalent to Australian La2 Zone (Assemblage 4; Cooper, 1979)

TREMADOC INTERVAL AT NORTH ARM POINT

22) 32 m; uppermost Cooks Brook Formation; black shale interbeds within lime mudstone; RKS

undet. Dendroidea

23) 52 m; Middle Arm Point Formation; thinly interbedded black/green shale interval overlying Woman Cove Member; RKS

Clonograptus sp.

24) 57 m; Middle Arm Point Formation; black shale interbeds within "dark parted lime grainstone interval"; RKS

undet. Dendroidea

LOWER NORTH ARM POINT MEMBER

latest Tremadoc, uppermost part of Assemblage 4 (Cooper, 1979)

25) North Arm Point section (73 m); thin grey shale beds within siliceous green shale-dominated interval; SHW

Adelograptus victoriae
?Tetragraptus/Temnograptus sp.
Kiaerograptus sp.
?Clonograptus sp.
?Bryograptus sp. (two-stiped)

26) "shear-bounded interval east of Northern Head, Middle Arm; lithology as above; SHW

Adelograptus sp.
?Tetragraptus/Temnograptus sp.
?Clongraptus sp.
?Bryograptus sp.

27) Grassy Cove, North Arm; lithology as above; SHW

<u>Kiaerograptus</u> sp.
?<u>Bryograptus</u> sp.

<u>UPPER NORTH ARM POINT MEMBER</u>

assigned to the Arenig <u>D. bifidus</u> Zone (Williams and Stevens, in press).

28) North Arm Point section (86 m); lithology as above; SHW

<u>Didymograptus bifidus</u> (narrow-stiped)
<u>Isograptus</u> cf. <u>I. primulus</u>
<u>Tetragraptus</u> ?<u>bigsbyi</u>
<u>Tetragraptus</u> sp.
?<u>Pendeograptus pendens</u>

29) lowermost interval at Eagle Island North section; lithology as above; SHW

<u>Pendeograptus pendens</u>
?<u>Goniograptus</u> sp.
<u>Tetragraptus</u> sp.

30) Eagle Island South section; lithology as above; SHW

<u>Tetragraptus</u> sp.
?<u>Pendeograptus pendens</u>

poorly preserved, regarded as "lower Arenig" and tentatively thought to be equivalent to the two localities listed above.

<u>UPPERMOST MIDDLE ARM POINT FORMATION</u>

31) uppermost Middle Arm Point interval within Woman Cove section; thin black shale bed within interval dominated by green shale; SHW

?<u>Pendeograptus pendens</u>
undet. graptoloid fragments

poorly preserved and regarded only as "lower Arenig"

32) Black Point section (Port au Port Bay); black shale; SHW

Isograptus victoriae lunatus
Phyllograptus typus
Pseudotrigonograptus ensiformis

assigned to the *I.v. lunatus* Zone (Williams and Stevens, in press)

33) Middle Arm Point section (5.2 m); black shale beds within thinly-interbedded black and green shale; SHW

Isograptus sp.
?*Holomograptus* sp.
?*Xiphograptus* cf. *bovis* (Williams ms name)

a poorly-preserved fauna, referred to the *I.v. lunatus* or *I.v. victoriae* Zone (Williams and Stevens, in press).

34) Eagle Island North section (59 m); black shale beds within thinly interbedded black and green shale; SHW

Isograptus victoriae victoriae
Pseudotriginograptus sp.
Xiphograptus bovis (Williams ms name)
?*Expansograptus*/*Xiphograptus* sp.

assigned to the *I.v. victoriae* Zone

EAGLE ISLAND FORMATION

The following three localities are all assigned to the *I.v. victoriae* Zone (Williams and Stevens, in press).

35) Rocky Point, West Bay (Port au Port Peninsula); thin to medium-bedded sandstone; SHW

Isograptus sp.
Holmograptus sp.
Xiphograptus cf. *bovis* (Williams ms name)

36) Middle Arm Point section (uppermost part, approx. 205 m); medium-bedded sandstone; SHW

Isograptus victoriae victoriae
Tetragraptus sp.

37) Black Brook North; medium-bedded sandstone; SHW

Isograptus victoriae cf. *victoriae*
Tetragraptus ?*serra*

APPENDIX D

MAJOR AND TRACE ELEMENT ANALYSES OF SHALES

Major and and trace element analyses of shale samples from the Northern Head group, and adjacent units, incorporated in this study are presented in this appendix.

The significance of abbreviations employed in the tabulated data is as follows:

Number
Shale samples were assigned consecutive numbers as collected. Samples were also collected from extraneous units, and are not incorporated in this study, hence apparent gaps in sample numbers.

Strat.
Samples were collected from known or inferred stratigraphic locations, and assigned a position in the composite stratigraphic section of the Northern Head group (and adjacent units). "Strat." is the stratigraphic position, in meters, within this section, above the base of the Cooks Brook Formation. Irishtown samples are assigned a negative number, measuring downward from the same datum.

FeTot is total Fe, expressed as Fe2O3.

Group
This refers to the 3 shale groups discriminated in Chapter 7:
Group "I" comprises black and grey shales of the Irishtown Formation
Group "A" comprises black, plus black and green shales of the Northern Head group and Eagle Island formation
Group "B" comprises green plus red/green shales of the Northern Head group and Eagle Island formation. These are commonly associated with detrital dolomite, and display evidence of current activity.

M1 and M2
These are "maturity indices" employed in Chapter 7.
"M1" - Al2O3+K2O/MgO+Na2O
"M2" - K/Rb (both expressed in ppm)

MAJOR ELEMENT ANALYSES

(wt.% oxide; Corg in wt. %)

Number	JB 001	JB 002	JB 003	JB 004	JB 006	JB 007
Colour	RED	GREEN	RED	GREY	BLACK	GREEN
Strat.	378	379.5	350.5	352	-2	360
SiO2	68.4	67.0	62.6	43.7	59.8	68.9
TiO2	0.48	0.44	0.42	0.20	0.53	0.51
Al2O3	12.20	12.10	11.70	5.50	15.90	10.70
MnO	0.03	0.05	0.48	1.08	0.01	0.11
MgO	3.83	5.39	4.55	4.92	4.99	4.82
CaO	0.20	0.22	2.24	20.12	0.32	0.62
Na2O	0.92	0.92	0.99	0.44	1.50	0.91
K2O	4.41	3.43	4.04	0.71	3.37	2.40
P2O5	0.05	0.10	0.10	0.07	0.19	0.12
LOI	3.94	4.37	6.45	19.85	6.65	4.26
FeTot	5.16	6.54	6.24	3.35	5.53	6.48
Corg	0.07	0.03	0.02	0.16	1.11	0.05
Group	B	B	B	A	I	B
M1	3.50	2.46	2.84	1.16	2.97	2.29
M2	137.81	129.21	126.97	139.46	149.48	146.67

Number	JB 008	JB 009	JB 010	JB 011	JB 012	JB 013
Colour	BLACK	GREEN	SLTST	GREEN	GREEN	GREEN
Strat.	360.5	419	427	397	356	471.5
SiO2	34.2	61.7	57.1	65.7	33.1	59.7
TiO2	0.10	0.63	0.72	0.57	0.18	0.53
Al2O3	18.10	13.50	13.70	11.80	6.40	14.30
MnO	0.25	0.19	0.24	0.20	6.50	0.11
MgO	16.17	5.83	6.09	6.72	9.98	6.69
CaO	0.14	0.72	2.76	0.38	13.02	0.24
Na2O	0.20	1.02	1.63	0.79	0.35	0.74
K2O	1.35	3.12	2.63	2.77	0.63	3.60
P2O5	0.05	0.11	0.17	0.11	0.04	0.08
LOI	9.42	5.23	7.86	4.87	22.26	5.28
FeTot	20.02	8.26	7.14	5.48	6.13	9.02
Corg	0.07	0.05	0.19	0.03	0.09	0.13
Group	A	B	B	B	B	B
M1	1.19	2.43	2.12	1.94	0.68	2.41
M2	119.76	147.93	164.38	167.42	157.50	154.69

Major element data (contd.)

Number	JB 014	JB 015	JB 016	JB 017	JB 018	JB 019
Colour	BLACK	GN(DOL)	GREEN	BLACK	BLACK	GREEN
Strat.	358	359	88	105	160.5	251.5
SiO2	51.3	48.4	45.8	44.8	80.2	59.9
TiO2	0.51	0.47	0.33	0.40	0.45	0.56
Al2O3	12.70	11.20	10.20	7.70	7.80	13.00
MnO	0.05	0.07	0.05	0.04	0.01	0.01
MgO	6.57	8.65	8.71	9.60	2.51	7.46
CaO	4.62	8.50	11.62	13.12	0.36	2.46
Na2O	0.95	0.81	0.76	0.96	0.80	1.52
K2O	3.69	3.09	2.04	1.38	2.02	3.35
P2O5	0.10	0.10	0.12	0.15	0.11	0.17
LOI	12.91	15.68	15.95	18.76	2.66	7.45
FeTot	4.10	3.52	4.16	2.93	2.19	2.99
Corg	1.31	0.07	0.18	0.33	0.28	0.11
Group	A	B	A	A	A	B
M1	2.18	1.51	1.29	0.86	2.97	1.82
M2	159.80	166.62	165.00	154.90	148.13	152.27

Number	JB 020	JB 021	JB 022	JB 023	JB 024	JB 025
Colour	GREEN	GREEN	GREEN	BLACK	GREEN	GREEN
Strat.	268	272	275	-5	111	289
SiO2	65.4	65.0	60.3	47.8	51.7	71.5
TiO2	0.47	0.56	0.47	0.53	0.44	0.24
Al2O3	12.60	12.90	10.80	17.00	9.54	6.97
MnO	0.03	0.20	0.14	0.05	0.03	0.53
MgO	6.61	5.37	9.80	3.19	8.15	4.22
CaO	0.46	0.62	0.24	8.06	8.98	3.12
Na2O	0.68	1.14	0.19	0.42	1.06	1.23
K2O	3.58	3.12	1.15	3.74	1.94	1.03
P2O5	0.07	0.10	0.14	0.19	0.13	0.81
LOI	4.84	4.34	5.09	12.72	14.14	6.09
FeTot	5.55	7.17	12.33	5.98	3.23	3.61
Corg	0.02	0.03	0.03	0.22	0.08	0.52
Group	B	B	B	I	A	A
M1	2.22	2.46	1.20	5.75	1.25	1.47
M2	155.04	146.67	158.13	171.42	190.54	195.34

Major element data (contd.)

Number	JB 026	JB 027	JB 028	JB 029	JB 030	JB 031
Colour	GN(DOL)	BLACK	BLACK	BLACK	BLACK	GREEN
Strat.	285	13	20	237.5	364	365
SiO2	34.9	54.7	59.2	59.4	67.3	64.2
TiO2	0.38	0.58	0.60	0.51	0.46	0.29
Al2O3	8.45	15.80	16.00	12.90	10.20	6.60
MnO	0.27	0.03	0.02	0.02	0.08	0.29
MgO	10.88	3.65	2.64	4.73	7.47	6.68
CaO	14.88	4.16	0.80	2.48	1.10	4.76
Na2O	0.51	0.76	0.52	1.56	0.93	0.49
K2O	1.74	3.76	3.88	3.30	1.99	1.07
P2O5	0.10	0.08	0.13	0.21	0.10	0.11
LOI	23.18	10.35	7.63	10.68	5.89	9.22
FeTot	4.07	4.04	4.04	3.42	4.86	5.43
Corg	0.05	1.12	0.14	2.73	0.35	0.04
Group	A	A	A	A	A	A
M1	0.89	4.44	6.29	2.58	1.45	1.07
M2	203.62	166.77	179.33	174.52	144.01	159.05

Number	JB 032	JB 033	JB 034	JB 035	JB 036	JB 037
Colour	GREEN	GREEN	BLACK	GN(DOL)	RED	RED
Strat.	355	362.5	226	224	310	319
SiO2	62.3	62.9	48.9	35.6	61.8	62.1
TiO2	0.47	0.52	0.38	0.28	0.56	0.53
Al2O3	12.20	13.50	8.50	6.90	15.50	14.60
MnO	0.07	0.07	0.04	0.20	0.04	0.21
MgO	5.24	6.09	5.75	13.48	2.95	3.30
CaO	1.64	0.20	13.78	14.10	0.42	1.18
Na2O	0.79	0.78	0.78	0.63	1.22	1.12
K2O	3.38	3.56	1.90	1.36	5.16	4.92
P2O5	0.14	0.10	0.11	0.11	0.14	0.11
LOI	6.12	4.68	15.17	22.59	4.81	5.59
FeTot	6.54	7.23	2.90	3.18	6.77	6.31
Corg	0.03	0.10	0.98	0.07	0.04	0.04
Group	B	B	A	A	B	B
M1	2.58	2.48	1.59	0.59	4.95	4.42
M2	158.89	148.33	168.55	182.44	157.67	138.77

Major element data (contd.)

Number	JB 038	JB 039	JB 040	JB 041	JB 042	JB 043
Colour	BLACK	GREEN	RED	GREEN	GREEN	GREY
Strat.	326	325	338	344.5	375	123
SiO2	62.1	64.8	62.7	47.2	54.0	52.8
TiO2	0.42	0.48	0.40	0.29	0.34	0.48
Al2O3	12.10	13.40	11.80	7.79	9.64	11.10
MnO	0.64	0.08	0.35	0.86	0.98	0.05
MgO	5.38	5.49	5.08	11.83	6.53	6.47
CaO	2.78	0.24	1.48	8.80	6.36	8.70
Na2O	0.72	0.78	0.87	0.57	0.55	0.96
K2O	3.08	3.36	3.70	1.26	3.06	2.32
P2O5	0.13	0.10	0.16	0.20	0.08	0.12
LOI	8.16	5.10	5.82	16.21	12.44	11.64
FeTot	4.55	6.55	6.19	4.67	4.89	4.05
Corg	0.14	0.05	0.04	0.09	0.06	0.13
Group	A	A	B	A	B	A
M1	2.49	2.67	2.61	0.73	1.79	1.81
M2	176.46	174.34	144.33	154.00	143.85	182.29

Number	JB 044	JB 045	JB 049	JB 050	JB 051	JB 052
Colour	GN(DOL)	GREY	BLACK	BLACK	BLACK	GREY
Strat.	140	220	-17	-8	56.5	175.5
SiO2	45.5	78.6	52.6	52.0	60.9	57.8
TiO2	0.24	0.22	0.73	0.71	0.60	0.40
Al2O3	7.79	6.80	21.60	21.00	16.80	12.10
MnO	0.08	0.02	0.03	0.03	0.02	0.03
MgO	9.68	5.72	2.79	3.59	3.87	8.53
CaO	11.78	0.40	0.90	0.96	0.24	3.90
Na2O	0.71	0.61	1.19	0.58	1.43	1.01
K2O	1.40	1.09	3.76	4.88	3.58	2.38
P2O5	0.13	0.15	0.12	0.12	0.09	0.10
LOI	17.75	2.91	7.00	6.76	5.44	8.30
FeTot	4.44	2.12	6.32	6.02	5.76	4.89
Corg	0.05	0.10	0.26	0.20	0.65	0.20
Group	A	A	I	I	A	A
M1	0.88	1.25	6.37	6.21	3.85	1.52
M2	183.33	157.76	139.73	156.96	169.74	184.37

Major element data (contd.)

Number	JB 053	JB 054	JB 063	JB 064	JB 065	JB 066
Colour	BLACK	BLACK	RED	GREEN	BLACK	RED
Strat.	0.5	10	329	328	331.5	406.5
SiO2	59.1	60.2	48.0	82.9	71.6	63.3
TiO2	0.49	0.53	0.31	0.16	0.27	0.40
Al2O3	14.70	15.50	8.30	4.80	8.20	10.90
MnO	0.03	0.01	0.27	0.02	0.07	0.32
MgO	4.62	5.07	9.63	3.03	4.80	4.06
CaO	2.74	0.76	8.28	0.08	0.82	0.58
Na2O	1.03	1.36	0.67	0.40	0.86	0.74
K2O	3.15	3.28	2.53	1.18	1.51	3.87
P2O5	0.19	0.13	0.06	0.02	0.47	0.14
LOI	7.50	5.13	17.38	3.93	5.95	10.00
FeTot	4.71	5.11	4.62	1.54	5.04	6.72
Corg	0.44	0.12	0.05	0.04	0.80	0.20
Group	A	A	B	B	A	B
M1	3.16	2.92	1.05	1.74	1.72	3.08
M2	163.44	162.52	141.99	166.41	162.84	139.12

Number	JB 067	JB 068	JB 069	JB 070	JB 071	JB 072
Colour	GREEN	GN(SLTST)	RED	GREEN	BLACK	GREEN
Strat.	413	416	422	60.5	60.5	365
SiO2	55.0	20.0	67.8	66.0	56.0	65.0
TiO2	0.60	0.22	0.31	0.49	0.40	0.51
Al2O3	14.00	4.70	9.24	14.10	10.90	13.60
MnO	0.10	0.54	0.53	0.02	0.06	0.22
MgO	6.06	4.30	4.71	5.13	5.57	4.67
CaO	1.82	33.00	0.76	0.42	7.24	0.68
Na2O	0.73	0.33	0.48	1.62	1.42	0.64
K2O	3.60	1.06	2.68	3.29	2.13	2.99
P2O5	0.14	0.08	0.06	0.22	0.11	0.11
LOI	11.31	31.53	8.48	3.99	9.96	4.41
FeTot	6.81	2.32	5.05	4.17	4.67	6.72
Corg	0.52	0.44	0.13	0.10	0.34	0.05
Group	B	A	B	A	A	B
M1	2.59	1.24	2.30	2.58	1.86	3.12
M2	152.31	138.81	161.98	179.16	183.05	156.62

Major element data (contd.)

Number	JB 073	JB 074	JB 075	JB 076	JB 077	JB 078
Colour	BLACK	BLACK	BLACK	BLACK	BLACK	BLACK
Strat.	-29	-34	-43	-50	-60	-68
SiO2	64.6	55.5	55.7	54.1	56.4	46.6
TiO2	0.46	0.57	0.42	0.52	0.64	0.76
Al2O3	15.00	20.00	20.00	22.90	21.80	30.30
MnO	0.04	0.03	0.07	0.05	0.04	0.02
MgO	3.00	2.98	2.67	2.38	2.36	2.19
CaO	0.84	0.72	2.28	0.20	0.30	0.14
Na2O	0.93	1.16	0.85	0.92	0.93	0.76
K2O	2.55	3.22	3.51	4.42	4.47	6.80
P2O5	0.10	0.08	0.11	0.09	0.11	0.07
LOI	4.82	7.11	7.37	6.24	5.19	6.95
FeTot	6.72	6.86	6.42	6.48	6.39	5.46
Corg	0.09	0.27	0.24	0.23	0.21	0.32
Group	I	I	I	I	I	I
M1	4.47	5.61	6.68	8.28	7.98	12.58
M2	166.96	130.22	125.36	133.57	138.12	150.20

Number	JB 133	JB 134	JB 135	JB 136	JB 137	JB 138
Colour	BLACK	GREEN	BLACK	BLACK	BLACK	BLACK
Strat.	366	366.5	359	362	368.5	369
SiO2	42.7	64.6	34.2	35.4	60.6	71.6
TiO2	0.24	0.36	0.48	0.48	0.32	0.24
Al2O3	6.27	10.60	18.60	18.30	8.32	6.63
MnO	4.00	0.17	0.23	0.28	1.70	0.70
MgO	8.07	5.05	15.70	15.75	6.34	4.31
CaO	11.84	0.50	0.10	0.16	5.34	3.38
Na2O	0.59	0.85	0.18	0.21	0.73	1.12
K2O	0.94	1.06	1.28	1.10	1.97	0.93
P2O5	0.29	0.31	0.04	0.02	0.17	0.43
LOI	18.67	3.86	9.21	9.09	10.56	6.59
FeTot	5.24	12.89	20.76	18.94	3.35	3.68
Corg	0.00	0.00	0.00	0.00	0.00	0.00
Group	A	A	A	A	A	A
M1	0.83	1.98	1.25	1.22	1.46	1.39
M2	143.61	129.56	140.80	147.56	159.34	150.44

Major element data (contd.)

Number	JB 139	JB 140	JB 141	JB 142	JB 143	JB 144
Colour	BLACK	GN(DOL)	BLACK	BLACK	GREEN	BLACK
Strat.	25	74	149	349	353.5	340.5
SiO2	53.9	63.0	57.4	55.4	58.3	58.5
TiO2	0.60	0.40	0.56	0.36	0.44	0.48
Al2O3	18.40	13.00	17.20	9.95	11.80	12.00
MnO	0.04	0.05	0.01	0.04	1.40	0.18
MgO	4.29	4.70	5.28	6.79	4.62	7.51
CaO	3.54	2.50	0.84	7.62	1.42	0.14
Na2O	0.79	1.20	0.62	1.08	0.74	0.80
K2O	4.61	2.87	4.54	2.03	2.29	1.24
P2O5	0.11	0.15	0.11	0.13	0.13	0.12
LOI	6.55	6.47	6.33	12.09	6.16	4.99
FeTot	3.91	5.76	5.55	3.44	13.37	13.90
Corg	0.00	0.00	0.00	0.00	0.00	0.00
Group	A	A	A	A	B	A
M1	4.53	2.69	3.68	1.52	2.63	1.59
M2	176.08	181.44	203.01	143.14	139.94	136.40

Number	JB 145	JB 146	JB 147	JB 148	JB 149	JB 150
Colour	GREEN	RED	GREEN	BLACK	BLACK	GREEN
Strat.	342	347	384.5	388.5	230	260
SiO2	61.3	64.3	65.5	78.6	74.8	61.5
TiO2	0.56	0.48	0.56	0.24	0.32	0.60
Al2O3	12.50	12.00	12.30	7.05	5.36	14.40
MnO	0.15	0.19	0.08	0.06	0.01	0.02
MgO	5.66	4.87	6.26	4.54	5.52	5.86
CaO	0.38	0.70	0.22	0.32	3.50	1.40
Na2O	1.13	0.93	1.01	0.69	0.68	1.27
K2O	2.12	3.24	2.92	0.86	0.79	4.50
P2O5	0.19	0.13	0.14	0.07	0.09	0.15
LOI	4.45	4.57	4.65	3.12	6.57	6.00
FeTot	10.98	7.70	6.37	4.66	1.65	4.57
Corg	0.00	0.00	0.00	0.00	0.00	0.00
Group	A	B	B	A	A	B
M1	2.15	2.63	2.09	1.51	0.99	2.65
M2	140.48	138.14	143.39	121.28	124.14	174.30

Major element data (contd.)

Number	JB 151	JB 152	JB 153	JB 154	JB 155	JB 156
Colour	BLACK	GREEN	BLACK	RED	RED	BLACK
Strat.	280.5	293	297	360	368	334
SiO2	51.6	68.1	56.3	73.5	70.6	73.5
TiO2	0.52	0.48	0.40	0.28	0.36	0.32
Al2O3	12.10	12.90	10.00	7.58	8.42	8.11
MnO	0.04	0.04	0.52	0.33	0.74	0.06
MgO	5.32	5.40	8.95	3.37	3.55	4.76
CaO	8.18	0.28	5.20	0.44	1.38	0.80
Na2O	1.14	0.93	0.68	0.41	0.46	0.86
K2O	3.24	3.34	2.09	2.29	2.58	1.29
P2O5	0.19	0.16	0.18	0.05	0.08	0.45
LOI	12.92	4.43	11.62	3.64	5.14	5.22
FeTot	3.48	4.34	4.46	6.88	5.79	5.09
Corg	0.00	0.00	0.00	0.00	0.00	0.00
Group	A	B	A	B	B	A
M1	2.37	2.57	1.26	2.61	2.74	1.67
M2	152.31	130.28	136.85	121.11	126.70	133.87

Number	JB 157	JB 161	JB 162	JB 163	JB 164	JB 165
Colour	GREEN	BLACK	BLACK	GREEN	GREEN	BLACK
Strat.	334.5	-11	7	322	32	42
SiO2	76.9	49.3	63.3	56.0	48.8	61.0
TiO2	0.28	0.56	0.56	0.40	0.48	0.40
Al2O3	6.98	20.00	17.50	12.10	13.40	13.70
MnO	0.06	0.04	0.03	0.14	0.08	0.04
MgO	4.68	3.03	3.72	5.04	6.34	4.21
CaO	0.18	4.94	0.58	7.38	6.96	3.66
Na2O	0.59	0.88	1.37	1.24	1.14	1.45
K2O	1.11	3.27	2.97	3.11	3.56	3.60
P2O5	0.04	0.09	0.15	0.13	0.13	0.06
LOI	3.69	9.85	4.73	10.04	11.63	7.37
FeTot	5.25	5.91	6.17	3.14	5.94	4.08
Corg	0.00	0.00	0.00	0.00	0.00	0.00
Group	B	I	A	B	A	A
M1	1.54	5.95	4.02	2.42	2.27	3.06
M2	117.40	116.03	143.29	155.50	199.80	188.57

TRACE ELEMENT ANALYSES

(all values in ppm)

Number	JB 001	JB 002	JB 003	JB 004	JB 006	JB 007
Colour	RED	GREEN	RED	GREY	BLACK	GREEN
Strat.	378	379.5	350.5	352	-2	360
Pb	41	13	24	21	29	66
U	10	7	2	0	15	4
Th	16	24	21	11	33	17
Rb	176	146	175	28	124	90
Sr	47	45	262	482	23	104
Y	22	19	26	13	17	30
Zr	93	85	106	29	125	84
Nb	13	12	12	6	14	13
Ga	14	12	12	6	18	11
Zn	206	60	42	21	76	43
Cu	77	0	0	2	24	60
Ni	23	35	20	16	39	16
La	51	55	34	7	62	34
Ba	577	404	642	110	580	2787
V	56	68	81	31	158	69
Ce	65	51	61	59	87	68
Cr	95	59	73	29	117	60

Number	JB 008	JB 009	JB 010	JB 011	JB 012	JB 013
Colour	BLACK	GREEN	SLTST	GREEN	GREEN	GREEN
Strat.	360.5	419	427	397	356	471.5
Pb	29	25	9	16	11	0
U	11	4	0	4	0	0
Th	43	25	15	19	0	10
Rb	62	116	88	91	22	128
Sr	20	55	88	42	580	56
Y	79	21	27	18	35	26
Zr	540	107	150	98	70	74
Nb	16	18	18	13	7	13
Ga	16	13	13	12	3	14
Zn	338	71	81	61	60	60
Cu	0	19	24	6	31	0
Ni	110	31	124	27	36	34
La	40	54	54	51	12	67
Ba	313	371	406	460	1558	705
V	54	129	147	86	90	87
Ce	0	61	76	65	59	91
Cr	60	78	174	66	42	83

Trace element data (contd.)

Number	JB 014	JB 015	JB 016	JB 017	JB 018	JB 019
Colour	BLACK	GN(DOL)	GREEN	BLACK	BLACK	GREEN
Strat.	358	359	88	105	160.5	251.5
Pb	42	14	11	2	19	15
U	21	9	1	1	3	8
Th	29	18	17	13	19	22
Rb	127	102	68	49	75	121
Sr	118	153	209	220	23	58
Y	17	25	19	17	20	13
Zr	114	107	119	118	43	137
Nb	16	12	10	9	9	13
Ga	15	11	11	5	8	14
Zn	121	44	37	24	36	34
Cu	30	34	11	15	47	21
Ni	71	11	16	17	15	17
La	54	45	36	25	38	39
Ba	446	350	356	261	408	598
V	447	116	103	149	213	91
Ce	52	72	77	77	34	69
Cr	100	66	60	39	73	76

Number	JB 020	JB 021	JB 022	JB 023	JB 024	JB 025
Colour	GREEN	GREEN	GREEN	BLACK	GREEN	GREEN
Strat.	268	272	275	-5	111	289
Pb	20	21	7	12	7	309
U	4	7	0	3	9	8
Th	33	20	13	19	10	11
Rb	127	117	40	120	56	29
Sr	30	48	19	101	179	58
Y	10	21	32	23	25	40
Zr	106	67	81	90	125	43
Nb	15	12	15	16	10	7
Ga	15	12	13	18	8	10
Zn	55	62	76	42	25	29
Cu	9	0	14	9	10	52
Ni	28	59	38	33	15	30
La	48	61	64	74	30	30
Ba	380	516	156	507	292	258
V	61	52	178	89	77	139
Ce	34	142	96	119	67	57
Cr	71	82	76	96	60	52

Trace element data (contd.)

Number	JB 026	JB 027	JB 028	JB 029	JB 030	JB 031
Colour	GN(DOL)	BLACK	BLACK	BLACK	BLACK	GREEN
Strat.	285	13	20	237.5	364	365
Pb	1	32	5	42	20	4
U	0	2	0	13	0	4
Th	10	24	14	19	20	10
Rb	47	124	119	104	76	37
Sr	132	121	56	64	63	157
Y	19	20	23	20	5	19
Zr	79	120	92	125	73	68
Nb	10	15	16	12	12	11
Ga	6	17	22	14	12	8
Zn	42	63	91	116	47	31
Cu	5	29	6	52	18	18
Ni	15	42	33	55	21	18
La	42	55	76	47	31	24
Ba	232	510	491	213	225	3154
V	47	165	86	293	165	59
Ce	60	42	101	42	16	52
Cr	50	110	101	84	92	49

Number	JB 032	JB 033	JB 034	JB 035	JB 036	JB 037
Colour	GREEN	GREEN	BLACK	GN(DOL)	RED	RED
Strat.	355	362.5	226	224	310	319
Pb	15	14	9	5	0	20
U	2	7	1	0	0	12
Th	19	19	13	21	5	33
Rb	117	132	62	41	180	195
Sr	114	49	266	212	129	99
Y	31	24	18	23	23	29
Zr	134	97	60	87	187	148
Nb	15	12	8	9	16	17
Ga	10	17	8	5	17	24
Zn	45	64	33	26	57	65
Cu	0	0	8	9	3	7
Ni	25	38	14	6	36	37
La	45	59	22	20	46	47
Ba	425	592	190	186	4358	1183
V	56	64	60	37	76	71
Ce	85	48	45	55	75	72
Cr	64	65	50	37	87	86

Trace element data (contd.)

Number	JB 038	JB 039	JB 040	JB 041	JB 042	JB 043
Colour	BLACK	GREEN	RED	GREEN	GREEN	GREY
Strat.	326	325	338	344.5	375	123
Pb	24	0	17	3	10	8
U	3	0	9	9	4	5
Th	16	3	21	11	6	14
Rb	96	106	141	45	117	70
Sr	75	50	104	119	121	193
Y	16	21	27	18	22	20
Zr	61	88	94	74	81	136
Nb	9	14	12	6	8	11
Ga	17	19	14	8	10	20
Zn	48	62	59	53	30	41
Cu	59	22	4	6	7	25
Ni	20	33	29	18	19	25
La	41	56	48	29	44	42
Ba	155	309	603	159	523	399
V	110	77	68	66	34	114
Ce	53	74	68	43	70	57
Cr	80	87	66	59	47	75

Number	JB 044	JB 045	JB 049	JB 050	JB 051	JB 052
Colour	GN(DOL)	GREY	BLACK	BLACK	BLACK	GREY
Strat.	140	220	-17	-8	56.5	175.5
Pb	1	8	22	2	20	7
U	0	4	0	3	19	2
Th	3	13	31	20	25	9
Rb	42	38	148	171	116	71
Sr	177	21	111	51	43	99
Y	22	8	29	27	26	16
Zr	115	33	131	132	98	143
Nb	9	7	15	19	13	11
Ga	8	9	27	27	21	17
Zn	109	48	86	91	65	57
Cu	29	60	24	26	28	31
Ni	12	15	47	43	47	31
La	33	32	88	90	49	42
Ba	292	160	625	762	598	335
V	56	148	123	114	152	142
Ce	64	53	116	119	79	72
Cr	42	66	143	135	122	88

Trace element data (contd.)

Number	JB 053	JB 054	JB 063	JB 064	JB 065	JB 066
Colour	BLACK	BLACK	RED	GREEN	BLACK	RED
Strat.	0.5	10	329	328	331.5	406.5
Pb	11	13	1	18	64	21
U	6	15	0	11	8	16
Th	14	20	4	20	16	21
Rb	106	111	98	39	51	153
Sr	63	37	67	37	75	98
Y	23	25	17	9	36	24
Zr	123	127	63	22	77	83
Nb	14	13	8	6	9	10
Ga	19	19	11	5	8	15
Zn	48	57	34	22	45	59
Cu	37	35	9	164	28	102
Ni	41	43	19	15	30	25
La	62	58	39	23	37	47
Ba	459	456	271	238	261	456
V	123	125	46	43	221	80
Ce	890	72	44	46	59	66
Cr	96	115	43	32	79	72

Number	JB 067	JB 068	JB 069	JB 070	JB 071	JB 072
Colour	GREEN	GN(SLTST)	RED	GREEN	BLACK	GREEN
Strat.	413	416	422	60.5	60.5	365
Pb	28	10	9	0	12	3
U	4	15	2	7	12	6
Th	24	18	10	16	18	14
Rb	130	42	91	101	64	105
Sr	83	383	50	27	229	35
Y	34	24	10	23	21	18
Zr	108	56	58	124	119	84
Nb	18	9	9	15	12	14
Ga	18	4	13	17	17	16
Zn	107	41	51	55	53	74
Cu	47	16	40	43	21	2
Ni	132	43	21	30	31	70
La	57	30	34	54	41	40
Ba	361	1446	302	511	333	628
V	168	44	52	121	79	83
Ce	69	45	49	91	37	89
Cr	155	49	53	104	72	85

Trace element data (contd.)

Number	JB 073	JB 074	JB075	JB 076	JB 077	JB 078
Colour	BLACK	BLACK	BLACK	BLACK	BLACK	BLACK
Strat.	-29	-34	-43	-50	-60	-68
Pb	19	20	14	11	15	27
U	5	19	6	4	9	4
Th	32	25	21	17	23	20
Rb	84	136	154	182	178	249
Sr	55	94	120	109	104	99
Y	37	24	27	36	26	22
Zr	177	148	109	97	124	215
Nb	16	16	16	18	17	24
Ga	19	23	21	27	26	41
Zn	90	99	78	85	87	65
Cu	16	20	25	32	29	17
Ni	50	50	42	48	46	34
La	71	78	80	101	90	108
Ba	495	628	647	916	908	1260
V	87	104	115	108	112	159
Ce	94	108	129	135	117	154
Cr	107	125	115	122	124	173

Number	JB 133	JB 134	JB 135	JB 136	JB 137	JB 138
Colour	BLACK	GREEN	BLACK	BLACK	BLACK	BLACK
Strat.	366	366.5	359	362	368.5	369
Pb	51	10	35	16	24	314
U	0	0	2	0	2	6
Th	10	10	30	30	6	16
Rb	36	45	50	41	68	34
Sr	472	54	21	17	198	81
Y	39	34	73	61	24	34
Zr	145	87	600	474	68	56
Nb	8	10	16	15	8	7
Ga	8	12	17	15	12	13
Zn	40	58	390	288	41	34
Cu	39	9	0	0	350	41
Ni	14	23	132	100	24	28
La	25	41	19	11	6	0
Ba	828	217	364	213	236	158
V	35	126	63	64	1210	131
Ce	51	90	0	23	71	61
Cr	15	53	66	209	68	20

Trace element data (contd.)

Number	JB 139	JB 140	JB 141	JB 142	JB 143	JB 144
Colour	BLACK	GN(DOL)	BLACK	BLACK	GREEN	BLACK
Strat.	25	74	149	349	353.5	340.5
Pb	37	9	22	26	30	35
U	0	0	0	3	3	3
Th	24	14	14	4	9	23
Rb	144	87	123	78	90	50
Sr	84	67	35	180	120	38
Y	16	22	19	15	29	29
Zr	135	180	98	104	92	88
Nb	14	12	12	10	12	10
Ga	24	15	21	12	14	13
Zn	62	55	41	30	69	83
Cu	30	5	17	16	1	24
Ni	44	28	36	32	34	30
La	48	41	47	19	39	35
Ba	561	257	447	176	325	210
V	190	73	104	117	80	221
Ce	110	63	77	106	130	45
Cr	83	48	81	35	45	49

Number	JB 145	JB 146	JB 147	JB 148	JB 149	JB 150
Colour	GREEN	RED	GREEN	BLACK	BLACK	GREEN
Strat.	342	347	384.5	388.5	230	260
Pb	21	18	12	36	16	13
U	0	6	0	0	0	0
Th	24	9	14	21	1	5
Rb	83	129	112	39	35	142
Sr	50	74	42	27	97	71
Y	31	28	25	15	11	23
Zr	104	109	116	61	40	219
Nb	13	12	12	7	6	12
Ga	13	12	16	9	16	22
Zn	68	67	57	38	62	54
Cu	37	3	10	11	23	11
Ni	23	32	26	15	16	29
La	43	35	36	15	0	35
Ba	260	2228	303	224	138	532
V	228	76	96	70	294	98
Ce	63	86	52	50	76	97
Cr	48	37	39	12	24	47

Trace element data (contd.)

Number	JB 151	JB 152	JB 153	JB 154	JB 155	JB 156
Colour	BLACK	GREEN	BLACK	RED	RED	BLACK
Strat.	280.5	293	297	360	368	334
Pb	24	25	35	24	34	61
U	0	0	1	0	0	0
Th	16	16	3	2	19	18
Rb	117	141	84	104	112	53
Sr	195	56	103	57	111	73
Y	21	20	20	18	24	29
Zr	135	99	88	83	101	82
Nb	13	12	8	7	9	9
Ga	20	14	14	11	8	11
Zn	36	67	66	40	46	44
Cu	36	65	38	20	16	17
Ni	38	43	24	23	30	25
La	6	35	21	21	10	20
Ba	360	294	206	3155	8246	250
V	185	136	164	59	47	208
Ce	70	85	73	35	110	57
Cr	61	50	44	16	19	45

Number	JB 157	JB 161	JB 162	JB 163	JB 164	JB 165
Colour	GREEN	BLACK	BLACK	GREEN	GREEN	BLACK
Strat.	334.5	-11	7	322	32	42
Pb	15	36	30	53	5	22
U	0	0	3	1	3	1
Th	0	23	16	15	19	14
Rb	52	155	114	110	98	105
Sr	39	159	38	223	129	91
Y	13	27	19	22	24	11
Zr	64	126	95	117	151	61
Nb	7	16	12	10	14	7
Ga	9	32	23	13	0	20
Zn	36	81	72	45	44	41
Cu	13	19	14	24	10	11
Ni	7	41	38	25	31	34
La	8	70	62	21	33	18
Ba	163	715	546	640	430	354
V	72	100	97	90	76	90
Ce	29	102	120	89	52	62
Cr	15	90	83	38	61	43

APPENDIX E

ANALYTICAL TECHNIQUES

E.1 Major element analyses

With the exception of CO2 and P2O5, all major element oxides were determined by atomic absorption spectrometry. Samples were prepared using the methods of Langmhyr and Paus (1968), and analysed on a Perkin-Elmer Model 370 Atomic Absorption Spectrometer with digital readout.

Loss on ignition (L.O.I.) was determined by heating an accurately weighed amount of sample to 1050 degrees C for at least two hours, cooling in a dessecator, and reweighing.

P2O5 was analysed with a Bausch and Loumbe Spectronic 20 Colourimeter, using a method based upon that of Shapiro and Brannock (1962).

Determination of ferric/ferrous Fe ratio in selected samples was by the titration technique of Wilson (1955) as published in Maxwell (1968).

The precision of major element analyses is indicated in Table E-1.

E.2 Trace element analyses

The concentration of trace elements was determined using a Philips 1450 Automatic X-Ray Fluorescence Spectrometer with a rhodium tube. Pellets were produced from powdered shale samples using 10 gm of sample and 1 to 1.5 gm of binding material (Bakelite Thermoset Resin TR-16933). Samples were compressed at 30 tons psi for one minute, and baked at 200 degrees Centigrade for 20 minutes.

Table E-1: Precision and Accuracy of Major Element Analyses

Wt. %	Published Value	Mean	Standard Deviation	Number of Determinations
SiO2	54.36	55.38	0.37	4
TiO2	2.24	2.35	0.18	4
Al2O3	13.56	13.50	0.27	5
Fe2O3	13.40	13.00	0.28	5
CaO	6.94	6.63	0.07	4
MgO	3.46	3.57	0.06	5
Na2O	3.26	3.23	0.05	5
K2O	1.67	1.73	0.05	4
MnO	0.19	0.18	0.01	5

Based upon determinations of Standard BCR1; published value from Abbey (1968).

Table E-2: Precision of Trace Element Analyses
(from Longerich and Veinott, 1986)

Standard deviation (in ppm) at given concentrations in samples

	.... PPM sample								
Element	0	50	100	200	300	400	500	1000	2000
V	2	2	2	3	3	4			
Cr	2	2	2	3	4	4			
Ni	1	1	1	1	2				
Cu	1	2	3	5					
Zn	3	3	3	4	4	5			
Ga	1	3	5						
Rb	1	2	3	4	5	7			
Sr	2	2	3	4	4	5	6	11	
Y	2	2	3	4					
Zr	1	2	3	4	6	8	10		
Nb	1	1	2						
Ba	12	12	13	14	15	16	17	21	31
La	3	5	7	10					
Ce	19	19	19	19	18	18			
Pb	4	5	6	8	10	12	14		
Th	3	4	5	8					
U	5	6	7	9	11	13	14		

Data reduction was done with a Hewlett-Packard 9845B mini-computer.

Precision of trace element determination using this system is indicated in Table E-2.

E.3 Microanalysis

E.3.1 Scanning electron microscope with energy dispersive x-ray analyser (SEM/EDAX)

Polished thin sections and mounted samples were examined using a Hitachi S570 Scanning Electron Microscope equipped with a GW Electronics Backscattered Electron Detector Type 113. Elemental composition was determined by spot analyses of areas of interest with a Tracor Northern TN-5500 X-ray Analyser - Microtrace Silicon X-ray Spectrometer Model 70152.

Characteristic spectral signatures thus obtained were useful in mineral identification, and compositional zoning was commonly apparent in backscatter mode. Spectra of selected samples were then further analysed using Tracor Northern's "SSQ" (Standardless Semi-Quantitative) program, which applied ZAF corrections to yield element or oxide concentrations. These analyses provided a qualitative assessment of composition, which was confirmed in selected samples, using the electron microprobe.

E.3.2 Electron microprobe

Analyses were performed on a JEOL JXA50A electron probe microanalyser with KRISEL automation. ALPHA matrix corrections were applied in data acquisition. Operating conditions were: beam current of 0.022 microA, accelerating voltage of 15 kV, beam diameter of 1-2 micrometers. Counting proceeded for 10 seconds, or until a count of 30,000 was obtained, whichever came first. All elements were standardized on a clinopyroxene "in-house" standard; Ca and Mg were then checked on a dolomite standard and Fe and Mn were checked on a hedenbergite standard.

Polished thin sections of selected carbonates were analysed for Ca, Mg, Fe and Mn. Selected authigenic feldspars were analysed for Na, Al, Si, K, and Ca.

The precision of microprobe analyses is indicated in Table E-3.

Table E-3: Precision of microprobe analyses

Core of unzoned dolomite grain within Sample PA2; four analyses

Oxide	mean wt. %	Standard Deviation
MgO	17.04	0.57
CaO	31.15	0.28
MnO	0.82	0.04
FeO	2.55	0.19

E.4 Organic carbon determination

Total organic carbon was determined, in selected samples, by infrared absorptiometry using a modification of the method of Bouvier and Abbey (1980). The contribution of carbonate carbon and organic carbon was separated by analysing pairs of samples. The first was untreated, and yielded a value for total carbon (i.e. carbonate plus organic). Before analysis the second sample was acidified over a hotplate with 20% HCl to remove carbonate carbon and hence yield only the organic carbon contribution. The precision of this method was not good, but was considered adequate for the qualitative use of the data. Precision is indicated in Table E-4.

Table E-4: Precision of organic carbon determination

Sample No.	Number of Analyses	Mean wt. %	Standard Deviation
JB 06	3	1.11	0.13
JB 14	3	1.31	0.15
JB 25	3	0.52	0.08
JB 27	3	1.12	0.15
JB 29	3	2.73	0.17
JB 46	3	0.71	0.09
JB 51	3	0.65	0.09
JB 55	3	1.12	0.13
JB 56	3	1.24	0.08
JB 60	3	0.92	0.07

E.5 Clay mineralogy

Thirty representative shale samples were qualititatively analysed by X-ray diffraction to determine the dominant clay minerals present; results are presented and discussed in Chapter 7.

Sample preparation

Clean shale chips were ultrasonically disaggregated in a calgon solution. A clay fraction of less than 2 micrometers in size was recovered from the resulting suspension by sedimentation and centrifuging, using a $MgCl_2$ flocculating agent. Three oriented clay mounts were produced for each sample, by suction onto Gelman Metricell 0.45 micrometer filters, which were then glued to glass slides. The first mount was left untreated. The second mount was exposed to ethylene glycol vapour for a 12 to 16 hour period, to indicate the presence of expandable clays. The third mount was acidified using 9 M HCl, in order to eliminate chlorite and allow the distinction of chlorite and kaolinite in peaks at approximately 12.5 and 25 degrees 2-theta.

X-ray diffraction

Samples were run on a Philips diffractometer, using Cu K-alpha radiation, operating at 40 kV and 20 mA. All mounts were scanned from 2 to 35 degrees 2-theta, at 1 degree 2-theta per minute and a chart speed of 1 cm per minute.

E.6 Cathodoluminescence

Selected carbonate samples were examined under cathodoluminescence using a Nuclide Corporation ELM-2A Luminoscope using ambient gas, a beam diameter of approximately 1cm, beam current of 0.6 mA, and an accelerating voltage of 16 kV.

APPENDIX G

CHANGING Eh UNDER PROGRESSIVE SHALLOW BURIAL CONDITIONS: A REVIEW

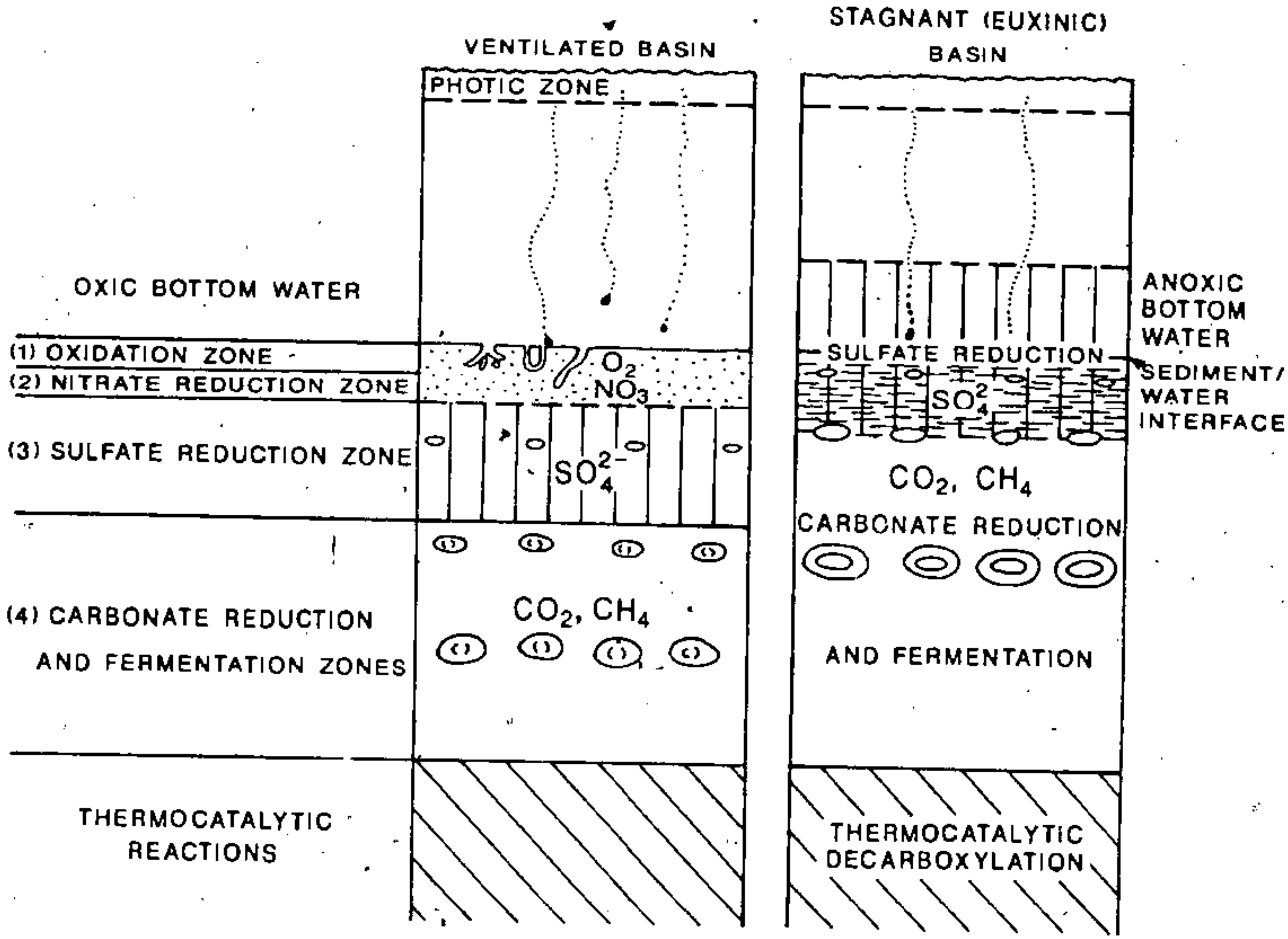
Theoretical considerations and studies of pore waters recovered from cores of recent pelagic sediments (Claypool and Kaplan, 1974; Froelich et al., 1979; Berner, 1980; summarized in Hesse, 1986) indicate that marine sediment undergoing progressive burial passes through a series of zones representing progressive reduction by bacterially-driven oxidation of contained organic matter. Individual oxidants are progressively consumed during burial in the ongoing oxidation of contained organic matter according to the free energy which they can provide (Froelich et al., 1979), and the reactions involved characterize the zones of progressive sediment reduction (fig G-1). Where dissolved oxygen is present in overlying seawater these zones are:

1) the oxidation zone: Within this zone dissolved oxygen within the overlying seawater, and diffused into sediment pore water supports macrofauna and aerobic bacteria, which directly oxidize initially-deposited organic matter. This zone may be millimeters to centimeters thick, depending upon the downward diffusion of oxygen, which in turn clearly depends in part on dissolved oxygen concentrations at the seafloor.

2) the nitrate reduction zone: This zone represents the onset of "suboxic diagenesis", where the level of dissolved oxygen has dropped below .5 ml/l H_2O, and dysaerobic bacteria participate in the reduction of nitrate. Eh decreases through this zone to zero at its base, and a significant result of this decrease is the reduction

Figure G-1

Stages of organic matter oxidation in anoxic sediments (redrawn from Hesse, 1986).


VENTILATED BASIN
PHOTIC ZONE
OXIC BOTTOM WATER
(1) OXIDATION ZONE
(2) NITRATE REDUCTION ZONE
O_2
NO_3
(3) SULFATE REDUCTION ZONE
SO_4^{2-}
(4) CARBONATE REDUCTION
AND FERMENTATION ZONES
CO_2, CH_4
THERMOCATALYTIC
REACTIONS
STAGNANT (EUXINIC)
BASIN
ANOXIC
BOTTOM
WATER
SULFATE REDUCTION
SEDIMENT/
WATER
INTERFACE
SO_4^{2-}
CO_2, CH_4
CARBONATE REDUCTION
AND FERMENTATION
THERMOCATALYTIC
DECARBOXYLATION

of manganese oxides and hydroxides, and the consequent introduction of reduced Mn into solution. Under lower Eh conditions, toward the base of the nitrate reduction zone and into the underlying zone, ferric iron oxides and hydroxides are reduced and ferrous Fe is introduced into solution. This difference is a function of the contrasting solubility of Mn and Fe under given Eh conditions (fig G-2).

3) the sulphate reduction zone: Upon the consumption of nitrate, the diagenetic system becomes anoxic, and continued oxidation of remaining organic matter proceeds by the bacterial reduction of sulphate. The resultant appearance of reduced sulphur is responsible for the appearance of H2S in this zone, and in the presence of the ferrous Fe mentioned above, will result in the early formarion of iron sulphides within this zone. Under conditions of well-oxygenated bottom water, upward diffusing reduced sulphur may be re-oxidized in a bacterially-mediated reaction (Tissot and Welte, 1978; Berner, 1980).

4) the carbonate reduction and fermentation zone: Upon the consumption of sulphate, the bacterial oxidation of organic matter proceeds by bacterial fermentation and the reduction of carbonate and results in the production of methane.

Under conditions of increasing burial (and consequent increasing temperature) bacterial activity ceases and oxidation of organic carbon proceeds by thermocatalytic reactions.

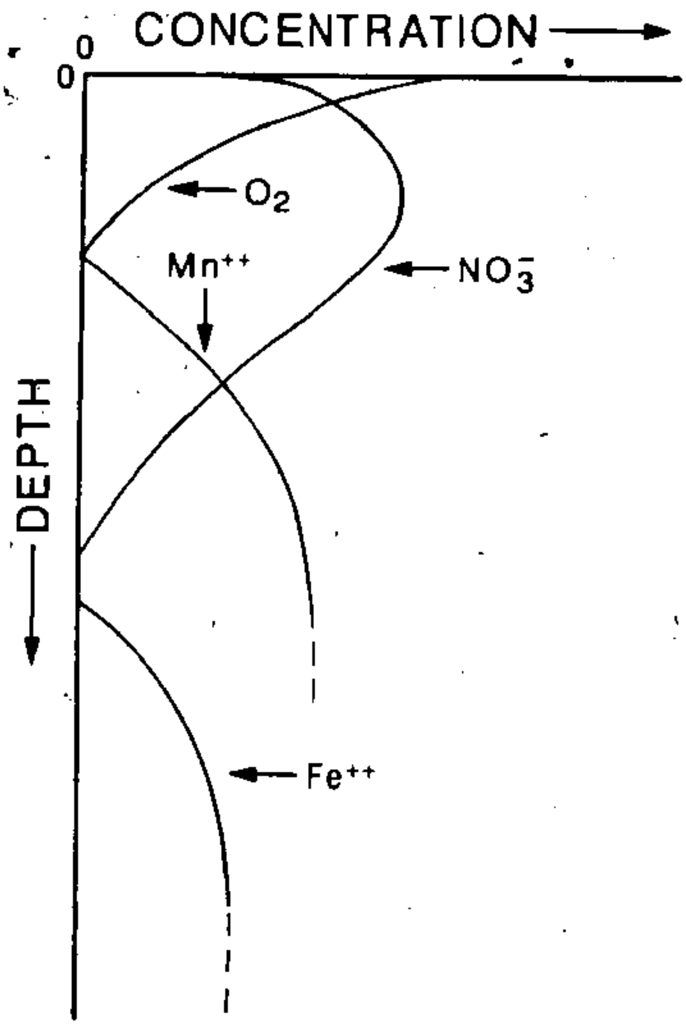
Under anoxic bottom water conditions clearly the oxidation zone, and nitrate reduction zone will be absent, and sulphate reduction will occur at the sediment-water interface (fig G-2). The style of early diagenesis, and development of the zones outlined above, will depend upon a variety of oceanographic factors which include i) the level of dissolved oxygen in bottom waters, ii) the concentration of organic carbon which is initially deposited and iii) the local sedimentation rate, (which determines how quickly sediment is buried, and hence removed from the oxidation zone). Any of these factors may change rapidly. The spectrum of resultant early diagenetic conditions may range from end-members where, in the first case, bottom water contains abundant dissolved oxygen, organic carbon input is relatively low and sedimentation rate is relatively low, resulting in a broad zone of oxygen diffusion into the underlying sediment and the relatively rapid consumption of organic carbon. At the other end of the spectrum, bottom water may be anoxic, organic carbon input high and sedimentation rate high, resulting in the early onset of sulphate reduction and a potentially high preservation factor for organic carbon.

Progressive Fe-enrichment and mobilisation of Fe and Mn

The progressive Fe-enrichment within calcite and dolomite cements of the Northern Head Group appears to be consistent with the model of progressive reduction during shallow burial which is outlined above. Fe and Mn present within the sediment as oxide and hydroxide coatings is reduced during burial, and enters solution in pore waters, where it is available for incorporation in progressively precipitating carbonate cements. The incorporation of Fe and Mn within these carbonates may vary with a number of factors,

Figure G-2

Schematic illustration of depth trends in concentrations of dissolved species found in pelagic sediments. The succession of processes is: 1) O_2 reduction, 2) nitrate formation, 3) nitrate reduction, 4) MnO_2 reduction, and 5) FeOOH reduction (redrawn from Berner, 1980).



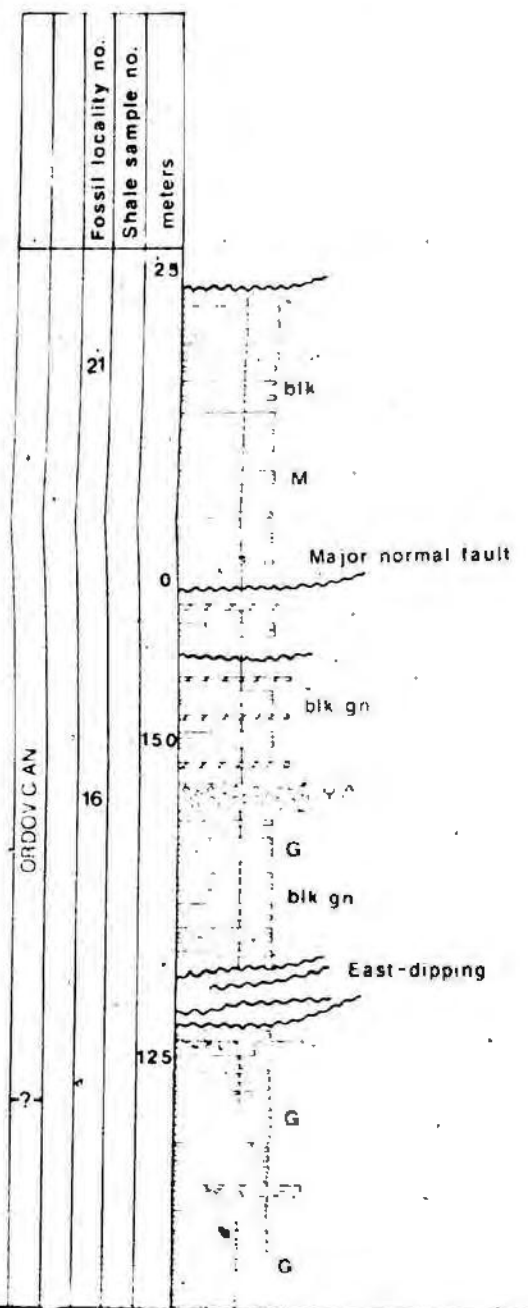
CONCENTRATION
0
0
DEPTH
O_2
Mn^{++}
NO_3^-
Fe^{++}

but will certainly depend directly upon the concentration (activity) of these species in aqueous solution (pore water) (Garrels and Christ, 1965).

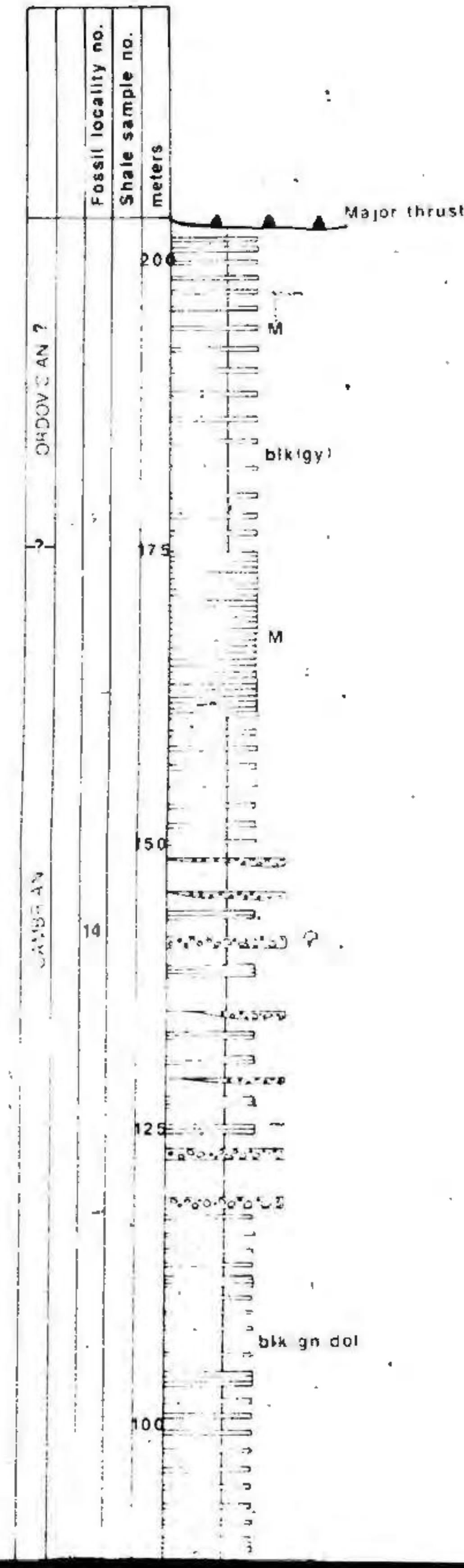
APPENDIX A: Sheet 1.

Measured sections spanning principally the Cooks Brook Formation

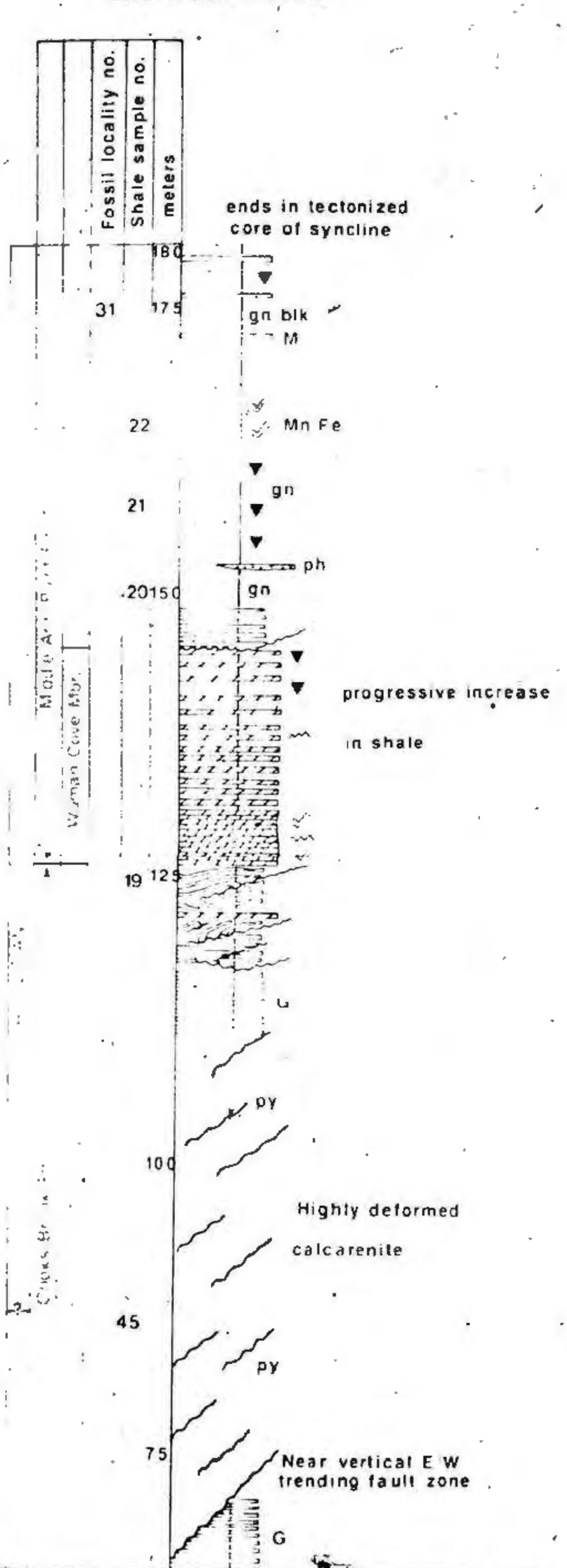
Northern Head



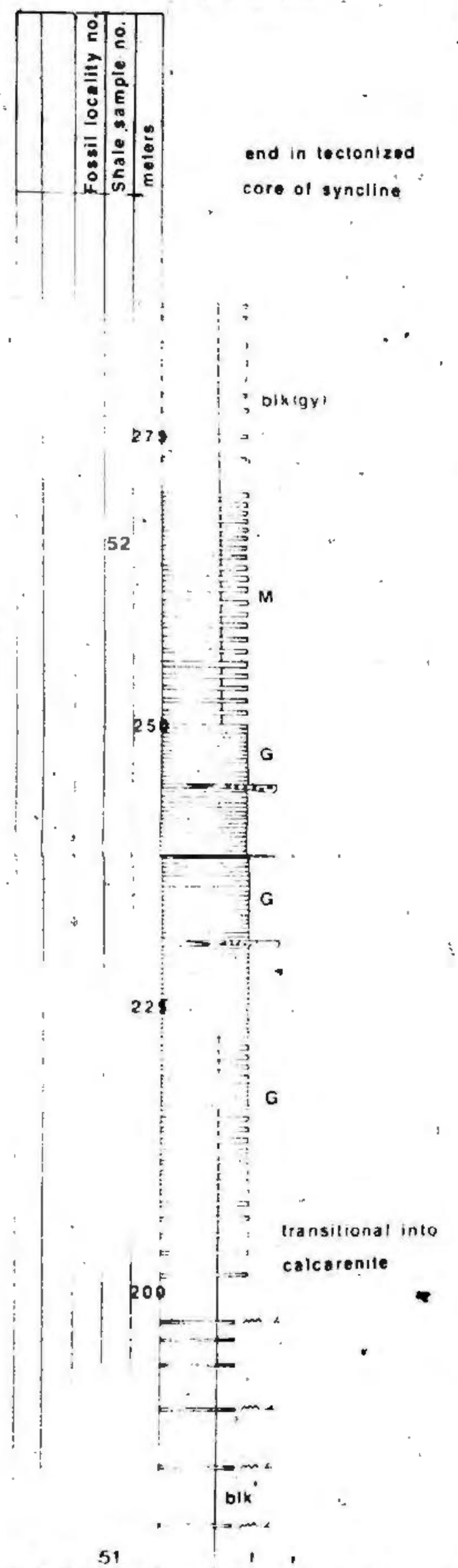
Seal Cove

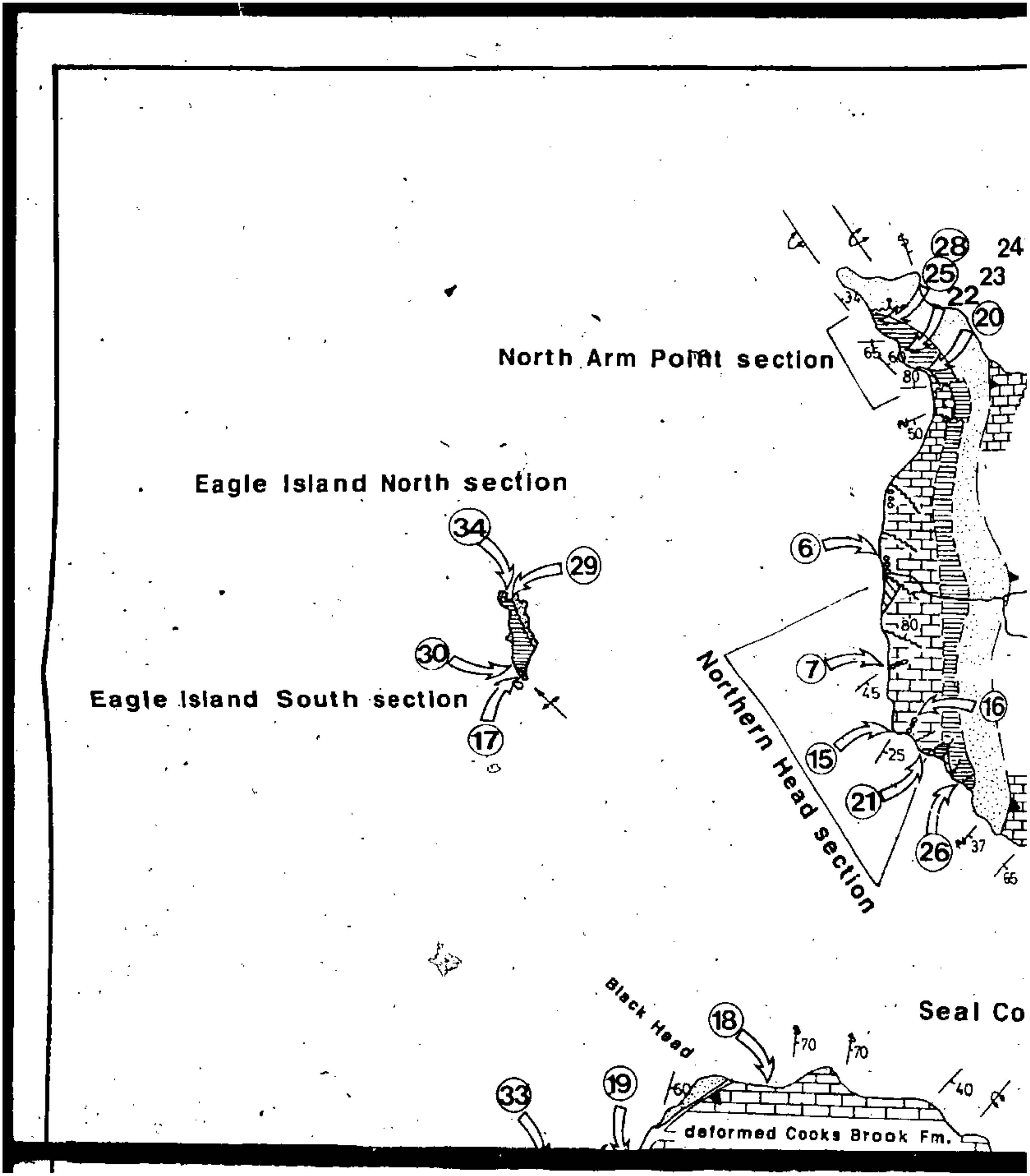


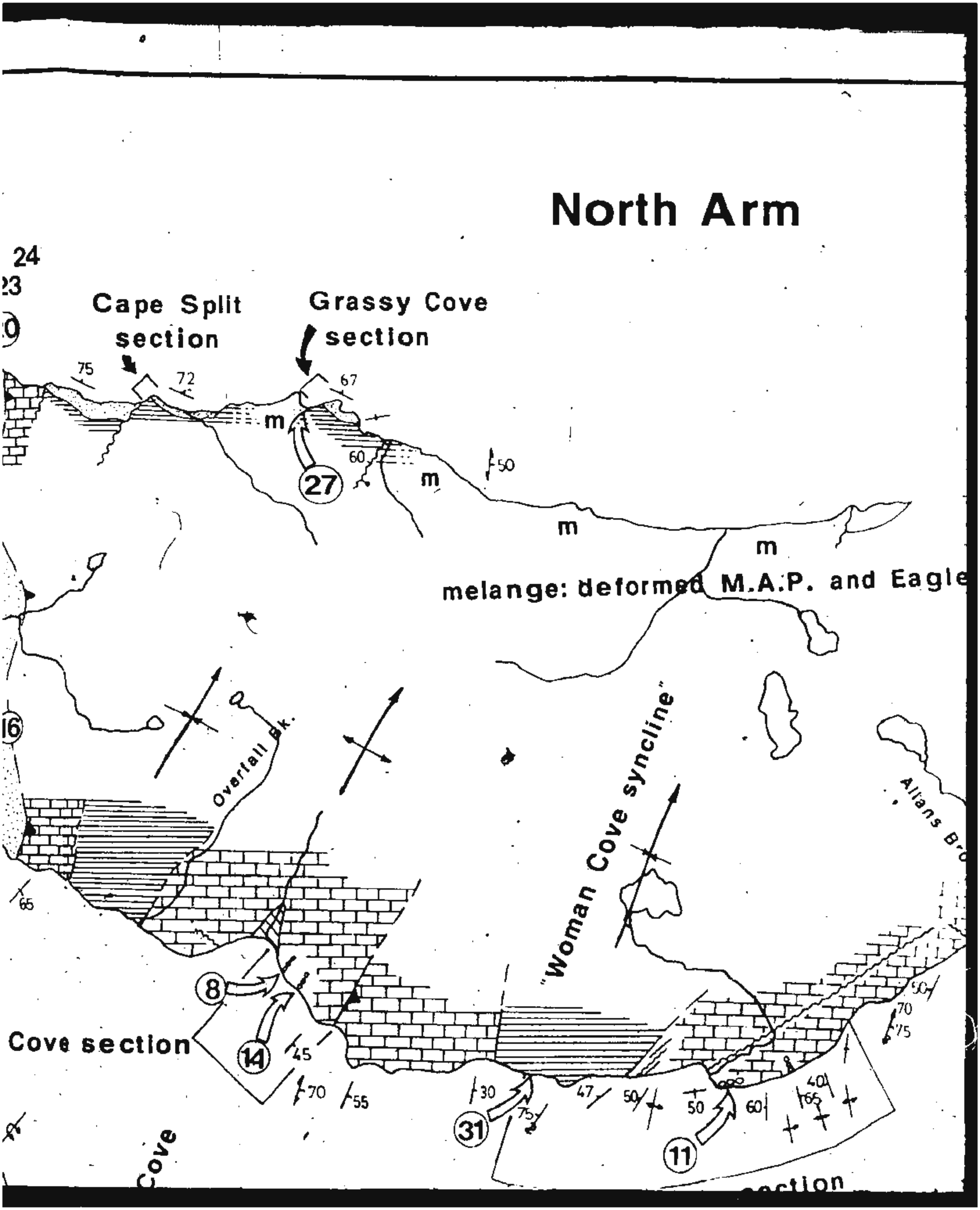
Woman Cove

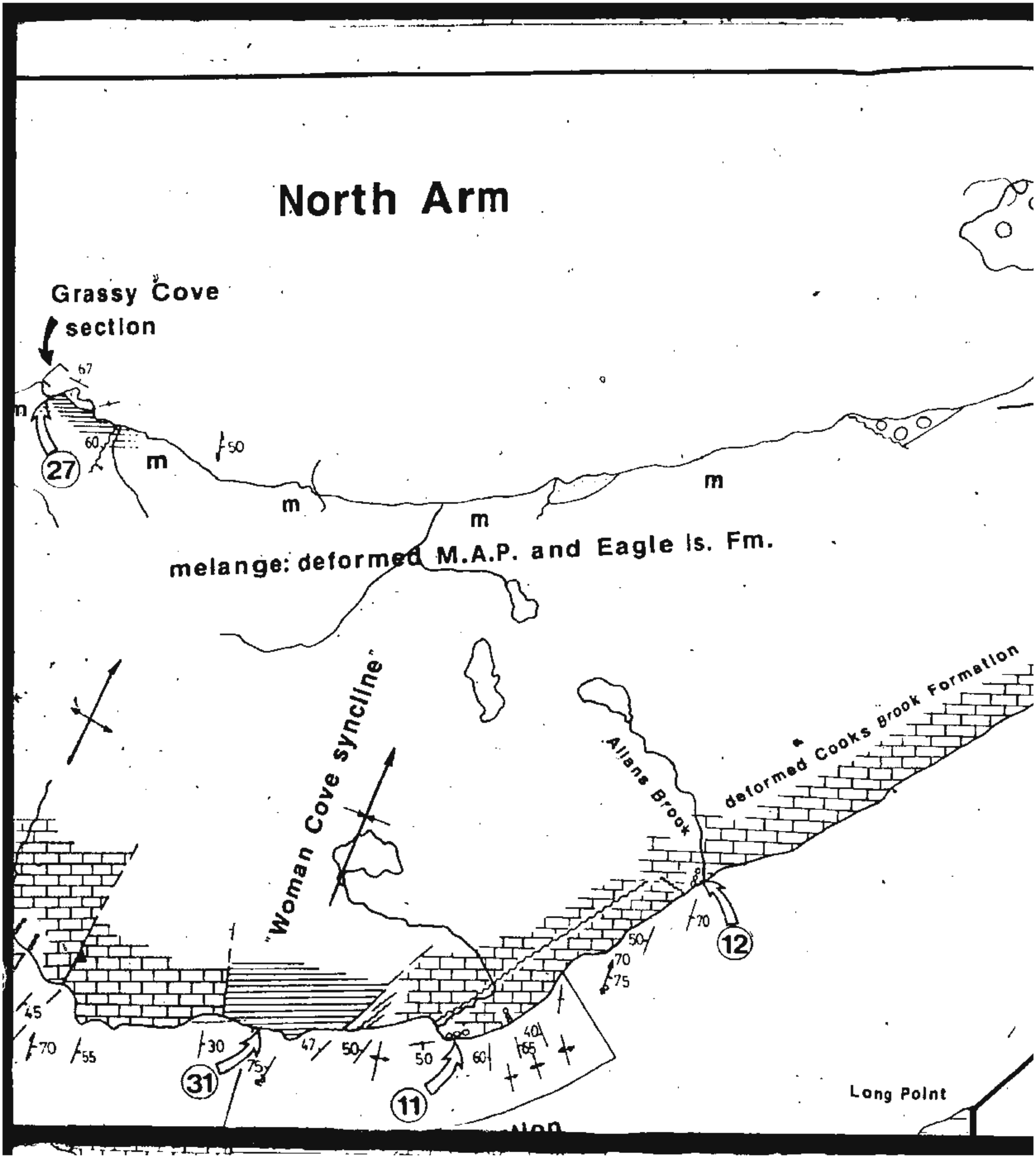


Halfway Point

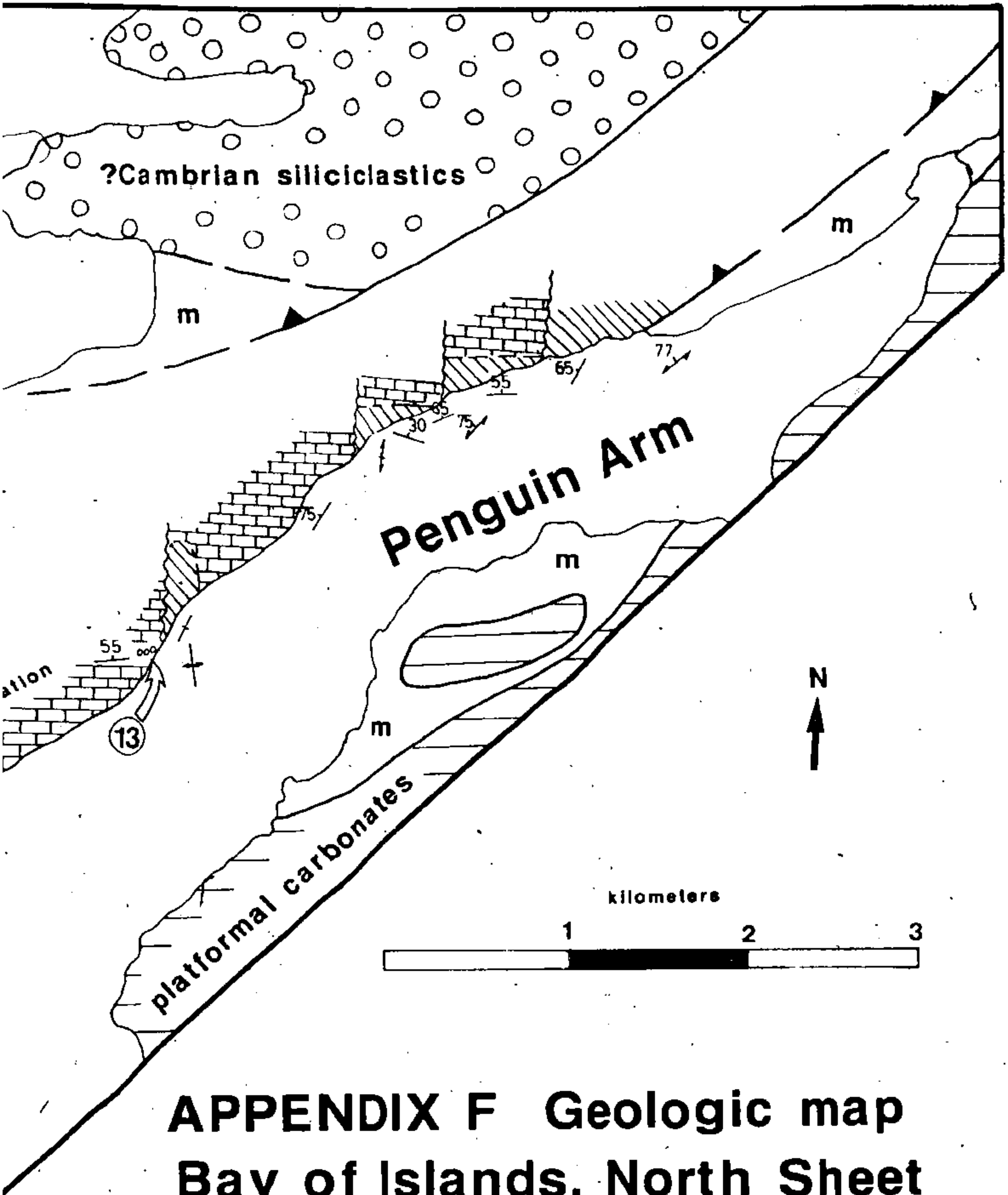



North Arm Point section
Eagle Island North section
Eagle Island South section
Northern Head section
Black Head
Seal Co
deformed Cooks Brook Fm.
28
24
25
23
22
20
34
29
30
17
6
7
16
15
21
26
18
19
33


North Arm
24
23
Cape Split
section
Grassy Cove
section
75
72
67
m
60
27
m
50
m
m
melange: deformed M.A.P. and Eagle
16
Overfall Bk.
"Woman Cove syncline"
Allans B'
65
8
Cove section
14
45
70
55
30
31
75
47
50
50
11
60
65
40
50
70
75
Cove
section



North Arm
Grassy Cove section
67
60
27
m
50
m
m
m
m
melange: deformed M.A.P. and Eagle Is. Fm.
"Woman Cove syncline"
Allans Brook
deformed Cooks Brook Formation
70
12
50
70
75
45
70
55
30
31
75
47
50
50
60
40
65
11
Long Point

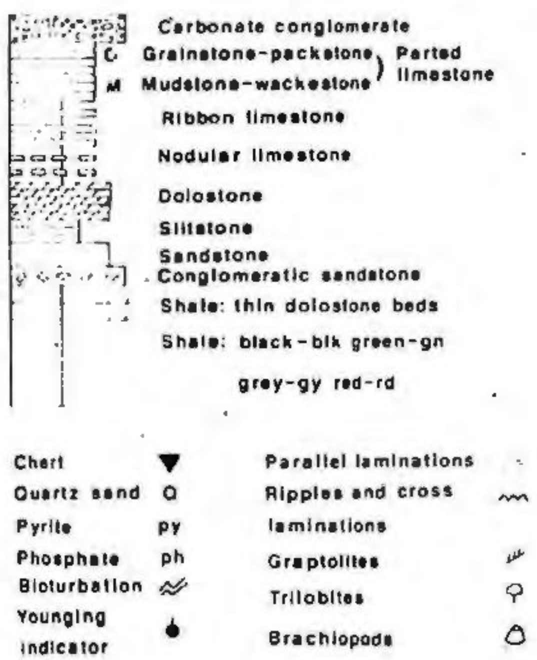


APPENDIX F Geologic map Bay of Islands, North Sheet

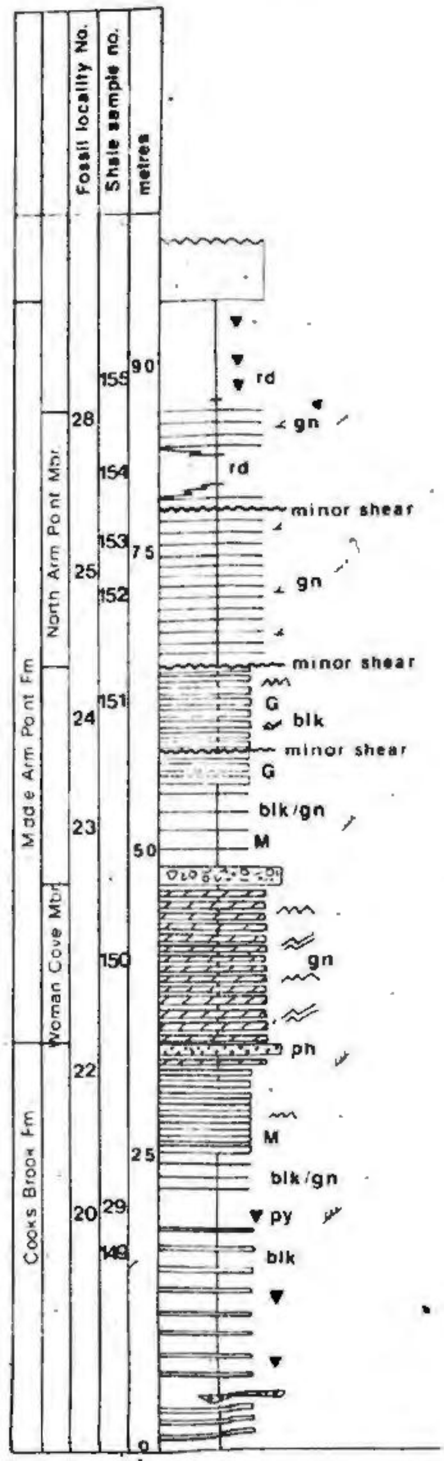
APPENDIX A: Sheet 2

Measured sections spanning principally the Middle Arm Point Formation

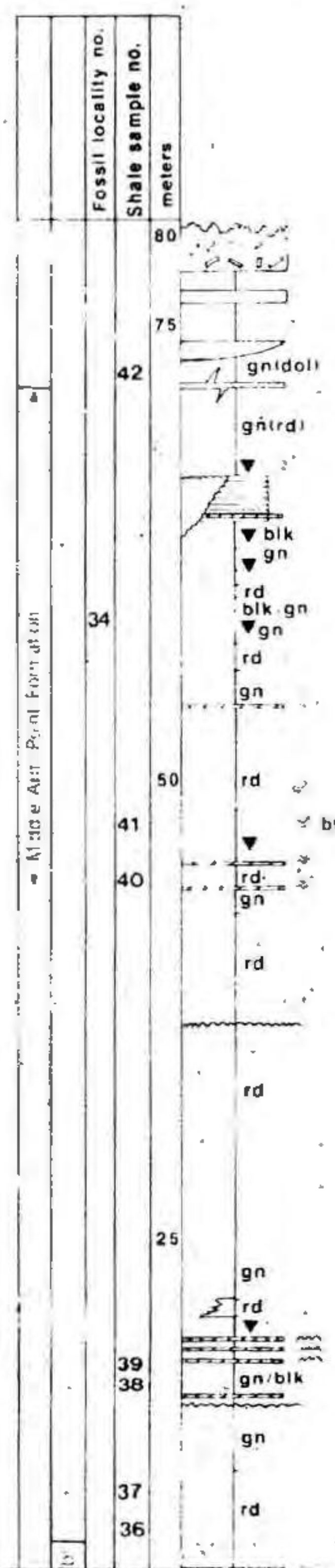
Legend

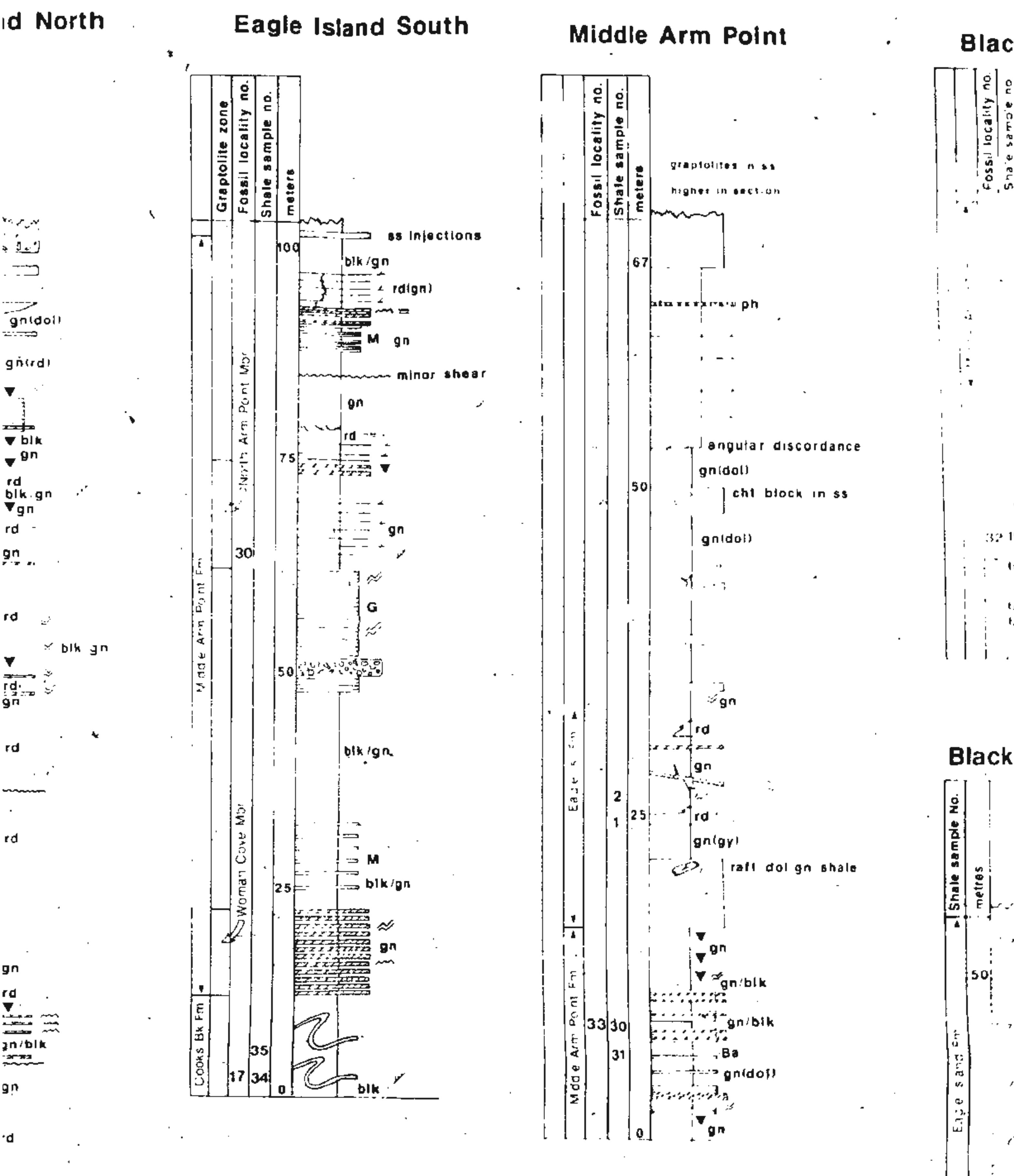


North Arm Point

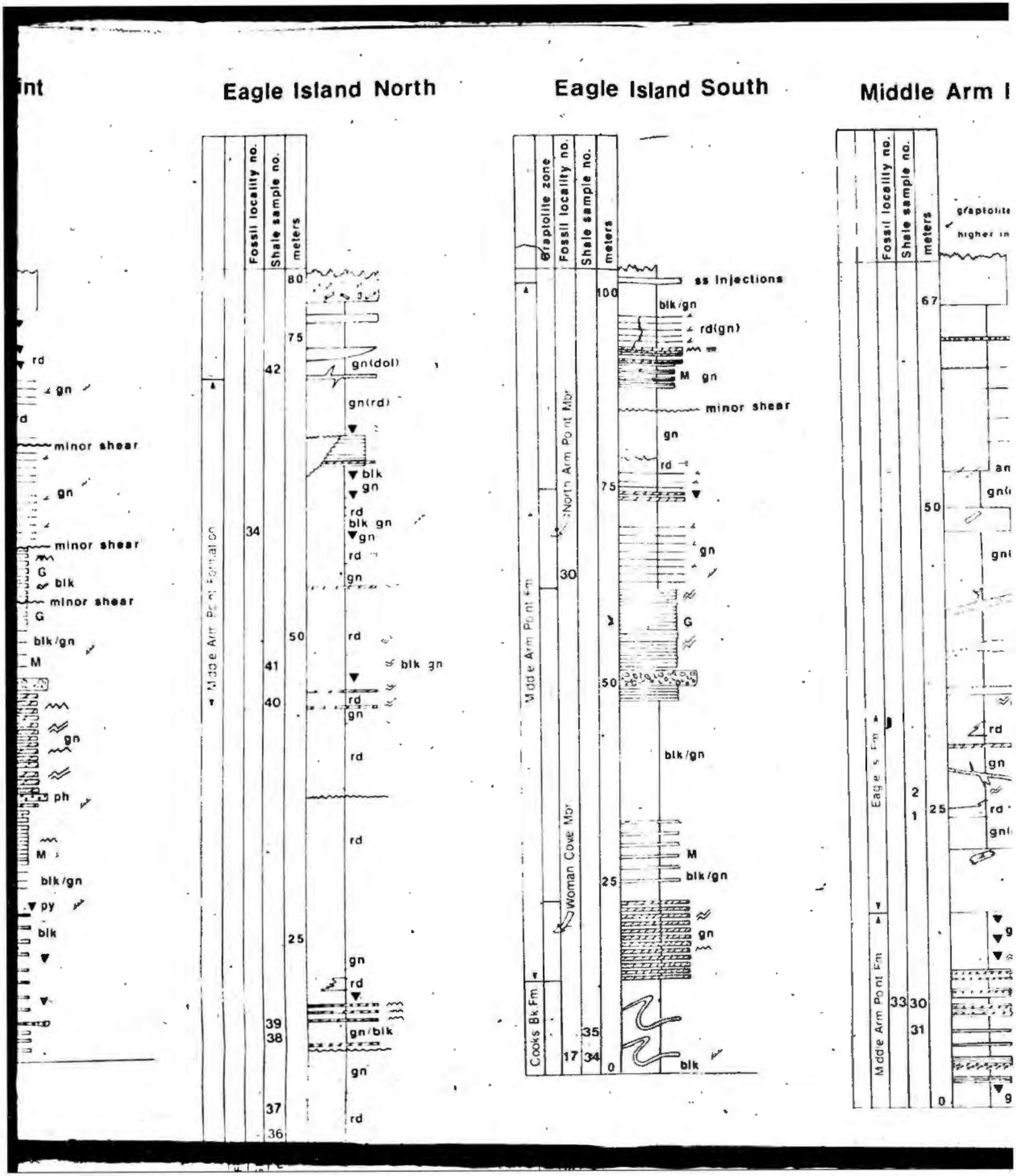


Eagle Island No

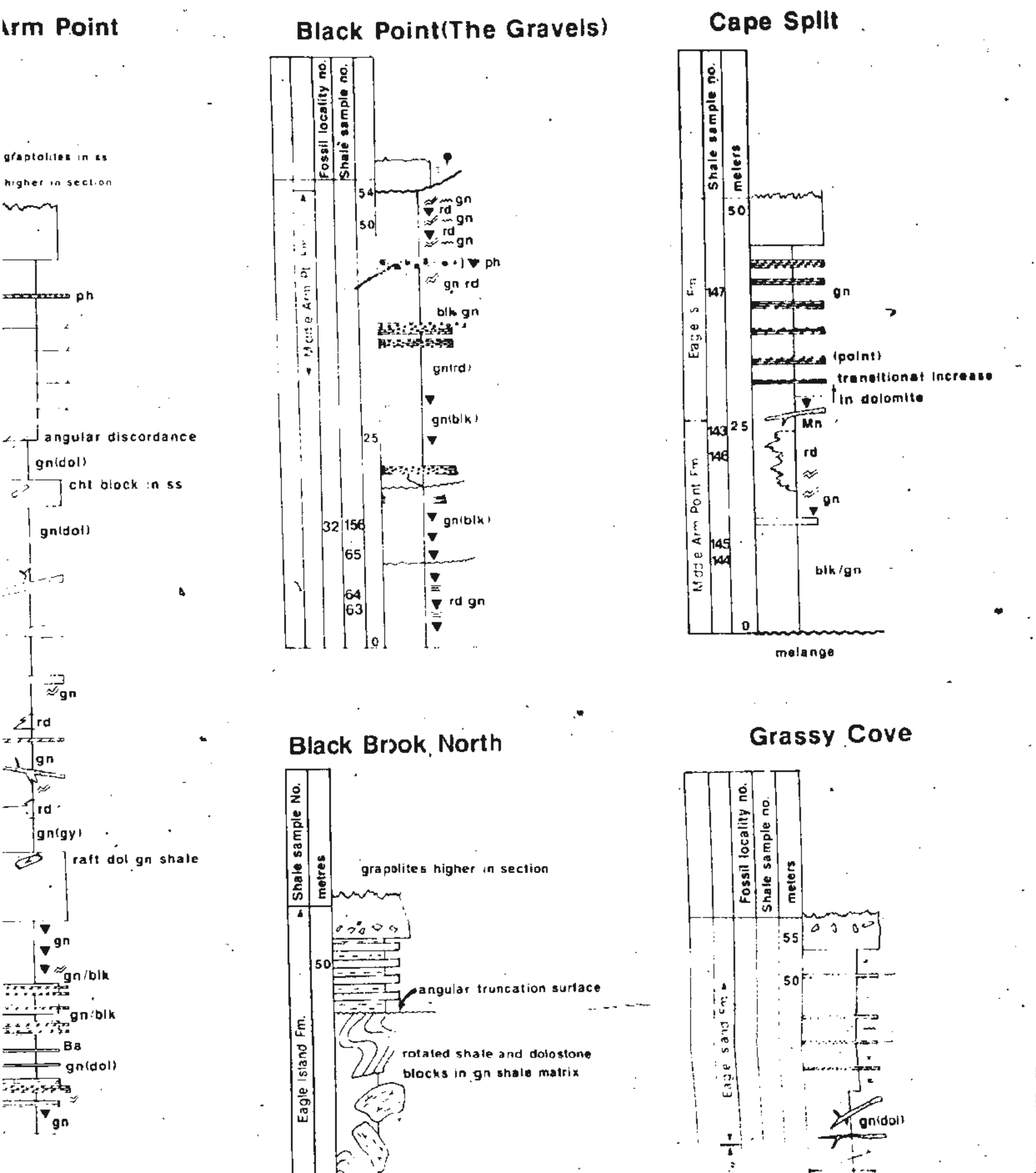




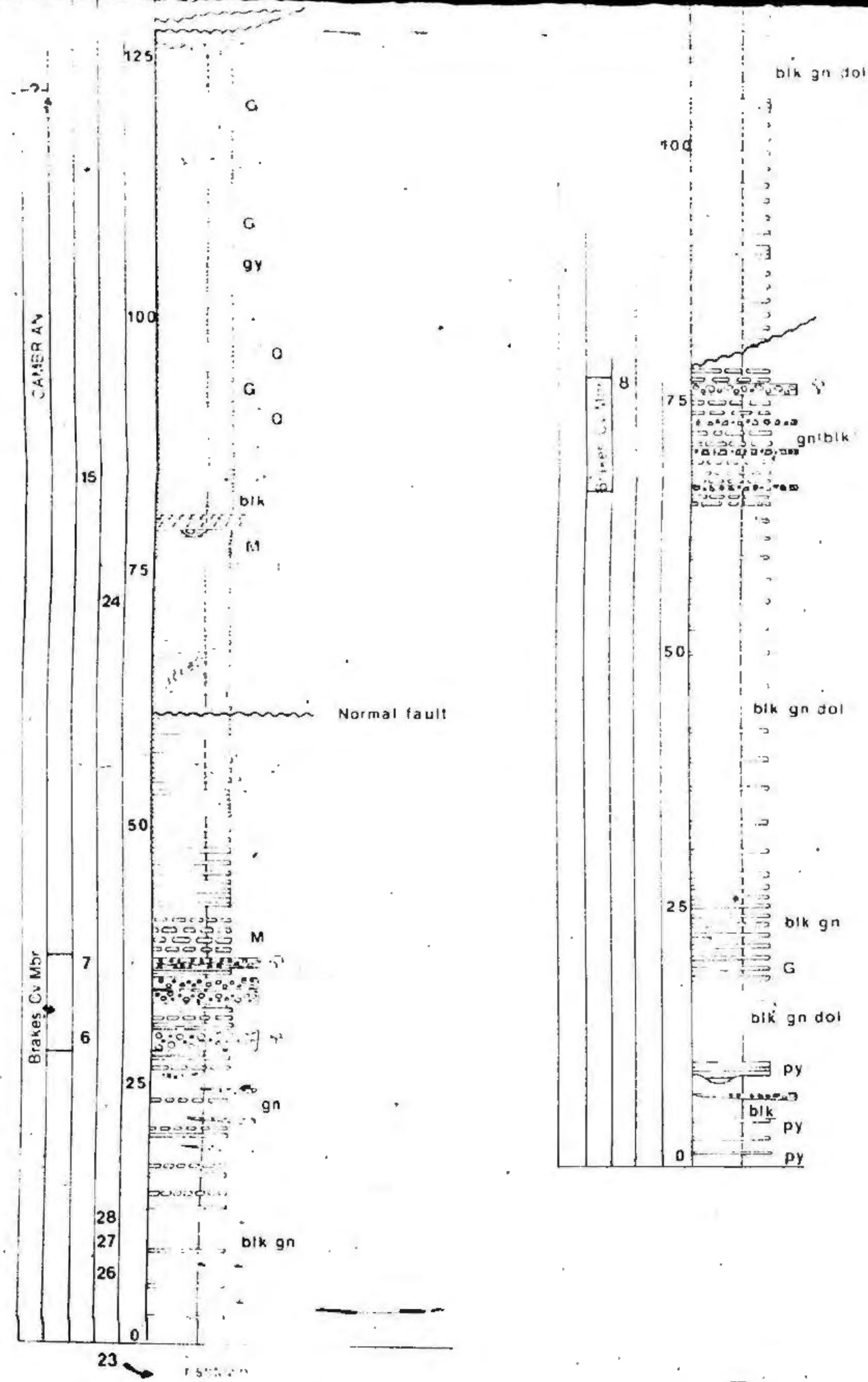
d North
Eagle Island South
Middle Arm Point
Black
Graptolite zone
Fossil locality no.
Shale sample no.
meters
ss injections
blk/gn
rd(gn)
M gn
minor shear
gn
rd
North Arm Point Mbr
Middle Arm Point Fm
30
G
blk/gn
Woman Cove Mbr
M
blk/gn
gn
Cooks Bk Fm
35
17
34
blk
graptolites in ss
higher in section
67
ph
angular discordance
gn(dol)
50
cht block in ss
gn(dol)
gn
rd
gn
2
1
25
rd
gn(gy)
raft dol gn shale
gn
gn/blk
Middle Arm Point Fm
33
30
gn/blk
31
Ba
gn(dol)
gn
0
gn(dol)
gn(rd)
blk
gn
rd
blk gn
gn
rd
gn
rd
blk gn
rd
gn
rd
rd
gn
rd
gn/blk
gn
rd
Black
Shale sample No.
metres
50
Eagle Island Fm



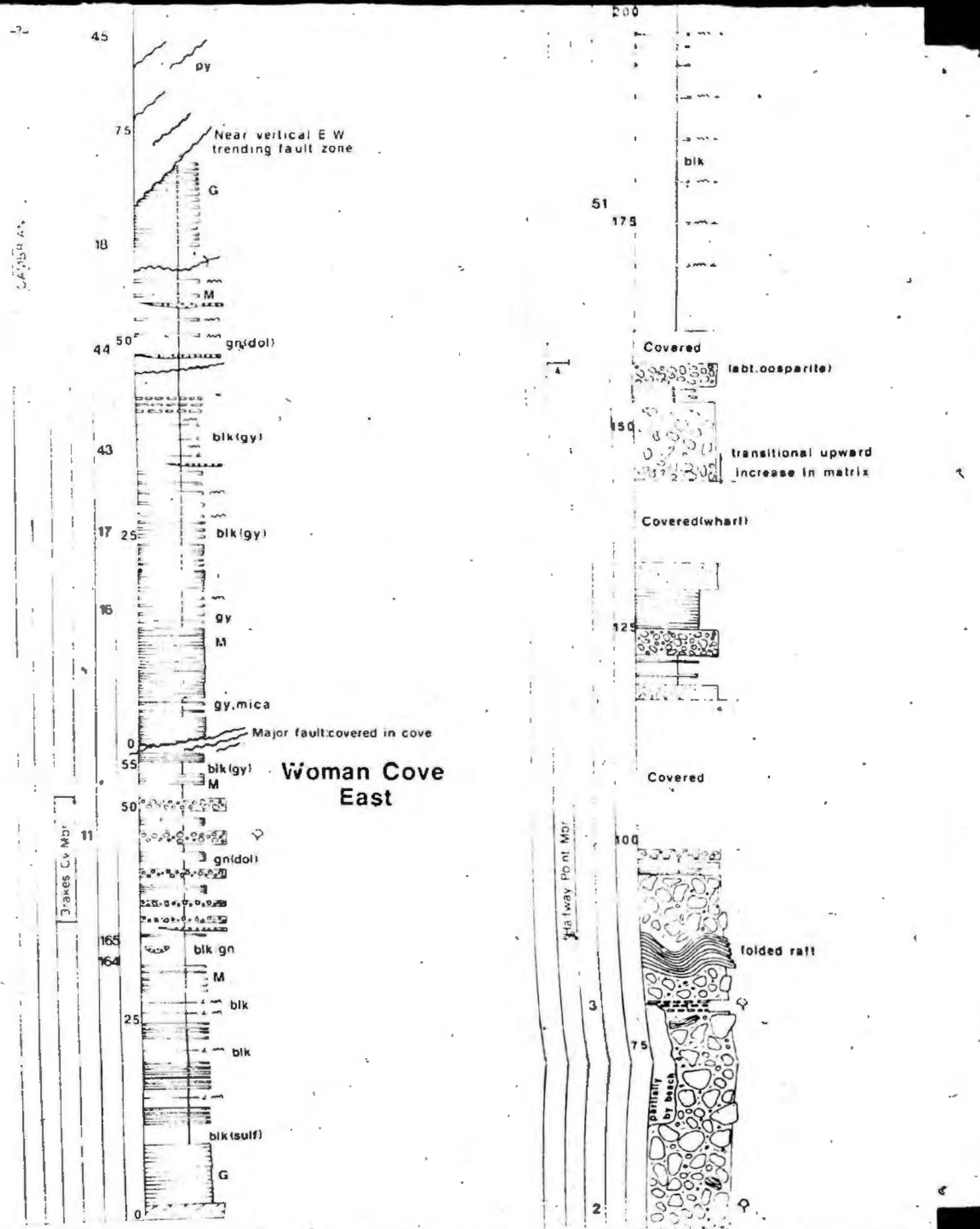
Eagle Island North
Eagle Island South
Middle Arm P
Fossil locality no.
Shale sample no.
meters
Graptolite zone
Middle Arm Point Formation
Middle Arm Point Fm
North Arm Point Mbr
Woman Cove Mbr
Cooks Bk Fm
Eagles Fm
ss injections
minor shear
blk/gn
rd(gn)
gn(dol)
gn(rd)
blk
gn
rd
G
M
ph
py
gn/blk



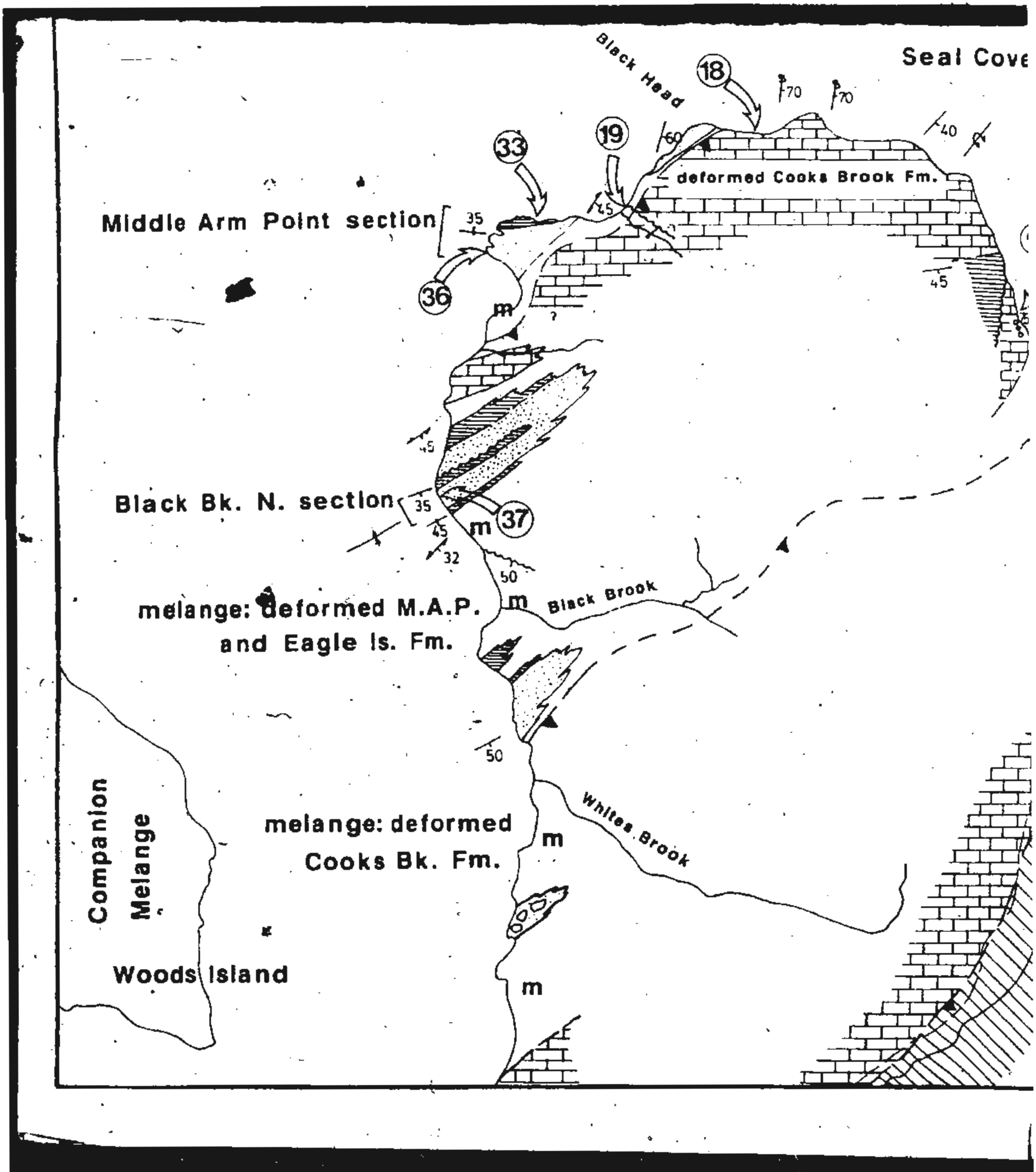
Arm Point
graptolites in ss
higher in section
ph
angular discordance
gn(dol)
cht block in ss
gn(dol)
gn
rd
gn
rd
gn(gy)
raft dol gn shale
gn
gn/blk
gn/blk
Ba
gn(dol)
gn
Black Point(The Gravels)
Fossil locality no.
Shale sample no.
Middle Arm Pt
54
50
gn
rd
gn
rd
gn
ph
gn rd
blk gn
gn(rd)
gn(blk)
25
32
156
65
64
63
gn(blk)
rd gn
0
Cape Split
Shale sample no.
meters
Eagle Is Fm
Middle Arm Point Fm
50
147
gn
(point)
transitional increase
in dolomite
143
25
Mn
146
rd
gn
145
144
blk/gn
0
melange
Black Brook North
Shale sample No.
metres
Eagle Island Fm.
grapolites higher in section
50
angular truncation surface
rotated shale and dolostone
blocks in gn shale matrix
Grassy Cove
Fossil locality no.
Shale sample no.
meters
Eagle Island Fm
55
50
gn(dol)


CAMBRIAN
Brakes Cv Mbr
Normal fault
blk gn dol
gn(blk)
blk gn
blk
py

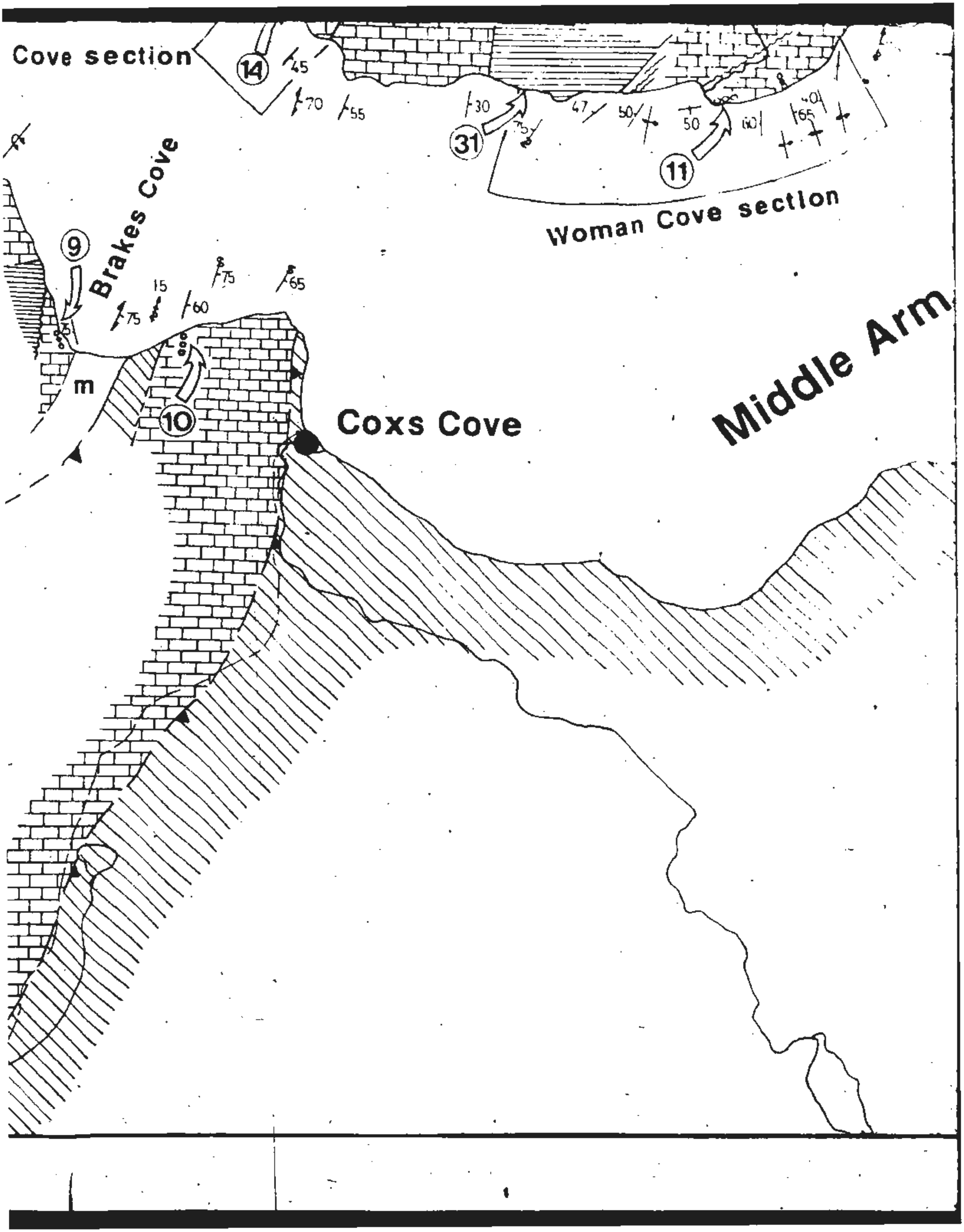
Legend



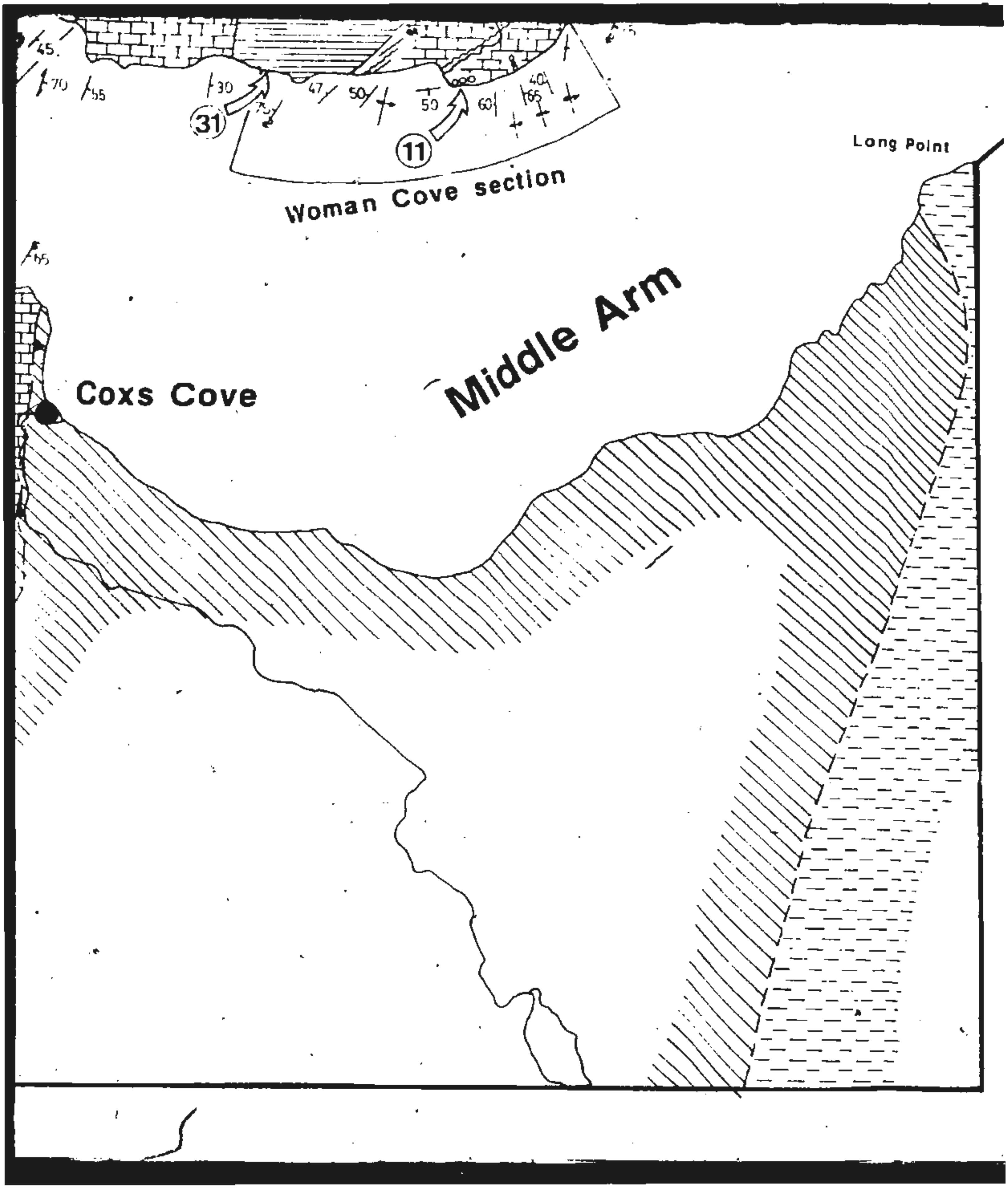
Woman Cove East
py
Near vertical E W trending fault zone
G
M
gn(dol)
blk(gy)
blk(gy)
gy
M
gy,mica
Major fault:covered in cove
blk(gy)
M
gn(dol)
blk gn
M
blk
blk
blk(sulf)
G
Brakes Cv Mbr
Halfway Point Mbr
blk
Covered
(abt.oosparite)
transitional upward increase in matrix
Covered(wharf)
Covered
folded raft
partially by beach



Seal Cove
Black Head
18
70
70
40
60
19
33
deformed Cooks Brook Fm.
Middle Arm Point section
35
45
36
m
45
Black Bk. N. section
35
37
m
45
32
50
m
Black Brook
melange: deformed M.A.P.
and Eagle Is. Fm.
50
Whites Brook
melange: deformed
Cooks Bk. Fm.
m
Companion
Melange
Woods Island
m



Cove section
14
45
70
55
30
31
47
50
50
60
65
11
Woman Cove section
Brakes Cove
9
15
75
75
60
65
m
10
Coxs Cove
Middle Arm

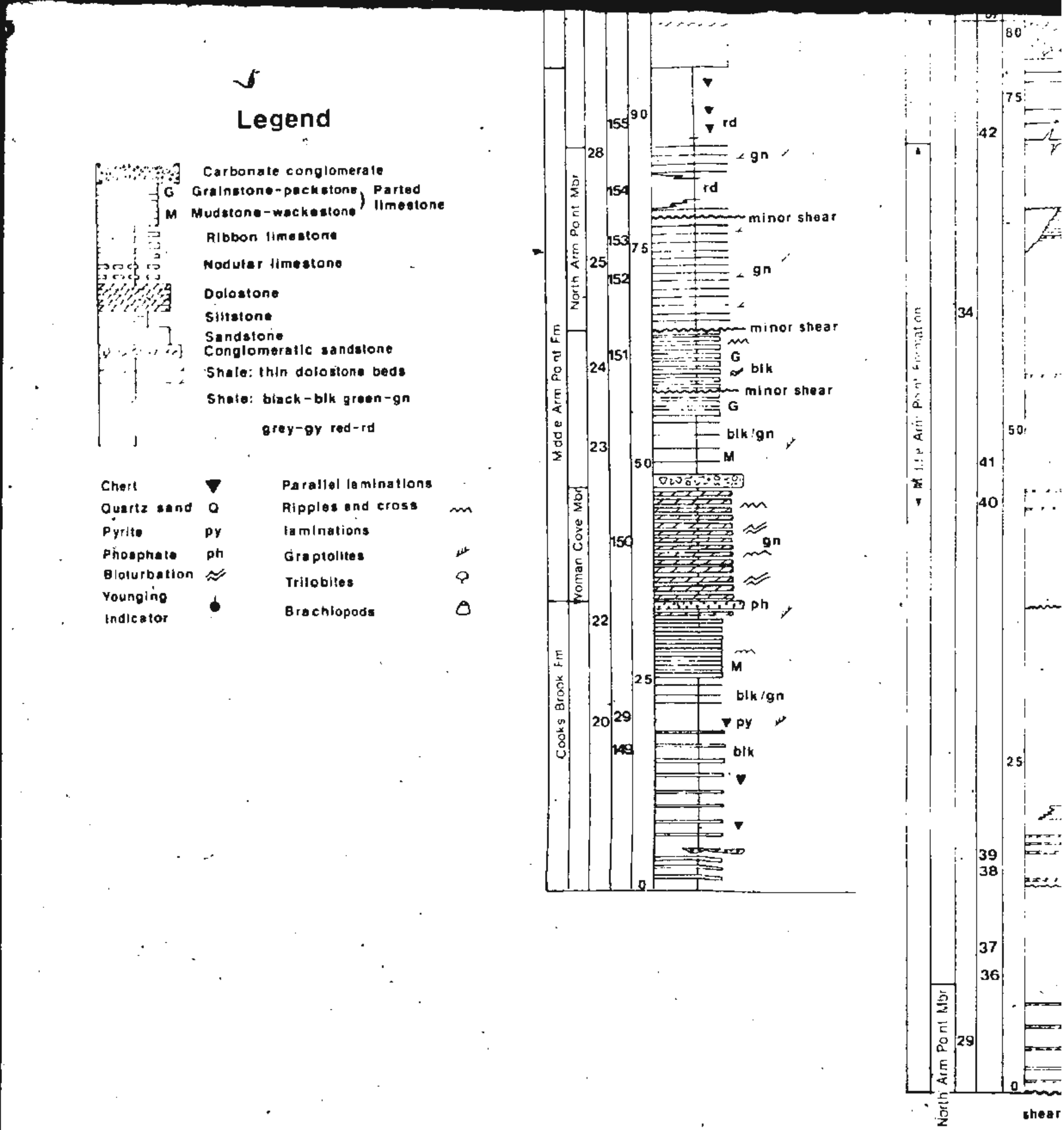


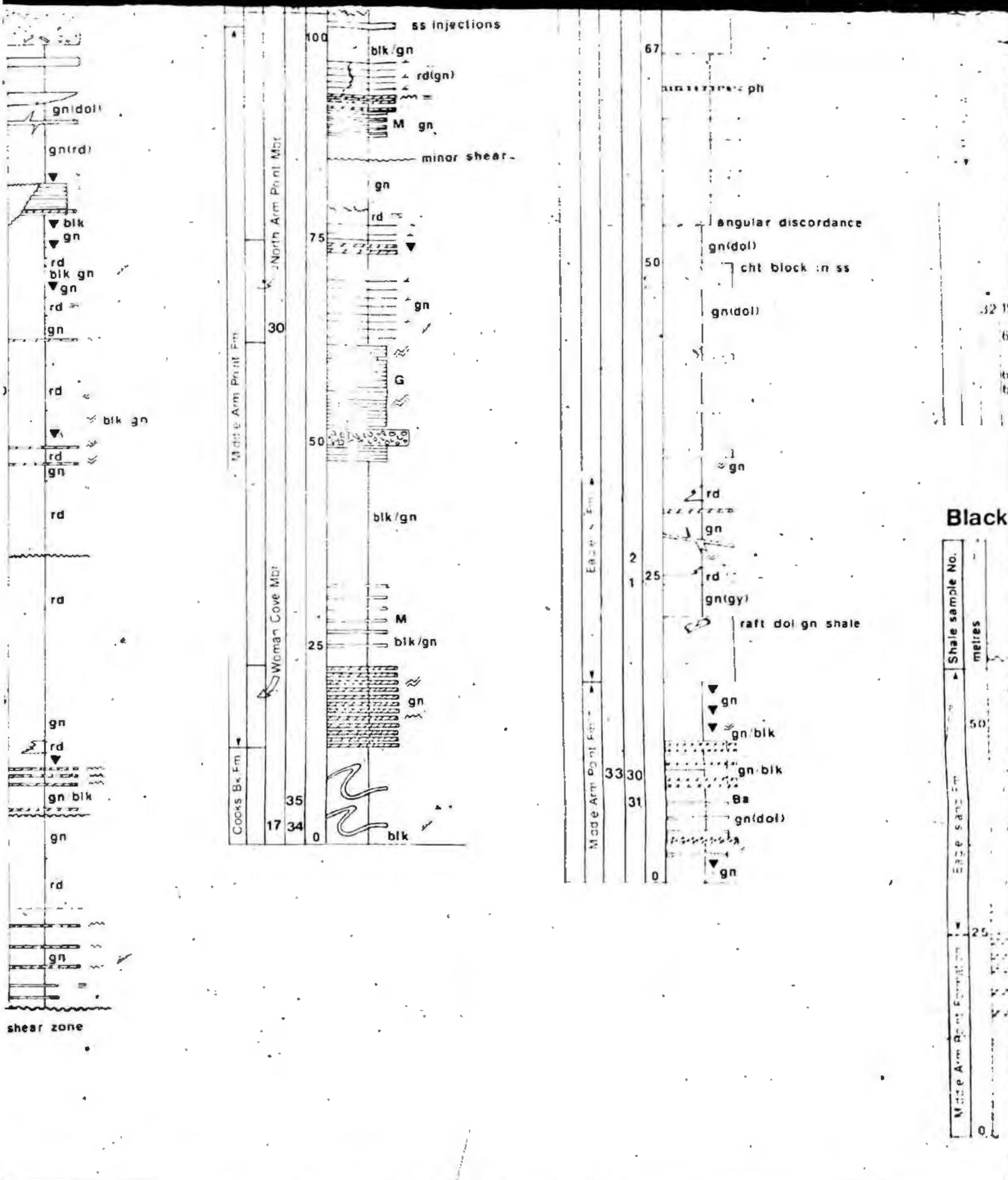
Woman Cove section
31
11
Long Point
Middle Arm
Coxs Cove

APPENDIX F Geologic map Bay of Islands, North Sheet

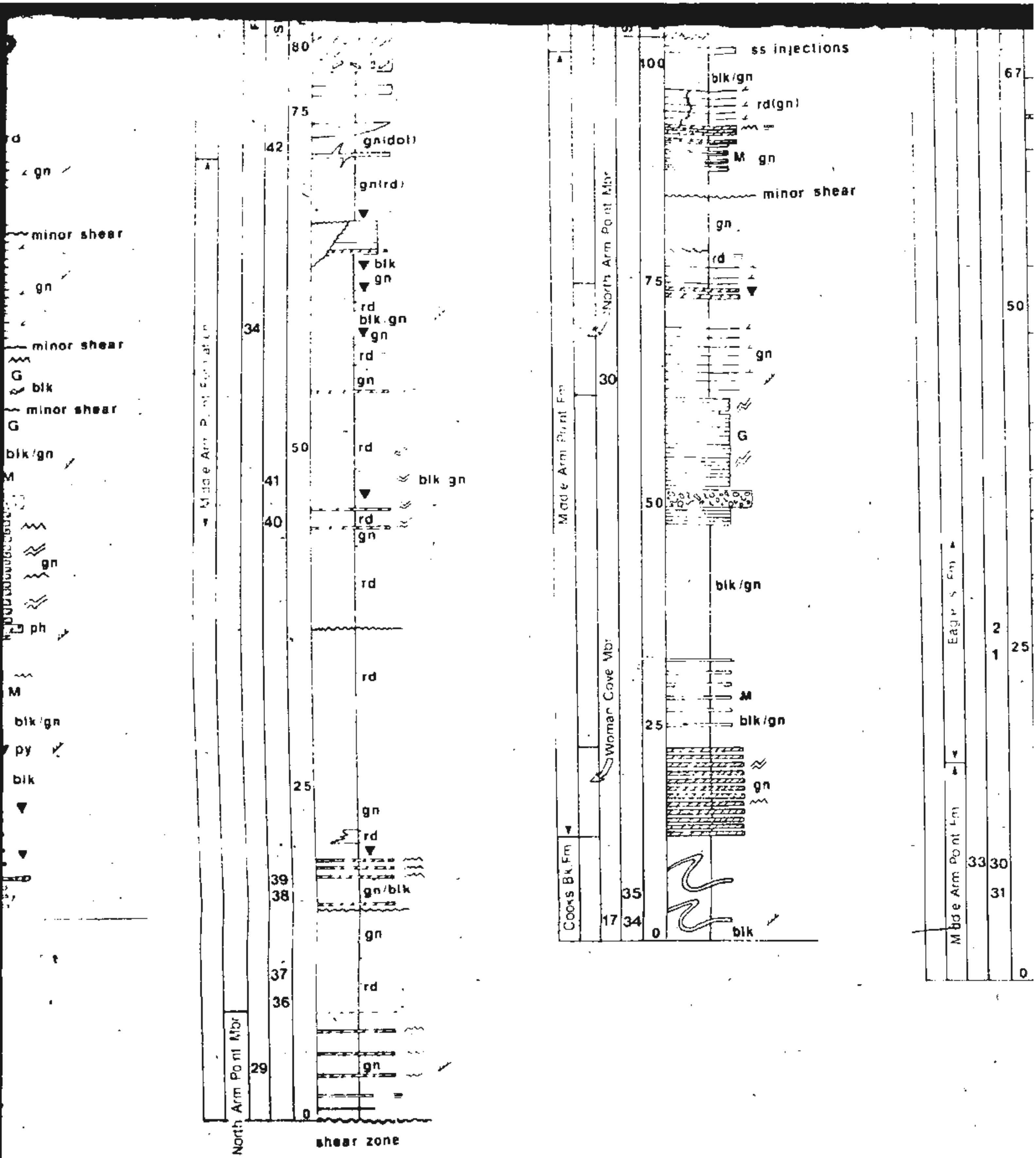
- Eagle Island Fm.
- Middle Arm Point Fm.
- Cooks Brook Fm. (undifferentiated)
- Cooks Brook Fm. (Halfway Point Mbr.)
- Irishtown Fm.
- Summerside Fm.
- m melange

- prominent conglomerate (commonly fossiliferous)
- 16 Fossil locality (Faunal assemblage listed in Appendix C).
- Stratigraphic contact; defined, approximate and assumed
- Thrust fault; defined, approximate and assumed
- High angle fault; dot indicates downthrown side
- 70 45 Bedding, tops known; inclined, overturned
- 50 axis of minor fold with plunge
- 45 cleavage (fabric in melange)
- anticlinal axis; upright, reclined
- synclinal axis; upright, reclined
- Road

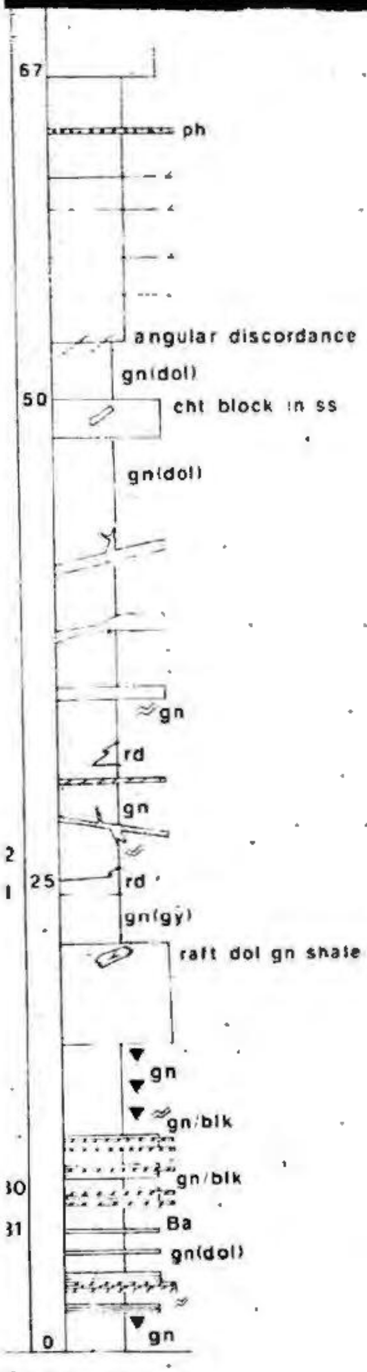

Legend
Carbonate conglomerate
G Grainstone-packstone
M Mudstone-wackestone
Parted limestone
Ribbon limestone
Nodular limestone
Dolostone
Siltstone
Sandstone
Conglomeratic sandstone
Shale: thin dolostone beds
Shale: black-blk green-gn
grey-gy red-rd
Chert
Quartz sand Q
Pyrite py
Phosphate ph
Bioturbation
Younging indicator
Parallel laminations
Ripples and cross laminations
Graptolites
Trilobites
Brachiopods
Middle Arm Point Fm
North Arm Point Mbr
Woman Cove Mbr
Cooks Brook Fm
rd
gn
minor shear
G
blk
blk/gn
M
ph
py
Middle Arm Point Formation
North Arm Point Mbr
shear

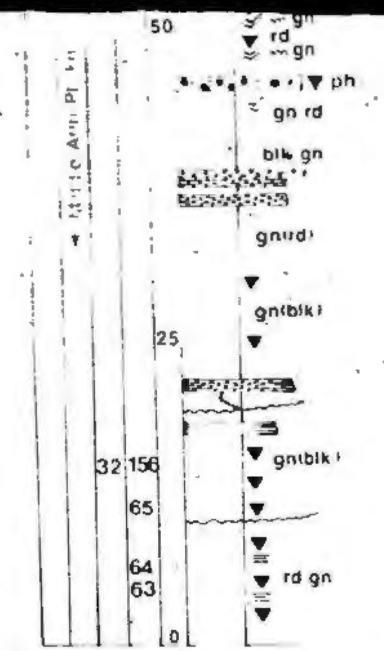


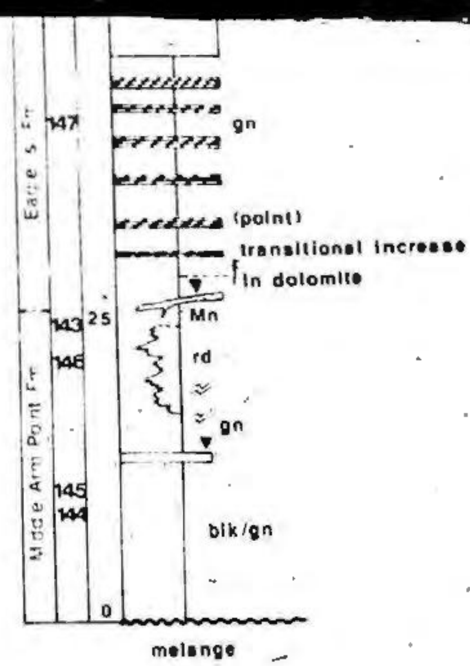
gn(dol)
gn(rd)
blk
gn
rd
blk gn
gn
rd
gn
rd
blk gn
rd
gn
rd
rd
gn
rd
gn blk
gn
rd
gn
shear zone
ss injections
blk/gn
rd(gn)
M gn
minor shear
gn
rd
gn
G
blk/gn
M
blk/gn
gn
blk
Middle Arm Point Fm
North Arm Point Mbr
Woman Cove Mbr
Cooks Bk Fm
100
75
50
25
0
30
35
17
34
67
ph
angular discordance
gn(dol)
cht block in ss
gn(dol)
gn
rd
gn
rd
gn(gy)
raft dol gn shale
gn
gn/blk
gn blk
Ba
gn(dol)
gn
Eagle Is Fm
Middle Arm Point Fm
2
1
33
30
31
50
25
0
Black
Shale sample No.
metres
Eagle Isl Fm
Middle Arm Point Formation
50
25
0



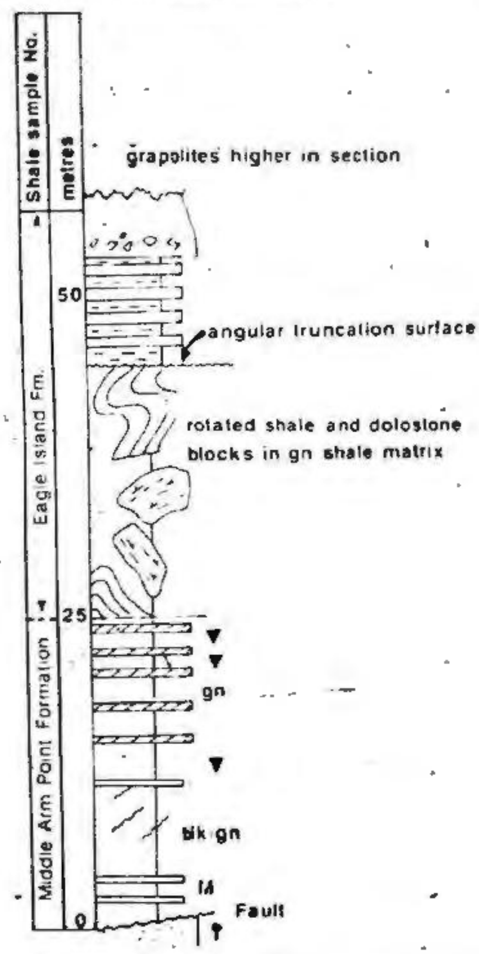
minor shear
blk/gn
ph
py
blk
Middle Arm Point Formation
North Arm Point Mbr
shear zone
ss injections
gn(dol)
gn(rd)
rd(gn)
bIk gn
gn/blk
Middle Arm Point Fm
North Arm Point Mbr
Woman Cove Mbr
Cooks Bk Fm
Eagle Is Fm



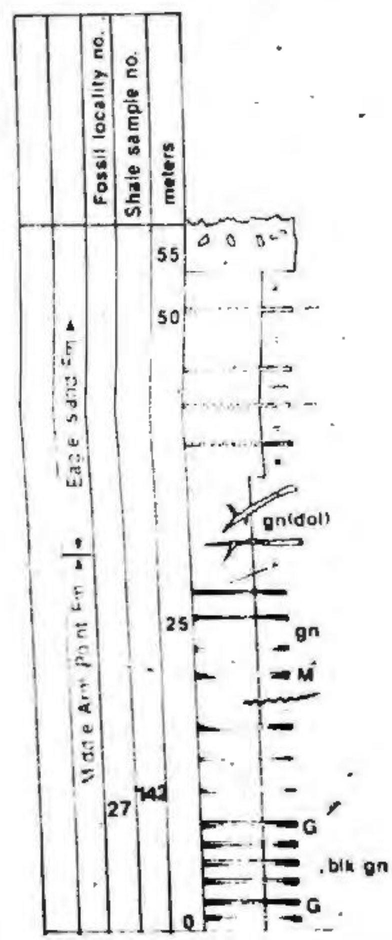


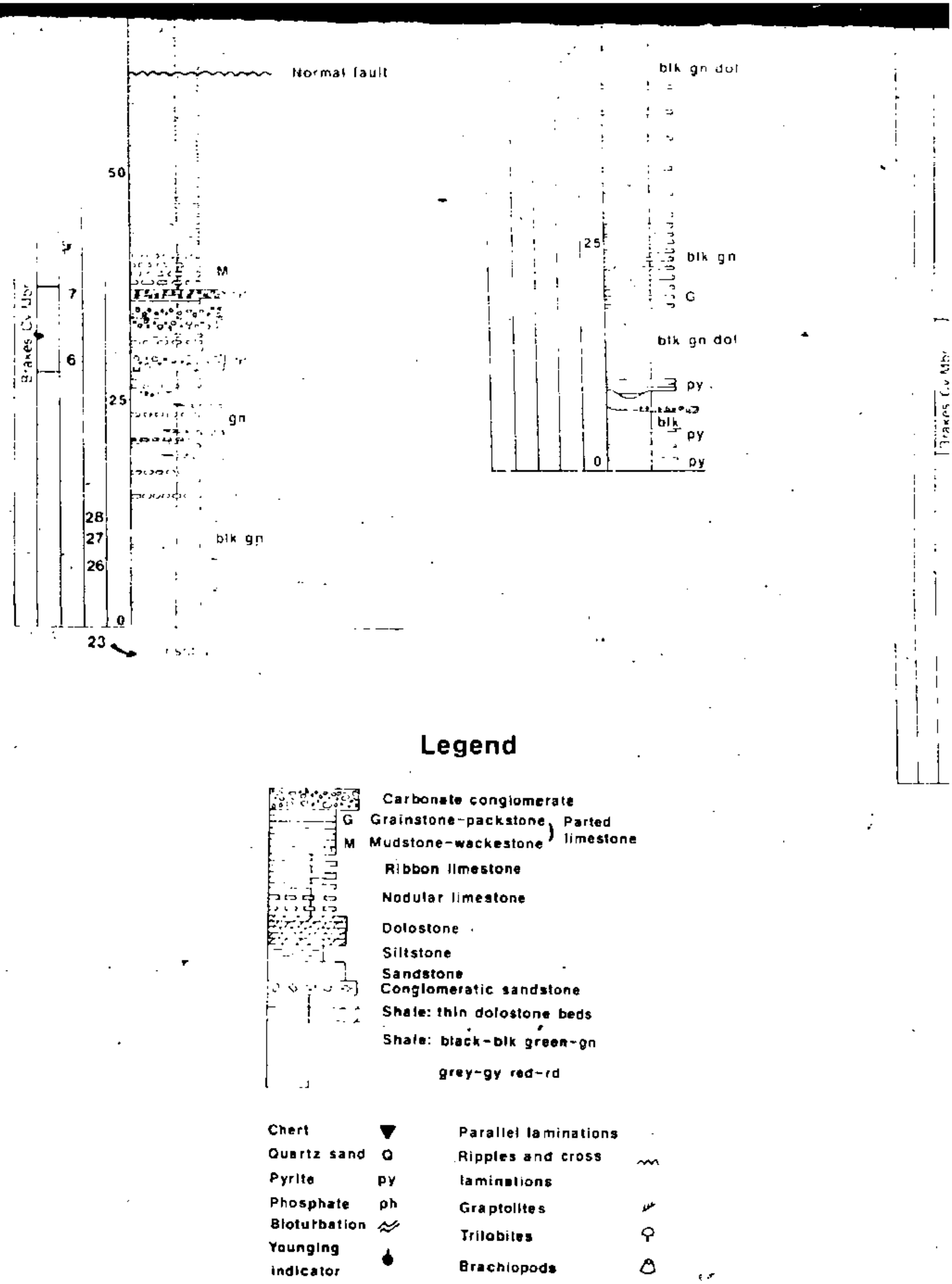


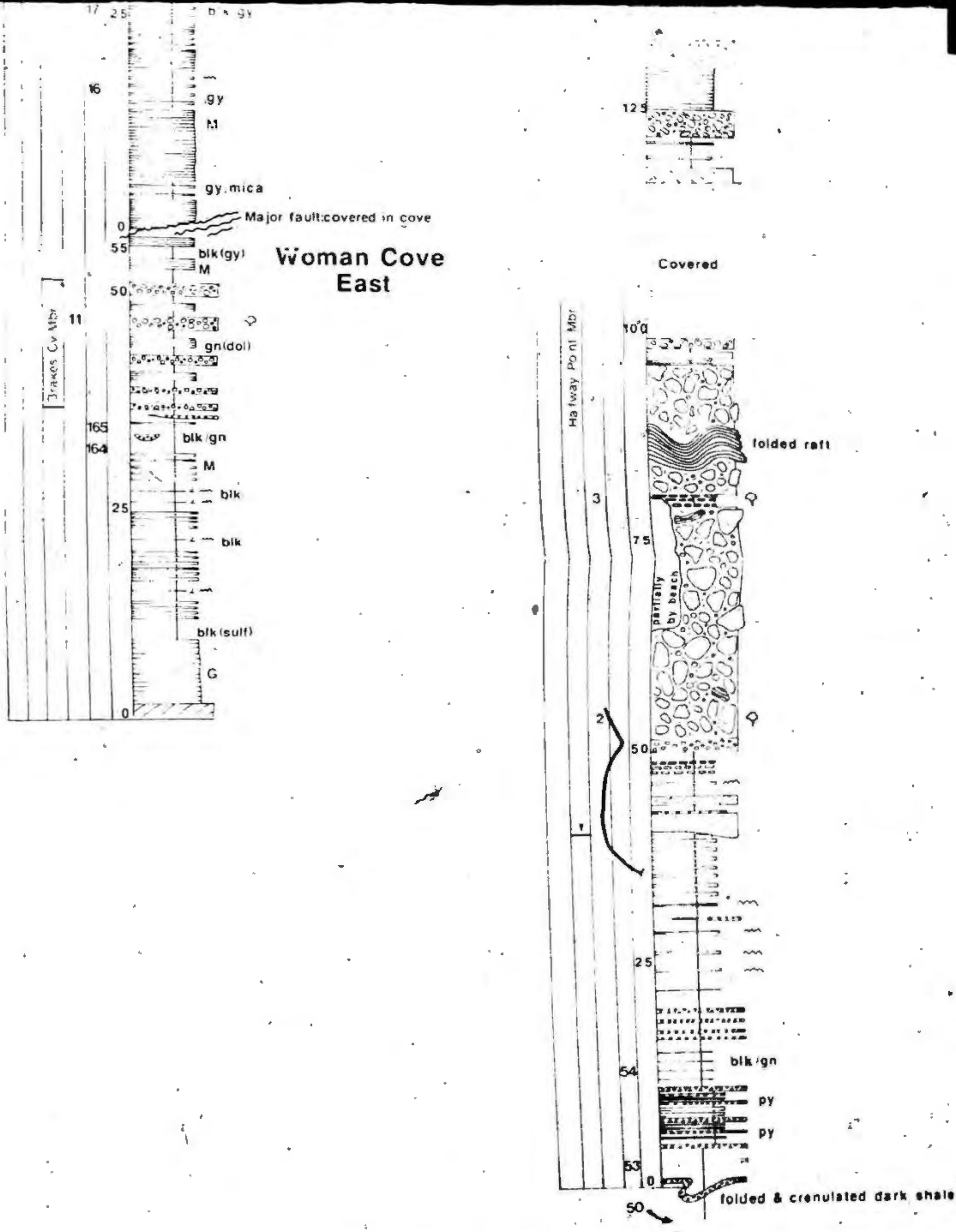
Black Brook North



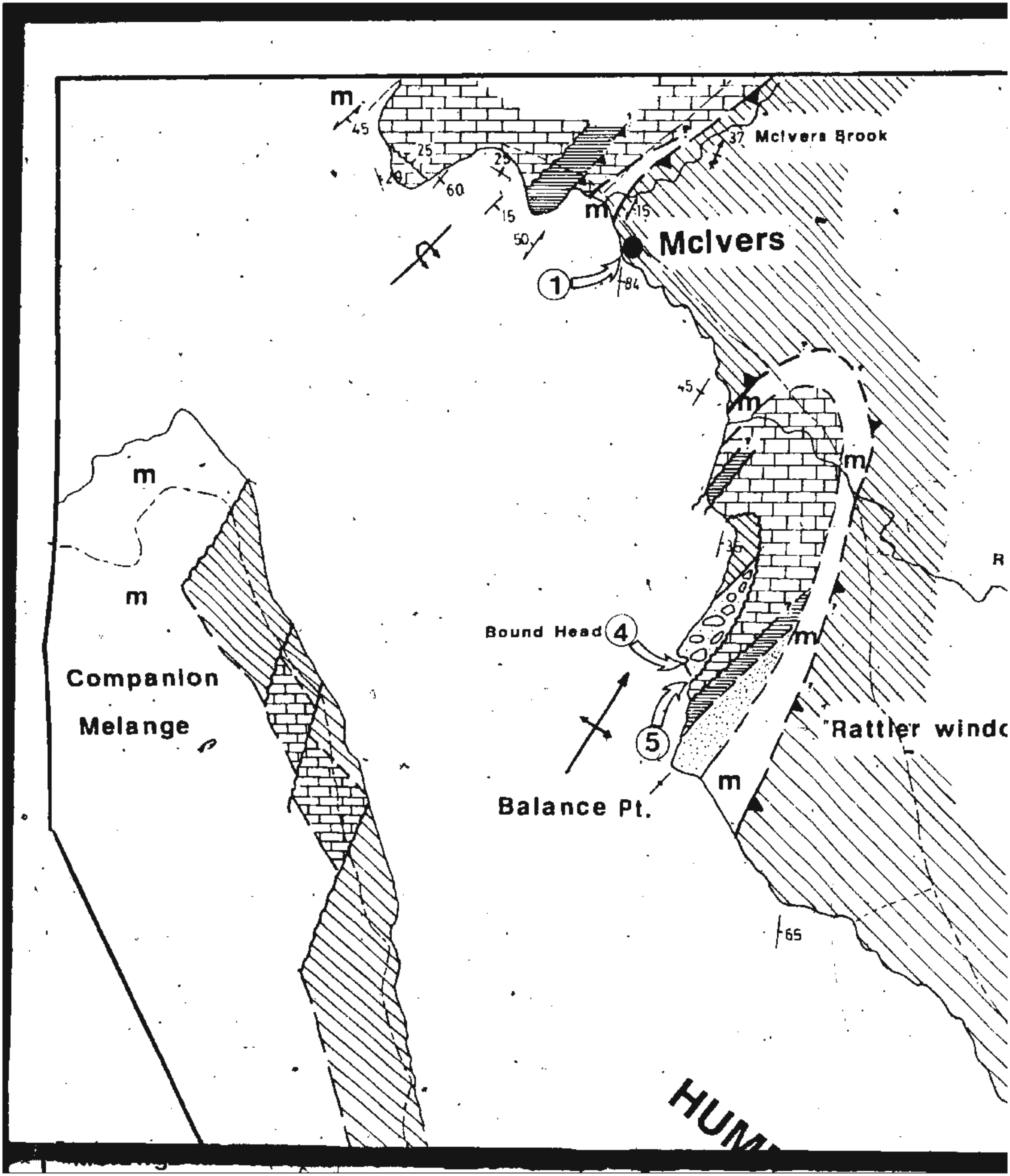
Grassy Cove



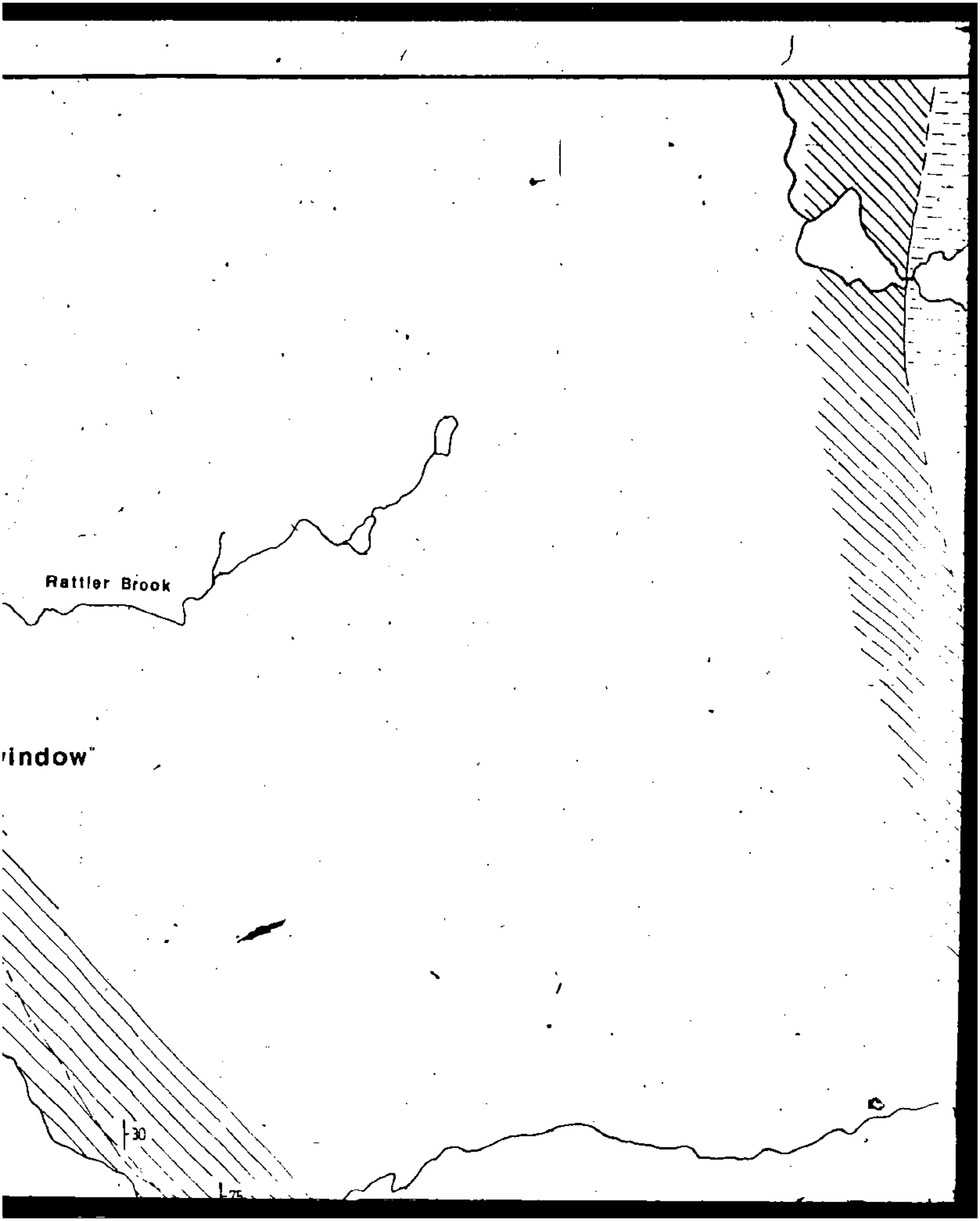

Normal fault
50
Brakes Cv Mbr
7
6
M
25
gn
28
27
26
blk gn
0
23
blk gn dol
25
blk gn
G
blk gn dol
py
blk
py
0
py
Brakes Cv Mbr
Legend
Carbonate conglomerate
G Grainstone-packstone
M Mudstone-wackestone
Parted limestone
Ribbon limestone
Nodular limestone
Dolostone
Siltstone
Sandstone
Conglomeratic sandstone
Shale: thin dolostone beds
Shale: black-blk green-gn
grey-gy red-rd
Chert
Quartz sand Q
Pyrite py
Phosphate ph
Bioturbation
Younging indicator
Parallel laminations
Ripples and cross laminations
Graptolites
Trilobites
Brachiopods

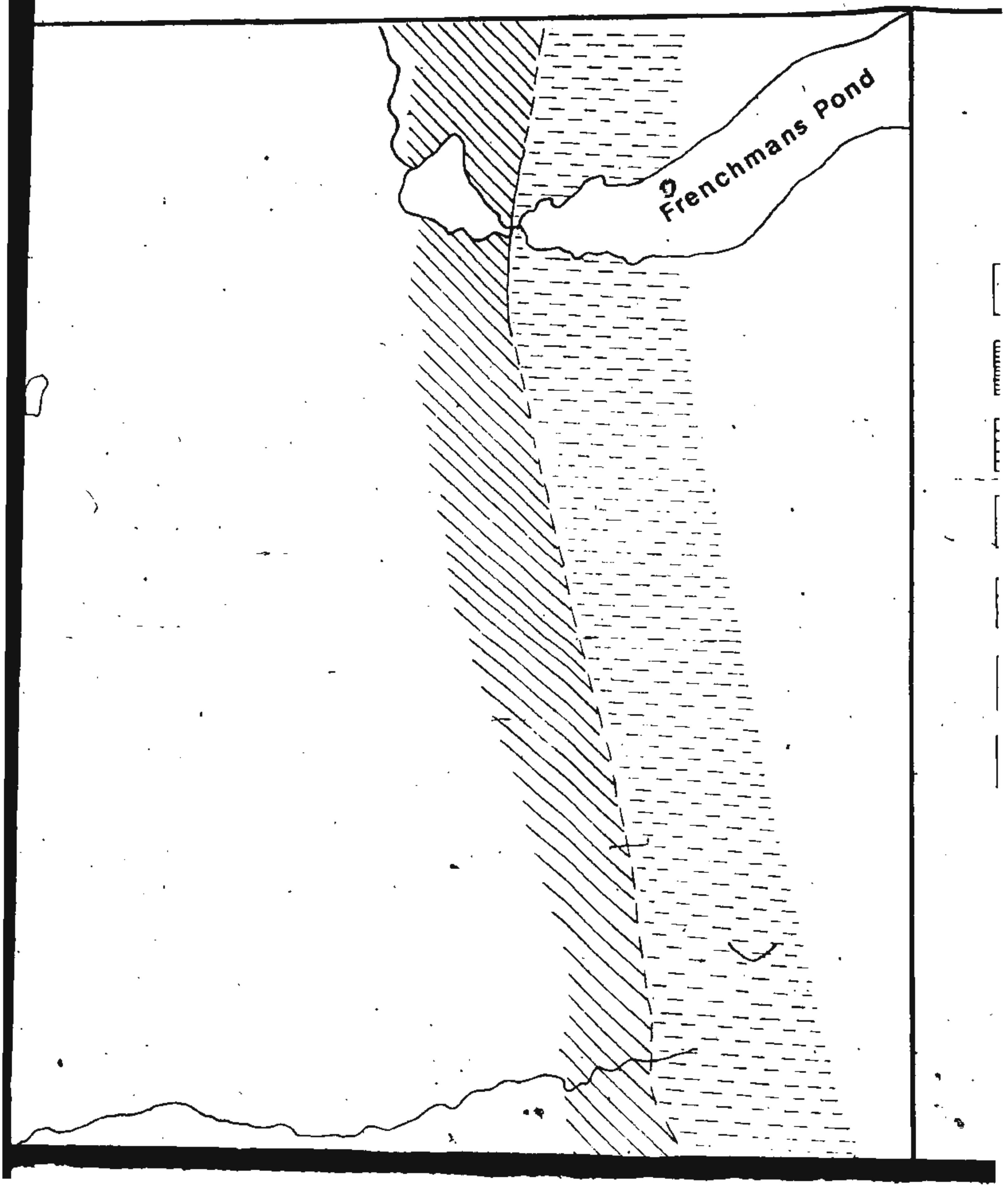


Woman Cove East
gy
M
gy.mica
Major fault:covered in cove
blk(gy)
M
gn(dol)
Drakes Cv Mbr
165
164
blk/gn
M
blk
blk
blk(sulf)
G
125
Covered
Halfway Point Mbr
100
folded raft
75
partially by beach
50
25
blk/gn
54
py
py
53
folded & crenulated dark shale
50



m
Mclvers Brook
Mclvers
1
m
m
m
Companion
Melange
Bound Head
4
5
Balance Pt.
m
m
m
"Rattler windo
HUM


Rattler Brook
indow"
30


Frenchmans Pond

APPENDIX F Geologic map
Bay of Islands, South Sheet

N

Eagle Island Fm.

Middle Arm Point Fm.

Cooks Brook Fm. (undifferentiated)

Cooks Brook Fm. (Halfway Point Mbr.)

Irishtown Fm.

Summerside Fm.

m melange

prominent conglomerate (commonly fossiliferous)

4 Fossil locality (Faunal assemblage listed in Appendix C)

Stratigraphic contact; defined, approximate and assumed

High angle fault; dot indicates downthrown side

45 70 Bedding, tops known; inclined, overturned

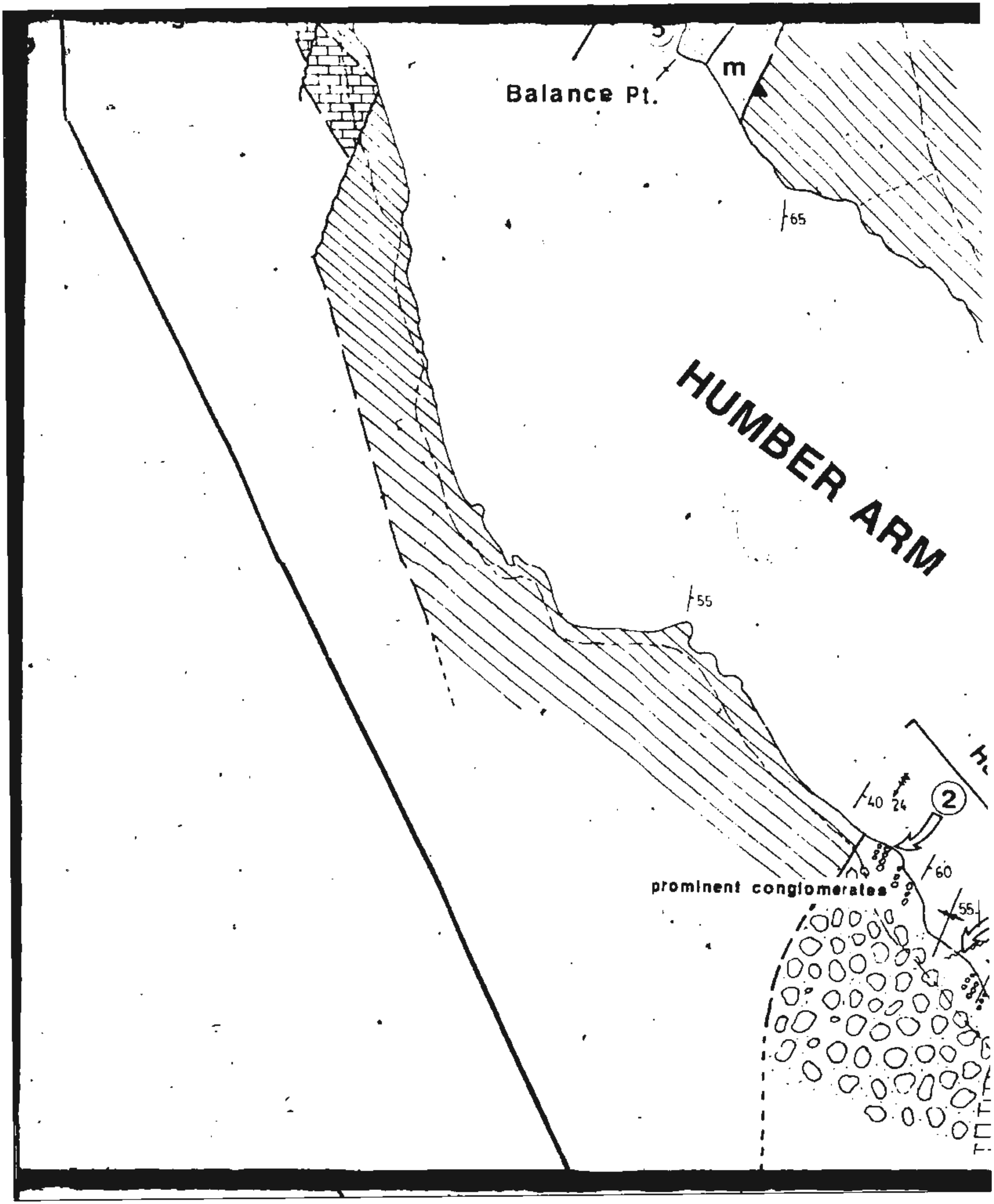
50 axis of minor fold with plunge

45 cleavage (fabric in melange)

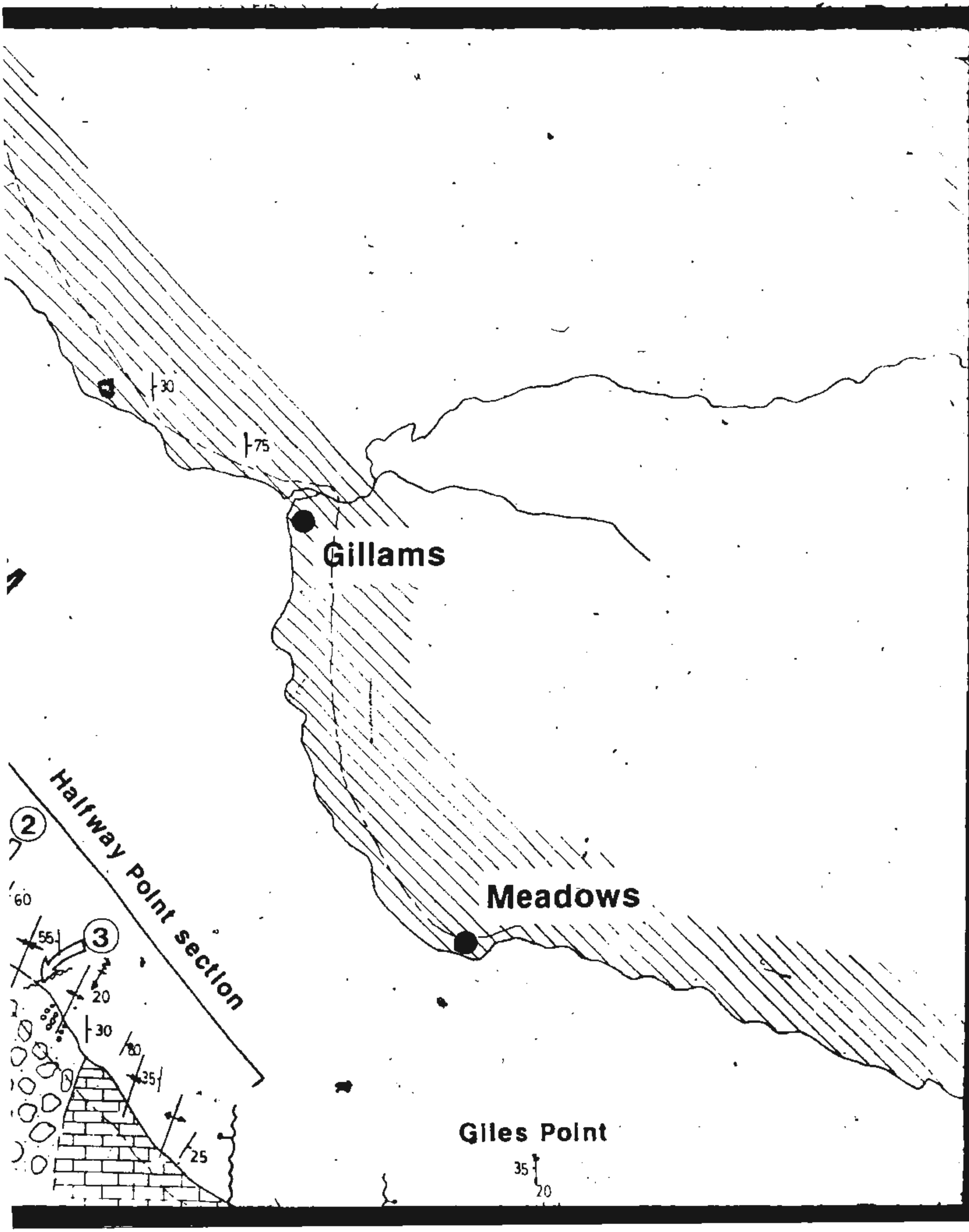
anticlinal axis; upright, reclined

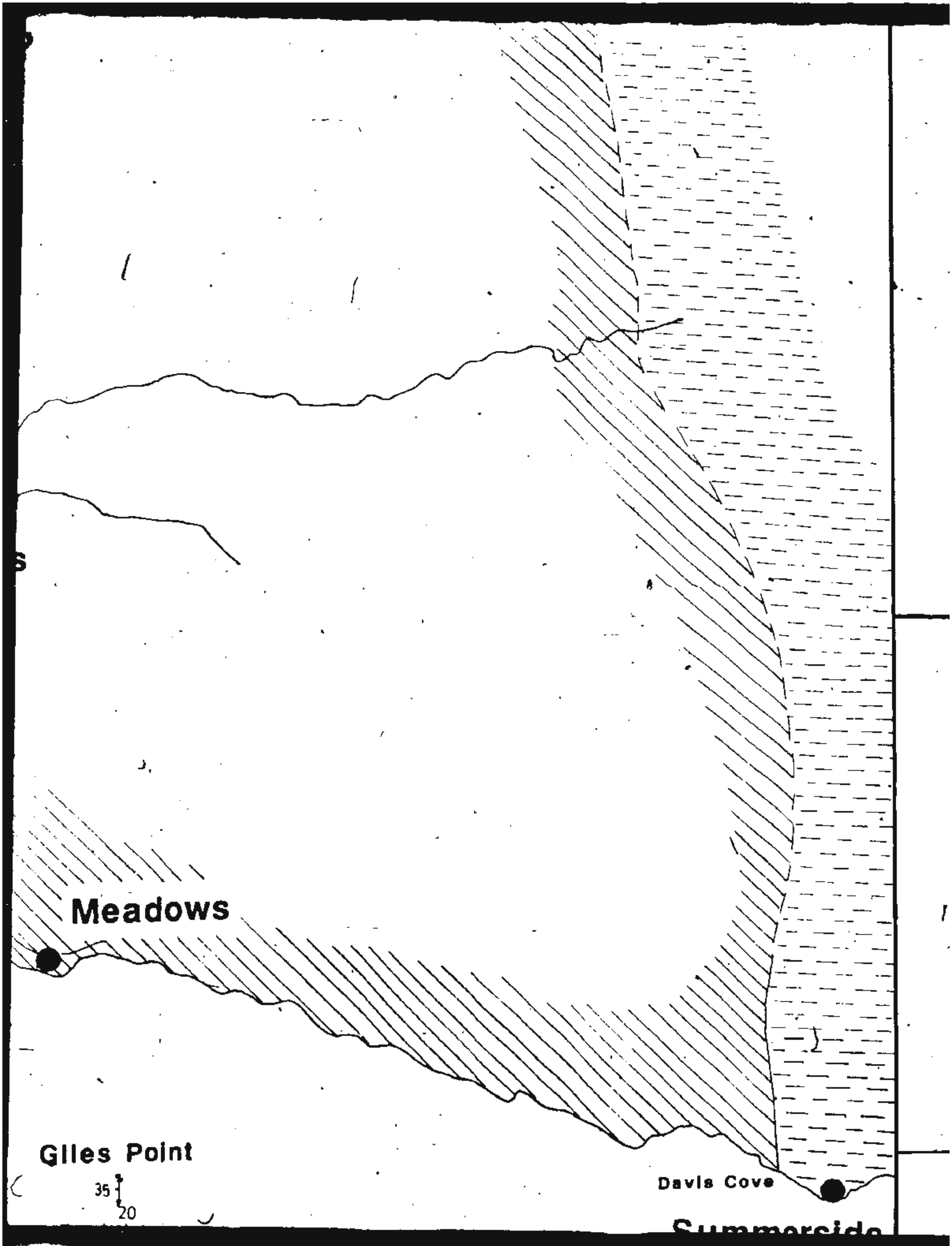
synclinal axis; upright, reclined

Road



Balance Pt.
m
65
HUMBER ARM
55
40
24
2
60
prominent conglomerates
55


Gillams
Meadows
Halfway Point section
Giles Point
2
3
30
75
60
55
20
30
80
35
25
35
20


Meadows
Giles Point
35
20
Davis Cove
Summerside

m melange

prominent conglomerate (commonly fossiliferous)

(4) Fossil locality (Faunal assemblage listed in Appendix C)

Stratigraphic contact; defined, approximate and assumed

High angle fault; dot indicates downthrown side

Road

Bedding, tops known; inclined, overturned

axis of minor fold with plunge

cleavage (fabric in melange)

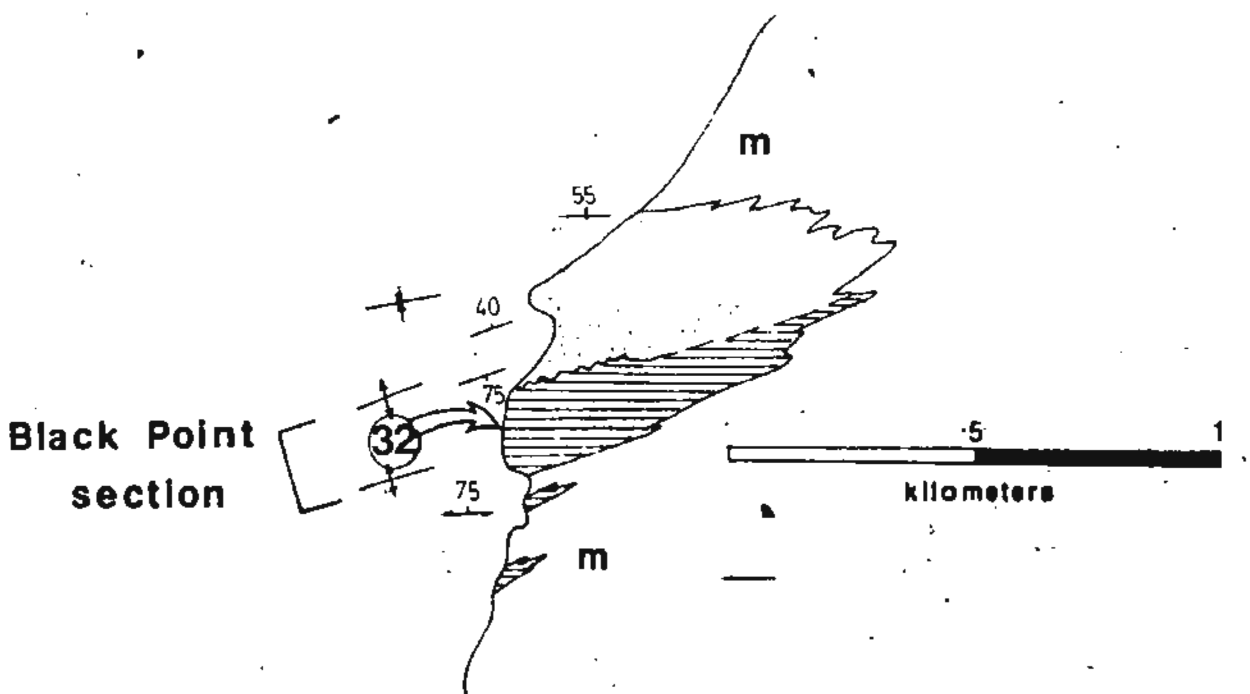
anticlinal axis; upright, reclined

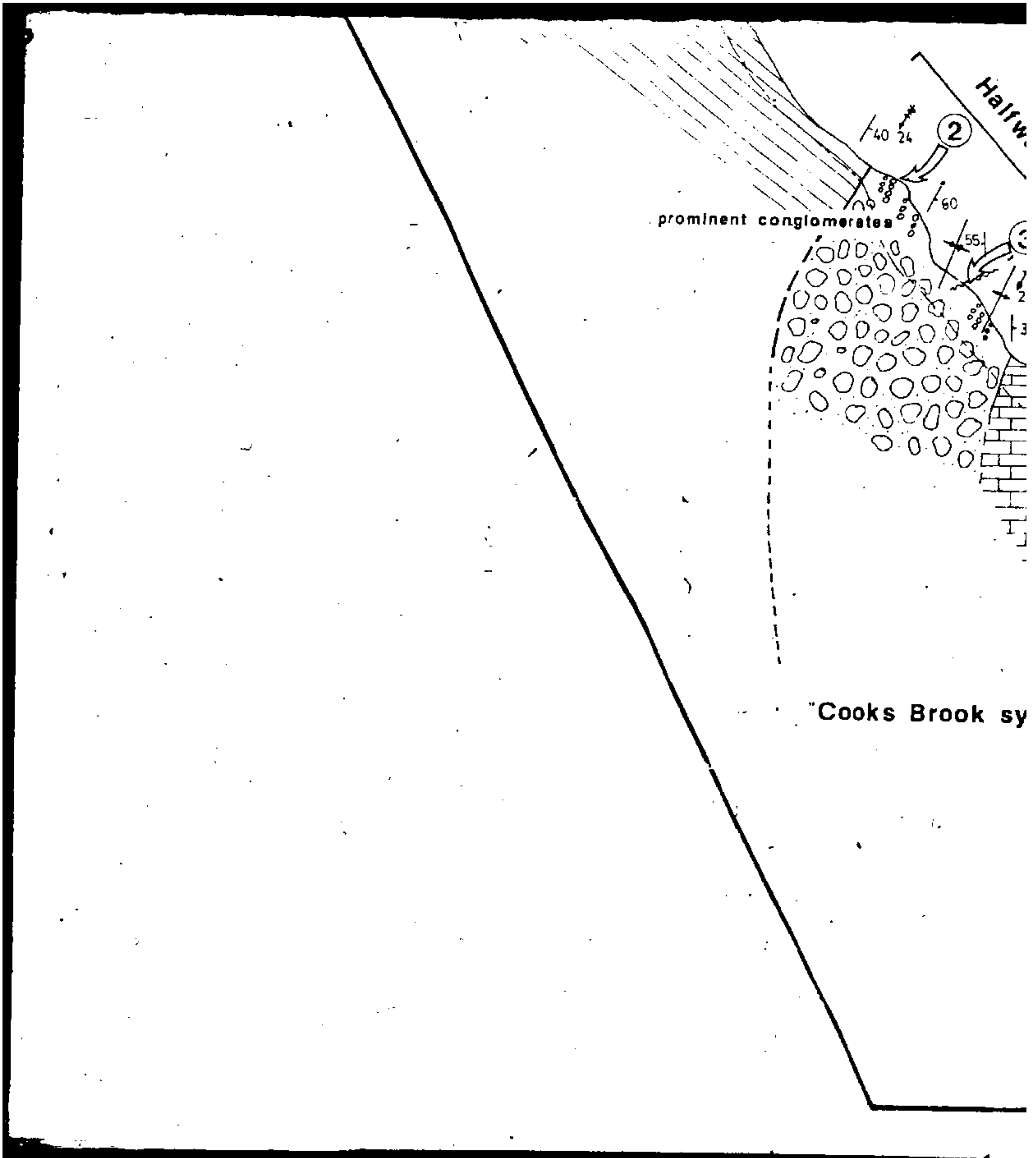
synclinal axis; upright, reclined

1 2 3

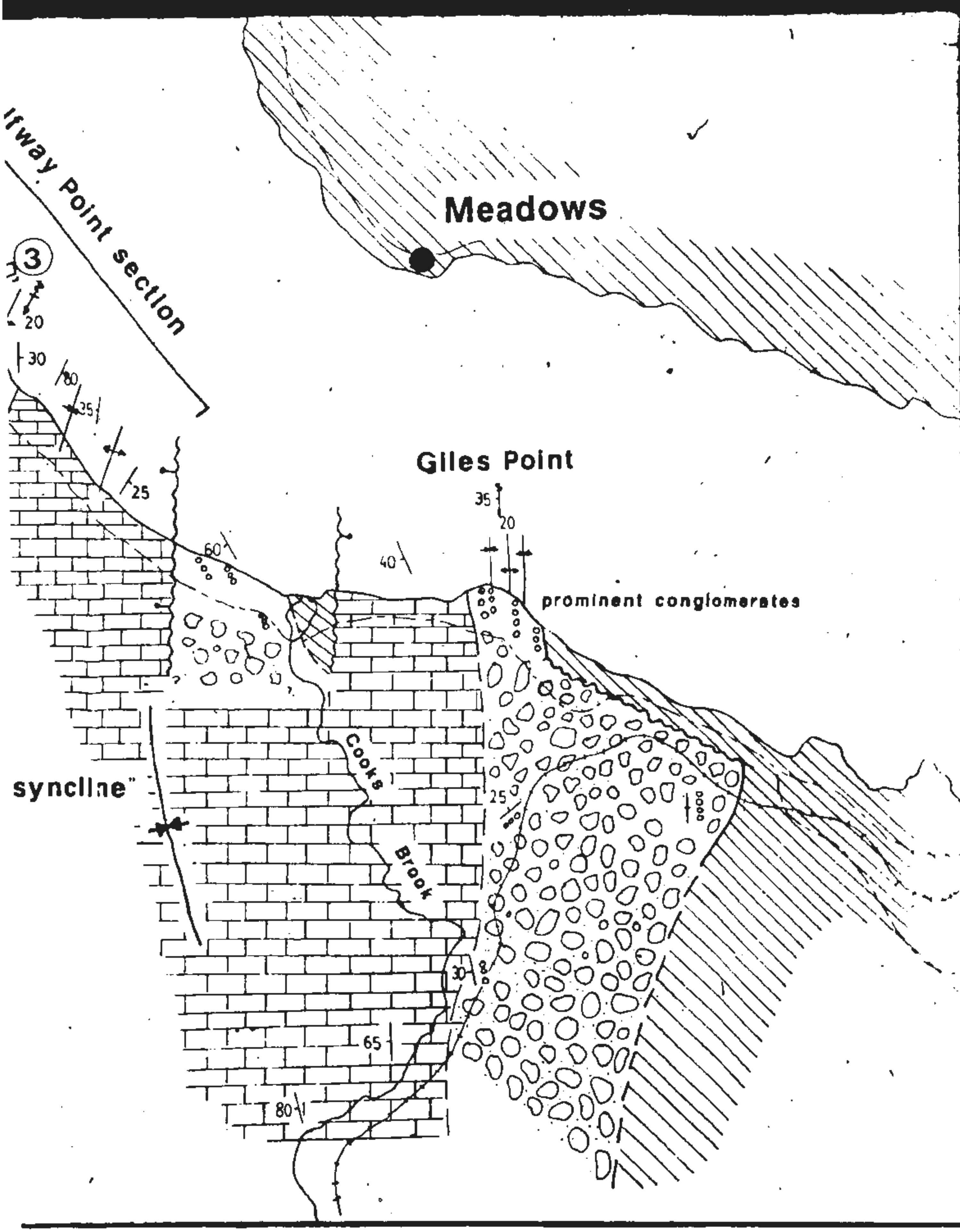
kilometers

INSET Port au Port Area

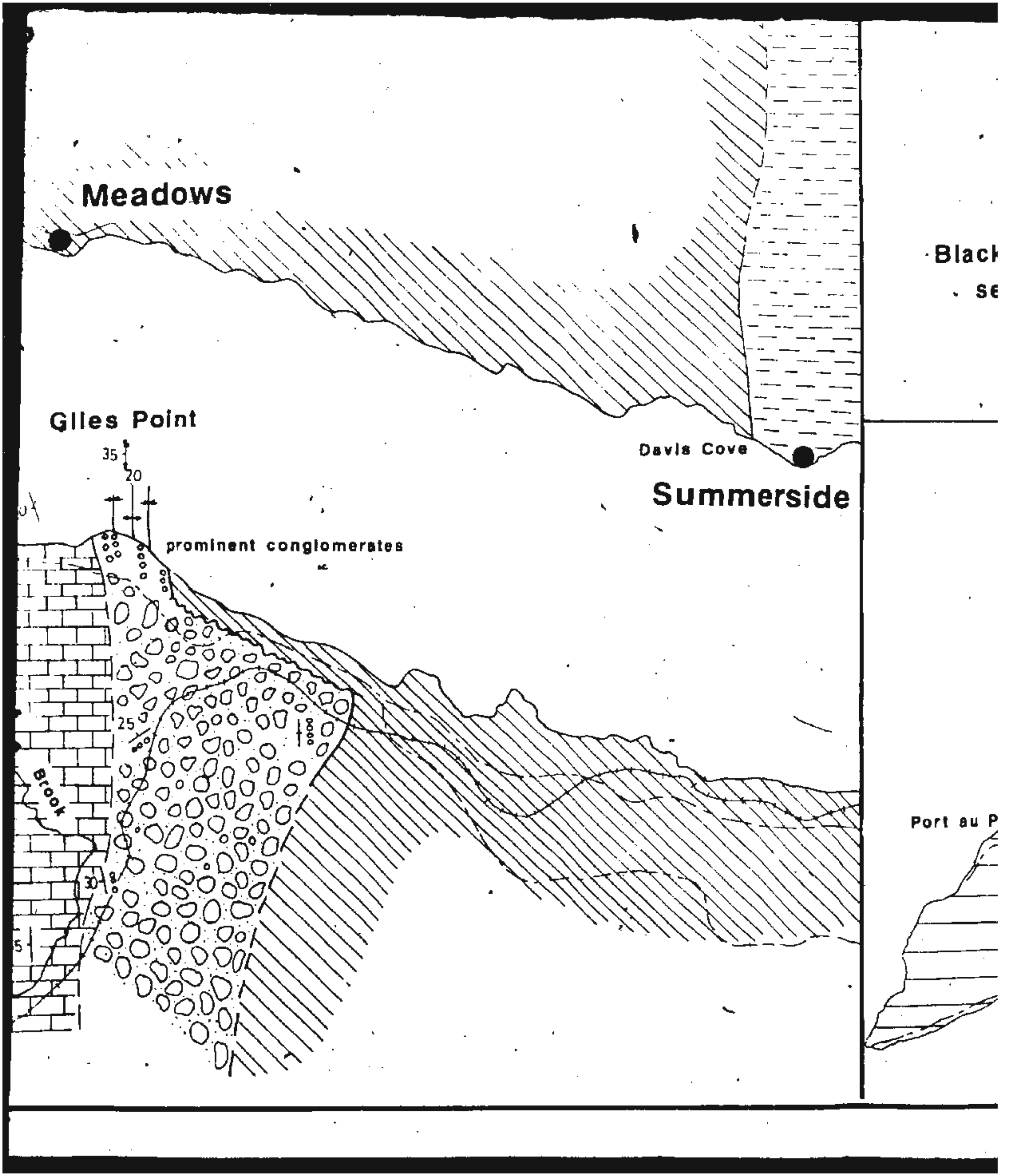


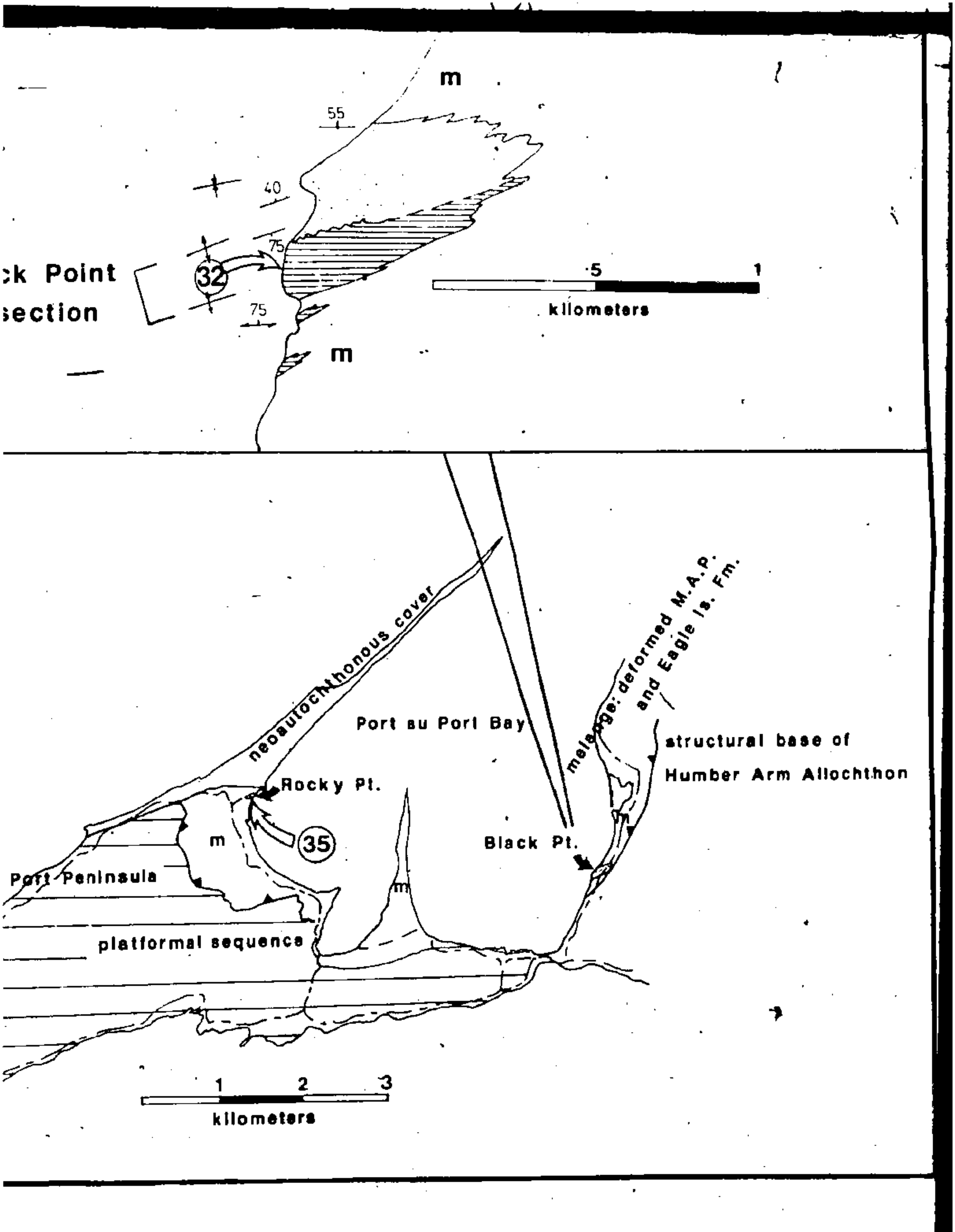


prominent conglomerates
"Cooks Brook sy



Meadows
lfway Point section
3
Giles Point
prominent conglomerates
syncline"
Cooks Brook
20
30
80
35
25
60
40
35
20
25
30
65
80


Meadows
Giles Point
35
20
prominent conglomerates
25
30
Brook
Davis Cove
Summerside
Black
se
Port au P



m
55
40
75
ck Point
section
32
75
.5
1
kilometers
m
neoautochthonous cover
Port au Port Bay
melange: deformed M.A.P. and Eagle Is. Fm.
structural base of Humber Arm Allochthon
Rocky Pt.
35
m
Black Pt.
Port Peninsula
m
platformal sequence
1
2
3
kilometers