THE CODROY GROUP (UPPER MISSISSIPPIAN) ON THE PORT AU PORT PENINSULA, WESTERN NEWFOUNDLAND: STRATIGRAPHY, PALAEONTOLOGY, AND DIAGENESIS

GEORGE ROGER DIX

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THE CODROY GROUP (UPPER MISSISSIPPIAN) ON THE PORT AU PORT PENINSULA, WESTERN NEWFOUNDLAND: STRATIGRAPHY, PALAEONTOLOGY, SEDIMENTOLOGY AND DIAGENESIS.

by

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A thesis
submitted in partial fulfillment of
the requirements for the degree of
Master of Science

Department of Geology
Memorial University of Newfoundland
October 1981

St. John's Newfoundland

Knowledge of its whereabouts
Accounts for time unknown.
Recovered by the elements, the
Surfaces there are shown,
To dissolve away the doubts.

* * * * * *

Carbonates and gypsum
Of a Carboniferous age,
Depict a climate that was hot;
Removed far from the Port au Port's present lot.
Onward time went, and, with a drifting continent,
Yarns of suntanned weather, are now cold Winter's lament.

Two Acrostics - GRD
(in the spirit of Lewis Carroll)

ABSTRACT

Upper Mississippian sediments of the Codroy Group on the Port au Port Peninsula, western Newfoundland, are remnants of a once extensive cover that mantled a karsted palaeoridge of Cambro-Ordovician strata. Today, the sediments are patchily preserved within karst depressions, and adjacent low-lying basins. The present topography of the peninsula is, in part, an exhumed Early Mississippian karst landscape featuring a variety of karren, karst valleys and caves. The Mississippian relic karst has been locally rejuvenated.

Codroy strata constitute three coeval lithofacies: (1) marine carbonates, mainly bioherms, and interbedded fluvial sandstones, (2) marine evaporites, primarily gypsum/anhydrite, with minor laminated limestone and fluvial clastics, and (3) alluvial-fan conglomerates and braided-stream sandstones. Prograding fluvial and alluvial sediments subsequently buried the marine basins.

Fauna and sedimentology indicate that the marine sediments were deposited in a schizohaline environment adjacent to a well-drained landmass. Preserved miospores and plant debris in the limestones, clastics, and gypsum indicate that plants, though not abundant, grew on the slopes of the ridge. Late Mississippian seas along the northern and western margins of the Port au Port ridge supported a prolific community of brachiopods, bryozoans, blue-green algae, molluscs, and ostracodes. Cephalopods, foraminifers, and conodonts are low both in species and individuals, whereas true corals, and crinoids/echinoids are absent.

Fauna traditionally used to differentiate between Upper and Lower Codroy strata are found to occur together within the marine carbonates, but, in two distinct facies. This indicates that the marine macrofauna, and probably microfauna, are facies-controlled prohibiting their use in detailed biostratigraphic zonation.

Marine carbonates infilling palaeokarst valleys may constitute either bryozoan/algal biolithites plastered against the valley walls and/or carbonate mounds of a similar lithology, with associated intermound sediment. The buildups were lithified early as evident by the abundant synsedimentary cement (interpreted to have been magnesium calcite and aragonite).

The complex diagenetic history of the marine carbonates records progression from a marine environment with synsedimentary cementation to a phreatic zone within which occurred fracturing, stylolitization, dissolution and cement precipitation. Mineralization by sulphides and sulphates spans the phreatic diagenetic history. Late stage phreatic cement is pervasive in all other sediments of the carbonate lithofacies as well as throughout the carbonate and clastic sediments of the other lithofacies.

ACKNOWLEDGEMENTS

The completion of the thesis has involved the resources of various people to whom I am indebted. I especially thank Dr. Noel P. James, my supervisor, who suggested the topic, as well as giving generously his time, valuable discussion and advice, concerning the thesis and carbonate geology in general. Bruce King, my field assistant, and "fossil-finder mágnifico", helped to produce an efficient and enjoyable summer of field work. I thank Dr. Bob Stevens for providing his country manor, near West Bay Centre on the Port au Port Peninsula, as living accommodation for the duration of the field work. Financial well-being over the last two years was provided by a Memorial University Fellowship, and field work supported by an NSERC grant to NPJ.

Palaeontological assistance was provided by Dr. R.J. Cuffey (Pennsylvania State University - bryozoans), Dr. P. von Bitter and Ms. H. Gerbel (Royal Ontario Museum - conodonts), Dr. M.S. Barss (Atlantic Geoscience Centre - miospores), Dr. W.H. Forbes (University of Maine - plant fossils), Mr. C. Dewey (Memorial University - ostracodes and tealliocarids), and Dr. R.G. Moore (Acadia University) who corroborated certain of my macrofauna identifications and allowed study of the fossil collection of the Windsor Group at Acadia University.

Dr. V.P. Wright (Cardiff University), Dr. D.F. Strong (Memorial University), and Drs. S. Stouge (Newfoundland Department of Mines and Energy) are thanked for other referenced verbal and/or written discussions concerning aspects of the thesis.

Many professors and graduate students at Memorial University gave valuable discussion concerning aspects of the thesis, Newfoundland and Appalachian geology, and/or anything in particular. Of the professors, I would especially like to thank Drs. Bob Stevens, and Hank Williams.

Thin sections were prepared by Messers. L. Warford and F. Thornhill, line drawings were printed by Mr. W. Marsh, and colourful Figure 46 was printed by Riley's Reproductions and Printing, Ltd., Calgary. Much appreciation is given to Gulf Canada Resources, Inc., for the photoreduction of plates and the time allowed for final preparation of the thesis.

My fingers suffered the typing of the first draft of this tome, and Mrs. Glenys Woodland, Miss Cynthia Neary, and GRD, typed the final draft.

Thank heaven for Red Zinger Tea, and that bolt of citrus flavour.

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CHAPTER I

INTRODUCTION

1.1. General Overview

In western Newfoundland, Lower Carboniferous sediments are preserved as areally extensive cover rock, in the Deer Lake-White Bay and southwest Newfoundland regions, and as small isolated outcrops infilling depressions cut into the underlying Cambro-Ordovician strata on the Port au Port Peninsula. Since Alexander Murray first visited western Newfoundland in the 1870's, the detailed study of Carboniferous stratigraphy and sedimentology has been confined mainly to strata in the two large basins. In both of these regions, cover and/or faulting may complicate the vertical and lateral correlation of stratigraphy.

Interest in the Upper Mississippian strata on the Port au Port Peninsula has largely been confined to (1) the economic potential of sulphide and sulphate mineralization in limestones and sandstones, and (2) the excellent preservation of fossils in the limestones. From the present study, the recognition, within the well exposed Upper Mississippian strata on the peninsula, of bryozoan/algal bioherms, facies-controlled fauna, and the coeval deposition of near-shore marine, evaporitic and terrigenous environments, gives an indication of the complex interrelationships in the stratigraphy and sedimentology that was not recognized by earlier workers.

This study documents the history of the Upper Mississippian strata in terms of their depositional setting, stratigraphy, sedimentology, palaeontology and diagenesis.

1.2. Location and Access

The area of study includes the Port au Port Peninsula, and a small region east, in the vicinity of Stephenville and Kippens (Fig. 1 - in pocket). Topographic maps, 1:50,000 scale, used for field locations, include NTS Map Sheets 12 B/6 (east half), 12B/7 (east half), 12B/10 (west half) and 12B/11.

There is easy access to the peninsula via Stephenville airport, and roads leading into the region from the Trans-Canada Highway. On the peninsula, paved and gravel roads, and walking short distances make most outcrops very accessible.

1.3. Geographical and Topographical Considerations

Most of the coastline on the peninsula and in the region to the east, is cliffed and often indented by numerous coves and bays. Rock exposure along this coastline is excellent though in part inaccessible. Inland, the heavy overgrowth conceals much of the outcrop and makes access by walking difficult.

The peninsula is topographically divided into two regions. The dividing line is represented by a NE-SW trending fault which bounds the western side of two valleys; a northeast-facing valley in the Piccadilly area, and a southwest-facing valley on the south shore near Ship Cove (Fig. 1). The western half of the peninsula is characterized by several plateaus, high elevations, and an approximate radial stream pattern in which many valleys are dry. The eastern part of the peninsula is dominated by a low, east-west trending ridge cut by several north-and south-facing valleys, some with streams. Valleys tend to have steep to vertical walls, are U-shaped, and taper inland with increasing elevation.

East of the peninsula, in the Stephenville-Kippens area, large deposits of Pleistocene glacial outwash cover most of the region, obscuring the Palaeozoic strata. The thick sequence of glacial sediments probably accounts for the lack of a definitive stream pattern, apart from a general southerly flow direction. On the peninsula itself only thin to locally thick Pleistocene glacial sediments are preserved.

1.4. Previous Work

The first detailed account of Carboniferous strata on the Port au Port Peninsula was given by Alexander Murray in 1876 (Murray and Howley, 1881). He recognized a series of north-south trending faults, cutting Carboniferous limestones in several coves on the northeastern shore of the peninsula, and considered the rocks to be 'let down amongst strata of (Ordovician)' (p. 331). Caverns and hollows within the Ordovician strata, encrusted with Carboniferous limestones, were thought to have formed during Carboniferous time by wave action undercutting the Ordovician cliffs.

Mineralization, primarily galena, was noted at Lead Cove, where a previous evaluation of the mining potential had been conducted. Murray (op. cit.) reported that this evaluation had indicated that the mining of the lead was not economically feasible. Other mineralization noted in the area was a thin coal seam at Blanche Brook, and gypsum at

Romaines Brook, both within Carboniferous sediments.

In their study of the stratigraphy of western Newfoundland, Schuchert and Dunbar (1934) also accounted for the preservation of Mississippian sediment on the peninsula by assuming the presence of grabens developed within Ordovician strata.

Hayes and Johnson (1938) collected fauna from very fossiliferous Mississippian limestones, called the Codroy Group by Hayes and Johnson (1937), in the region east and west of Aguathuna Quarry (Fig. 1). These were correlated with similar fossils from the Windsor Group in Nova Scotia and the assemblage was thought to represent a mixture of Upper and Lower Windsor fossils. The Windsor Group had previously been correlated, with Upper Mississippian (Viséan) strata in Britain (Bell, 1929), and was divided into five faunal subzones: the Lower Windsor, subzones A and B; the Upper Windsor, subzones C, D, and E. Hayes and Johnson (1938) also considered the Codroy to be deposited in graben structures in the Ordovician strata.

Sullivan (1940) briefly described Codroy strata in the Aguathuna region and in Big Cove, on the west shore of the peninsula, and listed part of the fauna collected from both regions. As with the previous authors, he thought the coves represented grabens filled with strata of Mississippian age.

Bell (1948) briefly resampled an outcrop of Codroy sediment in Aguathuna Quarry that Hayes and Johnson (1938) had reported. This is an "island" of Codroy and Ordovician strata left standing due to quarrying operations. He came to the conclusion that the preserved sediments were equivalent to the Upper Windsor sediments.

Bell was the first to consider the coves on the northeastern coast of the peninsula as karst in origin. In addition, at Boswarlos, west of Aguathuna, he recognized strata of the Codroy Group to be equivalent to and slightly younger than the type section in southwestern Newfoundland (the Ship Cove Limestone). Bell considered the Boswarlos strata to represent the first marine transgression in the region, with the second transgression represented by the more fossiliferous Aguathuna-type limestones. This stratigraphy was used by Weller _et al_. (1948) for the Port au Port region in their compilation of Mississippian formations of North America. The Boswarlos beds, however, were placed stratigraphically above a unit of red-beds. Though red-beds occur on the south side of the peninsula, no mention of this unit was made by Weller _et al_. (op. cit.) or their source of information listed as Hayes and Johnson (1938).

Baird (1951) mentioned the presence of large gypsum outcrops at Romaines Brook and in the subsurface south of Boswarlos. He considered the deposits to represent the filling of small basins which overlapped onto the Ordovician basement.

Johnson (1954) described various sulphate occurrences in Gillam's Creek, and Ronan Brook, both west of Aguathuna Quarry.

Riley (1962), in a summary of the stratigraphy of the Stephenville map area, noted that red-matrix conglomerates occur along the south shore of the peninsula, north of Cape St. George, and at Red Island west of the peninsula. These may be the red-beds mentioned by Weller _et al_. (1948). Riley (op. cit.) considered these deposits to be Late Codroy in age. Miospores taken from the coal seam, in Blanche

Brook, that Murray mentioned (Murray and Howley, 1881) yielded an age of Middle Pennsylvanian (cited in Riley (op. cit.)).

Belt (1968) refers to the presence of Barachois sediments (Lower Pennsylvanian) on the Port au Port Peninsula but does not state a location. The Barachois strata overlie the Codroy Group in southwestern Newfoundland. Apparently, these beds yielded miospores indicating a Barachois affinity (cited in Belt (1968) as: Barss - written comm., 1966). This conclusion is not substantiated by the results of the present study.

Fong (1972) described well preserved remains of a crustacean, <u>Bellocaris</u> <u>newfoundlandensis</u> Fong, recovered from the sediments in Aguathuna "Island". Bell (1948) had mentioned the occurrence of crustaceans in the basal Codroy strata at Boswarlos.

Besaw (1974), in a study of limestone evaluation on the peninsula, mapped the many Upper Mississippian localities. It is on the basis of his map that the writer was able to locate the Upper Mississippian outcrops.

Von Bitter and Gerbel (in press) sampled conodonts from the Upper Mississippian sediments in the northeastern part of the peninsula. Conodonts were recovered primarily from the Aguathuna Quarry "Island", the basal Codroy member at Boswarlos, and Romaines Brook (where it occurs as well). They consider all the outcrops to be of equivalent age, and, that based on sampling of the Ship Cove Limestone, the Port au Port outcrops are equivalent to Bell's subzone A. They also suggest, however, that the range of the diagnostic conodonts used for the correlation may extend throughout subzone B.

The most recent geological map for the Port au Port Peninsula is by Williams (Geological Survey of Canada, Open File No. 726, 1981).

Private companies have looked at the Upper Mississippian strata with interest toward the mineralization. The reader is directed to NTS Geoscan (1979) for a complete bibliography.

1.5. General Geology

To place Upper Mississippian strata of the Port au Port Peninsula into proper tectono-stratigraphic perspective, a brief review of the geology of western Newfoundland follows.

1.5.1. Pre-Carboniferous Strata

Newfoundland represents the northeasterly extension of the Appalachian Orogen exposed in North America. Williams (1964) recognized three geological provinces by which to subdivide the island: the Western Platform, the Central Mobile Belt, and the Avalon Platform. This tripartite division acknowledged a general geological symmetry of two platforms separated by a central volcanic region.

With the concept of plate tectonics, as proposed by Wilson (1966) and Bird and Dewey (1970), the symmetrical zonation in Newfoundland fitted well with the idea of two plates colliding with oceanic material caught in between. Williams (1979) subsequently divided the island into four zones based on general tectono-stratigraphic similarities: from west to east, the Humber, Dunnage, Gander, and Avalon Zones. Therefore, two discrete continental plates, the Humber and Avalon Zones, with the Gander Zone acting as a continental slope-rise sedimentary prism related to the Avalon (Kennedy, 1976), are separated by the Dunnage Zone, the vestiges of the ancient ocean, Iapetus.

The Port au Port Peninsula is the most westerly part of the Humber Zone in Newfoundland. Geologically, it contains part of the clastic-carbonate sedimentary prism that developed on the stable cratonic platform of proto-North America. The sedimentary units that characterize this are the Kippens Formation, March Point Formation and Petit Jardin Formation, all of Cambrian age, overlain by the St. George Group, Early Ordovician in age (Fig. 1). Evidence for deepening and destruction of the stable platform due to plate collision is reflected, in part, by the changing carbonate lithology within the Table Head Group (Klappa <u>et al</u>., 1980), which is Middle Ordovician in age. On the peninsula, the Table Head Group appears to unconformably overlie the St. George Group.

In western Newfoundland, the Taconic Orogeny is represented by westward-directed flysch, obducted ophiolites, and related transported sediments that were deposited and emplaced onto the Cambro-Ordovician strata (Williams, 1975). On the peninsula, only a sequence of transported sediments, and mafic volcanics, of the Humber Arm Supergroup reflect this obduction (Fig. 1).

The transported strata are overlain by the Long Point Group, Middle Ordovician in age, with an interpreted unconformable contact (Rodgers, 1965). The Long Point lithology, which includes reefal carbonates, indicates the return of stable shallow water conditions.

Overlying the Long Point Group are marine to non-marine sediments of the Clam Bank Formation, Silurian to Devonian in age.

During the Acadian Orogeny (Late Devonian), the peninsula was uplifted and faulted. A karst topography, exhibiting a variety of landforms, was developed on the carbonate strata of the St. George and Table Head Groups prior to deposition of Upper Mississippian sediments. A more extensive and detailed discussion of this karst is given in Chapter 2.

1.5.2 Carboniferous of Southwestern Newfoundland

(i) Introduction

Other sediments of Mississippian and Pennsylvanian age (Fig. 2) are located in the Deer Lake-White Bay district (Hyde, 1979), in southwestern Newfoundland (e.g., Hayes and Johnson, 1938; Bell, 1948; Baird and Cote, 1964; Fong, 1976; and Knight, 1976), small isolated regions in southeast Newfoundland (Strong, 1978), offshore, along the south, west, and northeast coasts of the island, and along the southeast coast of Labrador (cited, in Hyde, 1979; and Barss, et al., 1978). Upper Mississippian strata on the Port au Port Peninsula are equivalent in age, and similar in stratigraphy to part of the Carboniferous sequence along the southeast coast of St. George's Bay (southwest Newfoundland).

To place the Upper Mississippian sediments of the peninsula in proper perspective with regard to sedimentation in the southwestern Newfoundland Carboniferous basin, a brief summary is given of the lithostratigraphy, and interpreted environments to the south.

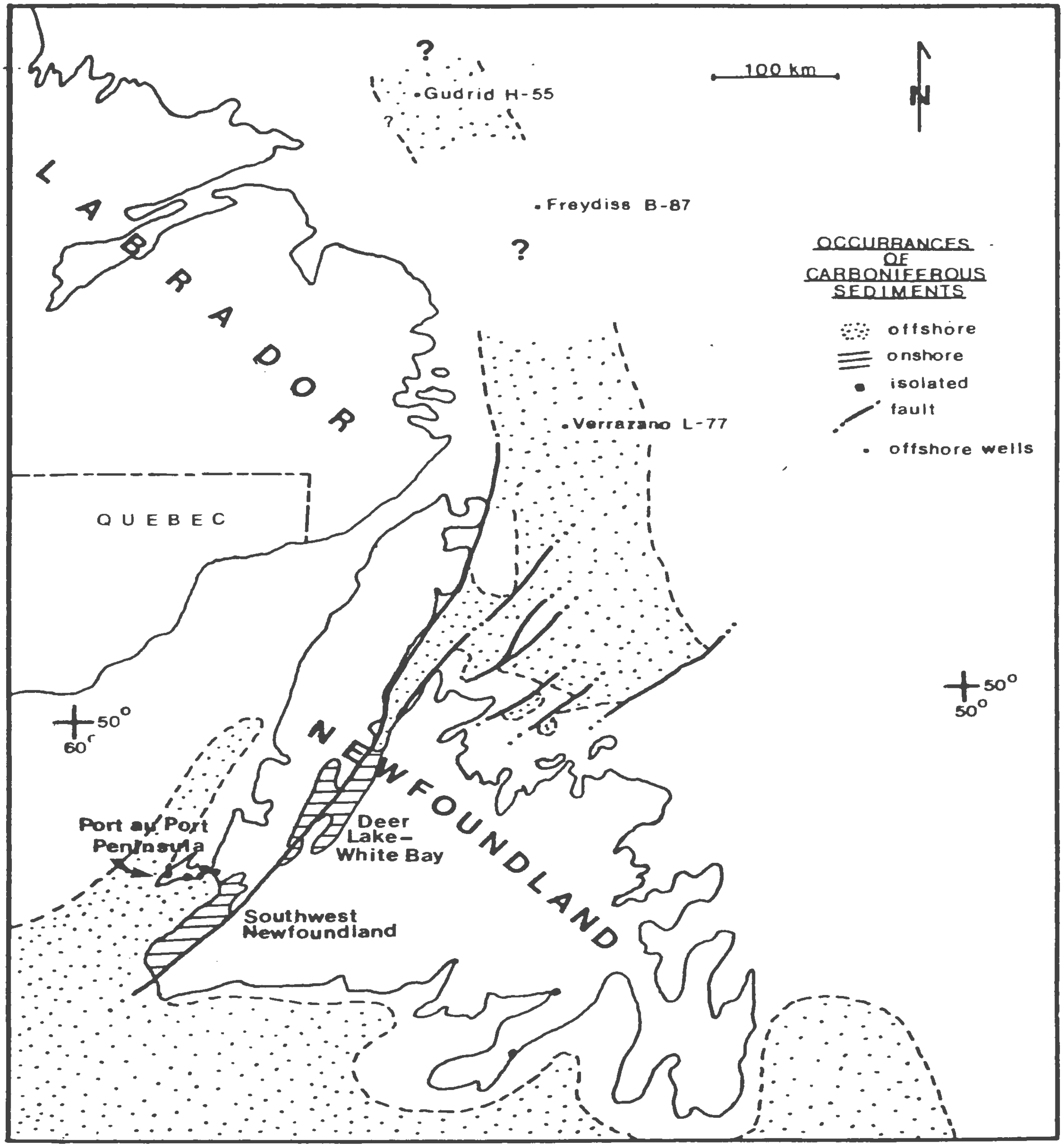

FIGURE 2: Distribution of Carboniferous strata in and around Newfoundland (data from Hyde, 1979; and Barss *et al.*, 1978)

(ii) General Background

The lithostratigraphic subdivisions of the Mississippian and Pennsylvanian sediments are shown in Figure 3, along with the stratigraphic interpretation of the Port au Port Upper Mississippian strata by Weller et al. (1948). Any estimate of thickness of the Codroy Group in southwestern Newfoundland is complicated by abundant folding and faulting throughout the section (Bell, 1948; and Baird and Coté, 1964).

Faults that initiate, and are coeval with, sedimentation prohibit the development of well preserved marker horizons (Hayes and Johnson, 1938; Baird and Coté, 1964), and a well developed faunal assemblage (Bell, 1948), making correct correlation estimates across fault zones very tenuous.

In southwest Newfoundland, the Codroy Group represents deposition of marine to non-marine sediments within a shallow basin that was fault bounded on the southeast by highlands (Belt, 1968). It appears that this same basin extended well into Nova Scotia and New Brunswick (Hacquebard, 1972).

(iii) Codroy Group

The initial sediments of the Codroy Group, the Ship Cove Limestone, record a marine transgression over alluvial braided stream sediments of the Lower Mississippian Anguille Group (Bell, 1948). The Ship Cove limestone is well-laminated, pelleted, and in certain facies, very arenaceous. Overlying the limestone are the Codroy Beds; a thick succession of well-bedded to laminated gypsiferous siltstones to

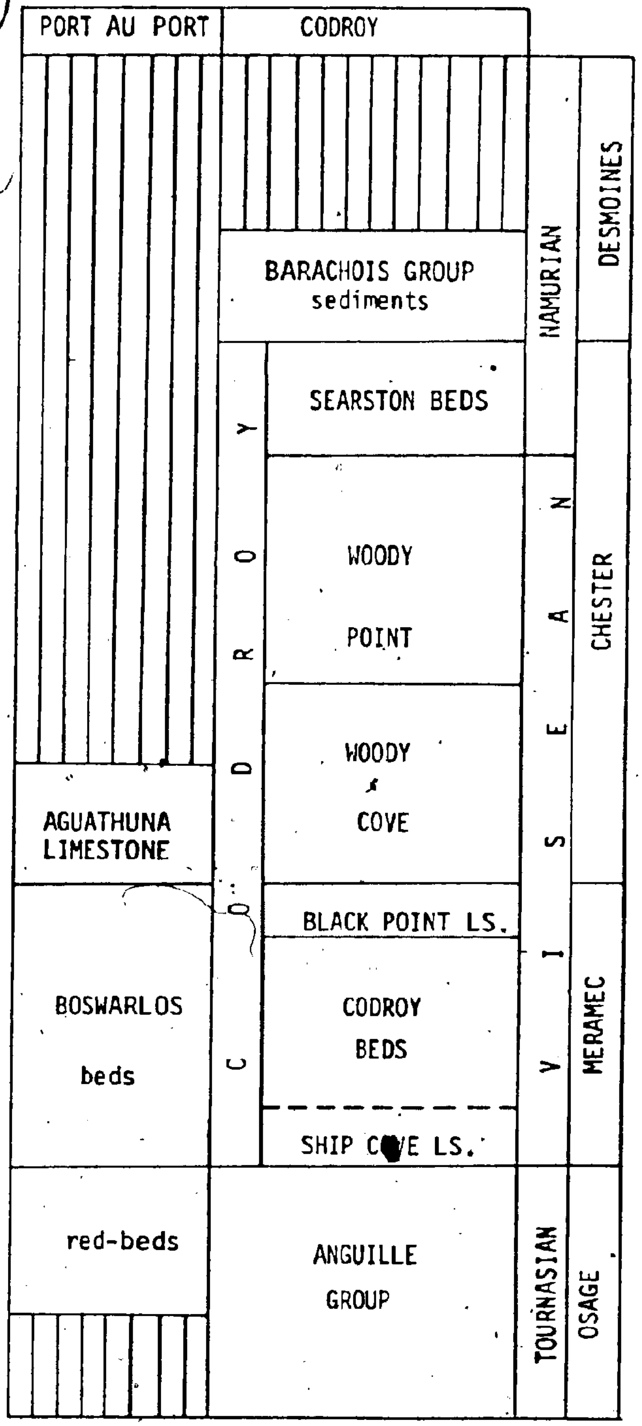

FIGURE 3: Stratigraphic chart for the Port au Port area (as per Weller <u>et al</u>, 1948), and the Codroy area (southwestern Newfoundland), (Bell, 1948).

mudstones, several distinct gypsum zones, and rare but distinctive limestone units within the upper part. The Ship Cove Limestone, the Codroy Beds, and the distinctive limestone units comprise the Lower Codroy.

Overlying the Lower Codroy are sandstones and siltstones of the Woody Cove beds. Rare and thin argillaceous limestones with both marine and freshwater fauna occur in this unit as well (Baird and Coté, 1964). Overlying the Woody Cove are the Woody Point strata which are also sandstones and siltstones, with pebble lenses and well developed cross-bedding becoming important in the sandstones eastward towards the faultbound highlands. Thin and very argillaceous limestone beds may also occur in this unit, containing freshwater to brackish water fauna (Bell, 1948).

(iv) Searston Beds

These sediments are composed of very distinctive micaceous green siltstones to sandstones, with pebble conglomerate lenses associated with abundant trough cross-beds. This unit was considered to be part of the Codroy Group and the overlying Barachois Group by Bell (1948). Knight (1976) suggested that the unit is either younger or equivalent with the Upper Codroy. The difficulty in correlation is due to faults which bound both the Upper Codroy units, and the Searston Beds. Plant and tree debris within the unit, as well as miospore data, indicate a very Late Mississippian (or Namurian) to Early Pennsylvanian age (Bell, 1948; Utting, 1964).

(v) Barachois Group

The Barachois Group consists of fine to coarse-grained brownish feldspathic sandstones often with ripples, trough cross-bedding, and abundant conglomeratic lenses (Hayes and Johnson, 1938). Several coal seams and abundant plant fossils are found in the unit. The age of these strata is Middle Pennsylvanian.

(vi) Tectonic-Environment Analyses

During the Late Mississippian (Viséan), a shallow sea transgressed the Codroy Basin depositing the Ship Cove Limestone. With fluctuations in sea level, gypsum and limestone (e.g. Black Point Limestone) were deposited with siltstones indicating the continuation of a very shallow sea. Uplift in the southeast highlands resulted in terrestrial and fluvial sediments being shed westward and northwestward into the basin (Woody Cove and Woody Point). With continual uplift, marine conditions completely disappeared and fluvial conditions prevailed during the time of the Searstôn Beds and the Barachois Group.

1.6. Summary

Certain elements of the southwest Newfoundland Carboniferous stratigraphy, tectonics, and environment are similar with the Upper Mississippian sediments on the Port au Port Peninsula. These similarities include the Ship Cove Limestone, laminated gypsum, bryozoan bioherms, fluvial clastics, alluvial red-beds, and similar times of red-bed progradation.

Two important differences, however, occur between the two regions. First, Port au Port sediments are generally well exposed and preserved, with important stratigraphic contacts preserved. This is primarily the result of little post-Mississippian faulting complicating or destroying the original stratigraphic assemblage. Second, a well preserved karst topography, of Lower Mississippian age, is developed on the Ordovician carbonates. This karst, with its valleys and other depressions, played a major role in controlling the style, distribution, and preservation of Upper Mississippian sediments.

CHAPTER 2

LOWER MISSISSIPPIAN KARST ON THE CAMBRO-ORDOVICIAN CARBONATES

2.1. Introduction

Karst topography is well developed on deformed Middle to Lower Ordovician carbonates which underlie most of the Port au Port Peninsula. On a large scale this topography is manifested by valleys and gullies. There is considerable variation in the width and depth of these depressions, from broad and shallow to narrow and deeply incised, with the interdepression 'plateaus' exhibiting an undulating microtopography of incised furrows, shallow basins, and microplateaus, which mimic the large scale features.

Karst landforms are best preserved and exposed along the coastline, and inland within two kilometres of the shore. With increasing elevation, the valleys and gullies either disappear or become too shallow to recognize. The microtopography, however, may still be present inland. There are three regions on the peninsula which exhibit a good exposed karst landscape (Fig. 4):

(1) the highlands from Cape St. George north to Big Cove;

(2) isolated locations along the south coast, notably between Sheaves Cove and Fiods Cove;

(3) the coastline, and parts inland, in the northeast region of the peninsula between Boswarlos and The Gravels.

Two other minor localities also display some karst features; (a) Dory Cove, and (b) South Head (Fig. 4).

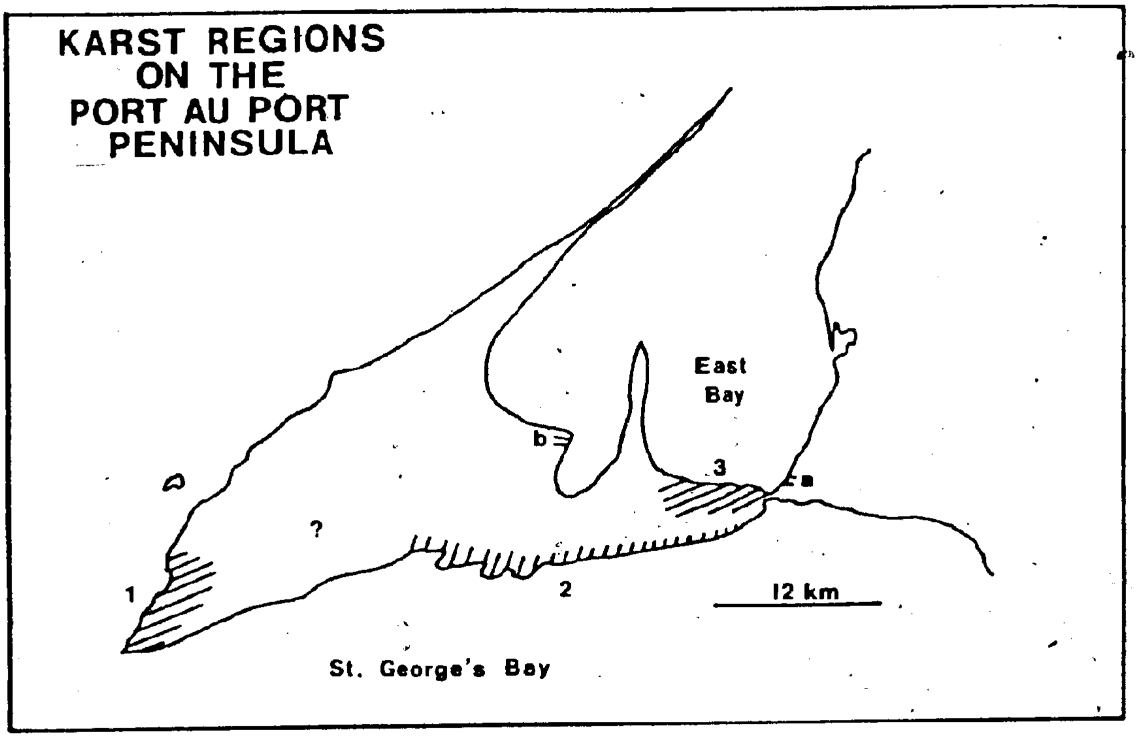

FIGURE 4: Distribution of karst on the Port au Port Peninsula.

Karst terrains have been exhaustively classified (see Quinlan, 1972; Sweeting, 1973; and Bögli, 1980). Terminology used in this present study is a mixture of the classifications used by these authors. Several types of karst (including bare, subsoil and mantled karst) and associated solution features can be recognized on the peninsula, and are described below in general terms, to provide a framework in which to place the Late Mississippian sedimentation.

Historically, the origin of the large deeply incised valleys and coves in the northeastern part of the peninsula were first considered to be related to graben development (Murray and Howley, 1881; Schuchert and Dunbar, 1934; Hayes and Johnson, 1938; Sullivan, 1940). Bell (1948) and Johnson (1954), however, attributed the origin of the coves to karstification. Upper Mississippian sediments clearly overlie the karst valleys and a few of the smaller solution features. Though faults do cut Mississippian beds, the contact between Ordovician and Mississippian strata is clearly depositional. Along the south coast of the peninsula, depressions, herein interpreted as karst depressions, developed on the St. George Group carbonates and later infilled with red-matrix conglomerates, were reported by Riley (1962) and Besaw (1974). Descriptions, or mention, of small scale karst solution features do not appear in the literature. Karst features along the south and north coasts cut across the attitude of the Ordovician strata. The uplift which has resulted in the northward dip of strata occurred during the Acadian Orogeny.

2.2. Parameters for Karst Development

> 'Karst may be defined as an aggregate of characteristic landforms and subsurface features produced primarily as a result of solutional removal of (bedrock)'
>
> (Quinlan, 1972; pg. 157)

Sediment solution, precipitation, transport and deposition usually accompany the karstification process. Karstification refers to the concomittance of any of the above processes during which the topography approaches that of a karst terrain. The degree of karst development in any region is dependent upon six parameters: (1) lithology, (2) permeability, (3) physiography, (4) hydraulic gradient, (5) climate, and (6) time. The hydraulic regime, fundamental for karst development is in turn determined and modified by the above factors. In turn, with time, the karst waters will modify the region's physiography.

No studies of the present day groundwater hydraulic regime or surface runoff were undertaken in this study. If modern karstification is affecting the Ordovician carbonates, it is observed only as a surface runoff phenomenon restricted to furrows and small shallow basins, some of which may possess soil cover. The furrows may be as deep as one metre, and it is uncertain whether the present runoff could produce these furrows. The recognition of similar features overlain by Upper Mississippian sediments suggests that the cover had been eroded and the karst rejuvenated (see Age of Karst). In terms of an analyses of parameters affecting pre-modern karst development, only the host rock lithology and permeability can be discussed with confidence.

Most karst landscapes are developed in limestone and dolomite, though gypsum karst is very common (Sweeting, 1973). The texture and composition of the host carbonate is reflected in the response of the strata to karstification. Relatively pure massive, thickly bedded carbonates are most susceptable to maximum development of karst, called holokarst (Sweeting, 1973). In areas underlain by massive impermeable carbonates, karst waters are channelled into joints and along faults within the rock. These structures become zones of permeability and may be widened by solution of the host rock, or infilled by precipitation of calcium carbonate from the karst waters. This type of karstification is well displayed by the Table Point Formation on the peninsula. Joints, and vertical to horizontal surfaces, exhibit surface solution textures.

In rock strata of alternating lithologies and permeabilities, preferential solution of the more permeable beds will allow intrastratal movement of the karst waters whereas the impermeable beds will only allow water to pass along joints or faults. With time, subsidence and collapse of strata will occur along the zones of karstification. This type of karstification is interpreted to have occurred in the St. George Group which is composed of interbedded dolomites, massive limestones, and dolomitic and limey shales. Surface features as formed on the Table Point limestone are rare and usually only occur on a massive limestone member of the St. George Group. The pre-existing northward dip of the Ordovician carbonates may enhance the percolation of karst waters along the bedding planes making strata, such as the St. George Group carbonates, more susceptable to cave formation. With respect to the Table Point limestone, karst surface features are enhanced downdip.

2.3. Types of Karst on the Peninsula

Karst may be classified on the basis of two criteria: (1) lithologic and stratigraphic relationships between the karst surface and overlying sediment (e.g. Bare karst, Subsoil karst, and Mantled karst), and (2) the present dynamics of the karst system (Modern and Relic karst).

2.3.1. Stratigraphic Criteria

Three varieties of karst can be observed in various locations on the Port au Port Peninsula.

(i) Bare Karst - Karsted strata which possess no cover are considered as bare karst. Examples of this can be found east and southeast of Big Cove well above sea level, and south of Gillams Cove, Aguathuna Quarry and Mistaken Cove (Fig. 35, in pocket).

(ii) Subsoil Karst - Karst with a covering of Holocene soil is called subsoil karst. Examples may be found just south of Mistaken Cove and Bellman's Cove, in areas south of Gillams Cove and Aguathuna Quarry (Fig. 35), and in isolated regions southeast of Big Cove (Fig. 1).

(iii) Mantled Karst - This term refers to a karst landscape that is covered by a relatively thin cover of post-karst strata. On the northeastern and southern shores of the Port au Port Peninsula, post-karst strata of Late Mississippian age, equivalent to the Lower Codroy, may be as much as 18 metres thick, infilling and overlying karst depressions. At Cape St. George, approximately 100 metres of conglomerate infills an interpreted karst depression. This is the largest karst feature on the peninsula. The base of many of the larger depressions is not exposed as modern beach deposits cover the contact.

Examples that show good karst contacts with the Upper Mississippian sediments are: (a) along the northeastern shore: Lead Cove, Mistaken Cove, Bellman's Cove, Aguathuna "Island", Gillam's Cove, and the shoreline west of Gillam's Cove (Fig. 35); (b) along the south coast: southeast of Felix Cove, southwest of Ship Cove, and southeast of Sheaves Cove (Fig. 1).

2.3.2. Dynamic Criteria

Modern karst is a surface which is undergoing active karstification whether the surface is bare, covered by soil, or mantled by permeable rock strata. Relic karst refers to a surface on which karstification was active before the Holocene. This relic surface is often undergoing modern karstification (rejuvenated relic karst). The classic karst in Jugoslavia is of this nature, being initiated in the Middle Tertiary (Quinlan, 1972). Relic karst not undergoing active karstification may also be called palaeokarst.

On the peninsula, an example of modern karst is found at the contact of the modern soil with the Upper Mississippian sediments (e.g. Lead Cove). Water percolating through the soil is causing dissolution in the underlying strata. The dissolution decreases markedly with depth and is confined primarily to the soil-strata interface. Any modern karst associated with the solution features on the Ordovician carbonates is considered to be primarily a rejuvenated karst surface (see Age of Karst).

2.4. Karst Landforms

A variety of solution and precipitation features are present within any karst terrain. Solution features exhibit standard characteristics that can be categorized qualitatively so that easy comparison can be made with karst regions of different geography and age. A comprehensive review of karst landforms is given by Sweeting (1973).

On the peninsula, solution features vary from circular depressions to furrows; their size ranging from millimetres to tens of metres. Many features are similar to those described by Sweeting (1973). Some solution furrows, or karren, appear to be gradational in size and morphology between the standard types of karren. This, however, should be expected in a dynamic karst system where continual solution alters the initial morphology.

All solution furrows on the peninsula display a similar overall morphology, despite the obvious scale differences. Furrows millimetres in depth (rillenkarren) to tens of metres in depth (karst valleys) are U-shaped in cross-section, have steep sided walls, taper in width and depth with elevation and bifurcate, or widen, downdip. The only difference is found associated with the surface textures; that is, smooth versus rough walls, and sharp versus smooth furrow margin edges.

Another similarity between the small and larg[illegible]rows is the relationship of the karst surface and the overlying sediment. Both rillenkarren and the karst valleys may be partially to completely filled with Upper Mississippian sediment. The interpretation of this gradation from micro- to macroscale features displaying similar morphologies, as well as good evidence of karst features developed within the valleys and associated coves, suggest the valleys are of karst origin, and in some cases modified by later faulting. A summary of karst solution and precipitation features along with their location is given in Figure 5.

2.4.1. Features of Karst Solution

(1) Karren - Grooves, furrows and small gullies are known as karren (Sweeting, 1973). These features cut across and down through the surface of limestone. A variety of well developed karren are displayed in two regions on the Port au Port Peninsula: (a) on the northeast coast: south of Gillam's Cove, Aguathuna Quarry and Mistaken Cove, and (b) on the west coast: east and southeast of Big Cove between 80 and 250 metres (approximately 250 and 850 feet) above sea level.

(i) Rillenkarren -- Two different styles of rillenkarren are developed on the Table Point limestone. To the west of Gillam's Cove, rillenkarren with rounded crests is well preserved on a seaward dipping bedding plane. A thin veneer of green arenaceous limestone of the Codroy Group partially covers the upper portions of the karren (Fig. 6). Another type of rillenkarren is associated with the edges of solution basins or kluftkarren (see below) giving a fretted appearance to the host feature. The crests may be sharp or rounded. Examples of this type are rare but may be found in both regions of karren

FIGURE 5: Karst features and localities on the peninsula.

KARST TYPES	LOCALITIES ON THE PENINSULA Southwest	 South	 Northeast	REMARKS
Rillenkarren			x	- mantled and bare
Rinnenkarren	x	x	x	- in the massive limestones of the St. George and Table Head Groups
Rundkarren			x	- mantled
Kluftkarren and flackkarren	x		x	
Karrenrohren			x	- mantled with red-brown sand
Solution gullies			x	
Karst valleys	x		x	
Limestone pavement	x		x	- mantled with red-brown sand and modern soil, as well as bare
Solution basins	x	x	x	- subsoil
Surf karren		x	x	- modern and palaeokarst
Solution surfaces	x	x	x	
Caves		x		
Open Depressions		x	x	- overlain by red-beds or limestone
Fissures and vugs		x	x	- infilled by muds and limestone
Speleothem Deposits				
(i) Drusy Calcite		x		
(ii) Travertine and red muds		x		
(iii) Moonmilk			x	- near South Head, West Bay
(iv) Cave deposits			x	- southwest of The Gravels

development. Both styles of rillenkarren exhibit bifurcation downslope.

(ii) Rinnenkarren -- Rinnenkarren, or solution grooves, occur where runoff water accumulates in streams (Bögli, 1980). The amount of water increases downslope with the result that the solution feature becomes wider and deeper. On the peninsula, these features are partially covered by soil and/or glacial sediments. Generally, the grooves attain a maximum depth of a half a metre. Examples of these solution grooves are found both along the northeast and west of the peninsula (Fig. 7).

(iii) Rundkarren -- As defined by Sweeting (1973), rundkarren are grooves that may be several metres wide and a metre in depth, and form by solution at a soil/rock interface. On the peninsula, one example of a shallow and narrow rundkarre is overlain by Codroy sediments (Fig. 8). This is at the same locality as the rillenkarren and covered by similar sediments.

(iv) Kluftkarren and Flackkarren -- Also known as grikes and clints (Sweeting, 1973), these solution furrows, and interfurrow 'plateaus', respectively, are associated with bare limestone pavements in the Gillam's Cove and Big Cove regions, and with soil/glacial sediment covered pavements, south of Aguathuna Quarry and Mistaken Cove (Fig. 9).

The kluftkarren are a maximum of one metre in depth with the intervening flackkarren one to two metres in width. The furrow troughs are typically covered with modern soil whereas the flackkarren are either bare or covered. Isolated furrows resembling kluftkarren may occur in regions where no pavement is present.

FIGURE 6: Rillenkarren is partially mantled by Upper Mississippian sediment (arrows and outlined), west of Gillam's Cove. Solution furrows bifurcate downslope (top of photograph). Hammer for scale.

FIGURE 7: Rinnenkarren increase in width and depth downslope (bottom of photograph), south of Aguathuna Quarry. An example of deep kluftkarren is present on the right side. Hammer for scale.

FIGURE 8: Narrow rundkarren are mantled by Upper Mississippian sediment; west of Gillam's Cove. Pitted Ordovician strata (arrow) contrasts with the relatively smooth Mississippian sediment surface (in outline). Hammer for scale.

FIGURE 9: Kluftkarren and flackkarren, with minor rinnenkarren, occur on an inclined limestone pavement south of Aguathuna Quarry. Hammer for scale.


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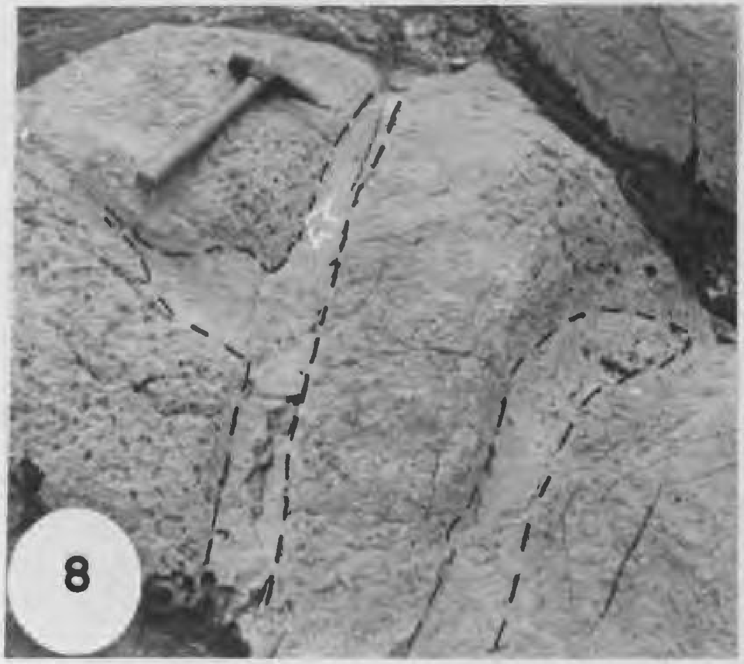
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South of Gillam's Cove, karren exhibit rounded troughs and margin edges, often with frets of rillenkarren which may have sharp crests extending down the smoothed furrow walls. East of Big Cove, kluftkarren have both sharp trough bottoms and margin edges, and roughened side walls (Fig. 10). Where isolated kluftkarren occur, the surfaces and margin edges may be of either texture.

(v) Karrenrohren -- Only one example of a karrenrohre, or solution pipe, was found. It is associated with the limestone pavement south of Gillam's Cove (Fig. 11). The pipe is partially infilled with a reddish-brown coloured coarse sand that also covers part of the pavement. It is approximately fifteen centimetres in diameter with half a metre of depth exposed. The sides and margin edges are smooth and rounded.

(2) Larger Solution Grooves - Incised linear valleys and shallow, but wide, gullies occur along the northeastern coastline of the peninsula. These features, though not strictly related to karren, possess a similar morphology.

(i) Solution Gullies -- Several relatively shallow gullies, partially covered by soil, occur southwest of Gillam's Cove, south of the main road. They are approximately five to ten metres wide, and one to three metres in depth, at maximum development, and taper in depth and width with increased elevation. Each gully appears to coalesce with others downdip and terminate in a small steepsided embayment on the shoreline. The cove and solution gullies exhibit vertical and approximately straight walls with rounded margin edges. Overhangs of the Ordovician limestone are sometimes present. One such overhang was found encrusted with limestone of Upper Mississippian age. The base of the gullies is usually covered with soil and trees. These gullies possess a topographic expression visible on maps (see Fig. 35). Sweeting (1973) makes reference to solution furrows that are larger than kluftkarren but too small to be karst valleys (see below). It is suggested that these solution gullies are either large scale rinnenkarren, or, have been produced in a region where extensive development of rinnenkarren formed a single large channel modified by continuing solution by karst waters.

(ii) Karst Valleys -- In the northeastern part of the peninsula (Fig. 35), several very prominent north-south, linear, incised valleys taper in width and depth (to the south) with elevation, and terminate along the coastline in U-shaped coves (both in plan view and cross-section). In cross-section, the valleys are generally flat-bottomed, U-shaped, with very steep to vertical walls. Many of these valleys and their associated coves are partially to completely filled with Upper Mississippian sediment, that is either flatlying or gently dipping to the north. Modern streams have cut through this cover, and talus deposits of both Upper Mississippian and Ordovician strata are found along the sides of the valleys (Fig. 12).

Evidence of undercutting and cave development in the Ordovician valley walls prior to Upper Mississippian sedimentation, can be seen at the present tide level in Lead Cove, and Bellman's Cove, and well above the present tide level at Aguathuna "Island". A cave with no Upper Mississippian sediments was found in Miner's Brook.

The preserved infilled caves, or hollows, appear to be shallow. No extensive cave system was encountered associated with the Ordovician strata. In Aguathuna Quarry, a well exposed undercut of several metres was reported by Johnson (1954, Fig. A, pg. 63). This has since been removed by quarrying operations.

The steep-walled valleys are very similar to allogenic karst valleys described by Sweeting (1973). Although the valleys on the peninsula are much narrower than those she describes, they exhibit similar characteristics: U-shaped cross-section, steep walls and tapering in width and depth with increasing elevation. The large solution gullies described above also display these features. The presence of solution surfaces, at Gillam's Creek (see below), and caves and undercuts along the walls of these valleys help to substantiate the interpretation of a karst origin.

Karst valleys are considered to develop from limestone solution either at the surface or in the subsurface, along a linear feature, such as faults or fractures. If the solution occurs in the subsurface, an underground drainage system develops. Collapse of the cave system progresses downslope from continued solution producing a linear depression, often incised with respect to the surrounding topography (Sweeting, 1973). If solution is restricted to the surface then erosion of the limestone would probably proceed in a similar manner as that in the formation of the small scale solution grooves (e.g. rinnenkarren). In the Port au Port area, this latter mechanism is considered to be more important though both karst styles may have coincided along the lineaments. On the basis of interbedded lithologies of differing composition, the St. George Group carbonates would be host to a cave system, and with continued solution the overlying Table Point limestones would become unstable, as the underground system became larger, and collapse would occur. Continued solution of collapse debris by the subsequent valley river would produce the characteristic valley morphology preserved today.

In contrast to this, surface solution along the lineaments (which may have been sites of fracturing) would penetrate down into the St. George Group carbonates allowing for faster solution and collapse of the strata. As solution occurs, development of overhangs and shallow embayments within the surrounding strata could occur. In this manner large scale collapse of strata is not an important function for valley formation.

(3) Limestone Pavement - As the name suggests, corrosion over a wide area leads to a planar limestone surface. Two examples of inclined planar pavement occur on the peninsula. The first, to the south of Gillam's Cove and Aguathuna Quarry, dips at 20 degrees northwards towards the sea. It is dissected by kluftkarren and its surface may be bare, soil/glacial sediment covered, and/or covered by a loose red-brown coloured coarse sand (Fig. 9). A non-karsted outcrop of possible Table Cove Limestone overlying the Table Point Formation, immediately south of the western part of Aguathuna Quarry (Fig. 11), indicates that the pavement has preferentially developed at the Table Cove/Table Point contact.

The second area of inclined payements occurs east of the northern end of Big Cove at approximately 300 feet above sea level (Fig. 10). They are inclined towards the sea as well, but to the west. The planar surfaces are bare and dissected by sharp-edged kluftkarren, and exhibit a more angular appearance than the pavement in the Aguathuna region. All pavements are only a few hundred square metres in area.

A horizontal limestone pavement occurs immediately south of Mistaken Cove. This example is well covered by soil and glacial sediments, with only a small portion visible.

(4) Solution Basins - These basins are shallow, less than a metre in depth, and circular to irregularly polygonal in shape with diameters rarely exceeding five metres. The edges are often bare and may be fretted with rillenkarren while the remaining part of the basin is filled with modern soil.

Where several of these basins occur together, the topographic relief is low and hummocky. Examples of these features are scattered throughout all regions of karst development on the peninsula.

(5) Surf Karren - This is a term used by Bögli (1980) for karst developed on limestones and dolomites that border a marine coastline. The surfaces are usually cockled with small pits giving a rough abrasive texture to the rocks. The pit edges are usually sharp, with the pits rarely greater than two centimetres in diameter. Coalescence of the pits may form larger pits. On the peninsula, this is very common as modern karst along the shoreline between Gillam's Cove and The Gravels, along the south coast where a limestone member of the St. George Group (similar

in lithology as the Table Point limestones) outcrops (e.g. south of Ship Cove), and as palaeokarst in contact with, or immediately adjacent to, Upper Mississippian sediments removed from any influence of the modern ocean, at Aguathuna "Island", and in Gillam's Creek approximately 200 metres south of the shoreline.

Along the northeastern shoreline, the limestone cliffs are undercut from zero to approximately two metres above mean tide level. The origin of the undercut is probably related to erosion by the sea. A wave cut bench (parallel to a bedding plane within the limestone) usually occurs at the base of the undercutting and is just covered at high tide.

(6) Solution Surfaces - Many examples of rock strata with vertical or horizontal surfaces exhibiting smooth solution surfaces occur on the peninsula. Along the south coast two caves (see below) display smooth and glossy surfaces in contact with Upper Mississippian strata. These surfaces are similar to wall surfaces in active caves as observed by the writer.

Surfaces associated with the karren developed on the Table Point limestone do not possess the glossy finish, but may be as smooth. Roughened karren walls are also common.

(7) Caves - Two caves within the St. George Group on the south coast are associated with localities of Upper Mississippian breccia (Sheaves Cove West, Fig. 20; Ship Gove West, Fig. 19). In both examples the extent of the filled cave inland is unknown. Both caves exhibit walls that have a smooth and glossy appearance. The caves are

narrow (less than 5 metres in width) and are approximately four metres in height).

(8) Open Depressions - Two different styles of preserved open depressions are present on the peninsula and may be considered as: (i) collapse, and (ii) modified caves and karst valleys.

(i) Collapsed Caves -- On the east wall of Lead Cove, a vertical fissure two metres wide, five metres in depth, and approximately circular in plan view, is filled with unoriented blocks of moderately rounded to angular Table Point limestone embedded in grey arenaceous micritic Codroy limestone. The large Ordovician blocks are chaotically oriented suggesting that at some point, the undercut limestones failed and collapsed, with the later Upper Mississippian limestone infilling the voids.

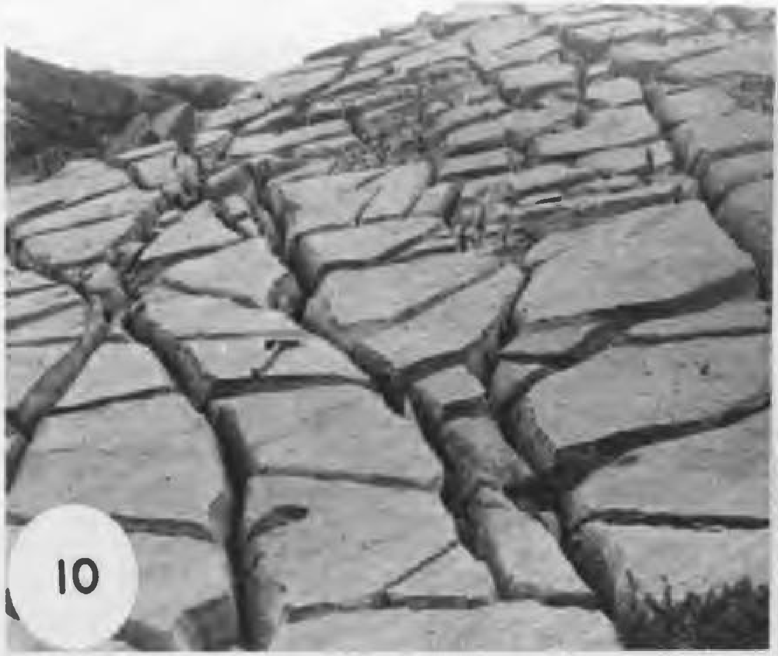
(ii) Modified sinkholes or caves -- Along the south and southwest coast of the peninsula about 15 depressions varying from five metres to 100 metres in depth cut through the St. George Group carbonates and are infilled with conglomerate, breccia, and sandstone. The depressions are generally circular in plan view, or may be similar to small gullies and valleys. The contact surface between the infill and host strata may be jagged or smooth. Several of the limestone blocks (St. George Group carbonates) possess smoothed surfaces characteristic of solution erosion. The smooth glossy wall surfaces associated with the cave (described above) may also be found associated with 'open' depressions (Fig. 13). Thus, it appears justified to consider some of the 'open' depressions as original caves that collapsed and were later modified by stream erosion.

FIGURE 10: Inclined limestone pavement, east of Big Cove. Note the angularity of features in contrast to FIGURE 9. Hammer for scale.

FIGURE 11: Karrenrohre. The Ordovician strata is overlain by a red-brown sand (outlined). This feature of karst was only found south of Gillam's Cove. Hammer for scale.

FIGURE 12: Karst valley (Gillam's Creek). Note the vertical scarp of Ordovician strata on the west side of the valley. On the east side, a terrace of Upper Mississippian sediment infills part of the valley. Exposed cliff section of Ordovician strata is approximately 30 metres in height.

FIGURE 13: 'Open' palaeokarst depression (Ship Cove West). It is infilled with chaotic Upper Mississippian breccia (above the dotted line). Note the smooth solution surfaces (arrows) extending underneath the breccia. Bruce King (approximately 1.7 metres in height) for scale.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The conglomerate infill in all depressions or caves does not exhibit increased concentration of limestone blocks with depth. Therefore, if collapse did occur, erosion had removed any talus prior to infilling of the depressions or caves by terrigenous clastics.

Inland, infilled and exhumed valleys can be traced seaward into several of the depressions along the shoreline. These valleys also taper in width and depth inland with elevation though they tend to be less incised compared to those on the north shore. The valleys on the south coast may have a similar origin.

(9) Fissures - Solution fissures developed in the Ordovician strata, and infilled by post-karst sediments, can be recognized on the peninsula. They are different from karren as they tend to be much narrower, usually extend down into the host strata much deeper, and are not as regular in form.

(i) Codroy sediment infill -- These fissures, found within the Table Point limestone in Bellman's Cove, taper with depth, are approximately five to six metres in depth and are filled with grey micritic limestone of the Codroy Group (Fig. 14).

(ii) Unfossiliferous mud-filled fissures and solution vugs - Southeast of the village of Felix Cove, behind the Irving gas station along the shoreline, a few vertical and narrow vertical fissures, filled with red and/or green mud, can be traced at depth to open into round, subspherical solution vugs that sometimes display geopetal sediment similar in composition to the fissure mud. The vugs may have drusy calcite crystals in the void space above the sediment. It is more common, however, to find solution vugs without any obvious connecting fissure. Geopetal sediment and crystals may be present in these as well. Fissures filled with red to brown calcareous mud, and displaying similar characteristics to those in the Felix Cove region, are also present throughout the Sheaves Cove - Fiod's Cove area of the south coast (Fig. 15).

The fissures that extend to the surface are overlain by either Pleistocene glacial sediments or modern soil; there is no obvious source for the red to green muds. Less than a kilometre north of Felix Cove, however, there is a small outcrop of Upper Mississippian red-matrix conglomerate which is located at the top end of a shallow broad valley that underlies the area. Within this valley, is a modern misfit stream. It is interpreted that the valley is related to a pre-Upper Mississippian karst, and, as the red-matrix conglomerate was laid down, the muds would filter down into the fissures and vugs related to the karst event.

2.4.2. Features of Karst Precipitation

Karst waters may act not only as a corrosive agent but also precipitate calcium carbonate (speleothem deposits) both in the subsurface and above ground level (Sweeting, 1973). The change from erosion to precipitation is dependent upon various factors, amongst the more important of which are water temperature and chemistry. On the Port au Port Peninsula, speleothems occur in the regions of Sheaves Head, Lower Head, Fiod's Cove, south of South Head, and near The Gravels. Four styles of deposition can be recognized.

(i) Drusy Calcite - The first style of deposit is characterized by fissures, a few centimetres to tens of centimetres in width, developed in St. George Group carbonates. The fissure walls, possibly modified early, after their formation by solution, are patchily lined with travertine in the form of thin laminae of beige-coloured cryptocrystalline calcite. Second stage travertine laminae consists of isopachous prismatic or cryptocrystalline calcite crystals, variegated in colours of red, white and brown, or simply white and grey. The isopachous crystals increase in size and may actually completely plug the remaining void space (Fig. 15).

Two generations of this latter stage travertine are present: (1) lining rims, and (2) surrounding clasts in the centre of fissures. The laminae microtopography is enhanced by rim surface irregularities. Void space, geopetal sediment or blocky calcite crystals represent a third stage and are usually found at the centre of very wide fissures. This style of deposit is found at Sheaves Head, Lower Cove, and Fiod's Cove.

(ii) Travertine and Red Beds - At Sheaves Cove West, another style of speleothem deposit is present: thin cross-bedded and fractured laminae of travertine partially infill a fracture within the host carbonates. Alternating with the laminae are interbeds and laminae of red calcareous muds. These are similar to travertine deposits described by Chafetz and Butler (1980; Fig. 10B, pg. 508).

At Dory Cove, an informal name given to a small cove two kilometres northeast of The Gravels, the east wall of the cove, consisting of karsted Table Point limestone is covered by a thin laminae of beige-coloured travertine.

(iii) Moonmilk - South of South Head, on the north shore, large blocks of moonmilk (see Thrailkill, 1971), beige in colour can be found in roadfill. The samples have surface textures similar to cauliflower. Galena and marcasite mineralization is associated with the moonmilk. The source area for this speleothem is unknown though Howley's map of Newfoundland indicates the occurrence of lead in the same region as the roadfill (Howley, 1907). This is interpreted to indicate that the source is probably close to the present locality.

(iv) Cave Deposits - The fourth style of speleothem deposition can be found at a small cave (discovered by B. Pratt) just southwest of The Gravels. Here, beige-laminated flowstone, similar in texture to some of the variegated travertine in fissures at Sheaves Head, dripstone structures, and carbonate sediment infill have completely plugged a cave or hollow in the St. George carbonates. The deposit is approximately two metres in diameter with the contact between the speleothems and host rock wall varying from smooth to jagged. Rare marcasite mineralization is present within the sediment infill. Fissures leading away from the base of the cave are filled with beige to brown laminated flowstone. The dripstone structures consist of stalactites and stalagmites, soda straws and flowstone with a knobbly surface (Fig. 16).

In Aguathuna "Island", flowstone in the form of cave popcorn is found in contact with Upper Mississippian sediments. Cave popcorn is also associated with Table Cove strata south of the quarry (see Thrailkill, 1971, for definition of this speleothem).

FIGURE 14: Fissure (arrow) cutting Table Point Formation strata is infilled with fossiliferous Upper Mississippian grey lime mudstone in Bellman's Cove. Note that the fissure extends down into bedded Upper Mississippian limestone infilling an undercut (above hammer).

FIGURE 15: Red muds infilling a fissure in Fiod's Cove within the St. George Group strata display minor cross-bedding (arrow) which consists of interlaminated red mud and travertine. Lens cap for scale.

FIGURE 16: Cave precipitates, Pratt's Cave, south of The Gravels, display flowstone and a possible stalagmite (arrow). Lens cap for scale.


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2.5. Age of Karst

2.5.1. Mantled Karst

Karst landforms that are mantled by Upper Mississippian sediments, and cut across structure imposed by Acadian deformation, prove an Early Mississippian age for karstification on the Port au Port Peninsula. Karst surfaces of the Ordovician strata associated with this period of karstification tend to be smooth and well rounded. Mantled karst is restricted primarily to the coastline of the peninsula; inland the Upper Mississippian sediments thin with higher elevation. Karst/Codroy contacts are well exposed only along the coastline.

2.5.2. Bare and Subsoil Karst

The age of bare and subsoil karst on the peninsula is problematic. These karsts are found primarily away from the shoreline and at higher elevations in contrast to the mantled karst. The surface morphology of associated landforms varies from smooth and well-rounded to rough and angular. A comparison of karst landforms that are mantled and those which are bare or covered by modern soil is shown in Figure 17. All bare and subsoil karst features, with exception of rinnenkarren and solution basins, are found as mantled karst. Surf karren found along the shoreline may be, in part, modern in age (Fig. 17). The evidence of a pre- to syn-sedimentary Late Mississippian surf karren development complicates interpretation. In Ship Cove East, a smooth glossy karst surface is gradually overprinted by surf karren within the modern spray zone. Within the depression, the smooth surface is in

	EARLY MISSISSIPPIAN AGE (mantled)	PROBLEMATIC AGE (bare or subsoil)
Rillenkarren	x	x
Rinnenkarren		x
Rundkarren	x	
Kluftkarren and flackkarren	x	x
Karrenrohre	x	
Solution gullies	x	x
Karst valleys	x	x
Limestone pavement	x	x
Solution basins		x
Surf Karren	x	x
Solution surfaces	x	x
Caves	x	
Open Depressions	x	x
Fissures and vugs	x	

Figure 17: Comparison of Karst Features and Age.

contact with the Upper Mississippian breccia. This suggests that the surf karren in this locality is modern.

South of Gillam's Cove, kluftkarren associated with limestone pavement is partially covered by the red-brown coloured coarse sand of unknown age and modern soil. The margin edges of the karst features are well rounded. The present distribution of these karren is well above sea level (from 20 to 100 feet). Upper Mississippian marine sediment is found at elevations above the lowest occurrence of kluftkarren (in Mistaken Cove, and parts of the Gillam's Cove pavement). This suggests that Upper Mississippian sediments may have been extensively eroded from the underlying karsted surfaces. Evidence for later erosion comes from solution gullies near Gillam's Cove, in which small patches of Upper Mississippian marine limestones were found encrusting the Ordovician strata and protected by an overhang. West of Gillam's Cove, Upper Mississippian sediment is preserved overlying or infilling rillenkarren and rundkarren. The Upper Mississippian sediments are very rubbly and could be easily removed over a short time interval.

Much of the karren found at elevations 500 to 800 feet above sea level along the west coast, are even more problematic in age. Using the similarity in surface textures between these karren and the proven mantled karren, the age of the smooth and well rounded karren on the west coast may also be of an Early Mississippian age. In contrast, east of Big Cove, an example of a limestone pavement exhibits sharp margin edges of kluftkarren and flackkarren. The angularity of these karren forms may be a function of age or karst process. Rillenkarren covered by Upper Mississippian sediment display rounded crests (west of Gillam's Cove). Modern rillenkarren exhibit sharp crests (Sweeting, 1973; Bögli, 1980). This suggests that the overall roundness of karst landforms on the peninsula is a function of age. Sharp crested rillenkarren do occur on the edges of solution basins and kluftkarren, possibly indicating a superposition of modern, or Pleistocene, karst on a palaeokarst. Bogli (1980) notes, however, that depending upon the amount of available runoff, rinnenkarren may have smooth or rounded features. Despite this, it is apparent that karst features on the peninsula, whether associated with bare, subsoil, or mantled karst, exhibit similar morphologies and surface textures. Noting that the Upper Mississippian strata thin onto the flanks of the peninsula, and that rare outcrops of Upper Mississippian sediment are preferentially preserved within a karst gulley, indicating that erosion has removed the rest of the strata, it is interpreted that most of the karst on the peninsula is initially Early Mississippian in age but subsequent periods of karst may rejuvenate and overprint these features. 6

2.5.3. Speleothems

Relationships between the speleothem deposits and Upper Mississippian strata, and with calcite veinlets related to Alleghenian deformation (see Chapter 4 - Structure), indicate that the deposits are pre-Alleghenian in age. In a few examples a pre-Late Mississippian age can be substantiated.

2.5.4. Summary

The interpreted general age of the speleothems emphasizes the importance of a period of extensive and peninsula-wide karstification occurring prior to the Pleistocene. The karst-mantled solution features indicate that the majority of landforms were developed in the Early Mississippian. Subsequent karstification is probably occurring at the soil-Ordovician strata contact rejuvenating these relict karst features.

2.6. Climate

The style of karstification that is preserved, represented by limestone pavements, sinkholes, caves, and various surface karren, is similar to karst described by Sweeting (1973) for temperate environments.

However, joints, fissures, and caves plugged with karst precipitates are common in tropical karst environments. Sweeting (op. cit., pg. 296) warns of the difficulty, and misuse, of applying karst landforms to define a particular ancient environment, as the parameters which control karstification may be so variable within any given region that type karst landforms, or variation thereof, of several geographical climates may be found together forming a karst landscape.

Palaeomagnetic studies indicate that during the Mississippian period, Newfoundland was situated at approximately 10 degrees south latitude (Morel and Irving, 1978). Countries situated along this latitude today exhibit environments varying from very arid to very humid. The absence of abundant preserved organic debris within the early Codroy sediments on the Port au Port Peninsula, and in southwest Newfoundland (Bell, 1948), suggests that the climate was arid or semi-arid. This is also considered to be the case in southern England and Wales during this same time interval (written comm., Wright, 1980). Assuming that the North American plate did not have any substantial movement between the Early and Late Mississippian, the peninsula probably had a similar environment during the Early Mississippian.

Thus, the presence of an arid, or semi-arid environment situated within a tropical region of the world, would probably give rise to a great variation in style of karst landforms.

2.7. Karst in Western Newfoundland

Other regions of karst terrains exist within western Newfoundland, though only one area is known to have been extensively studied.

Karolyi and Ford (1980) report a karst terrain, in the Goose Arm area of the Bay of Islands. They describe a pre-Wisconsin karst surface overlain by glacial till. Superimposed onto this surface is a modern karst.

Further to the north, in the Hare Bay region, a karst terrain, well covered with modern soil and bog, exhibits round ponds rimmed with trees, and disappearing creeks (pers. comm., Stouge, 1980). To the east and southeast in the Conche-Groais Island area, shales and conglomerates of Early Carboniferous age unconformably overlie Ordovician metasediments (Baird, 1957). The Mississippian clastics are preserved in a tight syncline, the structure suggesting that they may have onlapped onto the carbonates further to the west in a similar manner as in the Port au Port area.

Ford and Quinlan (1972; cited in Thompson, 1976, pg. 17) report the occurrence of a sinking stream, North Brook, on the southeastern coast of St. George's Bay.

Areas underlain by till-mantled gypsum of Late Mississippian age, in the Romaines Brook and southwest Newfoundland regions, often display a well-developed sinkhole topography due to the solution of the gypsum.

Just east of Corner Brook, at the Humbermouth Quarry, a collapsed sinkhole exhibits a cement matrix or orange-brown to pink coloured laminated, or very coarsely crystalline calcite, with occasional pockets of geopetal silt. 'Veins' and 'veinlets' of similar calcite cut across the vertical to steeply dipping Ordovician strata.

In the Deer Lake Quarry, north of Deer Lake, several cave and fissure-fill deposits occur within Ordovician strata: (1) large fissures; up to tens of centimetres in width are filled with green or red calcareous silt; (2) soda straw stalactites occur within the fissures; (3) small caves plugged with silt and breccia clasts, of Ordovician age, and coated with several laminae of travertine.

The presence of karst terrain developed on Ordovician strata is obviously widespread in western Newfoundland. It is interesting to consider the possibility that some of these karst terrains may be of an equivalent age to the mantled karst present on the Port au Port Peninsula.

2.8 Summary

Karst features preserved on the peninsula demonstrate that (a) a major karstification event occurred during the Early Mississippian producing a wide range of landforms, (b) surface karstification was predominant on the Table Point limestone, and in places possibly still active, (c) intrastratal karstification was predominant in the St. George Group carbonates forming caves which eventually collapsed, (d) surface and intrastratal karstification along major lineaments produced during the Acadian Orogeny formed the linear to sub-linear valleys that are found in the Ordovician carbonates, and (e) the present topographic relief of the peninsula is in part an exhumed Early Mississippian karst landscape.

Thus, Acadian deformation uplifted and fractured the peninsula; the edges of which would be susceptible to karstification along the fractures and faults. The inland portions of the peninsula, possibly not as fractured, would exhibit surficial karst. The distribution of the St. George Group and Table Point Formation carbonates, in part, also controlled the distribution of the style of karstification.

CHAPTER 3

STRATIGRAPHY AND GENERAL SEDIMENTOLOGY OF THE UPPER MISSISSIPPIAN SEDIMENTS

3.1. Introduction

Upper Mississippian sediments on the Port au Port Peninsula, and mainland immediately to the east, occur in three different lithologic associations: (1) red terrigenous clastics, (2) mixed carbonate/clastic sediments, and (3) mixed sulphate/clastic sediments. The preserved localities of these lithofacies are spatially distinct except in the Big Cove region, where red-beds overlie a carbonate/clastic sequence, and in the region east of Boswarlos, where all three lithofacies intercalate. It will be shown by lithostratigraphic analyses that all of the terrigenous red-beds are equivalent and younger than the carbonate and sulphate sequences.

On the peninsula, red-beds are preserved along the south coast between Felix Cove and Sheaves Cove, along the southwest coast and inland between Cape St. George and Big Cove, and in isolated patches inland and on the shoreline in the northeast portion of the peninsula east of Boswarlos (Fig. 1). West of Mainland, offshore, red-beds also underlie Red Island (Fig. 1). East of the peninsula, in the Rothesay Bay region, red-beds and associated calcretes are found along the shoreline (Fig. 1).

The carbonate/clastic lithofacies crops out along the northeast coast of the peninsula east of Boswarlos, at Dory Cove on the east side of East Bay, and in Big Cove on the southwest coast of the peninsula (Fig. 1, and 35).

The sulphate/clastic lithofacies is found on the peninsula in the Boswarlos-Piccadilly region, and east of the peninsula at Romaines Brook (Fig. 1 and 35).

A general intra-lithofacies stratigraphy can be established for the sulphate/clastic and carbonate/clastic lithofacies. The lack of a detailed correlation within, or between these lithofacies results from (a) the discontinuous nature of the strata, (b) local control of sedimentation by predepositional topography (karst depressions), and (c) sediment and possible facies contacts removed from between sections by later erosion. The stratigraphy is further complicated by faults which cut strata within some depressions. These faults appear to have had little effect upon surrounding Ordovician strata, producing at most a metre of dip displacement across a fault zone.

3.2. Terrigenous Red-Bed Lithofacies

3.2.1. Definition and Distribution

- Three rock units comprise this lithofacies: (a) chaotic oligomictic breccia, (b) well bedded to chaotic oligomictic conglomerate, and (c) feldspathic to lithic arenite. All rock types are distinctively red in colour, though green mottling due to reduction by percolating subsurface fluids is often evident. Isolated reduction spots may also occur. Strata are preserved along the south and southwest coastlines as well as inland (Fig. 1), infilling palaeovalleys and interpreted collapsed caves. The fact that strata are found in depressions even inland on the peninsula (e.g. east of Big Cove, Ship Cove, Abraham's Cove, and Felix Cove, Fig. 1) suggests that these red-beds were originally more areally extensive than at present and that much has been removed by erosion.

Because of this patchy distribution, the definition of a detailed lithostratigraphic sequence cannot be satisfactorily established. The karst depressions may be infilled with any combination of the three rock types: a sequence of interbeds of breccia/conglomerate, conglomerate/arenite, or breccia/arenite. In a few depressions, such as at Pigeon Head North and Sheaves Cove Central, gradation between the arenite and bedded conglomerate is apparent. Lateral and vertical facies changes, either abrupt or gradational, are characteristic of this lithofacies.

3.2.2. <u>Chaotic Oligomictic Breccia</u> - This is a clast-supported oligomictic breccia, composed of fragments ranging from pebble to boulder size (maximum diameter is 2 metres), derived primarily from limestones and dolomites of the St. George Group. Rare red calcareous quartzose arenite blocks of possible Clam Bank Formation affinity may also be included. The matrix of the breccia is a red feldspathic arenite with calcite cement. Quartz and total feldspar (dominated by potassic feldspar) comprise approximately 30-35 percent, and 6-15 percent of the rock respectively. Lithic carbonate fragments and muscovite grains may comprise as much as 10 percent of the rock. Mud matrix within the arenite is less than 10 percent. All of the above grains or clasts are angular to moderately angular. The red colouration is due to iron-oxide which coats grains and mud matrix.

Clast orientation is mostly chaotic with exception of rectangular blocks, often oriented parallel to the slope of the karst depression walls. Intercalations of well-bedded, lentitular lenses of feldspathic arenite, less than 2 metres long and 0.5 metres thick may occur within the breccia. In Fiod's Cove, along the northwest wall, a series of breccia lobes dipping at 10 to 15 degrees to the southeast are stacked vertically (Fig. 18). Within each lobe, the breccias remain chaotic. Some of the limestone blocks within these lobes are moderately rounded and have karst solution surfaces and pits.

The maximum preserved thickness of breccia is 18 metres, and occurs at Ship Cove West (Fig. 19) where the base of the breccia is covered by beach gravel. In some cases breccias thin laterally onto the flanks of the depressions. Where younger strata overlie the breccia (e.g. Fiod's Cove) this relationship is clearly a primary feature and not due to later erosion. The deepest and narrowest depressions, and caves (e.g. Ship Cove West and Sheaves Cove West, Fig. 20) illustrate no pinchout and are completely filled with chaotic breccia.

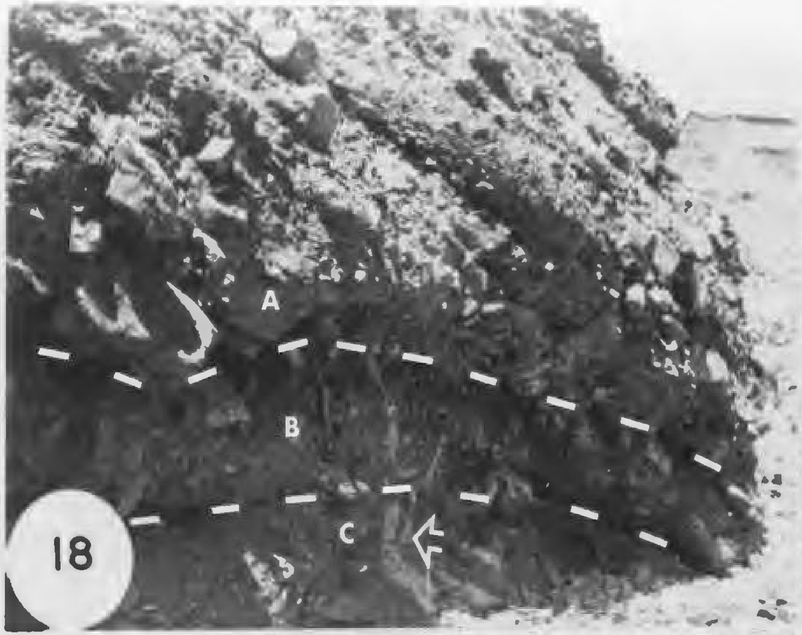
Inland, north of Felix Cove, and at the village of Abraham's Cove, pebble-breccias overlie shallow undulating palaeovalleys that face to the south (Fig. 1). The breccias are identical with those on the south coast except for a smaller clast size.

In summary, chaotic breccias may be interbedded with bedded conglomerate/breccia (Ship Cove East, Fig. 19), overlain by interbedded arenite and bedded conglomerate/breccia (Fiod's Cove, Fig. 21), or

FIGURE 18: Debris breccia lobes at Fiod's Cove within the terrigenous lithofacies. Three lobes are vertically stacked (A,B, and C), and dip to the southeast. Green mottling due to groundwater percolation (arrow) cross-cuts the lobes along fractures. Hammer for scale.

FIGURE 23: Bedded red-matrix conglomerate at Cape St. George. Approximately 60 metres of vertical section are shown in the photograph.

FIGURE 24: Green calcareous arenite (A), Late Mississippian in age, is in fault contact with St. George Group carbonates (B) at Sheaves Cove Central. Red arenite (C) conformably overlies the green arenite. The dotted line shows the approximate contact zone. Hammer (arrow) for scale.


18
A
B
C


24
A
B
C


23

completely fill the karst depression or cave (Ship Cove West, Fig. 19; Sheaves Cove West, Fig. 20).

3.2.3. Bedded Red-Matrix Conglomerate

This lithology is similar in many respects to the chaotic breccia. Differences between the two lithologies are: (a) the boulder-size clasts are much more rounded whereas the pebbles are typically angular, (b) bedding is present and generally dips to the south at 10 to 15 degrees; trough cross-bedding and channel development are common, (c) the sandy matrix surrounding the clasts may include up to 20 percent carbonate lithic fragments, and (d) red/green mottling parallel to bedding due to groundwater percolation is common (e.g. Fiod's Cove).

The rock unit is typically medium to thick-bedded though thin-bedded conglomerate/breccias do occur. Bedded conglomerates are interlayered with red feldspathic arenites in depressions east of Sheaves Cove Central, several depressions west of Lower Cove (Fig. 1), north of Pigeon Head (Pigeon Head North, Fig. 22), and at Fiod's Cove (Fig. 21). Fining-upward sequences, from conglomerate to arenite, are apparent at these localities. These successions are typically less than a metre thick and conglomerate tends to be the dominant lithology. Generally, abrupt contacts are more typical between the two lithologies. Well-bedded pebble to cobble red-matrix conglomerates outcrop east of Big Cove, Cape St. George, and on Red Island (Fig. 1). Along the west coast of the peninsula, isolated outcrops exhibit bedding dipping generally to the west (Fig. 1). It is evident from the attitude of the beds that the underlying palaeovalleys, or depressions, influenced palaeoflow

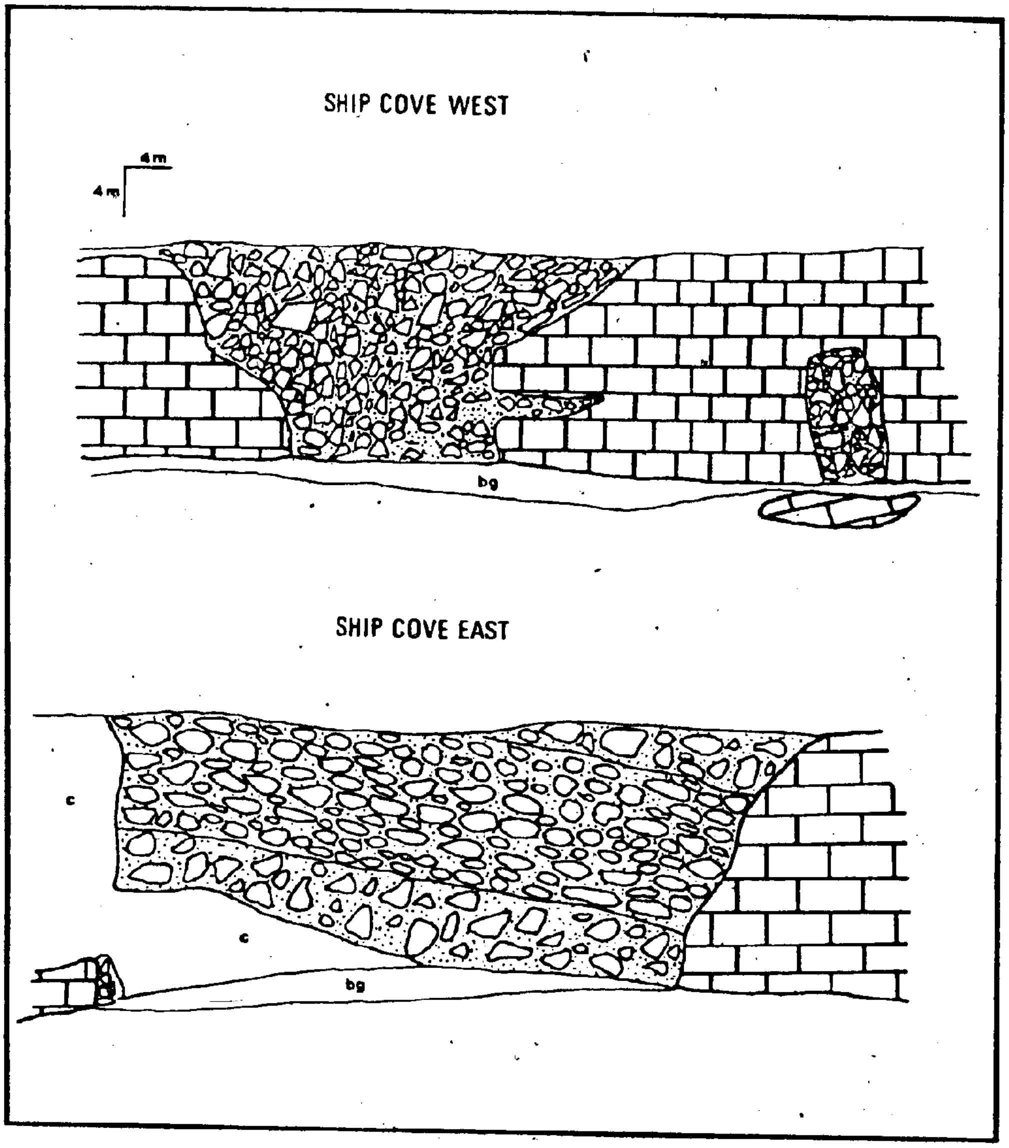


FIGURE 19: Geometry and lithology of Ship Cove West and Ship Cove East. (bg - beach gravel; c - cover)

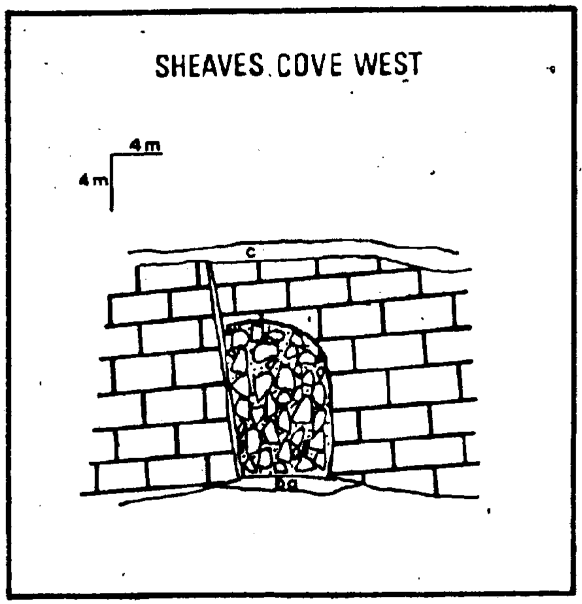


FIGURE 20: Geometry and lithology of Sheaves Cove West. (bg - beach gravel; c - cover)

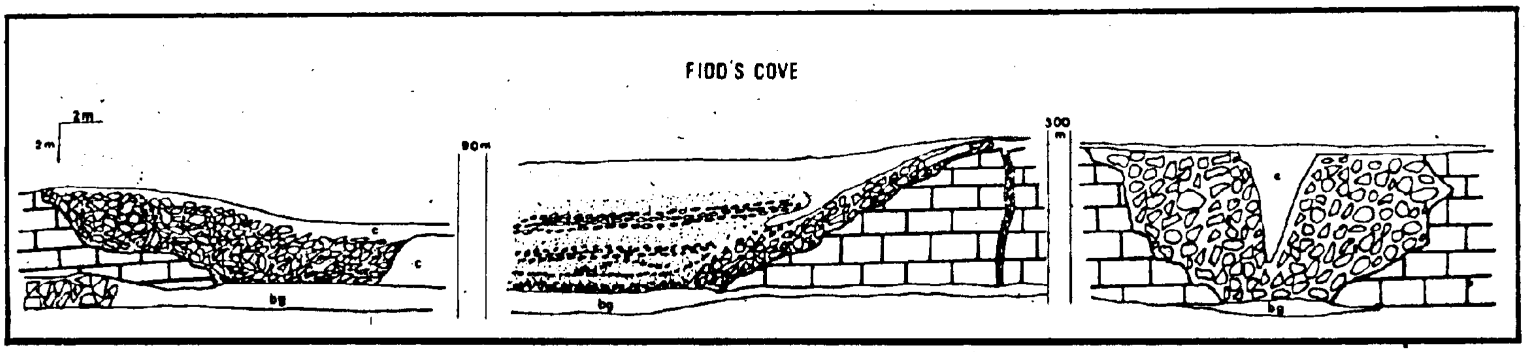


FIGURE 21: Geometry and lithology of Fiod's Cove. Bedded conglomerate, arenite, and chaotic breccia all occur in this cove. (bg - beach gravel; c - cover).

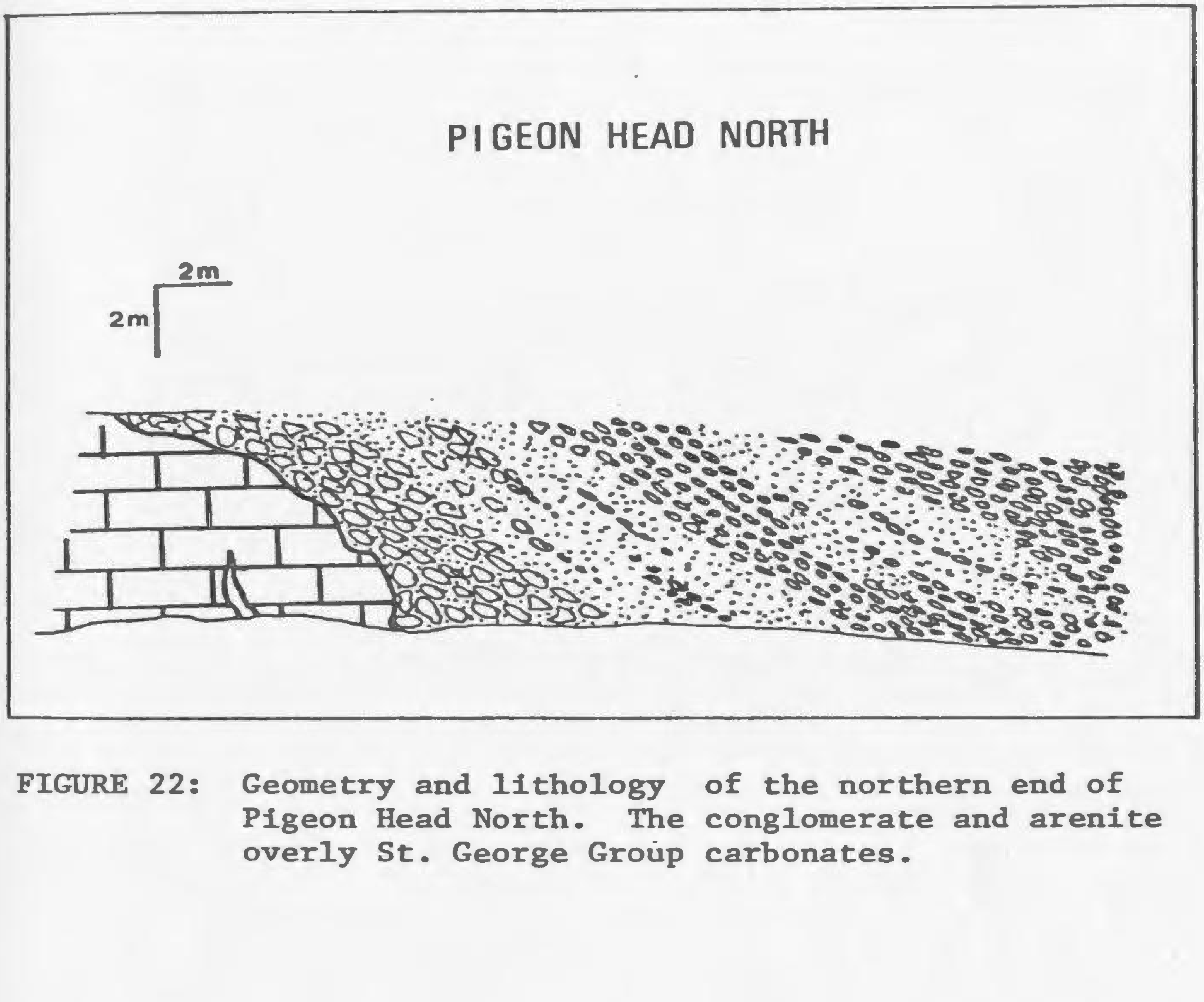


FIGURE 22: Geometry and lithology of the northern end of Pigeon Head North. The conglomerate and arenite overly St. George Group carbonates.

direction. Southeast of Big Cove, flow direction is interpreted as being both north and west (Fig. 1). On Red Island, conglomerates with good planar crossbeds and foresets dip to the northwest. Clasts are composed of Ordovician carbonates and red porphyritic volcanics, and are commonly found along the beaches between Lourdes and Winterhouse.

Thickness of the bedded conglomerate lithology found on the peninsula usually varies between four metres (Pigeon Head North) and 30 metres (west of Lower Cove region). An anomalously thick accumulation of bedded conglomerates is found near Cape St. George infilling a depression which is 100 metres deep (Fig. 23).

3.2.4. Red Feldspathic Arenite

This lithology is thin to medium-bedded, with trough cross-beds, or cross-laminations. The sediments dip shallowly to the south, and cross-bed orientation indicates that palaeocurrent flow was in the same general direction. The base of the cross-beds may be composed of well-rounded pebblesto cobbles of St. George Group carbonates, and green and red calcareous quartzite. These conglomeratic lenses grade laterally and vertically into the red arenite. Percentages of quartz and feldspar (dominated by potassic feldspar) in this lithology are approximately 30 and 14 percent respectively, with lithic clasts ranging up to 40 percent but typically less than 20 percent. The remaining portion of this lithology is a minor mud matrix, with rare detrital muscovite grains, and a calcite cement.

In Sheaves Cove Central, loosely indurated red-beds partially overlie well-indurated strata composed of green calcareous quartz arenite

(Fig. 24). Calcite veinlets form a stockwork through the green sediment and rarely penetrate the overlying red-beds. The difference in induration and colouration between the two units is probably due to the calcite stockwork. This is related to a fault which bounds the north side of the depression and deforms the bedding of both green and red strata. Why the stockwork is so localized is unknown.

In summary, the red arenites on the peninsula completely infill a depression (Sheaves Cove Central, Fig. 25), or are intercalated with pebble conglomerate/breccias (Fiod's Cove, and others). Inland along the northeast coast, east of Boswarlos, red-beds partially underlie the region, and overlie sulphate/clastic and carbonate/clastic lithofacies. The red-beds are poorly preserved and exposed in this region.

Along the shoreline of Rothesay Bay, thin to medium-bedded brick-red, red-brown, and green feldspathic litharenites, and shaley sandstone, dipping slightly to the southeast overlie with unconformity Precambrian gneisses of the Indian Head Complex. Plant debris is common especially in the more shaley beds, with calcium carbonate nodules, and a calcrete associated with the red-beds.

3.2.5. Discussion

The variable stratigraphic position of the three units described above, with regard to one another, and with the underlying St. George Group and Table Point carbonates, make it difficult to establish a valid intra-lithofacies stratigraphic sequence. Stratigraphic relationships that suggest this difficulty are the following:

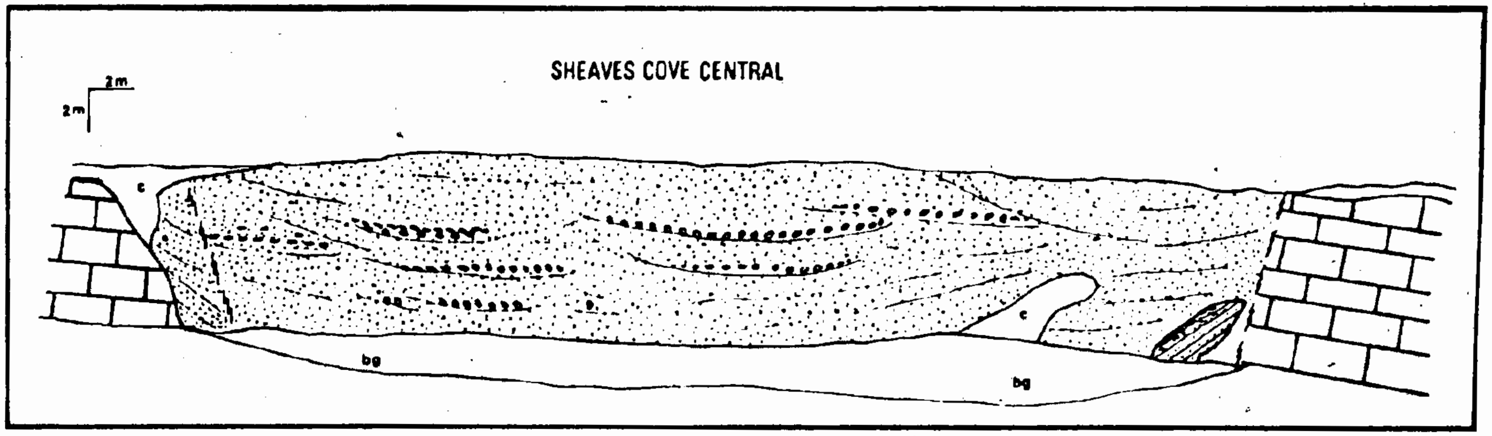


FIGURE 25: Geometry and lithology of Sheaves Cove Central. The arenite and conglomerate lenses overly St. George Group carbonates. (bg - beach gravel; c - cover)

(i) all three units may directly overlie the Ordovician strata at the same present-day topographic level.

(ii) a bedded conglomerate is found interbedded between two thick beds of chaotic breccia (Ship Cove East).

(iii) feldspathic and lithic arenites appear as vertical and lateral facies equivalents of bedded conglomerates.

(iv) the truncated bedding of the sediments at the present erosion surface (e.g. Ship Cove East) and the patchy distribution of strata inland, suggests that the red-beds were more areally extensive than now preserved, and that adjacent infills which are preserved today as distinct lithologies were probably intercalated in some manner.

(v) the sandy matrix of the breccia, and conglomerates, is similar in mineralogy and texture to the feldspathic and lithic arenites.

The textures of the red-beds (conglomerate/breccia versus arenite) would depend upon the topographic slope, amount of physical energy imparted on the source rocks and eroded sediments, the amount of transport medium available, the time interval available for deposition, and the distance travelled from the source. The similarity in mineralogy of the arenites (whether acting as matrix or distinct lithology) suggest a common source for the three lithologies.

The most abundant unit within this lithofacies is the bedded conglomerate, with associated arenites. The sedimentary features, the variable thicknesses of the red-bed sequence, and the relatively abrupt facies contrasts, suggest that this lithofacies is the product of an alluvial fan complex fringing and/or overlying the south, southwest, and northeast coasts of the peninsula, and on the mainland east of the peninsula.

Descriptions of modern and known ancient fans (Rust, 1979) indicate that bedded conglomerates, intercalated sands, as well as complex lateral and vertical facies changes are typical of alluvial fan development and progradation. The chaotic breccias, with evidence of lobe structures, are similar to described debris flows.

The degree of erosion prevents any lateral correlation between coves. It is considered that the karst topography would certainly control the initial style of deposition, which is preserved in the coves at present, but that as deposition continued and depressions infilled, the facies variation may have become more uniform blanketing the inland regions.

The source area for the red-beds on the peninsula was clearly the St. George Group carbonates along the south coast, and the Table Point limestones and St. George Group carbonates along the southwest coast. This implies that the clasts were transported only over a short distance. This is substantiated by many of the large clasts within the red-beds with preserved karst surfaces. The origin of the red calcareous quartzite clasts, the abundant angular quartz and feldspar fragments, and the muscovite flakes is problematic. Possible source rocks on the peninsula are the Clam Bank Formation and the Humber Arm Supergroup. The orientation of the red-bed strata indicate that the sediments were radially channeled away from the centre of the peninsula (Fig. 1), implying that the Clam Bank Formation and/or the allochthon sediments would have to be more areally extensive than now preserved. A random grab sample of arenite from the Clam Bank Formation, just west of Lourdes along the shoreline yielded quartz and feldspar percentages of 35 and 18 respectively;

mafic volcanic fragments comprised approximately 20 percent of the rock. With exception of the lithic fragments, the mineralogy is similar to that found in the Upper Mississippian red-beds. Reworking and transport could remove the unstable volcanic fragments prior to deposition within the depressions. A detailed study of the Clam Bank Formation lithology would shed light on this provenance problem.

The source of the red volcanic clasts on Red Island is even more problematic. There is no close exposed source for these volcanics. The cobbles, quartz-feldspar porphyry, are similar in lithology to volcanics of the Springdale Group in western-central Newfoundland (pers. comm., Strong, 1981). The Springdale Group is approximately Silurian-Devonian in age (Dean, 1978). The size of the cobbles on Red Island suggests that transport distance was not great, thus indicating a local source. Within the Clam Bank Formation, only sediments are exposed along the western coast of the peninsula. During the Silurian-Devonian, however, clastic sediments and associated felsic and mafic volcanics were deposited in Newfoundland and Nova Scotia (Douglas, 1970). Therefore, it is possible that the Clam Bank Formation possessed a similar suite of volcanics that were subsequently eroded and deposited to form the lithology underlying Red Island.

In summary, an alluvial fan complex which prograded to the south, west, and north is partially preserved fringing, and overlying, the peninsula. Initially, a complex of individual fans developed at the mouths of the karst palaeovalleys, but, with continued sedimentation, would coalesce to form an extensive apron, or bajada, fringing the 'peninsula' cliffs. Each karst depression would influence, at first, the style of sedimentation, but as the strata built up, the style of sedimentation may have become more uniform. Development such as this would produce complex vertical and lateral facies changes.

3.3. Sulfate/Clastic Lithofacies

3.3.1. Definition and Distribution

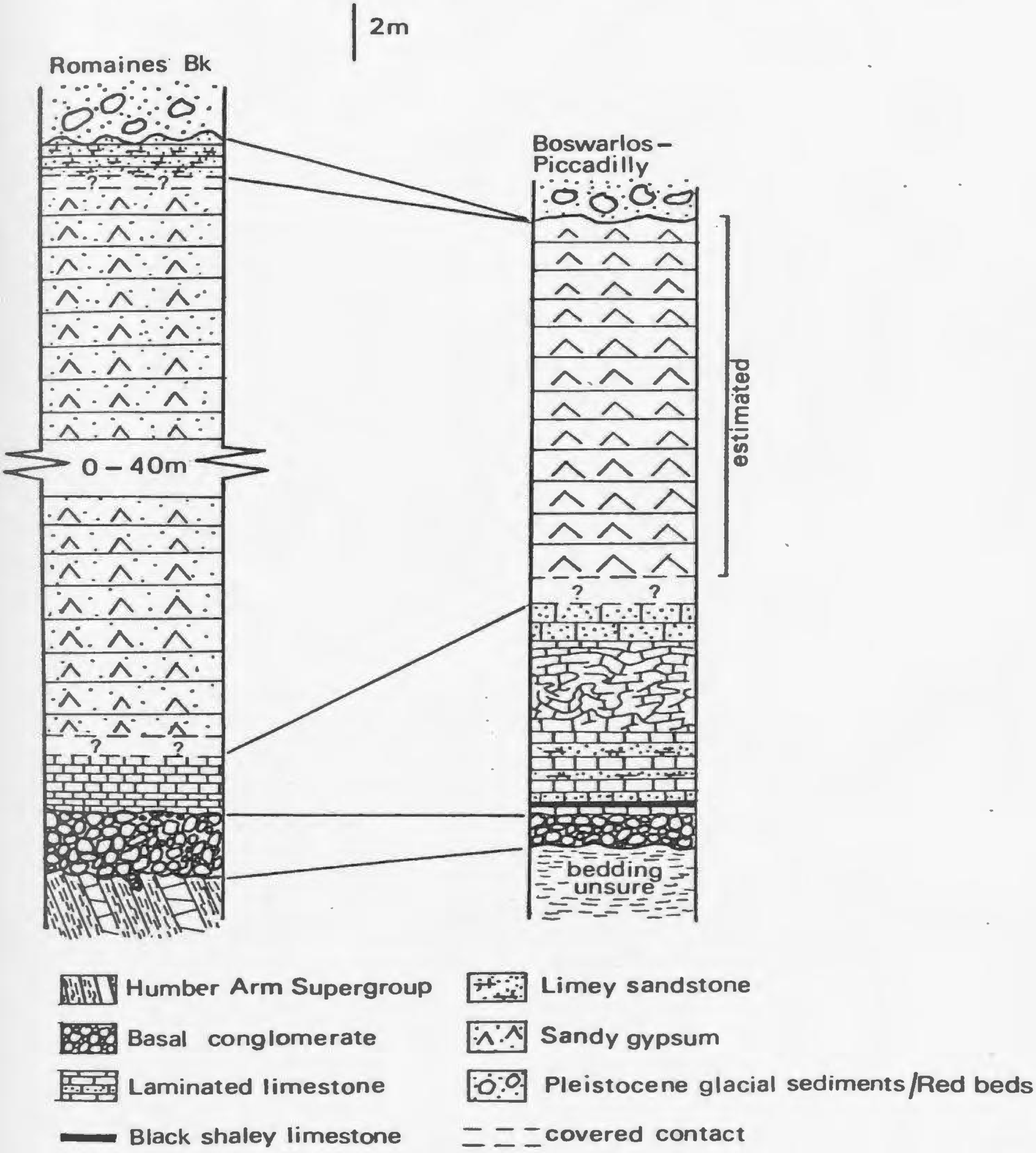
The lithologies associated with this lithofacies include limestone conglomerate, laminated limestone, sandy gypsum and green micaceous sandstone. These are preserved in two, small, spatially distinct basins: (1) at Romaines Brook, and (2) in the Boswarlos-Piccadilly region (Fig. 1). Both basins exhibit a similar sequence of lithologies (Fig. 26) which unconformably overlie Humber Arm Supergroup strata.

3.3.2. Basal Conglomerate

This is a poorly bedded oligomictic, clast-support conglomerate composed of well to moderately-rounded clasts, cobble to boulder size (up to 0.75 metres in diameter), of St. George Group carbonates and Table Point limestones with rare clasts of red calcareous quartzose arenites. The matrix of the conglomerate is a green calcareous quartzose arenite. In Romaines Brook, the unit is 2.1 metres thick whereas at the Boswarlos section the conglomerate is approximately 1.0 metre thick. Relief on the unconformable contact at Romaines Brook is less than 10 centimetres but well defined and sharp (Fig. 27). In the Boswarlos section, the relief appears to be as much as 1.0 metre but this may be enhanced by later tectonic events.

FIGURE. 26:

CORRELATION OF THE STRATIGRAPHY IN THE ROMAINES BROOK AND BOSWARLOS-PICCADILLY REGIONS



In both localities, the unit overlies red and green shales of the Humber Arm Supergroup. South of the shoreline at Boswarlos, Bell (1948; pg. 34) reported that no conglomerate was encountered during a drilling operation. This would suggest that the conglomerate is restricted to low lying areas. At Romaines Brook, only one outcrop of the unit is exposed. At both localities, the conglomerate is conformable with the overlying limestone.

3.3.3. Laminated Limestone

This unit differs greatly in appearance between the two regions, though the lithology is generally similar. In Romaines Brook (Fig. 27), the unit is a grey, well indurated, laminated pelletal packstone, 1.9 metres thick, with rare ostracod fragments. Angular quartz and potassic feldspars make up only about five percent of the rock. The laminae are smooth to wavy and may drape over the clasts of the underlying conglomerate.

At Boswarlos, along the shoreline, the unit is approximately 7.7 metres thick, and is composed of interbedded to interlaminated plant-bearing green calcareous feldspathic arenites, and intraclastic packstones (Fig. 28). Locally, the bedding is contorted and brecciated in two horizons (Section A, Fig. 29 - in pocket). The limestone interbeds typically possess a combined 10 to 15 percent quartz and potassic feldspar content; micaceous siltstone lithic clasts may also be common. Within the sandstone interbeds, quartz and potassic feldspar percentages are approximately 30 and less than 15 respectively. Fauna within the limey beds include ostracodes, brachiopods, and a telliocarid crustacean

(*Tealliocaris* sp.; pers. comm., Dewey, 1981) while within the sandstone interbeds plant debris and ostracodes are common.

In hand specimen, the intraclasts possess marked positive relief, are usually 1-2 millimetres in diameter, and are either rounded to angular clasts of micrite or pelsparite. These have previously been interpreted as oncolitic, or pellets (Bell, 1948; von Bitter and Gerbel, in press). No algal structures are evident, both angular and rounded micritic clasts are present, and the peloids within the pelsparite clasts resemble faecal pellets, clotted in a fine crystalline spar matrix. These latter clasts may either be eroded mounds of pellets, and/or grapestone. Usually, a thin micrite rim surrounds the clasts suggesting algal? micritization of the clast edges.

The limestone beds at Boswarlos are rubbly in appearance; porosity may be as much as 20 percent in the form of moldic porosity developed in the faecal/grapestone clasts, or as minute spaces, less than 30 micrometres distributed within the micrite matrix. Porosity is also associated with rare partially dissolved gypsum within the micrite matrix and sometimes associated with the intraclasts.

The limestone unit, in Romaines Brook, is confined to the same outcrop as the conglomerate unit. In the Boswarlos region, the unit, or parts thereof, is found along the shoreline north and east of Boswarlos (Figs. 1; Section A, Fig. 29; Halfway Point - Section B, Fig. 29), occurs inland along Miner's Brook (Fig. 1), and was encountered in the subsurface near Boswarlos by drilling as reported by Johnson (1954). The unit may overlie (1) Ordovician limestone (Miner's Brook;

North Shore Section - Section C, Fig. 29, (2) the basal conglomerate with conformity (Boswarlos, Section A, Fig. 29), (3) grey biohermal limestone and green sandstone (Halfway Point), or (4) be interbedded with beige to grey coloured biohermal limestones (Gillam's Cove - Section D, Fig. 29).

Inland, southwest of Boswarlos, drilling has shown that the unit pinches out toward the south (cited in Bell, 1948). These observations suggest that like the conglomerate, the laminated limestone is restricted to lower elevations and thins onto the flanks of the Ordovician highland to the south.

3.3.4. Sandy Gypsum

Gypsum with green-grey laminations (Romaines Brook) or gypsum described as sandy (Boswarlos; Hayes and Johnson, 1937) overlies the laminated limestone with apparent conformity. In both regions, the contact is not exposed though in drill core near Boswarlos, no evident break occurs with the underlying unit (Johnson, 1954). At Romaines Brook, the gypsum outcrop is spatially distinct from the limestone and conglomerate outcrop. At this locality, the laminated gypsum is exposed in a cliff section on the east side of the brook (Fig. 30), and has a well developed sinkhole topography on its upper surface. The laminations are commonly faulted and contorted due either to later tectonics which affect the area and/or anhydrite-gypsum hydration. The gypsum in the Boswarlos-Piccadilly basin rarely outcrops. The topography is low lying and generally hillocky suggestive of a karst topography developed on the surface.

FIGURE 27: Basal sulphate/clastic lithofacies, Romaines Brook. Conglomerate unconformably overlies Humber Arm Supergroup strata, and is overlain conformably by well-indurated laminated limestone. Hammer for scale.

FIGURE 28: Basal sulphate/clastic lithofacies, Boswarlos section. Rubbly interlaminated limestone and calcareous sandstone overly the basal conglomerate with conformity. Lens cap for scale.

FIGURE 30: Sandy gypsum at Romaines Brook. Approximately 20 metres of section is exposed. Note faint laminations and well developed sinkhole topography within the gypsum.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The thicknesses of the gypsum units are everywhere approximate. Based on the exposed structure of the Romaines Brook strata, it is estimated that the gypsum may vary from 20 to 60 metres. Twenty metres of gypsum is exposed in the cliff section and it is unknown how far it extends in the subsurface. As the strata are dipping approximately 5 to 10 degrees to the south, the maximum computed thickness, based on the exposed thickness, is about 60 metres. It is doubtful, however, that the gypsum would act as a coherent block during the later uplift of the strata and would probably flow producing a greater apparent thickness. Near Boswarlos, the gypsum has been estimated to be about 14 metres in thickness (Hayes and Johnson, 1937). Inland, drilling has shown that the unit thins onto the Ordovician highland and directly overlies the Table Point limestone (Bell, 1948). In the Romaines Brook region, all contacts of the gypsum with the surrounding Ordovician basement are covered.

3.3.5. Micaceous Green-Grey Sandstone

This unit is found in the Romaines Brook basin only, and occurs both faulted against the gypsum, east of the bridge, and overlying the gypsum, southeast of the bridge along the shoreline (Fig. 1). In the latter outcrop, the sandstone, a few centimetres thick, may not be in situ as it is overlain by Pleistocene outwash deposits.

The unit is a thinly bedded, platey, green-grey, micaceous plant-bearing calcareous feldspathic arenite with maximum exposed thickness of 3.5 metres. The mica (muscovite) and plant debris are abundant along the bedding planes. Quartz and potassic feldspars are angular to subangular, and comprise 35 and 16 percent of the rock respectively. A mud matrix may be present but is rarely greater than a few percent.

3.3.6. Red-Beds and Glacial Sediments

Thin red-beds, poorly exposed, overlie the gypsum unit in Boswarlos-Piccadilly region. It is unknown whether the green sandstone, found in Romaines Brook, occurs between the gypsum and the red-beds.

In both Romaines Brook and the Boswarlos-Piccadilly region, deposits of outwash sands and conglomerates of Pleistocene age, varying up to tens of metres in thickness, overlie, with unconformity, the sulphate/clastic and red-beds. Some of these deposits are described by Brookes (1974).

3.3.7. Discussion

The presence of plant-bearing calcareous sandstones interpreted as fluvial in origin interbedded and/or overlying arenaceous limestones (e.g. Boswarlos) and gypsum (Romaines Brook) suggests that deposition of the laminated limestone unit and the gypsum occurred in nearshore shallow water basins influenced by fluvial conditions. The lack of sandstone within the Romaines Brook laminated limestone unit implies less influence of the nearshore processes and perhaps slightly deeper water. The occurrence of apparent early gypsum within the limestone beds at Boswarlos, suggests that local increases in salinity occurred for the precipitation of the sulphate.

The basal conglomerate is similar in appearance to conglomerates found in creek valleys, or wadis, draining highlands in arid climates

(Reineck and Singh, 1977; Fig. 289, pg. 193). As the green sandy matrix within the conglomerate is similar to the fluvial sandstones in the overlying units, the conglomerate is a probable proximal facies of the sandstones, and/or represents deposition under flood conditions within a wadi (e.g. Gillam's Cove) or in shallow basins (e.g. Romaines Brook, and Boswarlos).

In summary, marginal carbonate and sulphate environments influenced by fluvial clastic deposition developed in two spatially distinct basins. The similarity in stratigraphic sequence and lithologic types is considered to be controlled primarily by the underlying basin geometry. Both basins are developed on the soft shales of the Humber Arm Supergroup in contrast to the resistant limestone of the intervening region of the Port au Port Peninsula; erosion prior to marine transgression would produce relatively broad shallow basins. With an increase in sea level much of the basin would be covered by very shallow water creating an environment susceptible to high evaporation rates and increased salinities.

3.4. Carbonate/Clastic Lithofacies

3.4.1. Introduction

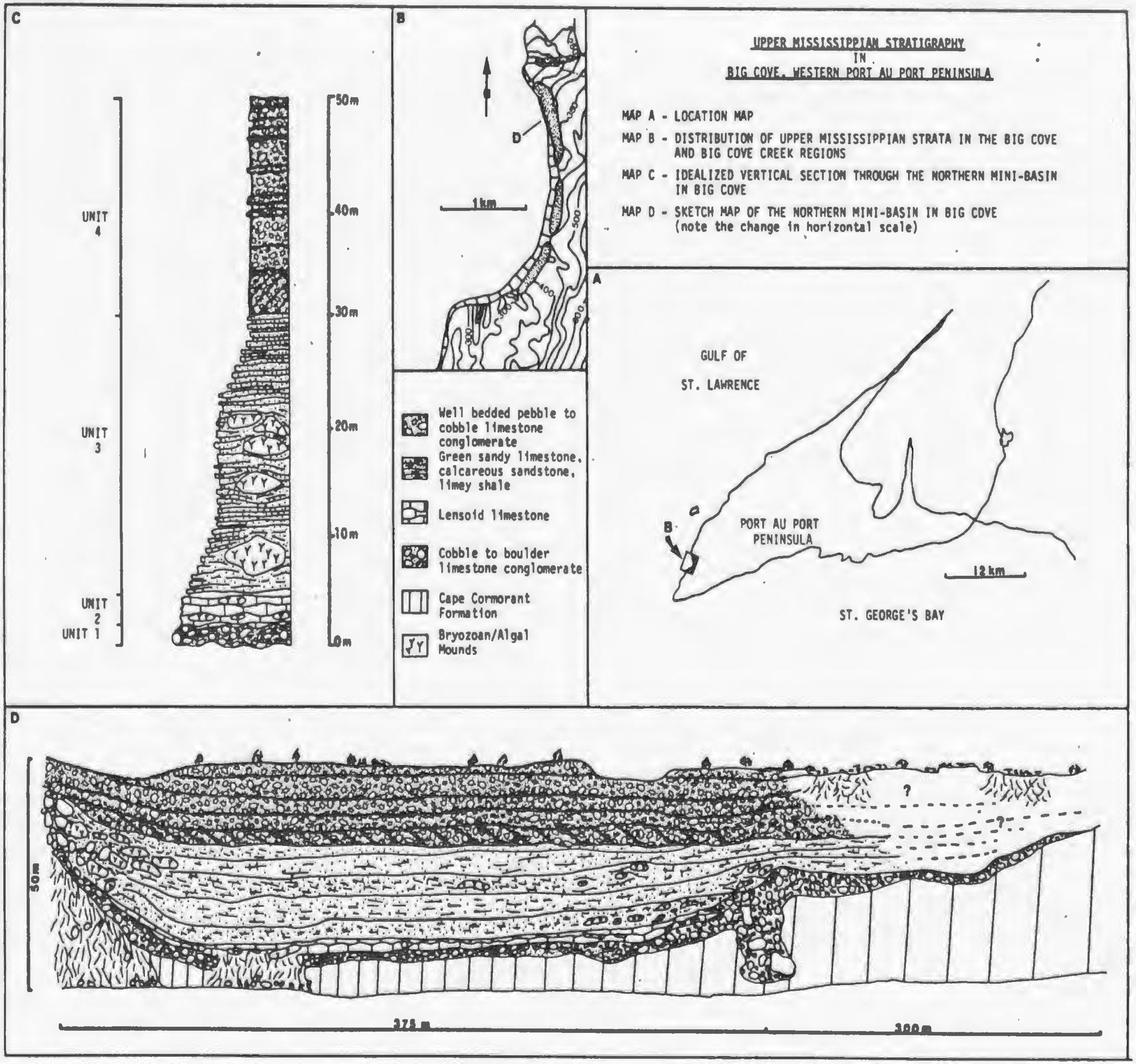
This lithofacies is found on the peninsula again in two spatially distinct regions: (1) Big Cove, on the southwestern coast, and (2) in the northeastern part of the peninsula between Boswarlos and The Gravels (Fig. 1). A small outcrop of this lithofacies occurs as well at Dory Cove on the east shore of East Bay. In both main regions, the sediments can be traced inland along valleys where they thin with increasing elevation. The stratigraphy within each region is described and correlated.

3.4.2. Definition and Distribution in Big Cove.

A well exposed sequence of interbedded carbonates, calcareous sandstones, and limestone conglomerates/breccias occur at Big Cove, in cliff-section, and along the lower portion of Big Cove Creek (Fig. 1, and Fig. 31). In the cliff-section, three discrete lenses of this lithofacies overlie with pronounced angular unconformity steeply-dipping strata of the Ordovician Cape Cormorant Formation. Each lens is composed of subhorizontal strata which dip to the west and thin both to the north and south onto the flanks of the underlying depression. Only the northern basin, depicted in Figure 31, and its extension inland is described in detail because of its accessibility. The upper 29 metres of the cliff is vertical and inaccessible, therefore the thickness and description of lithologies can only be estimated.

Four distinct units can be defined within the cliff section. First, a basal poorly-bedded limestone conglomerate unconformably overlies the steeply-dipping Ordovician strata. This is a similar-looking conglomerate to that found in the basal Boswarlos section. This unit is overlain, in ascending order, by (2) lensoid and biohermal limestone, (3) interbedded calcareous sandstones/limey shales/sandy limestone breccia, with well-developed bryozoan bioherms, and (4) an uppermost unit of well-bedded limestone conglomerate/breccia.

FIGURE 31:



UPPER MISSISSIPPIAN STRATIGRAPHY
IN
BIG COVE, WESTERN PORT AU PORT PENINSULA

MAP A - LOCATION MAP

MAP B - DISTRIBUTION OF UPPER MISSISSIPPIAN STRATA IN THE BIG COVE AND BIG COVE CREEK REGIONS

MAP C - IDEALIZED VERTICAL SECTION THROUGH THE NORTHERN MINI-BASIN IN BIG COVE

MAP D - SKETCH MAP OF THE NORTHERN MINI-BASIN IN BIG COVE (note the change in horizontal scale)

(1) Basal Conglomerate - The texture of this conglomerate is similar to the Boswarlos basal conglomerate. Lithologies of the clasts are Table Point limestones, St. George Group carbonates, and Cape Cormorant limestones. Clasts, up to 1.0 metre in size, may exhibit karst solution surfaces and pits. The thickness of the unit varies from 1.0 to 4.0 metres; an approximate general thickness is 2.0 metres. The conglomerate is continuous along the base of the lens with masses extending down to the waterline apparently draping down over the steep Ordovician strata.

(2) Lensoid and Biohermal Limestones - This unit is 2.2 metres thick and is conformable with the underlying conglomerate. A thin bed of green calcareous quartz arenite, pebble-rich at the base and becoming shalier towards the top, marks the gradation between the two units. The limestone unit is composed of beds, tens of centimetres thick, of fining-upward pebble breccia. A thin bed of black shaley limestone is found near the base of the unit. The fragments in the limestone beds may be several centimetres in length and are surrounded by a packstone matrix. The fragments are Ordovician carbonates, dark micaceous siltstone, and less than 10 percent of quartz and feldspars. Each bed of this breccia grades upward into an argillaceous packstone top. The beds are often lensoid in shape and usually incorporate mounds of brown micrite within which a colloform structure is present. These mounds are 0.5 metres thick and up to 6.0 metres in length. Smaller, more oblate mounds, tens of centimetres to 2.0 metres in length and thickness, consist of upward branching bryozoans. Thick brown calcite crusts, up to 2.0 centimetres in thickness and with a mammellose surface texture often coat the bryozoans (Fig. 32).

Gradational with and overlying the lensoid limestones is a sub-unit of bedded green arenaceous packstones. No macrofossils are present, although some ostracodes may be found. Terrigenous clastics may comprise up to 50 percent of the unit. Distorted and contorted bedding similar to that described at Boswarlos occurs within this subunit.

(3) <u>Calcareous sandstones/limey shales/sandy limestone breccia</u> - These strata are composed of alternating resistant calcareous cliff-forming and shaley recessive slope-forming sections. Generally, each section is composed of beds, centimetres thick, of feldspathic arenites, calcareous shale, and limestone breccia. The bedding is typically flaggy, with very shallow lenticular trough cross-beds. The shalier strata have abundant plant and wood fragments along the bedding planes. Current lineations directed east-west are commonly found within the sandstone beds. The limestone breccia beds are similar in lithology to those described in the underlying unit, although the clast size is generally larger (2.0 to 4.0 centimetres in diameter).

Within the basal 17 metres of this unit, towards the northern and southern ends of the margins of the depression, large bryozoan bioherms, up to 4 metres thick and 8 metres in length, and generally biconvex in shape, are found either isolated or stacked vertically on lower mounds (Fig. 33). The mound density rapidly decreases towards the centre of the minibasin.

(4) <u>Bedded Limestone Conglomerate/Breccia</u> - Blocks of this unit are found as talus at the base of the cliff. Strata, <u>in situ</u>, are inaccessible within the cliff section. The unit, 20 metres thick, is

FIGURE 32: Mammallose texture of possible magnesium calcite cement (now altered to calcite). The marine cement coats skeletal elements within the Lower Sequence carbonates. The solid arrow points to the smooth outer surface of one mammallon, whereas the open arrow indicates a fresh broken surface. Scale bar is 3.0 centimetres.

FIGURE 33: Bryozoan mounds surrounded by sandy and lime intermound sediment. In the photograph, one isolated mound and several stacked mounds (forming a bioherm complex) are shown. Scale bar is 1.5 metres.

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divided into two sub-units. The basal unit, 4.0 metres thick, is a medium-bedded oligomictic pebble clast-support conglomerate/breccia. Clasts are subround to angular, less than 4.0 centimetres in diameter, and of Table Point Formation and St. George Group affinity. The matrix, a grey calcareous arenite, is usually less than 5 percent of the rock. This sub-unit displays well-developed planar foresets, dipping approximately 10 degrees to the south.

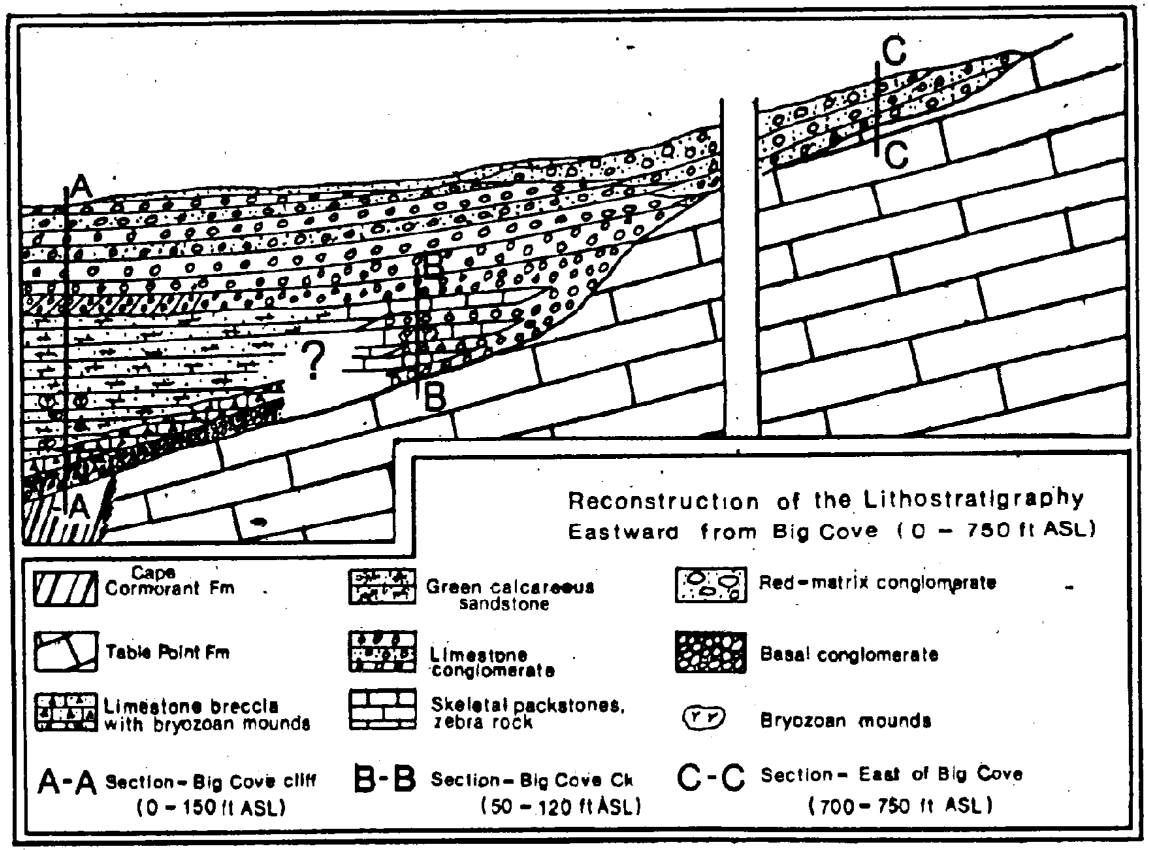
The upper sub-unit is composed of horizontal to sub-horizontal beds of conglomerate/breccia, dipping to the west, that are identical in lithology with the sediments in the underlying sub-unit. Clast diameter is generally larger but less than 10 centimetres. Interbeds of pebble to sand-size clasts may be present within the upper part of this subunit.

3.4.3. Distribution in Big Cove Creek

A compilation of the Upper Mississippian section found along the creek is given in Figure 34. The creek cuts down through Upper Mississippian and Ordovician strata and empties into the Gulf of St. Lawrence just north of Big Cove. Erosion has removed much of the Upper Mississippian section along the creek making correlation between outcrops difficult.

The basal part of the preserved section along the creek consists of bedded limestone conglomerate/breccia, with little matrix and a calcite cement. This lithology is similar to the uppermost unit described in the cliff-section at Big Cove. Within the creek the strata unconformably overlie Ordovician carbonates and grade upward into a

FIGURE 34:


A
A
B
B
C
C
?
Reconstruction of the Lithostratigraphy
Eastward from Big Cove (0 – 750 ft ASL)
Cape Cormorant Fm
Green calcareous sandstone
Red-matrix conglomerate
Table Point Fm
Limestone conglomerate
Basal conglomerate
Limestone breccia with bryozoan mounds
Skeletal packstones, zebra rock
Bryozoan mounds
A-A Section - Big Cove cliff (0 - 150 ft ASL)
B-B Section - Big Cove Ck (50 - 120 ft ASL)
C-C Section - East of Big Cove (700 - 750 ft ASL)

1.0 metre thick matrix-rich conglomerate. The matrix comprises up to 30 percent of the strata and is a green calcareous arenite. This lithology is not unlike the basal conglomerate in the cliff-section.

Overlying these conglomerates with conformity are massive biohermal limestones approximately 5.0 to 7.0 metres thick. In another outcrop, upstream from the latter, limestone conglomerate/breccia dipping approximately 10 degrees to the west, is overlain by interbedded sandstones and sandy limestone within which occurs a bioherm. Locally, near the base of the bioherm, there is laminated biomicrite consisting of alternating calcite and mudstone, very similar to what has been called zebra rock (e.g., Lees, 1964).

The most easterly outcrop of Upper Mississippian sediments along the creek is massive skeletal packstones sandwiched between two thick beds of conglomerate/breccia. Immediately to the north of this locality, the conglomerate/breccia thins onto the underlying Ordovician strata.

3.4.4. Discussion of Big Cove Stratigraphy

It is apparent that east of the cliff-section, limestone beds and thin sandstone beds are interbedded with the limestone conglomerates/breccias. In the cliff-section at Big Cove, this relationship does not occur, and it is interpreted that the thick sequence of green arenites, shales and limestones in the cliff are basin-centre facies equivalent to the conglomerate/breccias and/or the interbedded skeletal carbonates (Fig. 34). The basal conglomerate in the cliff-section and the 1.0 metre thick conglomerate in the creek section are very similar and may indicate that the basal conglomerate in the cliff-section extended inland, and is a facies of the conglomerate/breccia which overlies it in the cliff-section. Clearly, a significant input of green sandy arenite during deposition of the bedded uppermost conglomerate/breccia unit would produce a lithology not unlike the basal conglomerate.

The green sandstones, in the cliff-section, exhibiting shallow lenticular cross-bedding parting lineations, plant debris, and a paucity of marine fauna suggest that these beds were deposited in a fluvial-influenced environment. The orientation of the crossbeds, parting lineations, and strata suggests that the palaeocurrent direction was from east to west. The bryozoan bioherms both in this unit and the underlying unit, however, indicate the presence of marine conditions. Thus, the environment was one of brackish conditions.

Overlying the Big Cove cliff-section are thin, poorly preserved, beds of the red-bed lithofacies. This relationship can also be seen in colour air-photos where red tinges appear on the ground just east of the cliff edge at Big Cove, and implies that the red-beds eventually prograded out over the depressions, and are probable facies equivalents of the bedded limestone conglomerate/breccia (Fig. 34). Bedding of the red-matrix conglomerates well east of the cove (Fig. 1) would suggest that palaeocurrent direction during their deposition was generally from east to west. The southward directed foresets at the base of the uppermost unit in the cliff-section may represent a local variation caused by control of the fluvial system by the surrounding basin topography. As the cliff only gives a two-dimensional representation of the foresets, however, the true direction of currents is unknown.

The relationship of limestone conglomerate/breccia prograding over and infilling small marine depressions is also found in New Guinea both during the Pleistocene and Holocene (Chappell, 1974). Deltaic gravels are recognized overlying and laterally equivalent with coral reefs. The progradation occurs during lowering of sea level. Within the Pleistocene succession, several generations of reef and deltaic gravel are preserved. It is of interest to note that the study area of Chappell's, in New Guinea, possesses a similar latitude as that interpreted for the Port au Port region during the Upper Mississippian (Morel and Irving, 1978).

3.4.5. Definition and Distribution in the Northeastern Port au Port Peninsula

Bedded limestones with bioherms, calcareous sandstones, and sandy limestone breccias lie unconformably on the karsted Ordovician Table Point and St. George carbonates along the northeast shoreline of the peninsula, and inland along major valleys and gullies (Fig. 35). This assemblage of lithologies is quite different to that found in the adjacent Boswarlos-Piccadilly region. East of Boswarlos, sediments characteristic of the sulphate/clastic lithofacies intercalate with those of the carbonate/clastic and red-bed sequences. Such a transition is not evident in the Romaines Brook basin.

The most exposed, and best preserved carbonate/clastic sequence is found along the shoreline at Bellman's Cove, Mistaken Cove, and Lead

Cove. Other localities which help to define the stratigraphic sequence include Aguathuna Creek, Aguathuna "Island", and Aguathuna East (Figs. 29 and 35). Despite the discontinuous nature of the strata, a general lithostratigraphy can be defined.

The carbonate/clastic lithofacies can be subdivided into two groups: (1) a lower sequence composed of carbonates, interbedded calcareous sandstones and sandy breccias all with bioherms, and (2) an upper sequence made up of calcareous sandstones, limestone conglomerate/breccia and minor lime mudstone. The division between the two is marked by an interpreted break in sedimentation. The generalized geological history is shown in Figure 34.

(1) Lower Sequence

(i) Biohermal Limestone -- This unit is composed of beige to grey, massive, unbedded bryozoan mounds intermound bedded skeletal to pelletal packstones/grainstones, and well developed biolithites of similar lithology to the mounds but lacking the associated bedded sediments (Fig. 37). A detailed discussion is found in Chapter 6.

Biolithites are located in Lead Cove, and in Bellman's Cove (Fig. 29) where they are plastered against the depression walls and have built out towards the centre of the depressions. These deposits may be as much as 16 metres thick and tens of metres in width. They are overlain abruptly by the middle unit of this sequence with evidence of an erosional contact. The contacts may be vertical or subhorizontal. The centre of the depressions are filled with the younger units of the Lower Sequence.

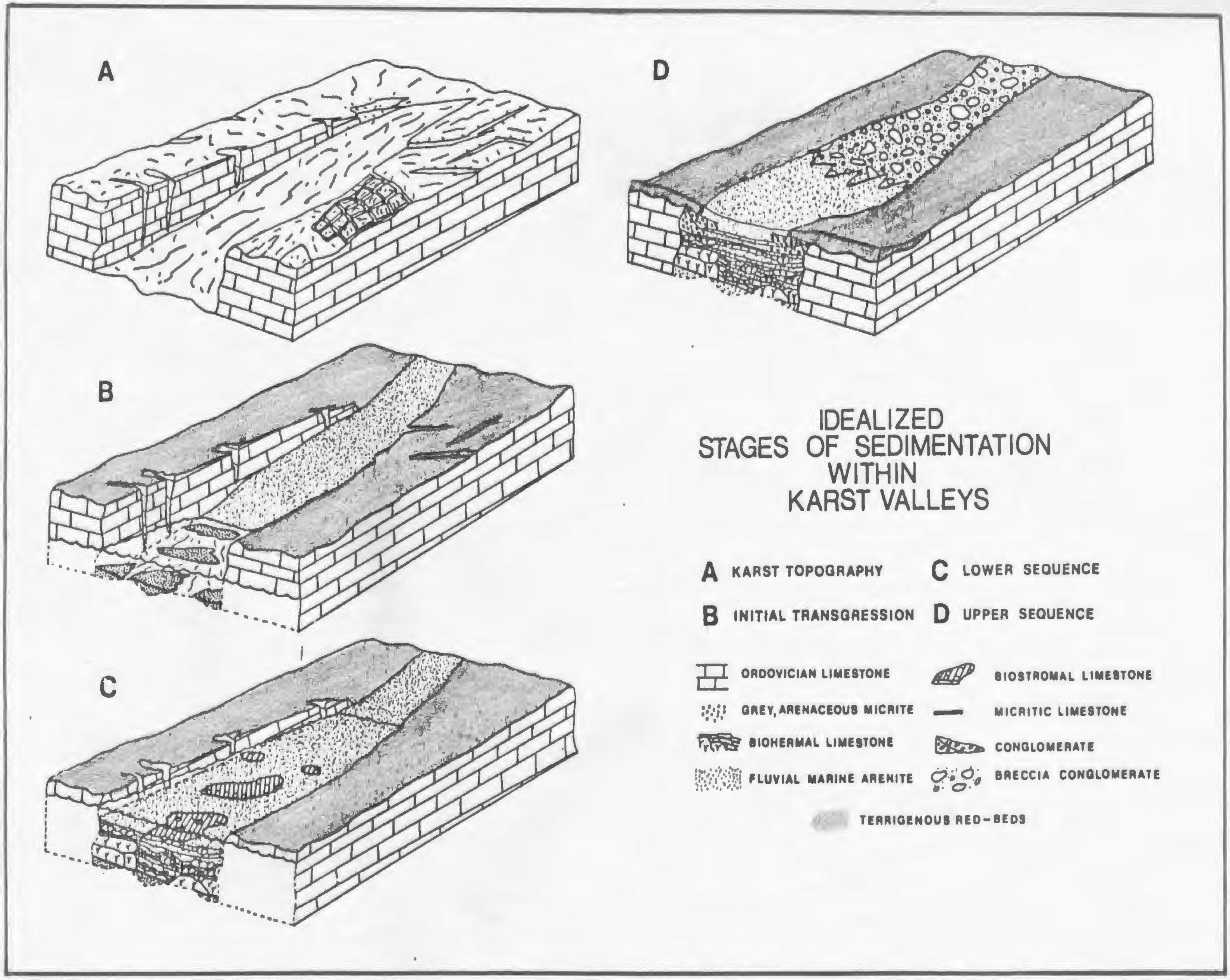
The mounds may comprise up to 60 percent of this unit within individual depressions. Their shape and size vary (Chapter 6; Fig. 64) though they are generally lensoid to ellipsoidal. Within the depressions, it is evident that mounds and associated sediments accreted inward toward the centre. The largest mounds are found within the largest depressions, while abundant intermound sediment and small mounds are associated with the smaller depressions.

Lithologically, the mounds and biolithites are composed of tiny colloform structures with cores of bryozoans, algae and serpulid-type worm tubes. Associated fauna include brachiopods, pelecypods, and large cylindrical worm? tubes. The intermound sediments are typically skeletal and pelletal packstones/grainstones, though thin black shaley limestones (Mistaken Cove) may occur. Intermound sediments display onlap-offlap drapes with the mounds. Apparent dips of the strata, toward the centre of the depressions, may be as much as 30 degrees (Mistaken Cove).

In Mistaken Cove, Bellman's Cove, Lead Cove, and Aguathuna "Island", the biohermal limestones are locally separated from the Table Head limestones by a grey-green micritic and arenaceous limestone (Fig. 38). In Bellman's Cove, and Lead Cove, the limestone infills fissures and a collapsed cave respectively.

(ii) Sandy Limestone Breccia and Sandstone -- This unit, up to 10 metres thick, is composed of well-bedded to poorly-bedded clast-support to matrix-support limestone breccia with a green calcareous quartzose arenite matrix. The clasts are pebble to granule in size, and typically very angular (Fig. 39). Their composition is similar to

FIGURE 36:


A
B
C
D
IDEALIZED
STAGES OF SEDIMENTATION
WITHIN
KARST VALLEYS
A KARST TOPOGRAPHY
C LOWER SEQUENCE
B INITIAL TRANSGRESSION
D UPPER SEQUENCE
ORDOVICIAN LIMESTONE
BIOSTROMAL LIMESTONE
GREY, ARENACEOUS MICRITE
MICRITIC LIMESTONE
BIOHERMAL LIMESTONE
CONGLOMERATE
FLUVIAL MARINE ARENITE
BRECCIA CONGLOMERATE
TERRIGENOUS RED-BEDS

that of Table Point and St. George Group carbonates. Locally, some fragments of the underlying biohermal limestone are present. Interbedded with the breccia, are plant-bearing green calcareous quartzose arenites. Quartz and feldspar clasts may comprise a total of 50 percent of the rock. Cross-bedding is common, as are channels of breccias within these sandier beds. Breccia lenses may thin and thicken laterally very rapidly. In Bellman's Cove, Mistaken Cove, and Lead Cove (Fig. 29), this unit dips toward the centre of the cove, and northward into East Bay. It is best exposed in Bellman's Cove and varies in thickness from 0 to 10 metres.

Thin lensoid-shape bryozoan mounds (less than 15 centimetres thick) and ragged-looking blocks eroded from the underlying biohermal unit occur within the sandy breccia and sandstones.

Green plant-bearing calcareous sandstones and shaley limestone, in Aguathuna "Island" is an equivalent facies of the unit (Section E; Fig. 29). It overlies the biohermal limestone unit but is only approximately 30 centimetres thick. It is interpreted that this is indicative of the unit thinning to the west.

(iii) Biostromal Limestone with Mounds -- Bedded skeletal packstones and wackestones with small bryozoan mounds occur as discrete lensoid bodies within green calcareous to shaley sandstones similar to the sandstones of the underlying unit. The limestone lenses vary in preserved thickness from 0 to 5 metres and preserved lengths are approximately 1 to 10 metres. This unit is poorly exposed and found in Bellman's Cove, Lead Cove, and an equivalent facies in Aguathuna "Island" (Fig. 29). At the latter locality, only mounds and bedded

FIGURE 37: Biohermal limestone, Lower Sequence, of the carbonate/clastic lithofacies at Aguathuna "Island". Note intermound sediment above the hammer.

FIGURE 38: Contact of biohermal limestone with grey lime mudstone (within dotted lines). Both lithologies unconformably overly Table Point limestone. The lateral distribution of the grey lime mudstone is very local.

FIGURE 39: Typical breccia within siliclastic unit of the Lower Sequence, Bellman's Cove. Width of scale is 3.0 centimetres.

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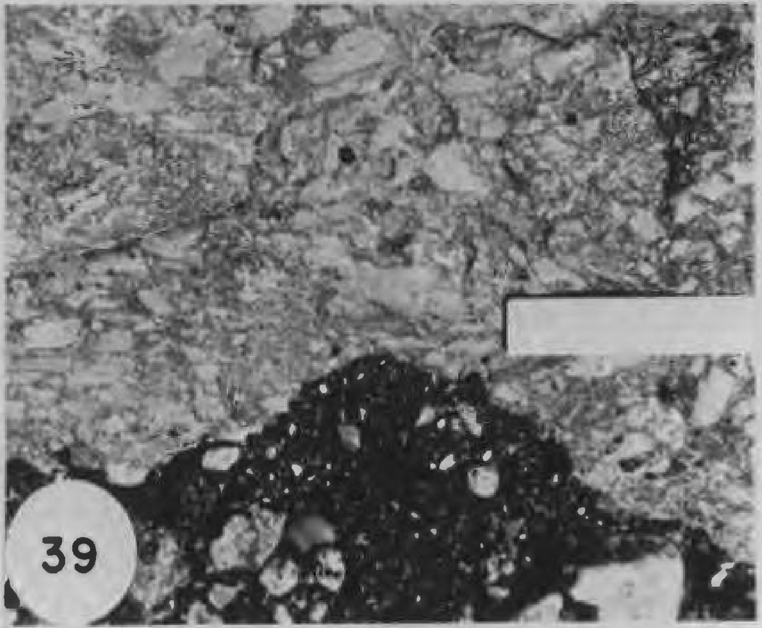

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limestones are present. A large rounded bioherm (3 metres in diameter) surrounded by the green sandstones occurs at the same stratigraphic level as the biostromes in Bellman's Cove (Fig. 40).

The upper contact of these biostromes may be (a) faulted, and in contact with the Upper Sequence sediments, (b) the present erosion surface, or (c) overlain by the interbiostromal sandstones. Fractures within the lenses may be infilled with green calcareous sandstone similar to arenites associated within the Upper Sequence (Fig. 41).

(B) Upper Sequence

The Upper Sequence is characterized by calcareous sandstones, conglomerates/breccias, and minor limestone. Lithostratigraphic correlation between outcrop localities is tenuous except in a few instances. Therefore, lithologies and localities are not described in any particular order. Discussion of the correlation is given later.

(i) Sandy Pebble Conglomerate -- This unit is found in Bellman's Cove and Dory Cove, and consists of well-bedded sandy pebble to cobble conglomerate/breccia; the clasts are of Ordovician lithology. In Bellman's Cove, calcareous green sandstone locally underlies the unit. Both the conglomerate/breccia and arenite overlie with sharp unconformity the underlying limestones of the Lower Sequence (Fig. 42). The clastics dip steeply (less than 30 degrees) towards the centre of the depression in both localities. The thickness of the unit varies from 0 to 6 metres. In Bellman's Cove a fault parallel to the cove axis repeats part of this section.

The unit is overlain with abrupt to gradational contact by

FIGURE 40: Large mound in Bellman's Cove, surrounded by argillaceous intermound sediments. This mound is stratigraphically equivalent with biostromal limestones in the cove as well. Hammer for scale.

FIGURE 41: Fracture in biostromal unit infilled by Upper Sequence calcareous arenite (within dotted lines) in Lead Cove. Hammer for scale.

FIGURE 42: Upper Sequence arenite and breccias dipping toward the centre of Bellman's Cove (above dotted line). These overly, with apparent unconformity, Lower Sequence carbonates and breccia (below line). Hammer for scale.


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a thin grey micritic limestone in Bellman's Cove. In Dory Cove, Pleistocene deposits overlie the sandy pebble conglomerate with sharp unconformity.

(ii) Calcareous Sandstone and Shaley Limestones -- Interbedded calcareous plant-bearing sandstone and shaley limestone are found in Aguathuna Creek. These cover biohermal limestones of the Lower Sequence, and underlie a grey limestone conglomerate/breccia. The thickness of the exposed portion of the unit is 2.0 metres. Both the upper and lower contacts are covered. Abundant plant and tree fossils, as well as whole shelled and fragmented ostracodes are preserved in the sediments. The strata are similar to the calcareous sandstone/shaley limestone unit in Big Cove.

(iii) Grey Micritic Limestone -- Laminated grey mudstone is found in Bellman's Cove, Lead Cove, and Aguathuna Creek overlying or interbedded with conglomerates or breccias. The thickness varies from 0 to 1.0 metre (Aguathuna Creek) and is approximately half a metre at the other localities.

(iv) Calcareous Feldspathic Arenite -- Grey-green and red feldspathic micaceous arenites with calcite cement, and abundant plant debris are on top of the micritic limestone in Bellman's Cove and Lead Cove (Fig. 29). At the northern end of Aguathuna East (Section F; Fig. 29) the unit overlies the Lower Sequence. Typically, the basal part of the unit is pebble to granule-rich and fines upwards into arenite. Clasts are generally derived from the Ordovician strata. Pebble lenses and beds may be common in the lower 10 metres of the unit interbedded with sandier beds. The thickness of the unit varies between 25 metres (Lead Cove) and 1.5 metres (Aguathuna East).

The strata in this unit are thin and platey-bedded, poorly indurated with abundant small planar and trough crossbeds, current lineations parallel to the north-south axis of the depressions, and pebble channels and small ripple drift structure directed to the north (Fig. 43). These sedimentary structures suggest that the palaeocurrent direction was to the north and that the sediments were deposited under a mid- to upper flow regime.

Locally, nodules with relic chickenwire texture occur within the arenite. The nodules are completely calcitized.

Later faulting has uplifted or broken the strata in Bellman's Cove and Lead Cove. Pleistocene deposits cover the top of the unit in all localities except Aguathuna East where a limey pebble breccia overlies the unit.

<u>(v) Limestone Breccia</u> -- This unit is found in the upper reaches of Aguathuna Creek, and at Aguathuna East (Fig. 35). Two breccias are preserved in Aguathuna Creek: (a) the oldest, and less extensive, is a dark limestone breccia with sandy calcareous matrix, overlain conformably? by (b) a light grey well-bedded breccia with a limey matrix (Fig. 44). Fragments of the dark breccia occur locally at the base of the upper breccia unit. Other fragments within the breccias are all of Ordovician carbonate lithology, with rare clasts of the underlying Lower or Upper Sequence sediments. Locally, pink barite may act as cement and matrix in the second breccia.

FIGURE 43: Upper Sequence feldspathic arenite, in Bellman's Cove. Alleghenian faulting has fractured and uplifted the strata. Scale bar approximately 1.0 metre.

FIGURE 44: Upper Sequence conglomerate/breccia in Aguathuna Creek. Hammer for scale.

FIGURE 45: Lower Sequence limestones (a) are overlain by Upper Sequence feldspathic arenite (b), and pebble breccia (c). The latter two units thin onto a well-karsted Ordovician boulder of Table Point lithology. Scale bar is 1.5 metres.

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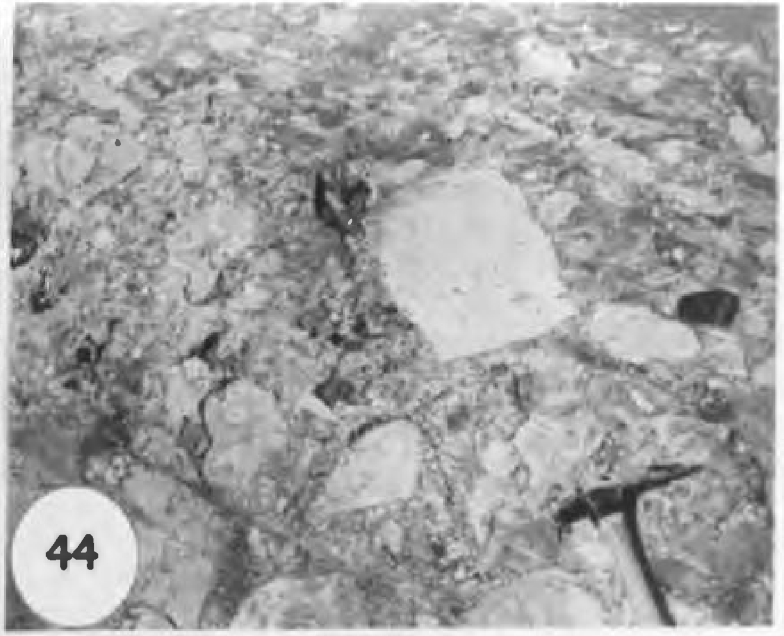

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overlie, and are probably conformable with, the limestone breccia in Aguathuna Creek though no outcrop of the contact is preserved.

3.4.7. Discussion of Northeast Port au Port Stratigraphy

The relationship between the Upper and Lower Sequences of the carbonate/clastic lithofacies is reflected in Lead Cove. A fracture within the uppermost limestone of the Lower Sequence is filled with green sandstone indicating that prior to the deposition of the Upper Sequence, a break in sedimentation occurred. The extent of erosion of the limestones and sandstones during the break, or, by the sediments in the Upper Sequence upon resumption of sedimentation is unknown.

It is apparent that the biohermal limestone in the Lower Sequence developed on the sides of depressions and built outwards into the basin centre. Subsequent deposition of younger units would produce a relationship in which the older beds could possibly be topographically higher than the clastics without any erosion. This is seen in Bellman's Cove, Aguathuna East, Lead Cove, and considered for the distribution of the breccias and biohermal sediments in Aguathuna Creek. Thus, within the Lower Sequence contemporaneous deposition of the biohermal limestones and sandy breccias and sandstones is possible. The lack of abundant Lower Sequence sediments in the breccias of the Upper Sequence in Aguathuna Creek can be explained by a channeling of the terrigenous clastics down the middle of the depression where no biohermal sediments had been deposited. Only in the lower sections of the creek do these limestones occur within the centre of the depression. Unfortunately, all other sediments that may have overlain the limestones have been eroded or are well covered.

3.4.8. Other Outcrop Localities

Many isolated, poorly exposed to well exposed outcrops of the Lower and Upper Sequences have not been fully described in the above descriptions (Fig. 35). These localities, however, fit well with the stratigraphy as established above.

In Miner's Brook, Gillam's Creek, and in the lower part of Aguathuna Creek, massive bedded to thinly bedded biohermal limestones are poorly exposed. In Gillam's Creek and Miner's Brook these are overlain by a green-grey sandstone which may be found locally at a lower topographic level than the limestones. Here, a similar relationship is preserved between the sandstone and underlying limestone as found in Aguathuna Creek. The sandstones are interpreted to be Upper Sequence equivalents.

In Gillam's Cove, Boswarlos-type laminated limestone is interbedded with beige-coloured biohermal and bedded limestones. A basal conglomerate similar to conglomerates in Romaines Brook, Boswarlos section, and the Big Cove cliff-section, is found plastered against one wall of the Gillam's Cove and grading upwards into rubbly limestones of the Lower Sequence (Fig. 29).

In Aguathuna East, beige-coloured biohermal limestones underlie the Upper Sequence at the northern end of the section, but are topographically higher towards the southern end. Again, no obvious fault displacement has occurred.

It appears certain that the stratigraphy along the shoreline can be extended inland along the valleys. During the Late Mississippian, the environments of deposition in the karst depressions were relatively uniform along the northeast shore of the peninsula. As a result, a stratigraphy can now be recognized despite the present isolated nature of the carbonate/clastic outcrop localities.

3.5. Lithofacies Correlation

Intercalation of the three lithofacies occurs in two regions: (a) Big Cove, and (b) east of Boswarlos.

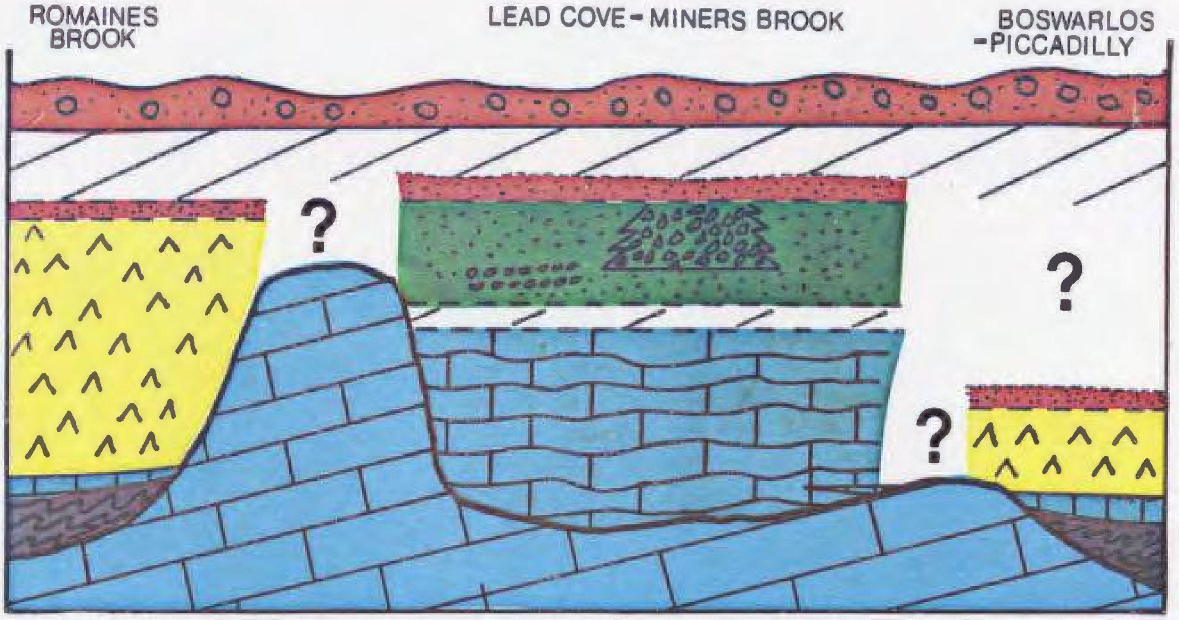
In the Big Cove region, as described previously, red-beds overlie and are interpreted as facies equivalents of the grey limestone conglomerate/breccia found in the cove. South of Big Cove, red-matrix bedded conglomerates can be found at the same present topographic level rather than the carbonate sequence in Big Cove. East of Big Cove, in well-exposed outcrop, red-matrix conglomerates lie at a higher topographic level that the carbonate (Fig. 1). As no major faults cross-cut the region between Big Cove and the areas to the east and south, deposition of the red-bed sequence is interpreted to have been initially coeval with the carbonate/clastic succession, and, with time, prograded out over the carbonate basin.

East of Boswarlos, all three lithofacies are intercalated. In Gillam's Cove, the laminated limestone of the sulphate/clastic lithofacies is interbedded within beige limestones of the carbonate/clastic sediments typical of the coves to the east. Just west of Gillam's Cove in a small depression (Section C; Fig. 29), red-matrix conglomerates with green mottling of the matrix lie spatially distinct from the beige-coloured limestones and the laminated limestone, but all within metres of one another. Inland, underlying the present erosion surface, red sediments are patchily exposed. Therefore, a complicated lateral and vertical facies intercalation between the three lithofacies is obvious in the northeastern part of the peninsula, and indicates that the sulphate and carbonate sequences were contemporaneous followed by development of an overlying red-bed lithofacies (Fig. 46). A transition between carbonates and sulphates does not occur with the Romaines Brook basin because of the presence of a palaeoridge (Ordovician carbonates) that is still preserved between the two areas.

Correlation of similar styles of deposition between Big Cove, and the Aguathuna Creek region is possible despite the 40 kilometre distance between the regions. In both localities there is a similar sequence of calcareous sandstones and shaley limestones (Lower Sequence) overlain by coarse limestone breccia which grades up into red-beds (Upper Sequence). The similarity in stratigraphy and lithologies suggests that environments of deposition as this stratigraphic level, and the causes for progradation of sandstones and breccias seaward, were relatively uniform across the peninsula. In southwestern Newfoundland, alluvial red-bed progradation (represented by the Upper Codroy Group) was caused by uplift in the southeast along the faulted basin margin (Belt, 1968). A similar, and probably related, uplift is envisaged for the cause of the fluvial and red-bed progradation on the peninsula.

FIGURE 46: Interpreted schematic geometry and correlation of lithofacies between Boswarlos-Piccadilly and Romaines Brook. Note the Ordovician palaeoridge creating two distinct basinal regions. Relative thicknesses are approximate. Karst valleys are not shown.

Legend:
Blue - limestone with straight angled lines is Cambro-Ordovician in age.
- limestone with vertical lines is the laminated limestone and limestone conglomerate of the sulphate/clastic lithofacies.
- limestone with horizontal wavy lines is the Lower Sequence of the carbonate/clastic lithofacies.
Purple - allochthonous Humber Arm Supergroup.
Yellow - gypsum/anhydrite.
Green - clastics of the Upper Sequence.
Red - clastics of the terrigenous lithofacies.
Orange/Red - Pleistocene sediments.
/// - non-deposition and/or erosion


ROMAINES BROOK
LEAD COVE - MINERS BROOK
BOSWARLOS -PICCADILLY
?
?
?

Palaeontological evidence, however, suggests that it may have occurred somewhat earlier than in southwest Newfoundland (Chapter 5 - Palaeontology and Biostratigraphy).

3.6. Summary

In summary, initial Carboniferous sedimentation on the peninsula, involved terrigenous sediments along the south and southwest coasts, marine carbonates along the southwest and northeast coasts, and sulphates/carbonates along the northeast and in the Romaines Brook vicinity. Basins in which carbonates and sulphates were deposited were always influenced by continual input of fluvial clastics. Subsequently, progradation of the fluvial sediments over the marine basins occurred as a result of uplift of the peninsula. The style of fluvial sedimentation varied, controlled by karst topography, as evident from the strata in the Upper Sequence. The presence of relic chickenwire gypsum within the sandstones indicates that locally the arenites were subjected to hypersaline conditions. This probably occurred after burial but prior to lithification. With continued uplift breccias were deposited as deltaic sediments followed by red-beds of alluvial fan-braided stream origin (Fig. 47). Thus, the Upper Mississippian stratigraphy on the Port au Port Peninsula records a change from marine to terrestrial conditions.

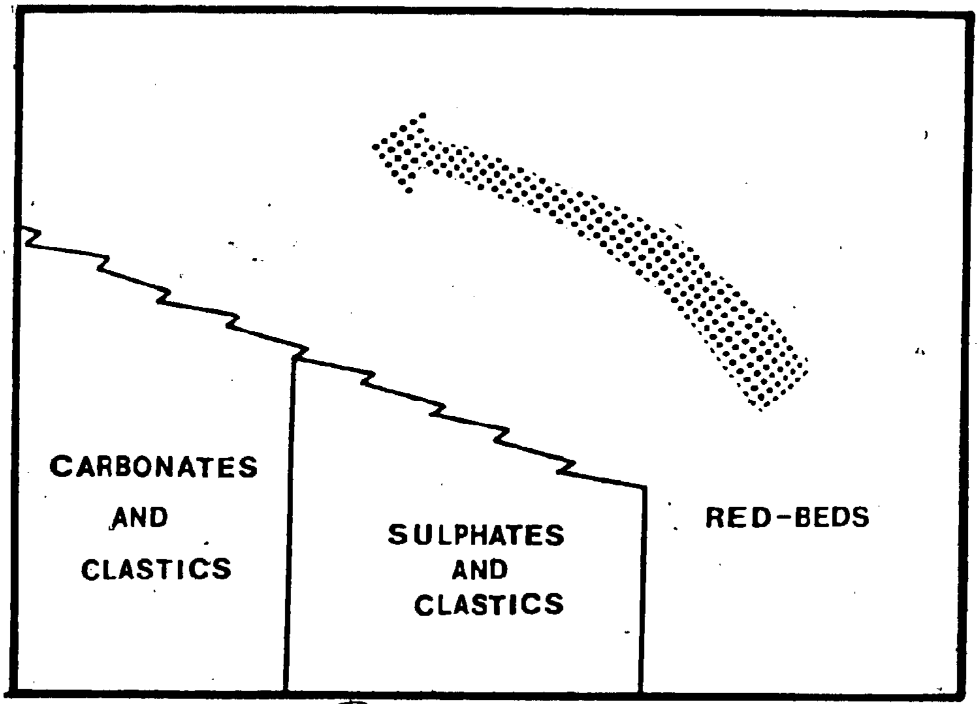


FIGURE 47: Interpreted lithofacies correlation and red-bed progradation during the Late Mississippian.
The diagram shows the three initially-coeval lithofacies; but, with time, the red-bed lithofacies progrades out over the other two sequences.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M
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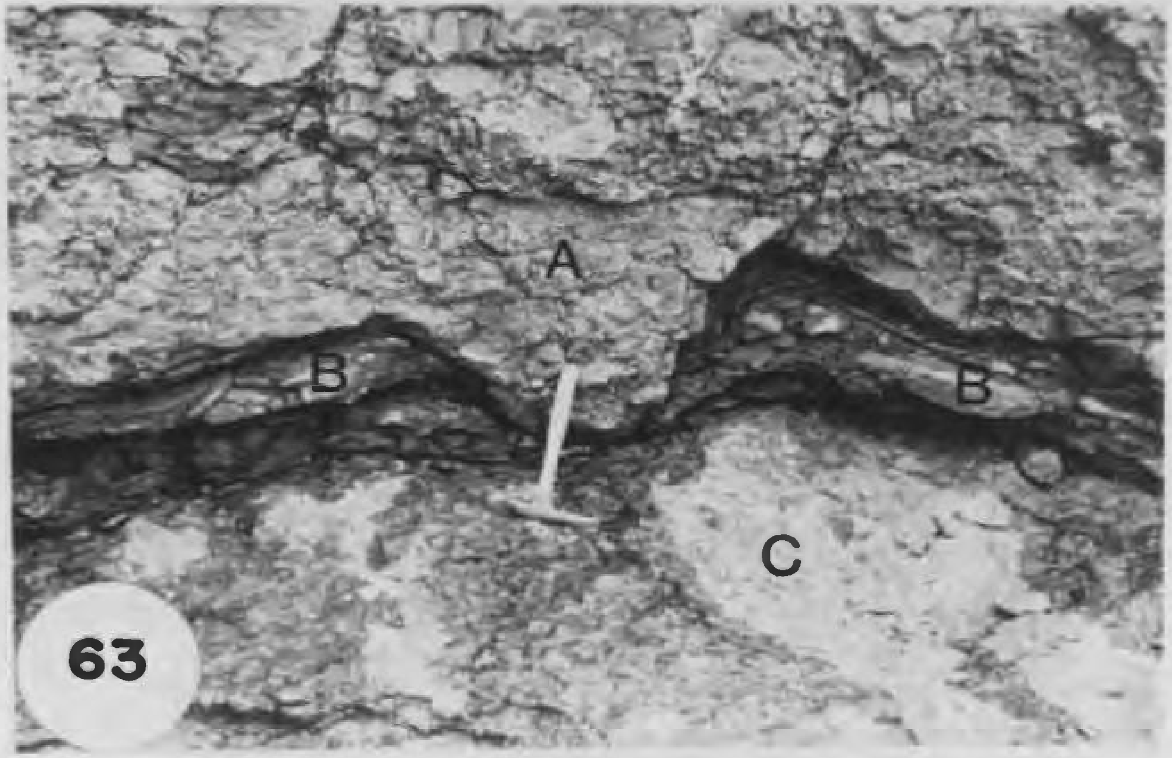
A
B
B
C
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CHAPTER 4

DEFORMATION OF THE UPPER MISSISSIPPIAN STRATA IN THE PORT AU PORT AREA

4.1. Introduction

Three periods of deformation have affected the Palaeozoic strata of western Newfoundland: (i) the Taconic Orogeny, Middle Ordovician in age, reflected by transported sediments and ophiolites, with relatively flat thrust contacts and west-facing folds, (ii) the Acadian Orogeny, Late Devonian in age, characterized by high angle faulting, and (iii) the Allegenian Orogeny, Pennsylvanian-Permian in age, which locally is typified by high angle faults (see Williams, 1979, for summary). The latter deformation is restricted to narrow zones whereas the other two deformational events are regional.

4.2. Pre-Carboniferous Structure on the Peninsula

The Taconic Orogeny is reflected by the superposition of transported sediments and mafic volcanics of the Humber Arm Supergroup on top of autochthonous Cambro-Ordovician carbonates and sandstones (Williams, 1975) (Fig. 1). Prior to the development of karst and Upper Mississippian sedimentation, Acadian deformation tilted the Ordovician strata underlying the present peninsula gently to the northwest. On the western side of the peninsula, Lower and Middle Ordovician carbonates, the Middle Ordovician Long Point Formation, and Silurian-Devonian Clam Bank Formation are faulted and steeply dipping to the west and northwest, with portions of the Clam Bank overturned (Fig. 1).

Flatlying Upper Mississippian conglomerates in the Big Cove region overlie portions of this steep structure. Several major faults, not covered by Carboniferous strata, transect the peninsula from north to south (Fig. 1). However, association with either the Acadian or Alleghenian Orogenies is difficult to determine.

4.3. Deformation of the Upper Mississippian Strata on the Peninsula

Deformed Upper Mississippian strata are found (a) along the south coast at Sheaves Cove, Lower Cove, and (b) along the northeast coast at Lead Cove, Bellman's Cove, and Boswarlos, and (c) at Big Cove on the west coast.

4.3.1. South Coast

In the Sheaves Cove region, two outcrops of red-beds, Sheaves Cove West, and Sheaves Cove Central, are bounded on their northern sides by normal faults striking 50 degrees and dipping steeply to the south. At Sheaves Cove Central, a parallel fault within the red-beds occurs near the southern contact of St. George Group strata and red-beds. The centre of the outcrop is dropped down a few metres at most.

Cutting red-beds, Ordovician strata, and speleothem-filled fissures, are numerous veins and veinlets composed of white fine to coarsely-crystalling equant calcite. In the Sheaves Cove region, the veinlets are parallel to the fault that bounds the northern side of the Upper Mississippian outcrops. In Sheaves Cove West, a 15 centimetre thick calcite vein partially coincides with the fault trace.

West of Lower Cove, large metre-wide fault zones infilled with red conglomerate and sandstones, are cut by coarse crystalline equant and drusy calcite veins. Dip displacement on the faults may be up to two metres. Fragments within the conglomerate are red sandstones which appear to be reworked Codroy red sandstones. It is here interpreted that faulting and veins postdate the sediment infill.

4.3.2. Northeast Coast

In Bellman's Cove and Lead Cove, normal faults displace the Codroy strata vertically as much as ten metres. In Bellman's Cove, faults are parallel to the cove-valley axis, are found on both sides of the cove, and are contained within Codroy strata. The faults are high-angle and dip steeply towards the middle of the cove resulting in a graben structure. In Lead Cove, a fault zone has flexed the Upper Sequence sandstones from a horizontal attitude in the mid-cove region to a 30 degree west dip adjacent to the fault on the eastern side of the cove. Lower Sequence limestones and sandy breccia beds, in the fault zone, are steeply dipping as well. Only one fault zone is recognized in the cove, though Pleistocene cover and later vegetation may cover another zone near the west side.

In Romaines Brook, strata are tilted 5 to 10 degrees to the south. Cover prevents exposure of the contact relationships of the Upper Mississippian strata and the underlying Ordovician strata.

In the Bogwarlos region, two types of deformation are exposed: (i) high-angle normal faulting, and (ii) intrastratal brecciation due to solution collapse. Several small high-angle faults with a north-south orientation cut the Table Point limestone. At Halfway Point, a fault parallel to these minor faults juxtaposes Table Cove limestone and the laminated limestone of the sulphate/clastic lithofacies. In the Boswarlos section itself, the Upper Mississippian beds are preserved in a shallow syncline plunging gently to the northeast. This syncline is either a result of the high-angle faulting or reflects the palaeotopography of the underlying Humber Arm Supergroup.

The second style of deformation, intrastratal brecciation, consists of distorted and brecciated beds sandwiched between undisturbed calcareous sandstones and arenaceous limestones (Section A, Fig. 29). This brecciation only occurs in the most westerly outcrop on the shoreline at Boswarlos. It is not found at the same stratigraphic level in the adjacent outcrop to the east. This style of deformation also occurs in Big Cove.

In the Aguathuna region, veinlets of calcite often containing marcasite and galena cut Ordovician strata. Calcite veinlets, in Upper Mississippian strata, lack sulphide mineralization but may have rare barite.

4.4. Discussion

The style of faulting in Bellman's Cove, Sheaves Cove Central, and Lead Cove, suggests that mini-grabens developed, downfaulting the centre of the coves. There is no visible displacement of the Ordovician strata across these coves except for Sheaves Cove Central. In Bellman's Cove, and Lead Cove, depositional contact between the Codroy and Ordovician strata is well preserved. It is apparent that graben structures do affect some coves on the peninsula but only the distribution of the Codroy strata, and the Ordovician carbonates underlying the Codroy strata within the grabens themselves.

In the other coves, and inland along the valleys, no apparent large fault displacements of Ordovician strata are recognized. It is, however, difficult to discern faulting within the Codroy sediments along the valleys where cover is so extensive. In Aguathuna "Island", the strata orientation changes dramatically from 10 degrees northwest to 60 degrees westward over a distance of 10 metres. The change in dip is continuous with no fracturing present along the flexure. Quarrying has removed the western Ordovician-Codroy contact thereby making it difficult to determine whether the structure is caused by faulting.

The intrastratal brecciation in Boswarlos had been suggested to be due to landslides (cited in Bell, 1948). It is interpreted, in this study, to be caused by solution collapse due to the solution of gypsum within limestones. Evidence to suggest this conclusion is as follows:

(i) the deformed structure grades laterally and vertically into undisturbed bedding;

(ii) the matrix of the breccia is identical to the lithology of the fragments;

(iii) the limestones are very porous; some pore spaces have remnant gypsum whereas others are filled with late stage calcite cement, or are empty;

(iv) the deformation is preserved as a spatially localized "event".

The presence of a thick gypsum unit overlying the laminated limestones inland at Boswarlos, and the evidence of partially dissolved gypsum within the pores of the limestone suggest that local ponding within the Boswarlos basin raised salinities high enough to precipitate gypsum and gypsiferous sediments. Alteration between saline and brackish conditions (interbedded limestones and sandstones, respectively) would create unstable conditions for any gypsum previously deposited. During sandstone deposition, the groundwater would be more brackish, facilitating early dissolution of the gypsum. The presence of contorted and brecciated sediments suggests that the strata were still wet and/or semi-lithified such that flexing of the beds during collapse would not necessarily lead to complete fracturing. If this interpretation is correct, then dissolution would need to be early. A similar environment relationship is considered for Big Cove.

4.5. Summary

Two styles of deformation affect some of the Upper Mississippian strata on the Port au Port Peninsula: (i) high angle normal faults due to Alleghenian deformation which may develop graben structures; and (ii) intrastratal brecciation caused by solution of gypsum.

Faults associated with Alleghenian deformation are clearly defined only where they cut Upper Mississippian strata. Faults that deform these strata within the karst valleys strike generally parallel to the valley axes, which in turn are parallel to some of the major faults that deform pre-Mississippian strata in the central and western parts of the peninsula. Minor faulting along the northeastern coastline, however, which is parallel to these major faults is interpreted to be the result of Alleghenian deformation as well. These minor faults, as well as the karst valley faults, do not appear to transect the peninsula.

CHAPTER 5

PALAEONTOLOGY AND BIOSTRATIGRAPHY

5.1. Introduction

Numerous, well-preserved fossils are associated with the carbonate-clastic and sulphate-clastic lithofacies on the Port au Port Peninsula, and at Romaines Brook, and in the Barachois Group sediments in Blanche Brook to the east. Systematic descriptions of the fossils within these sediments have never been published. In the following discussion, macrofaunal identification is based on descriptions of Upper Mississippian fauna in Nova Scotia by Bell (1929), and Moore and Ryan (1976), and the description of a crustacean in Newfoundland by Fong (1972). Miospore names are used according to Utting (1978). The foraminifera and conodont nomenclature is used according to Mamet (1970) and von Bitter and Gerbel (in press).

5.2. Macrofauna

The macrofauna found in Upper Mississippian strata of the Peninsula, along with their various locations and lithologies, are listed in Figure 48. Though previous workers have sampled some of the outcrops (Hayes and Johnson, 1938; Sullivan, 1940; Bell, 1948) no description of the precise lithology surrounding each fossil was noted.

In general, the most fossiliferous sediments are the carbonates associated with the carbonate/clastic lithofacies along the northeast coast of the Port au Port Peninsula. The most unfossiliferous sediments with poorly preserved, or no macrofauna, are the clastic units (e.g., as in Bellman's Cove, and along the south shore).

In Mistaken Cove and Aguathuna "Island", the biohermal limestones are locally separated from the underlying Table Point Formation by a grey to grey-green arenaceous lime mudstone. In Bellman's Cove and Lead Cove, this same rock-type occurs within fissures and a collapsed cave. These latter outcrops are now spatially distinct from the nearby biohermal limestones and are interpreted to be laterally equivalent to the biohermal limestones. The most common, and diagnostic, fossil associated with the grey lime mudstone is the spirifer Martinia galataea Bell (Fig. 49A). Other species include brachiopods and one pelecypod. In Mistaken Cove, on the northern end of the east wall, a dense accumulation, or cluster, of these brachiopods is present (Fig. 49B). Most of the fauna associated with this rock type are not found within the biohermal beige-coloured limestones.

The biohermal limestones have an abundant and diverse faunal assemblage. The most common brachiopod found is Beecheria sp. (Fig. 50). These may be found as individuals or comprise colonies of varying dimensions. Beecheria sp. was found in many forms and no attempt was made to classify to a specific level as in Moore and Ryan (1976).

FIGURE 48:

FOSSIL TYPES	DISTRIBUTION											
										LITHOFACIES		
										CARBONATE - CLASTIC		SULPHATE - CLASTIC
	Lead Cove	Mistaken Cove	Bellman's Cove	Aguathuna Creek	Aguathuna East	Aguathuna Island	Gillam's Cove	Boswarlos	Big Cove	beige, rubbly, biohermal limestone	grey, arenaceous, micritic limestone	laminated limestone
COELENTERATA												
Paraconularia planicostata (Dawson)	x	x		x	x	x	x		x	o		
BRYOZOA												
Diploporaria sp.					x					o		
Stenoporella? sp.	x	x	x	x	x	x	x		x	o		
BRACHIOPODA												
Ambocoelia acidica Bell			x								●	
Beecheria sp.	x	x	x	x	x	x	x	x	x	o		+
Camarotoechia acadiensis (Davidson)	x	x				x				o		
Camarotoechia atlantica Bell	x		x								●	
Composita sp.	x	x	x	x	x	x		x		o		+
Cranopsis? sp.	x										●	
Diaphragmus avonensis (Bell)			x								●	
Diaphragmus tenuicostiformis (Beede)						x				o		
Hartella parva Bell							x			o		
Martinia galataea Bell	x	x	x			x					●	
Martinia thetis Bell			x								●	
Ovatia dawsoni (Beede)	x	x				x				o		
Ovatia lyelli (Verneuil)	x	x					x			o		
Schellwienella sp.			x								●	
Schuchertella? sp.			x								●	
Spirifer nox Bell			x			x					●	
undetermined encrusting brachiopod						x				o		
PELECYPODA												
Aviculopecten lyelli Dawson		x	x							o	●	
Leptodesma acadica (Beede)	x	x	x	x	x	x			x	o		
Leptodesma dawsoni (Beede)	x	x	x	x	x	x	x		x	o		
Lithophaga poolii (Dawson)		x			x	x				o		
Modiolus dawsoni (Bell)		x			x	x				o		
Pteronites gayensis Dawson	x	x			x	x				o		
Sanguinolites parvus Bell	x				x	x				o		
GASTROPODA												
Stegocoelia abrupta (Bell)	x	x	x	x	x	x	x	x	x	o		+
Stegocoelia compactoidea (Bell)	x	x			x	x			x	o		
Straparollus minutus De Koninck	x	x			x					o		
CEPHALOPODA												
Diodoceras avonensis (Dawson)							x			o		
Michelinoceras vindobonense (Dawson)							x			o		
ANNELIDA												
Serpula annulata (Dawson)	x	x					x			o		
Spirorbis caperatus McCoy	x	x	x	x	x	x	x		x	o		
undetermined worm tubes	x	x	x	x	x	x	x			o		
FORAMINIFERIDA												
Biseriammina? sp.	x	x				x				o		
Earlandia sp.	x	x				x				o		
OSTRACODA												
undifferentiated	x	x	x	x	x	x	x	x	x	o		+
ALGAE												
undetermined blue-green algae	x	x	x	x	x	x	x			o		
Calcisphaera sp.	x	x		x		x				o		
OTHER												
Bellocaris newfoundlandensis Fong	x	x	x	x	x	x	x			o		
Telliocaris sp. cf. T. loudonensis	x	x	x	x	x	x	x	x		o		+
Cornulites? sp.						x				o		
undetermined calcareous tube							x			o		
fish teeth				x						o		

Two types of bryozoans were noted. The most common is Stenoporella? sp. (Cuffey, pers. comm., 1981) found both as individuals and as a framebuilder within the biohermal limestones (Fig. 51). This bryozoan may be free-standing or encrusting. Often columns are present, composed of vertically stacked encrusting forms. The other common bryozoan is a delicate branching pinnate form called Diploporaria sp. These are found as individuals only (Fig. 52).

Other abundant macrofauna within the biohermal limestones are the pelecypods, Leptodesma acidica Beede, Leptodesma dawsoni Beede, and Pteronites gayensis Dawson, the gastropod Stegocoelia abrupta Bell, the conularid Paraconularia planicostata Dawson (Fig. 53), worm tubes of Spirorbis caperatus McCoy (Fig. 51), and large laminated tubes of possible annelid affinity (Fig. 54).

These latter tubes are particularly common as individuals in the biohermal limestones. In addition, a cluster of several individuals occurs in Lead Cove on the southwest wall. The tubes are roughly circular in cross-section, taper with length, are curved or sinuous in long section and possess a laminated wall of fibrous brown-coloured calcite which is similar to cement lining various cavities within the sediment. This cement may have coated a membranous tube. The walls also include discrete voids aligned parallel to the walls along the length, and concentric in cross-section (Fig. 55). Microfossils, somewhat similar to ostracodes in outline, may be incorporated within the walls. These calcareous tubes are typically broken at each end and may be as much as 20 centimetres in length. A complete tube was never found.

FIGURE 49A: Three views of *Martinia galataea*: brachial, lateral and anterior. Three different individuals are figured. True size.

FIGURE 49B: A monotypic shell bed of *M. galataea* within the grey lime mudstone immediately overlying Ordovician strata. Two individuals are indicated: (1) the large arrow points to a specimen in positive relief whereas (2) the smaller arrow indicates a cross-section of the fossil. Hammer head for scale.

FIGURE 50: *Beecheria* sp.. Brachial view of two individuals. True scale.

FIGURE 51: A photomicrograph of *Stenoporella*? sp. encrusting *Spirorbis caperatus*. Scale bar is 1.2 millimetres.

FIGURE 52: One branch of a *Diploporaria* sp. colony is shown. Preservation of these bryozoans is generally poor. This specimen is approximately 2.2 millimetres in length.

FIGURE 53: *Paraconularia planicostata*. The length of this individual is 10 centimetres.

49A

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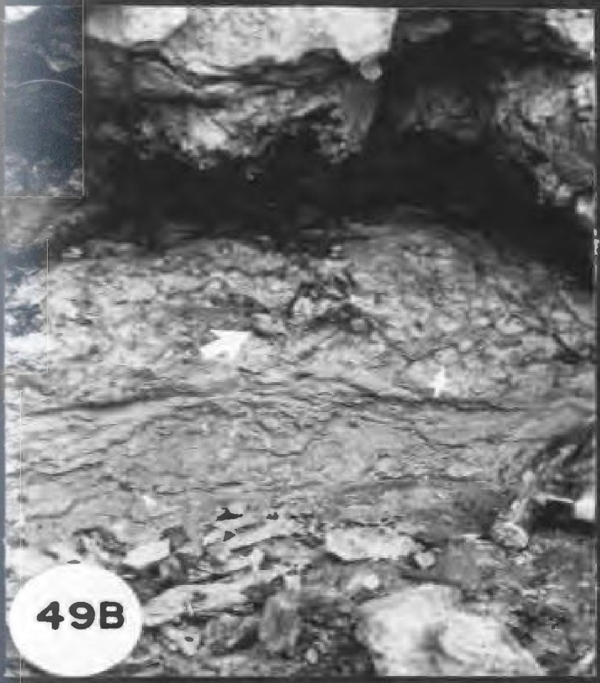
49B



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The lack of septae or cameral deposits removed any possibility that these are orthoconic cephalopods. The presence of multiple geopetal fabrics of differing orientation within some of these tubes suggests ~~that~~ they were freely rolling on the sediment surface. There is no similarity between these tubes and worm tubes described in the Treatise (Moore, 1965). The closest analogy in form may be the large worm tubes that have been found near the Galapagos Rift (Ballard and Grassle, 1979). The broken nature of the tubes suggests that they were broken from an original habitat and deposited on the sea floor.

Another unusual but common fossil is the shrimp-like crustacean, *Bellocaris newfoundlandensis* Fong (1972). Detailed sampling has shown that this crustacean is located in all major coves along the northeastern shoreline from Lead Cove to Gillam's Cove. A similar organism, *Tealliocaris* sp., is always associated with *Bellocaris newfoundlandensis* in the carbonate/clastic lithofacies but occurs alone in the sulphate/clastic lithofacies in the Boswarlos section (pers. comm., Dewey, 1981). Bell (1948) mentioned the presence of a crustacean in the Boswarlos beds but did not describe the fossil.

In general terms, within the bioherms of the carbonate units, brachiopods, bryozoans, and *Spirorbis caperatus* dominate the assemblage. Within the intermound calcarenites, the assemblage is typically dominated by bivalves and gastropods.

5.2.1 Brachiopod Colonies

Colonies of Beecheria sp., roughly circular to irregular in cross-section, are found within the biohermal limestones in Lead Cove, Aguathuna East, and at Aguathuna "Island" (Fig. 56). Rarely associated with the colonies are individuals of Composita sp. (Fig. 57), Pteronites gayensis, and small conularids. Vague stratification may be found within the colonies. As the clusters are exposed in cliff faces, only two dimensions are visible. Studies of population density and length-frequency analyses were undertaken. Unfortunately only in two of the five localities studied could all the individuals be removed. In localities where no specimens could be removed, only population density was calculated. Figure 58 gives the locality of the colonies, the number of individuals removed and/or measured, and the population density. Figure 59 indicates the form of the length-frequency curves.

It is apparent from Figure 59 that the five colonies studied all display a normal distribution curve. Another important aspect of the distribution of the various curves is that two of the large colonies have curves indicating a larger average size for the brachiopods sampled than the average size in the small colonies. As only portions of the large colonies could be sampled, however, this variation may be a sampling bias.

FIGURE 54: Worm? tubes. Three views, from left to right: middle section of tube; a tube cut open showing the wall; and a base of tube showing taper and curve. Tube bases are very rare in outcrop. Scale: True size.

FIGURE 55: A section of a worm? tube 'wall' showing faint laminations and vugs (now filled with late stage calcite cement) roughly parallel to the length-direction of the wall. The flat bases of the vugs are oriented towards a dark lamination running the length of the 'wall' (arrow). This lamination may have been the site of the original tube membrane around which cement later precipitated. Note the microfossil (ostracode? - open arrow) in the bottom left of the photograph, encorporated within the wall. Photomicrograph with cross-polarized light. Scale bar is 1.5 millimetres.

FIGURE 56: Brachiopod colony (outlined) within biohermal limestone. Hammer head for scale.

FIGURE 57: One individual of Composita sp. shown in brachial view. True size.

FIGURE 60: Typical blue-green algal columnar thrombolites from biohermal limestone mounds. Photomicrograph with cross-polarized light. Scale bar is 1.5 millimetres.

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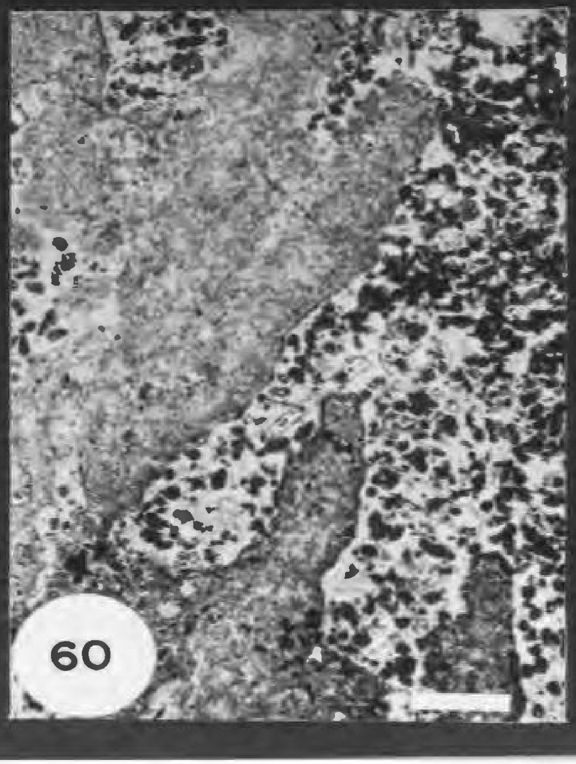

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Brachiopod clusters in limestones are known in other areas, such as England (Hallam, 1961). The presence of normal distribution plots for length-frequency diagrams was suggested by Boucot (1953) to indicate a fossil death assemblage. Olson (1957) stated that this theoretical approach could only be realized if population dynamics were considered negligible; that is, in beds deposited during an interval greater than a few years. Craig (1966) suggested that the curve form is initially related to the interplay of mortality and growth rates within a colony. It becomes apparent that there are three conditions that will help produce a normal distribution plot within a living colony: (i) predation; (ii) a high mortality/growth rate; and (iii) strong currents or wave action. The first and third conditions will physically remove the young and weaker individuals.

Evidence for the brachiopod clusters found on the Port au Port Peninsula as being life assemblages are the following:

(i) the colonies are composed only of brachiopods with rare occurrences of pelecypods and conularids;

(ii) the irregular shape of the colonies are not suggestive of currents sweeping the shells together;

(iii) some individuals are visibly attached to other specimens or the substrate;

(iv) the relative similar density in all colonies despite the different localities;

FIGURE 58: **Brachiopod colonies - size and location**

Location	Number of Brachiopods	Colony Area (cm^2)	Brachiopod/Area
Aguathuna East:			
(a) most easterly depression	69	166	1:2.98
(b) second depression from the east	714	2083	1:2.92
(c) most westerly depression	736	1944	1:2.64
Aguathuna 'Island' 1	362	1260	1:3.48
Aguathuna 'Island' 2	298	900	1:3.02
Lead Cove 1	1810	5355	1:2.96
Lead Cove 2	82	225	1:2.74

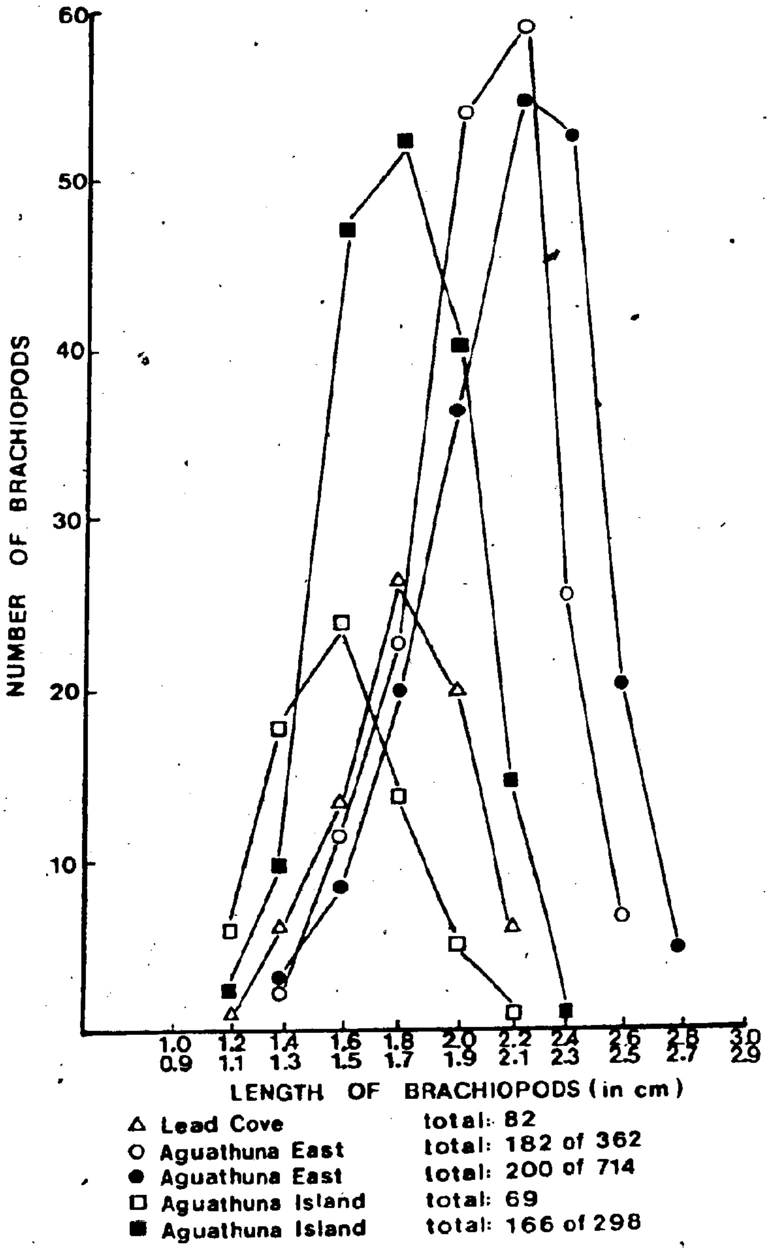


FIGURE 59: Size-frequency diagram for five brachiopod colonies.

(v) there is a wide range in shell size, not suggestive of intense sorting by currents;

(vi) the good preservation of whole complete shells; intense agitation by currents would tend to separate the valves.

Stratification within some of the colonies suggests that currents did orient the individuals either during life or after death. It is difficult to determine the effect of predation, or whether the mortality/growth rates were high. No borings are visible on brachiopod shells and no fractured shells could be found.

The colonies are overlain and surrounded by beige-coloured packstones. It is not clearly understood why colony growth was terminated. Sediments within the surrounding carbonates display rare local concentrations of synsedimentary gypsum. This suggests that salinity conditions fluctuated, possibly creating unsuitable environments for brachiopod colony growth.

5.2.2. Carbonate Mounds

The fossils commonly associated with the bioherms are the bryozoan, Stenoporella? sp. the worm Spirorbis caperatus, blue-green alga, the large worm? tubes, accessory molluscs and few conularids.

The bryozoans and algae from a baffle within the bioherms, around which a cement and later sediments accumulate. The algae occurs as small columnar thrombolites (Fig. 60). *Spirorbis caperatus* may be found encrusting both the bryozoans and alga, or by itself. The large worm? tubes may constitute the only fauna within a mound.

5.3. *Microfauna*

The microfauna in these rocks consist of ostracodes, conodonts and foraminifera.

(1) *Ostracodes* - These arthropods are abundant in all lithologies except red-beds, gypsum, and the uppermost green sandstones. More ostracode species occur in the biohermal limestones as compared to the arenaceous and argillaceous limestones in the carbonte/clastic and sulphate/clastic lithofacies (pers. comm., Dewey, 1981). Exact details of this diversity are the focus of a present thesis by Dewey and therefore only the typical ostracodes found are listed here for completeness. Synonyms for the forms Bell (1929) considered in the superfamily *Paraparchitacea* are *Shishaella* sp., *Shivaella* sp., and *Canishaella* sp. Belonging to the superfamily *Bairdeacea* are: *Bairdia* sp., *Orthobairdia* sp., *Rectobairdia* sp., *Macrocypris* sp., *Bythocypris* sp., and *Fabalicypris* sp. Palaeocopids that occur in the sediments are *Aechmina* sp., *Moorites* sp., *Amphissites* sp. and *Binodella* sp. One example of a Cytheracean, *Basslerella* sp., and a specimen of *Monoceratina* sp. of unknown affinity are also found in the ostracode assemblage.

(ii) Conodonts - Limestone samples from two to five kilograms were collected, for conodont processing, from all major Upper Mississippian outcrop localities along the northeastern shoreline of the peninsula, and at Big Cove. Unfortunately, no conodonts were recovered. Fish teeth, phosphatic tubes and possible fish scales were the only fossils found after processing the rocks. These were recovered from the grey laminated limestone in Aguathuna Creek.

Conodonts have been recovered from Boswarlos, Aguathuna Quarry region, and the laminated limestone in Romaines Brook by von Bitter and Gerbel (in press). Fauna recovered include *Cavusgnathus windsorensis* Globensky, and the form-genus *Diplognathodus*. Miner's Brook, Bellman's Cove, Lead Cove, and Dory Cove were also sampled but only a single Oz element of *Cavusgnathus windsorensis* was recovered (written comm., Gerbel, 1981).

(iii) Foraminifera - Two identifiable types of forams consistently occur within the biohermal limestones: (i) *Biseriammina*? sp. and *Earlandia* sp. The forams are micritized and poorly preserved but relatively abundant.

5.4. Flora

5.4.1. Macroflora

Plant and tree debris in the Upper Mississippian strata on the Peninsula are typically too carbonized and poorly preserved to be identifiable. Organic carbon fragments are always found in the sandstones of the carbonate/clastic and sulphate/clastic lithofacies. They also occur only in the Ship Cove West outcrop along the south shore. Thin coal seams approximately two to three centimetres thick occur in sandstones of the Boswarlos section, and in Aguathuna Creek. Well preserved macroflora samples were obtained in Blanche Brook approximately one kilometre north of Stephenville, in Barachois Group sediments. This location overlies a thin coal seam approximately 12 centimetres thick previously mentioned by Murray and Howley (1881). As of yet, the list of plant names is not complete, though an age (see below) was obtained (pers. comm., Forbes, 1971).

5.4.2. Microflora

(i) Algae - Blue-green algae are present as discrete thrombolitic columns (Fig. 60), and as encrusting layers covering other fossils in the biohermal limestones. Within the columns, chambers may be discerned but differentiation into species was not possible.

Calcispheres are rare to common within the biohermal limestones. They may range up to 200 micrometres but are commonly 100 micrometres in diameter. No preserved specimens of dasyclad algae or other calcareous algae have been noted.

(ii) Miospores - Miospores are common in the green limey sandstones, all limestones, and gypsum, in the Lower and Upper Sequence of the carbonate/clastic and sulphate/clastic lithofacies. The red-beds do not possess any preserved miospores though wood and unidentifiable plant debris in the Ship Cove West outcrop indicate the presence of vegetation during deposition. Preservation of miospores varies from good to poor. The assemblage of spores recovered (pers. comm., Barss, 1981) include:

<u>Rugospora</u> <u>minuta</u> Neves and Ioannides
<u>Schopfites</u> <u>claviger</u> Sullivan
<u>Rugospora</u> <u>polyphycta</u> Neves and Ioannides
<u>Crassipora</u> <u>trychera</u> Neves and Ioannides
<u>Punctasporites</u> <u>planus</u> Hacquebard
<u>Retusotriletes</u> <u>incohatus</u> Sullivan
<u>Vallatisporites</u> <u>ciliarus</u> (Luber) Sullivan

Other forms include several undescribed species of <u>Discernisporites</u> sp. and <u>Spelaeotriletes</u> sp.

5.5. Chronostratigraphy Based on Fauna and Flora

All fauna and flora associated with the Carboniferous sediments on the peninsula and at Romaines Brook indicate an Upper Mississippian age. The flora found in Blanche Brook indicate a Westphalian C (Middle Pennsylvanian) age (pers. comm., Forbes, 1971). The coal seam underlying these flora had been dated as Pictou-equivalent, or Middle Pennsylvanian (cited in Riley, 1962).

The fauna and flora of the Codroy Group on the peninsula are correlative with those in the Windsor Group of Nova Scotia (Hayes and Johnson, 1938). This has been verified by work of Sullivan (1940), Bell (1948), and von Bitter and Gerbel (in press).

(i) *Macrofauna* - Bell (1929) subdivided the Windsor Group of Nova Scotia into five faunal subzones (A to E). The Lower Windsor (A and B) was distinguished by the presence of *Composita dawsoni*, whereas the Upper Windsor (C, D, and E) was characterized by the presence of the coral *Dibunophyllum lambii* and the abundant occurrence of the brachiopods *Martinia galataea* and *Martinia thetis* (Bell, 1929; pg. 71). This zonation by Bell (1929) was confirmed by later work done in Nova Scotia by Stacy (1953), Sage (1954), and Moore and Ryan (1976).

Prior to this study, a mixture of Upper and Lower Windsor fauna was recognized in Aguathuna "Island" (Hayes and Johnson, 1938; Bell, 1948). Bell (1948; pg. 34) states:

> "...the fauna includes many species most commonly found in subzone B, e.g., (*Beecheria*) *latum*, (*Ovatia*) *lyelli*, *Leptodesma acidica*, *Leptodesma dawsoni*, *Edmondia rudis*, (*Paraconularia*) *planicostata*, and. *Serpula annulata*. But, in addition, the fauna includes species, e.g., *Martinia galataea*, *Ambocoelia acadica*, *Spirifer nox*, and (*Ovatia*) *avonensis* that are indicative of an Upper Windsor age."

(The brackets surround generic names now used, as defined by Moore and Ryan (1976)).

Despite this strange assemblage of fauna, the age of the sediments was said to be "not older than subzone C and may be as young as subzone E" (Bell, 1948; pg. 34). Other localities studied such as Big Cove, Boswarlos, and the coves to the east were considered to be subzone B in age (Sullivan, 1940; Bell, 1948). Several genera found by Bell and others were not found by the author. This may be due to the localities being "picked clean" of the fossils by later enthusiastic collectors, or, in the case of Aguathuna "Island", quarrying operations having removed portions of the outcrop some of which may have included areas where Bell and the other workers sampled.

Detailed sampling has shown that the grey to grey-green micritic limestone underlying the beige-coloured limestones, at Aguathuna "Island" and Mistaken Cove, and within fissures and a collapsed cave in Bellman's Cove and Lead Cove respectively, have a fauna of Upper Windsor affinity. The diagnostic fossil for this unit (Martinia galataea) is clearly restricted to this rock type. The associated, but less abundant brachiopods are also restricted to this lithology with one exception (Fig. 48). Similarly, the brachiopods Beecheria sp. and the less abundant Composita sp. are confined to the beige biohermal limestones. It would appear that in the Port au Port Upper Mississippian sediments, Beecheria sp. is replacing Composita sp. as the most abundant fossil (in contrast to the Windsor Group).

Lithostratigraphic relationships indicate that the grey limestone is older than, and equivalent to, the beige-coloured limestones; that is, it is found either at the bottom or sides of the depressions (Chapter 3). The presence of Upper Windsor fauna underlying or equivalent to Lower Windsor fauna suggests that the faunal zonation established for the Windsor Group in Nova Scotia is not applicable when used to zone the sediments on the Port au Port Peninsula.

(ii) Miospores - Further complications with the zonation of Bell (1929) arise when the miospore data is considered. The assemblage of miospores found in the sediments correspond to the Assemblage Zone 1, of Utting (1978; 1980), confined to the Lower Windsor strata. The undescribed species of Discernisporites and Spelaeotriletes are not similar to species of the same genera described by Utting (1978) in the Upper Windsor (written comm., Barss, 1981). Therefore, Upper Sequence and Lower Sequence sandstones, Lower Codroy as defined by the miospores, overly, or are equivalent to, the grey micritic limestones which, based on Bell's zonation, possess an Upper Codroy fauna.

(iii) Conodonts - The conodonts found in the Upper Mississippian sediments have been assigned to the Diplognathodus zone which is equated to Bell's subzone A (von Bitter and Gerbel, in press; and written comm., Gerbel, 1981). One of the areas sampled was the biohermal limestones within Aguathuna "Island". Therefore, again, conodonts equated to the subzone A overly a lithology possessing Upper Codroy (Windsor) fauna.

5.6. Facies Control of Fauna

From the foregoing, it appears that macrofauna are restricted to certain lithologies. Correlation of microfauna and miospores with macrofauna produce incompatible results. In Nova Scotia, the concept of facies controlled fauna in the Windsor Group was first put forward by Schenk (1967) and reiterated by Kelley (1967).

The restriction of certain fauna on the Port au Port Peninsula to the grey micritic limestone suggests that they were more tolerant of restricted conditions; that is, increased salinity and/or a muddier environment. The presence of the monotypic *Martinia galataea* shell bed, or cluster in Mistaken Cove, suggests that, assuming the bed was not created by the currents sweeping together the individuals, the species was opportunistic and quickly invaded the locality with the initial marine transgression. With the influx of more "open" and possibly turbulent waters (biohermal limestones) the species disappeared completely, probably due to competition by *Beecheria* sp. which was more suited to the changed environment. This concept has also been used by Fürsich and Hurst (1980) to explain the colonization patterns of marginal marine environments by articulate brachiopods.

Martinia galataea may also be considered more suitable for feeding in muddy substrates with its strongly folded shell, as opposed to the smooth forms of *Beecheria* sp. and *Composita* sp., another spirifer (Fürsich and Hurst, 1974). Such conditions would be found in the more protected portions of the coves such as the fissures and underhangs along the side walls where muds would preferentially be deposited.

5.7. Correlation with the United States and England

Correlation of the age of the Lower Codroy sediments on the Port au Port Peninsula with similar strata in the United States and England is figured in Figure 61. Utting (1978) recognized a similar assemblage of miospores in Britain, within the Arundian stage of the Dinantian, to his Assemblage Zone 1. He considered the zone to be as young as Holkerian or Asbian. Bell (1929) correlated the macrofauna with the Visean of Belgium and England. In England, the Upper Caninia (C_2S_1) zone to the Lower Dibunophyllum (D_1) zone is correlated with the Lower Windsor Group.

With respect to the United States, the Lower Codroy appears equivalent to the Early to Middle Meramec of the Mississippian. This is based on the correlation of fauna between Britain and the United States by George et al. (1976).

Bell (1929) noted that the correlation of Nova Scotian brachiopods with brachiopods of similar age in the United States was tenuous, and that a much better correlation could be made with fauna from Britain. This lack of correlation is considered to be due to a faunal barrier, the exposed Appalachian belt, dividing the Atlantic Carboniferous basin from the mid- and western United States faunal provinces (Bell, 1929).

SYSTEM	AGE			BRITISH ISLES ▽		U.S.A. ▽		PORT AU PORT ▼
				STAGES	MACROFAUNAL ZONES	STRATIGRAPHIC UNITS		STRATIGRAPHIC UNITS
CARBONIFEROUS	DINANTIAN	UPPER MISSISSIPPIAN	VISEAN	Asbian	D_1	St. Louis	MERAMEC	
				Holkerian	S_2			Lower Codroy
				Arundian	C_2S_1	Salem Warsaw		
		LOWER MISSISSIPPIAN		Chadian	C_2S_1	Keokuk	OSAGE	

▽ adapted from Utting (1980)

▼ extent determined by comparison with miospore zonation of Utting (1978, 1980)

FIGURE 61: Correlation chart.

5.8 Fauna Peculiarities on the Port au Port Peninsula

5.8.1. The Peculiarities

The Upper Mississippian sediments are notable for the excellent preservation of fauna, the enlarged size of certain species, and the reduction in diversity and total absence of certain species. It is interpreted here that these peculiarities are governed by one controlling factor: the presence of a marginal marine depositional environment with fluctuating salinities.

Many of the fossils can be removed as whole, intact, specimens. The inside structures are typically dissolved, the shells recrystallized, and infilled with combination of silt, coarse spar or sulphide/sulphate mineralization.

The size of some fossils with those described by Bell (1929) indicates that several species tend to be much larger; e.g., well preserved conularids may be as much as 10 centimetres in length. Other good examples are Martinia galataea, Beecheria sp., and Pteronites gayensis. Not all individuals conform to this generalization. There appear, however, to be enough large forms for this peculiarity to be recognized.

The most peculiar aspect of these sediments is the absence, or reduction in diversity, of certain fauna in comparison to fauna collected by Bell (1929) in Nova Scotia. Absent from the sediments are:

(i) true corals
(ii) fragments of calcareous algae
(iii) crinoids/echinoids.

Reduced to a few individuals are: (i) cephalopods.

Reduced to two genera are: (i) forams, and (ii) conodonts.

The complete absence of corals, and crinoids/echinoids, from these sediments indicates somewhat unusual marine conditions; the reduction of cephalopods to a few individuals also suggests such conditions. The absence of large numbers of crinoids and echinoids is found throughout the Codroy and Windsor Groups in eastern Canada (Bell, 1929; 1948). This is in complete contrast with equivalent to slightly older rocks both in Britain and the United States where crinoids are an integral part of the faunal assemblage (Wilson, 1975). The low foram and conodont diversity suggests that the environment was not of normal marine conditions but one of high stress, excluding a large number of genera that were abundant at this time in the Mississippian. The conodont Cavusgnathus sp. is considered to be restricted to near-shore environments (Higgins, 1981). The numerous peculiar large worm? tubes also suggests an odd environment. This latter fossil does not appear to have been reported elsewhere from Carboniferous sediments.

The presence of only a few cephalopods is of great importance when considering the faunal heirarchy. Missing are obvious numbers of this primary predator. The reason for the numerous complete articulated brachiopods and other fauna may be the reduced to complete lack of predation of this organism.

5.8.2. Discussion

As faunal control by lithology is well defined in the Upper Mississippian sediments along the northeastern shore of the peninsula, the diversity and numbers of each phyllum may also be controlled by the overall environment.

The carbonate/clastic and sulphate/clastic lithofacies have been interpreted to represent near-shore marginal marine environments (Chapter 3). The changing lithology of the intermound sediments in the Lower Sequence biohermal limestones, and the change in lithology from limestone to sandstone units within the Lower Sequence, suggests that physical parameters were continually changing, strongly influenced by the fluvial clastic sedimentation. This type of environment would stress fauna and flora and remove the forms intolerant of changing conditions (e.g., salinity being the most important). These forms would include corals, crinoids/echinoids, and various calcareous algae (Tasch, 1973). The environment would also reduce the diversity of the remaining marine fauna, such as forams, conodonts, cephalopods, to only the more tolerant forms.

Gigantism of fauna is usually attributed to environmental influence (Brouwer, 1967). In the Port au Port example, the nutrient-rich waters draining the exposed landmass, and the abnormal salinity conditions may have been factors.

5.9. Environment Interpretation Based on the Occurrence of Fauna and Flora

The genera within the biohermal limestones are recognized as shallow water fauna. Recent studies indicate that some articulate brachiopods and bryozoans are capable of colonizing slightly saline to brackish environments (McKinney and Gault, 1979; Furisch and Hurst, 1981). The restriction of *Martinia galataea* and other associated fauna to the grey arenaceous limestones on the Port au Port Peninsula is therefore either a function of mud content and/or salinity. The biohermal limestones are a more open environment though influenced by salinity changes.

The Upper and Lower Sequence sandstones may contain ostracodes but always plant and wood debris. The ostracode diversity is lower in the sandstones than in the biohermal limestones (pers. comm., Dewey, 1981) suggesting an environment of increased stress. Plant and flora content as well as sedimentary structures in the sandstones (Chapter 3) suggest a fluvial influence, probably indicating a brackish environment where fresh and marine waters were mixed.

A similar relationship of alternating marine/fluvial environments occurs in the sulphate/clastic lithofacies. Few fossils of ostracodes, and crustaceans, are found in the arenaceous limestones whereas abundant ostracodes and flora occur in the interbedded sandstones. Evidence of early gypsum in the limestones beds suggest salinities were higher than those in the sandstones. Again, this is interpreted as suggesting the influence of fluvial conditions reducing the salinity of the environment as clastics and plant debris are deposited.

Along the southshore, rare plant debris occurs in the red-beds. This, along with sedimentary structures, implies a completely terrestrial environment for these deposits.

5.10. Summary

It is apparent that the biostratigraphy established in Nova Scotia for the Windsor Group is inapplicable as applied to the Port au Port Peninsula. This in turn has implications for the validity of macrofaunal subzones and resultant stratigraphic interpretation. As the macrofauna are facies-controlled, the brachiopod Martinia galataea cannot be used in a detailed time-stratigraphic sense as Bell (1929). It would appear that the only good control on age may be miospore zonation.

The environment of deposition for the carbonate/clastic and sulphate/clastic lithofacies is suggested to be a near-shore shallow water marine environment episodically influenced by fluvial clastic deposition. This influence creates fluctuating chemical and physical conditions such that changes in the environment from hypersaline to brackish occur. This fluctuation is interpreted to restrict fauna in numbers and diversity. Notably absent are true corals and crinoids/echinoids which cannot tolerate such conditions. The presence of bryozoan- and brachiopod-rich sediments in an abnormal marine environment adds to the increasing recognition that these fauna, normally considered open marine, may colonize brackish to hypersaline environments.

CHAPTER 6

BRYOZOAN/ALGAL BIOHERMS

6.1. Introduction

In the Early Carboniferous, carbonate mud mounds (called Waulsortian mud mounds from their type locality in Belgium) developed in what is now the United States, Britain and Europe (Wilson, 1975). These mounds are mud buildups characteristically containing crinoid and bryozoan debris, and developed in open marine facies. The biogenic buildups in Upper Mississippian strata on the Port au Port Peninsula (this study), in southwestern Newfoundland (Knight, 1976), and buildups with similar affinities in Nova Scotia (Giles et al., 1978) differ from the Walsortian mounds in structure, lithology, and associated sedimentary facies.

The carbonate/clastic lithofacies in the northeast part of the peninsula, and equivalent lithologies in Big Cove, represent bioherm development in a shallow-water marine environment which was periodically dominated and always influenced by fluvial clastic sedimentation. These areas of marine/fluvial deposition were contemporaneous with basins of evaporite deposition and alluvial fan development. Thus, the carbonate/clastic lithofacies is part of a complex interplay of terrigenous and marginal marine environments that developed immediately adjacent to, and on the edge of, an exposed highland.

6.2. Intermound Sediments

Three different lithologies comprise the sediments deposited with the bryozoan/algal buildups in the Lower Sequence of the carbonate/clastic lithofacies: (1) limestones; (2) calcareous sandstones/shales; and (3) black shaley limestones.

(1) Thin to medium, well bedded skeletal and pelletal wackestones to grainstones, and pebble limestone breccias with a packstone matrix (in Big Cove) may surround the mounds. The fauna is typically dominated by molluscs and ostracodes. Local concentrations of brachiopods occur as colonies and in discrete beds (except in Big Cove). Other allochems in these sediments are pellets and minor intraclasts. Bioturbation is common although not so extensive as to destroy bedding. These intermound sediments onlap onto, and drape over, the mounds and may exhibit marked lateral thickening away from a mound (Fig. 62). Pinchout of the strata either against or under a mound are common, though less extensive when associated with the smaller mounds.

(2) Calcareous sandstones and shales, with associated arenaceous limestones, described in Chapter 3, comprise a major part of the Big Cove cliff section where they surround and overlap bioherms.

(3) Thin fissile beds of black shaley limestone underlie and overlie several bioherms in Mistaken Cove, as well as interfingering with limestone intermound sediments in a thick drape structure on the

south wall of the cove. Loading structure due to overlying biohermal limestones may cause pinch and swell fabric within the shaley limestone beds (Fig. 63). Though black shaley limestones are found in sections at Boswarlos and Big Cove, they do not occur as intermound sediments.

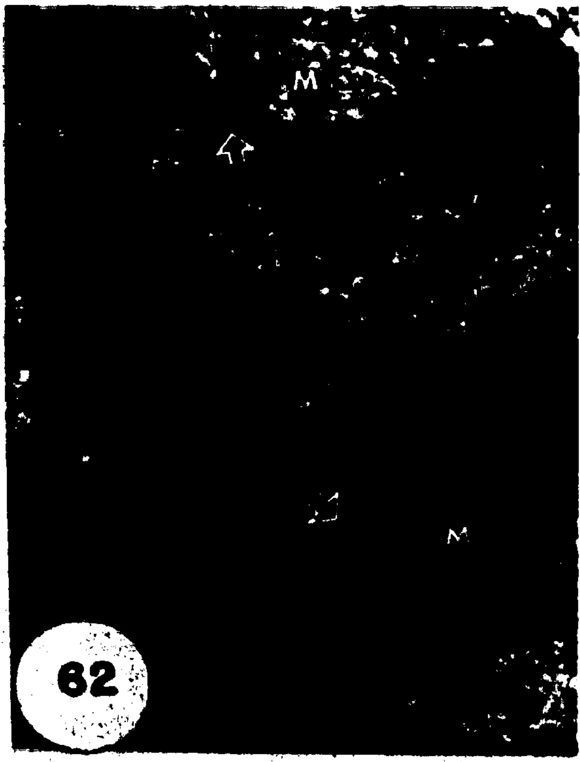
6.2.1. Discussion

The onlap and drape relationships of intermound sediments with the buildups indicate that bioherms possessed positive relief during sedimentation. It is difficult to estimate the percentage of relief at any particular time; however, some mounds may have possessed up to one or two metres relief on the sea floor. Positive relief of the biostromal limestone (upper unit of the Lower Sequence) was probably no more than tens of centimetres. Biostrome-intermound relationships suggest that regions of the sea floor during this period of deposition were "islands" of biogenic buildup with surrounding channels? of siliclastics. Poor exposure of this unit prevents conclusive evidence.

The alternating mound development and black shaley limestone, in Mistaken Cove, is interpreted as being caused by changing salinity conditions, restricting fauna growth and/or changing physical energy conditions within the depression, allowing the deposition of mud and creating rather turbid conditions for carbonate development. Mistaken Cove, unlike the adjacent coves, does not have an extensive incised

FIGURE 62: Intermound sediment, fossiliferous carbonate and black shaley limestone, are sandwiched between two mounds (M and arrows) in Mistaken Cove. Note the sediment drape and thickness increase away from the lower mound. Hammer for scale.

FIGURE 63: Load structures. Pinch and swell of black shaley limestone (B) due to load of biohermal limestone (A). This package of sediment overlies more biohermal limestone (C). Mistaken Cove. Hammer for scale.



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karst valley extending inland from the coast. Within the adjacent coves, it is interpreted that fluvial deposition of sandstones was in part contemporaneous with the biogenic buildups along the depression walls (Chapter 3). Therefore, the lack of a valley south of Mistaken Cove, may have restricted the fluvial influence to mud and silt deposition. The middle unit of the Lower Sequence, however, is represented in the cove overlying the mound-shaley limestone sequence. This suggests that during periods of increased fluvial activity (lower sea level?), the cove, as with others in the region, was inundated by fluvial sedimentation.

6.3. Biogenic Buildups

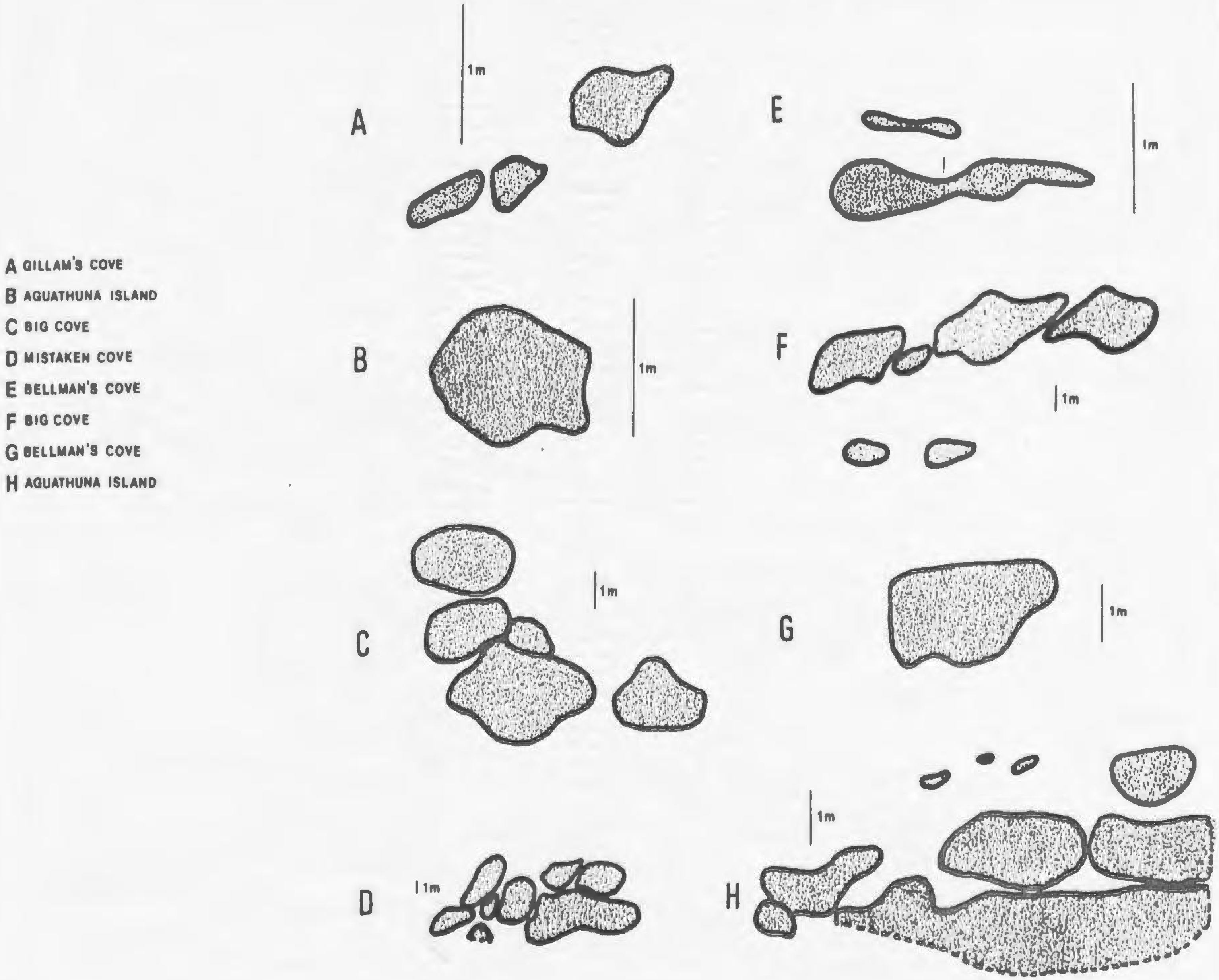
6.3.1. Physical Shape and Size

Biogenic buildups, in the form of bryozoan/algal bafflestones are found either as: (1) discrete mounds within intermound sediment; or as (2) large biolithite masses with little or no intermound sediment, generally plastered up against the walls of depressions (Bellman's Cove and Lead Cove).

The buildups vary considerably in size and shape generally having an irregular polygonal cross-section (Fig. 64). Both three-dimensional and plan views of the mounds are rare due to cover by soil and vegetation, or intermound sediment overlapping these structures.

FIGURE 64:

CROSS-SECTIONS OF MOUNDS, INDIVIDUALS AND COMPLEXES



Isolated mounds are generally biconvex in cross-section whereas those associated with mound complexes are irregular to lensoid in shape. The biolithites attached to walls of depressions are the largest buildups preserved in the study area and tend to be roughly rectangular (higher than wide) in shape.

Mounds in the lower limestone unit of the Lower Sequence exhibit sharp boundaries with the intermound sediments. Mounds in the biostromal unit (upper unit of the sequence) in contrast have less distinct boundaries and grade laterally into the biostromal limestone. Mounds in any of the units may be isolated or vertically to horizontally stacked to form a bioherm complex. Within small depressions a mound complex may completely fill the depression.

6.3.2. Composition

The biogenic buildups are made up of: (i) skeletal elements; (ii) syn-sedimentary cement; (iii) fauna/cement structures; (iv) intracement sediment; and (iv) geopetal sediment.

(i) Skeletal Elements - Carbonate mounds are typically composed of the trepostome bryozoan Stenoporella? sp. and/or columnals of blue-green algae. Bryozoans may be found as upward branching free-standing "bushes" or as encrustations. In thin section, each branch of a bryozoan "bush" may be composed of several, vertically stacked, generations of encrustation (Fig. 65).

Digitate algal columnals exhibiting poorly preserved internal structure occur in prone to vertical orientations (Figs. 60 and 66). Internal structure may appear as slightly inflated chambers with micritic walls. Vague laminations of these chambers roughly perpendicular and/or parallel to the growth direction of the columnal may occur. More commonly, the structure resembles the clotted texture of a thrombolite (Fig. 67).

Both bryozoans and algae in turn encrust other organisms such as worm tubes, ostracods, molluscs, and brachiopods, or one another.

Spirorbis caperatus and the large worm? tubes are locally significant in the buildups. Algae and bryozoans encrust both, and in some cases use the fossils as a base for colony growth. Spirorbis caperatus and the large worm? tubes may also be the sole fossil types in a buildup (Fig. 68). Other fauna associated with the mounds are listed in Figure 48 under the heading "beige-coloured limestones". Typically faunal variation between mounds is negligible.

(ii) Synsedimentary Cement - Surrounding the bryozoans, algae and Spirorbis caperatus are thin (less than 50 microns) to thick (several tens of millimetres) laminations of fascicular-optic calcite and/or equant pseudospar. These are interpreted as neomorphic replacements of early cements (see Chapter 8 - Diagenesis).

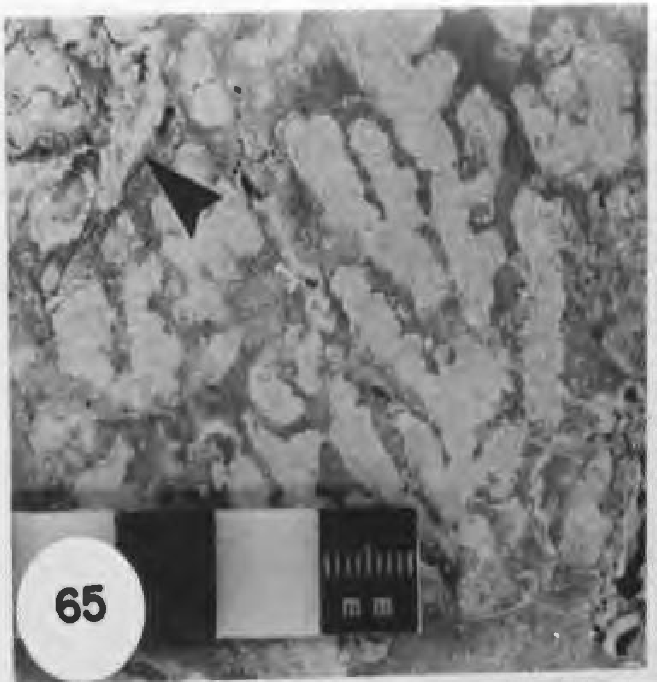
The fascicular-optic calcite coatings are usually smooth-edged and connect adjacent faunal elements leaving potential cavities or pore spaces which are filled by later geopetal sediment. The multiple cement generations are defined by thin micritic laminae which can be traced from one coated structure to the next. In outcrop,

FIGURE 65: Bryozoan bushes composed of vertically stacked encrusting Stenoporella? sp.. An algal thrombolite (arrow) is also present. Scale as shown.

FIGURE 66: Prone blue-green algal thrombolites grow right to left in biohermal limestone. Bases of several 'colonies' are apices of the outlined areas on the photograph (e.g., at arrow). Scale bar is 10 centimetres.

FIGURE 67: Detailed structure of algal thrombolite. The poorly defined chambers give the structure a fuzzy appearance. Photomicrograph with plain light. Scale bar is 230 micrometres.

FIGURE 68: Structures (outlined by dotted line) composed of cement (open arrow) and Spirorbis caperatus (solid arrow) may occur in biohermal limestones. Photomicrograph with cross-polarized light. Scale bar is 500 micrometres.



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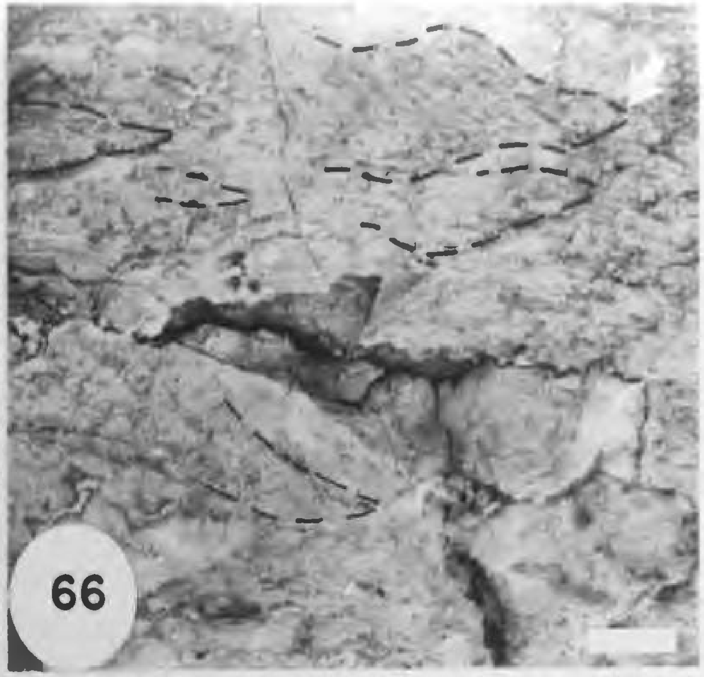

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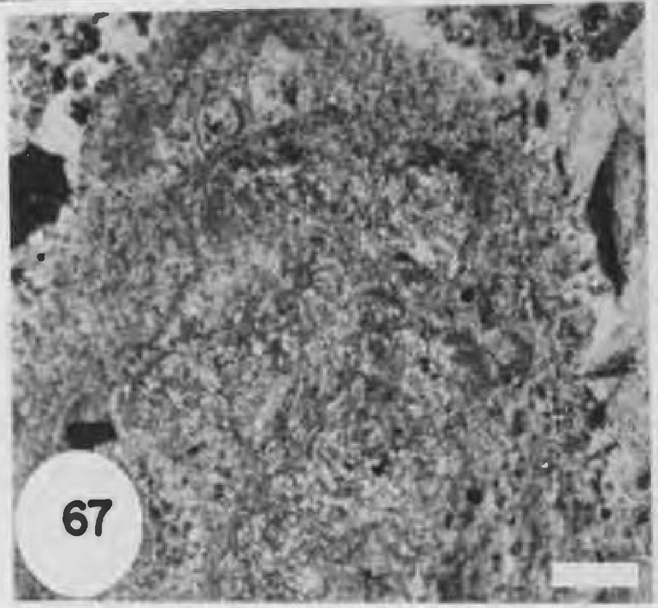

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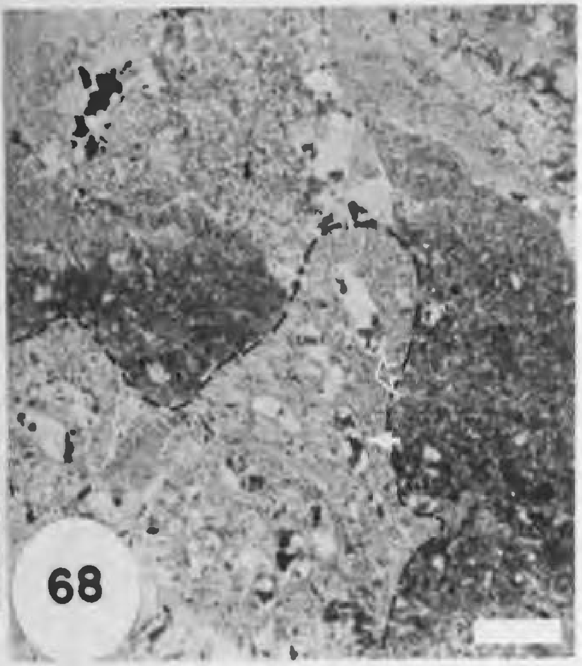

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these laminae, beige to yellowish-white in colour, can be traced for tens of centimetres. In many cases, there is no visible fossil core to many of these cement structures, and in thin section, under cross-polarized light, the structure appears as a spherulite (Fig. 69A). In hand specimen, this cement is a dark beige to brown laminated to non-laminated coating. Cements may comprise up to 60 percent of a mound.

The micrite laminae may also surround discrete "bodies" of brown-grey to beige coloured crystalline mudstone (Fig. 69B). In thin section, the mudstone is pseudospar. These spar bodies are irregular in shape as defined by the bounding laminae, and often have a wavy to contorted outline (Fig. 69C). Several of these "bodies" may be stacked in such a manner that each subsequent cement generation is built away from the core (whether skeletal or sediment).

(iii) Fauna/Cement Structures

Intergrowths of cement and skeletal elements produced rigid structures around which sediment was deposited. Often the outer edge of a fascicular-optic calcite fauna/cement structure is lined with discontinuous crystallites? of possible manganese oxide. This rim may be in contact with intramound sediment, or late stage phreatic cement (Fig. 70).

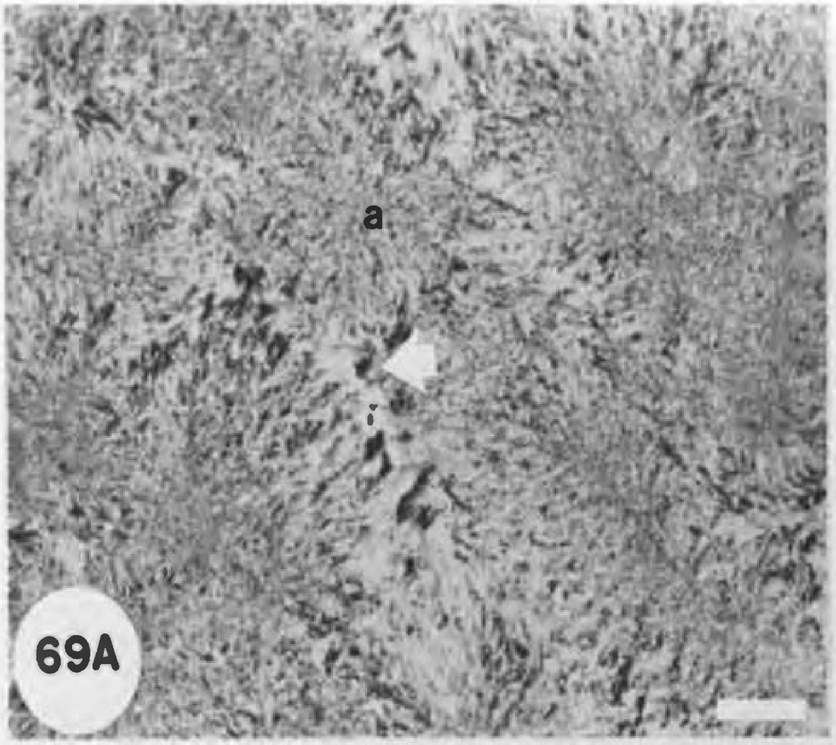
(iv) Intracement Sediment

Intracement sediment includes peloids, skeletal debris (whole-shelled ostracodes, forams, and *Spirorbis caperatus*), micrite and few angular quartz and feldspar clasts (Fig. 71). The distribution

FIGURE 69A: Spherulite structures (a). Originally composed of possible magnesium calcite cement, these structures show no faunal or sediment core around which the cement precipitated. Coarser crystalline cement appears to infill voids between these structures (arrow). Photomicrograph with cross-polarized light. Scale bar is 500 micrometres.

FIGURE 69B: Micritic laminae (white in photograph) define non-geostrophic to geostrophic (vertically stacked) mudstone bodies (grey in photograph). Large dotted arrow indicates geopetal? micrite fill surrounding finger-like mudstone stuctures (large white arrow) composed of laminae and mudstone. Various size micritic laminae, shown by smaller arrows, may be found. Photograph of a slabbed hand sample. Millimetre rule for scale.

FIGURE 69C: Details of micrite laminae within mudstone, as in FIGURE 69B. Pseudospar and rare peloids occur between the laminae. Very similar geometries occur in FIGURES 83, 84, and 85. Photomicrograph with plain light. Scale bar is 230 micrometres.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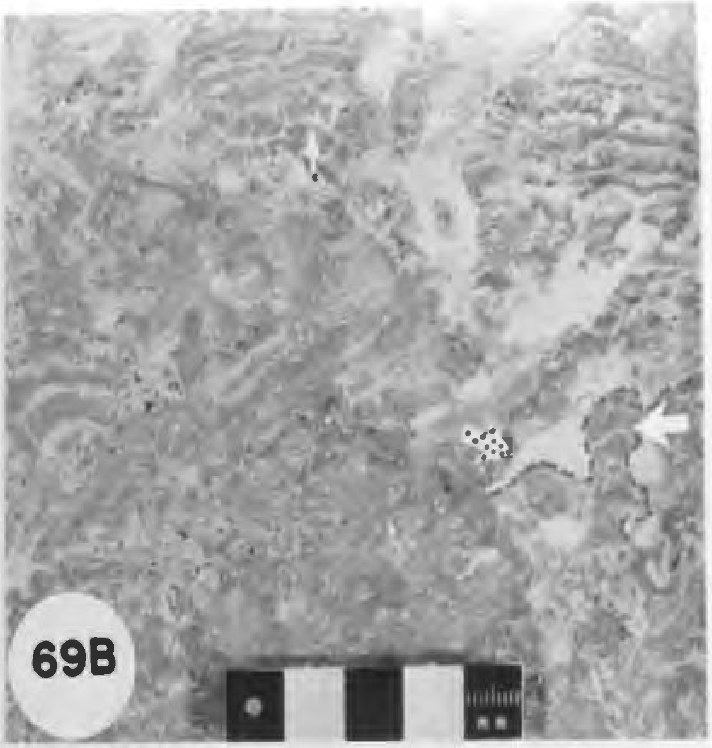
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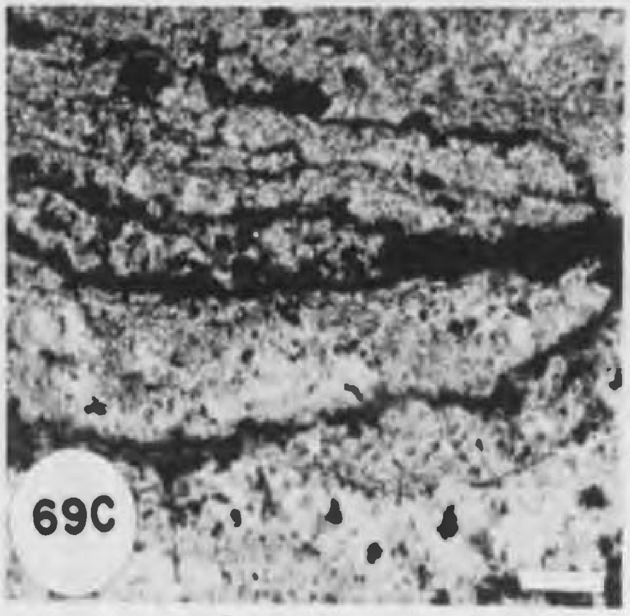

69C

of sediment within the cement may be dispersed, concentrated to form clotted textures, or as laminae which exhibit the same orientation as the cement laminae. Intracement matrix is sporadic in distribution.

(iv) Geopetal Sediment

This sediment is characterized by multigeneration sedimentation (Fig. 71 and 73), and varies in composition from bioturbated micrite to biosparite. The most common allochems are peloids; skeletal fragments and/or whole shells of molluscs, brachiopods, forams, and ostracodes; intraclasts (some of which are fragments of the cemented structures); and less than five percent quartz and feldspar grains. Spirorbis caperatus is notable in its absence from this type of sediment. Each successive deposit of sediment is recognized by a graded sequence and has a geopetal fabric. Subsequent generations of sediment become more micrite-pellet rich: the skeletal content decreasing very abruptly. Microspar occurs as a geopetal fabric within last stage coarse calcite cement infilling pores, and commonly in the last sediment generation underlying the above fabric. In some mounds, thin beds of euhedral gypsum crystals occur near the top of the graded sequences (Fig. 72).

Fascicular-optic isopachus cement is usually found between sediment generations and as an intraparticle cement in packstones or grainstones within the mounds (Fig. 73). Towards the top of each generation of sediment the cement increases in abundance. Contact between the fauna/cement structures and these sediments is always sharp

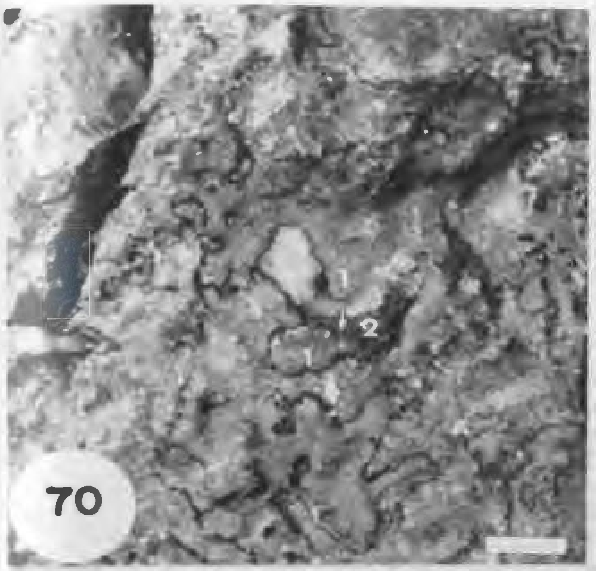
FIGURE 70: Large scale micritic laminae (large arrow) within biomicrite and coated with possible manganese oxide (black in colour). A central cavity displays two geopetal sediments (1 and 2) and late stage calcite cement (white). At A, complex geometry and stages of sediment infill within cavities is evident by the various laminae. Field photograph. Scale bar is 10 millimetres.

FIGURE 71: Intracement matrix, along with cement, form rigid structures (e.g., above scale bar). Intermound sediment, composed of four generations (1, 2, 3, and 4), is capped by late stage cement. Note the abrupt decrease in allochem percentage between the first and second sediment generations. Photomicrograph with cross-polarized light. Scale bar is 1.5 millimetres.

FIGURE 72: Euhedral anhydrite/gypsum crystals within geopetal sediment (arrow). Photomicrograph with cross-polarized light. Scale bar is 230 micrometres.

FIGURE 73: Well preserved multigeneration cement and sediment. At least seven generations (bottom of photograph) of sediment possess cement-enriched horizons. These horizons occur primarily at the top of each generation (arrows). In the upper left of the photograph (arrow), a fauna/cement structure appears to have blocked the flow of sediment (no sediment occurs to the right of the structure). Photomicrograph with cross-polarized light. Scale bar is 1.5 millimetres.

FIGURE 74: 'Reworked' geopetal sediment. The infilled worm? tube (open arrow) displays an early lithified sediment (dotted arrow) inverted with respect to later geopetal sediment (a). Small arrow indicate tops of each respective sediment infill. In the upper left of the photograph, another worm? tube shows only earlier inverted sediment. The remaining porosity in both tubes is filled with late stage calcite cement. Field photograph. Scale bar is shown in inches.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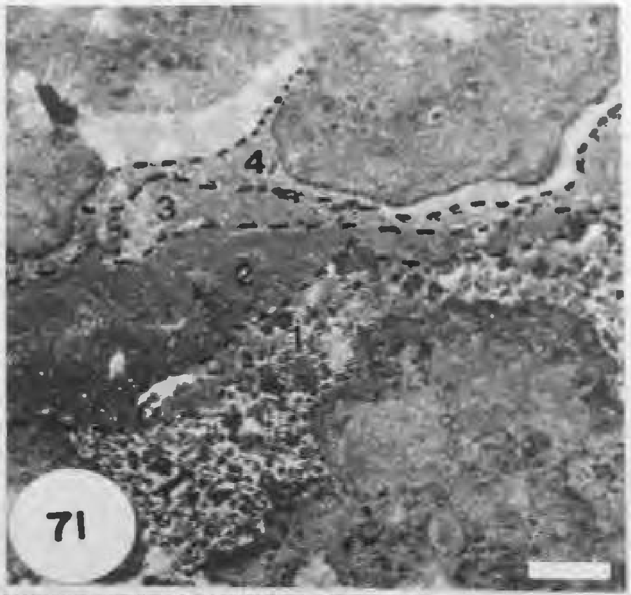
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and well defined (Figs. 71 and 72). It is apparent that there is much more cement associated with the fauna/cement structures than with the multigenerations of matrix. The cement laminae in the matrix are not part of the fauna/cement structures, and it is apparent that the development of these structures was near completion prior to the matrix deposition. In a few examples, cement laminae comprising part of a structure do overlie matrix; however, this is not common.

"Reworked" geopetal fabric (Fig. 74) and evidence that the cemented structures were actively blocking sediment deposition (Fig. 73) are two other features associated with the second type of matrix. Most geopetal fabrics with brachiopods, mounds and worms? tubes are oriented horizontally to shallow subhorizontally with respect to the present sea level. Within the worm? tubes, the fabric is usually parallel to the length of the tube. Geopetal fabric of differing orientations (some inverted with respect to the present sea level) may occur within a single worm? tube. This indicates early lithification of the initial matrix prior to subsequent reworking of the fossil, and infill by a second sediment generation. This fabric also suggests that the worm? tubes are rolling freely on the sea floor.

6.4. Discussion

The following sedimentologic and diagenetic criteria suggest that the buildups within the Lower Sequence were rigid positive features on the sea floor, and that this was in large part due to early lithification:

(1) intermound sediments show onlap onto and drape over the mounds; some drapes originating from a mound thicken dramatically away from the mound along the flank;

(2) fragments of the mounds may be found in an overlying unit (e.g., the siliclastic unit of the Lower Sequence) as well as in intramound matrix;

(3) fascicular-optic calcite, and pseudospar, associated with micrite laminae, are interpreted as neomorphic replacements of early cements, and are pervasive throughout the mounds coating and cementing together bryozoans, algal columnals and early matrix sediment; the cement and skeletal elements form a framework around which the matrix is deposited;

(4) multigeneration internal geopetal sediment, decreasing in skeletal content and becoming more micritic towards the top of each graded layer suggests a constriction of sediment flow related to the changing pore size and permeability of a rigid cement framework;

(5) evidence that sediment being deposited within the mound was actively blocked by a rigid cement structure;

(6) multiple geopetal orientations within worm? tubes suggest early lithification; syn-sedimentary cementation by fascicular-optic calcite is associated with

multigenerations of matrix; the increasing abundance of this cement towards the top of each sediment generation, suggests that pulses of sedimentation inhibits cementation;

(7) sharp boundaries between the cement and the interstitial matrix occurred prior to deposition of the matrix;

(8) the orientation of <u>Spirorbis</u> <u>caperatus</u> within the fauna/cement structures suggest that the worm was encrusting a hard substrate.

Mounds developed in a nearshore environment would probably be affected by wave action, tides, and storms, which would create a continually agitated environment. This agitation would have sufficient energy to provide a pumping action to drive the several generations of sediment into the pores and cavities of the mounds. Other processes that may be involved in producing the sediment are: (1) sediment fallout, after a period of agitation, percolating into the cavities, and (2) intramound generation of the sediment. This last process, however, would not adequately explain the several generations of fining upward sediment sequences as observed. As a mound accretes, the grain size of the interstitial sediment is determined by the changing fabric of the cemented framework. The centre of a bioherm could receive only the finest material whereas the edge would receive coarser skeletal material.

One peculiar aspect of these bioherms and intramound sediment is the lack of boring. The occurrence of Spirorbis caperatus apparently encrusting the fauna/cement structures suggests that cementation provided a hard substrate. It is possible that the microenvironment on the cement surface occluded boring organisms.

In summary, these bioherms are interpreted to have formed from abundant synsedimentary marine cements coating skeletal elements. The subsequent fauna/cement framework was a labyrinth of interconnected pores and cavities which effectively trapped sediment. Seawater pumping, and/or sediment fallout from periods of agitation are interpreted as the mechanisms which provided multigeneration sediment that was trapped within the mounds according to the changing framework fabric of the bioherms. At times of quiescence, marine cementation lithified the intramound sediment. Buildup of geopetal sediment in the more constricted cavities produced microenvironments of high salinity in which layers of gypsum crystals and nodular gypsum were occasionally precipitated, whereas in the more open cavities, oxidation produced a manganese coating at the cement/seawater interface.

6.5. Mound Development in the Lower Carboniferous

Bioherms in the Upper Mississippian sediments in the Port au Port region are almost contemporaneous with the Waulsortian-type mound development in the Lower Carboniferous in the United States (e.g., Pray, 1958; Troell, 1962; Cotter, 1965), England (Parkinson, 1957; Bathurst, 1959), and Ireland (Schwarzacher, 1961; Lees, 1964). Similar mounds are also found in France, Belgium, and parts of central Europe. Waulsortian mounds are characterized by sparse crinoid and bryozoan fragments within a mud matrix. The mounds are generally found in an open marine shelf-margin facies, or open shelf facies, with negligible influence from an exposed landmass (Wilson, 1975). The size of the buildups varies considerably from tens to hundreds of metres in thickness and hundreds of metres in length. There is no preserved skeletal framework, or baffle structure, nor any visible evidence of early multiple generations of syn-sedimentary cement such as the fascicular-optic calcite in the Port au Port mounds. Early lithification is suggested by redeposited fragments of the mound facies along the periphery of a mound (Schwarzacher, 1961). Other features that may be associated with the mounds are stromatotactoid structures (zebra rock). It is thought that the sparse crinoids and bryozoan fragments are remnants of colony of baffles that were not preserved. Sea grasses may also have helped to stabilize the muds. Halos of crinoid debris may surround the mud mounds lending support to the idea of crinoids originally acting as baffles (Cotter, 1965).

It is apparent that the Port au Port mounds are unlike the Waulsortian-type mounds in size, lithology, and palaeoenvironment. One exception is a mound that is underlain by an outcrop of zebra rock in Big Cove Creek. The zebra rock may be acting as the basal part of the mound.

Mounds similar to those on the peninsula occur in southwestern Newfoundland in the Ship Cove region, and inland to the southeast (Knight, 1976). At Ship Cove, the Cormorant Limestone, a black bryozoan-brachiopod rich limestone is laterally equivalent to, and overlain by, evaporites and/or evaporite-rich siltstones. It attains a maximum exposed thickness of 15 metres and extends laterally for at least several hundred metres. In thin section, there are similar cement textures to those in the Port au Port mounds. Although Bell (1948) commented on the fauna within this limestone he did not consider it as a discrete mound or reef. Knight (1976) reported the occurrence of a black patch reef on the North Branch of the Grand Codroy River, southeast of the Ship Cove region. No description of its lithology was given, but it is assumed correlative to the mound at Ship Cove. Bryozoan-algal carbonate banks in the basal Windsor Group in Nova Scotia are mentioned by Giles et al. (1978), but, unfortunately, the geometry of these banks (or mounds?) was not fully described. Thin sections of the bank facies, as depicted in photographs within the report, look very similar to structures within the mound facies of the Port au Port mounds. In all the above examples, red-beds and evaporites are either lateral equivalents, or overlie the bioherm (or bank) facies.

6.6. Comparison with Upper Carboniferous Reefs in the Canadian Arctic

In the Sverdrup Basin, as exposed in northwestern Ellesmere Island in the Canadian Arctic, Upper Mississippian to Permian strata record the change in sedimentation from the initiation and deposition of non-marine red-beds (Borup Fiord Formation) through shallow water evaporite and limestone deposition (Otto Fiord Formation) to deep water and foreslope carbonates of the Hare Fiord and Nansen Formations, respectively (Davies, 1978). Carbonate mounds are preserved within the evaporites in the Otto Fiord Formation and in the carbonates of the Hare Fiord Formation and Nansen Formation.

Within the Otto Fiord Formation, the mounds are primarily composed of tubular algae, though other marine fauna including brachiopods and fenestrellid bryozoans are associated (Davies, 1978). The algal mounds are bounded by thin limestone units that sit within thick evaporitic sequences. Towards the basin margins, the red-beds of the Borup Fiord Formation intertongue with the evaporite/limestone succession of the Otto Fiord Formation.

Within the basal Hare Fiord Formation well preserved fabrics occur in bryozoan reefs. Isopachous multigeneration cement and sediment are common (Davies, 1977). Encrustation of the early cement by marine organism in these reefs is analogous to the interpreted encrustation of cement by <u>Spirorbis caperatus</u> in the Port au Port mounds. An interesting aspect of the cements described by Davies

(1977) is the occurrence of micritic laminae which separate generations of cement. These laminae are similar, both in composition and orientation, to the laminae found throughout the Port au Port mounds. A more detailed comparison and discussion of cements is given in Chapter 8 - Diagenesis.

6.7 Summary

Mound development as recognized in the Upper Mississippian sediments on the Port au Port Peninsula represents one style of biogenic buildup that occurred during Early Carboniferous time. It is apparent that these mounds differ from the typical Waulsortian-type mounds which are considered characteristic of this time interval (Bathurst, 1975; Wilson, 1975). The Port au Port mounds show similar textures and facies relationships to described mounds and reefs in the Upper Carboniferous in Arctic Canada. A peculiarity of the mounds and intermound sediments in the Port au Port region is the lack of crinoid/echinoid debris which is ubiquitous during the Early Carboniferous in United States and Europe. This peculiarity is general in the Upper Mississippian sediments in Nova Scotia and southwestern Newfoundland (Bell, 1929; 1948) indicating that the marine sediments represent abnormal salinity and/or physical conditions.

CHAPTER 7

SULPHIDE/SULPHATE MINDERALIZATION OF THE UPPER MISSISSIPPIAN SEDIMENTS

7.1. Introduction

On the Port au Port Peninsula, uneconomic sulphide and sulphate mineralization occurs as stratabound deposits associated with Upper Mississippian sediments, and as vein deposits which cut both Ordovician and Upper Mississippian strata.

Compilation of the mineral types and occurrences related to the Upper Mississippian strata is given in Douglas (1976; p. 73-74). There is no attempt in this study to compile or synthesize the previous work, mainly by private companies, concerning various aspects of the mineralized sediments on the peninsula. Mineral evaluations over the last hundred years has produced a voluminous amount of literature and the reader is directed to NTS Geoscan 1979; Newfoundland, for the most up-to-date bibliography. The observed stages of mineralization which occur in the Codroy strata, are predicated on the detailed carbonate diagenesis, which is fully discussed in Chapter 8. For the purpose of the following discussion, the reader is directed to Figure 102, p. 192, which places the timing of mineralization in context with the overall diagenetic sequence.

7.2. Distribution and Types of Mineralization

Sulphide and/or sulphate mineralization occurs as stratabound deposits within the carbonate/clastic and sulphate/clastic lithofacies along the northeast coast of the peninsula, and at Romaines

Brook to the east. No mineralization was found at Big Cove. Sulphide-bearing calcite veins and veinlets cut Ordovician strata along the northeastern shoreline of the peninsula near Gillam's Cove, along the north coast near The Gravels, and the Piccadilly region (Sullivan, 1940), and in the Lourdes region (Watson, 1943).

7.2.1 Sulphates

Gypsum, anhydrite, barite, and celestite are the most common sulphates associated with the carbonate/clastic and sulphate/clastic lithofacies.

(i) Gypsum and Anhydrite - Economic potential of the thick deposits of the gypsum at Romaines Brook and in the Boswarlos-Piccadilly region has been described by Hayes and Johnson (1937). Within the limestones of the carbonate/clastic sequence, euhedral to anhedral crystals of gypsum and anhydrite occur within the packstone to micrite matrix of some bioherm complexes. These are typically found as thin layers at the top or close to the top of graded geopetal sediment. Gypsum also occurs rarely as large euhedral crystals within late stage calcite cement, and in the micrite matrix of the laminated limestone of the sulphate/clastic sequence in Boswarlos. Calcite pseudomorphs of lenticular gypsum (Fig. 75) occur in micrite found at the base of the upper limestone unit of the Lower Sequence in Lead Cove. Prismatic calcite pseudomorphs of possible anhydrite were found partially infilling a palaeocavity within a mound (Fig. 76).

(ii) Barite and Celestite -- Barite and celestite are commonly found together as replacement mineralization within the limey sandstones of the Upper Sequence at Gillam's Cove, the upper limestone unit in the Lower Sequence at Aguathuna "Island", and within the limey sandstone in Ronan Brook. Descriptions of the deposits in Gillam's Creek and Ronan Brook are given in Johnson (1954).

Barite also occurs as a cavity-filling mineral within the limestones of the lower bioherm sequence in Bellman's Cove, Lead Cove, Mistaken Cove, and the deposits in the Aguathuna Quarry region. Barite is present as a cement locally, within the limestone breccia in Aguathuna Creek, and in the chaotic red-matrix breccias in Ship Cove West.

Within the limestones, barite, in thin section, commonly covering marcasite and galena, typically has an interlocking sutured crystalline appearance often developed as crystalline aggregate splays and spherulites within the cavities (Fig. 77). Late stage calcite often overlies the barite and infills the rest of the cavity. In hand sample, the barite is found in the form of crystallized botryoids surrounding and overlapping sulphides. Strontium content in the barite may be as much as one percent. Chemical analyses of the barite and celestite associated with Gillam's Creek and Ronan Brook are found in Johnson (1954).

8.2.2. Sulphides

Marcasite, sphalerite, galena, and minor pyrite are the common sulphide minerals associated with calcite veins, and cavity-fills within the carbonate/clastic lithofacies.

(i) Calcite Veins - Thin to thick equant crystalline to drusy calcite veins and veinlets cross-cut Ordovician strata on the north and south coasts, and Upper Mississippian red-bed lithologies along the south coast. Veinlets of calcite cross-cut Upper Mississippian strata on the north coast of the peninsula but do not carry sulphide mineralization. Associated sulphides in the veins commonly occur along the contacts of the calcite and the host rock (Fig. 78). Generally, euhedral galena crystals are developed on colloform marcasite. A mineralogically and paragenetically complex vein deposit in the Lourdes region (the Goodyear Prospect) is outlined by Watson (1943).

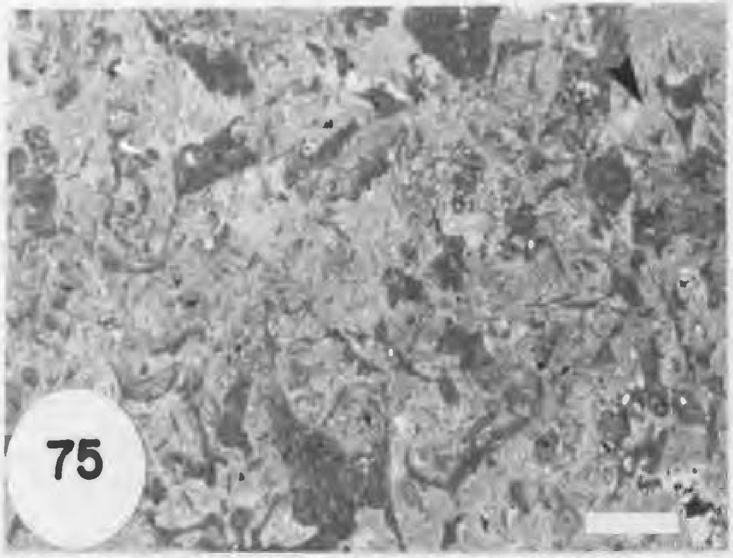
(ii) Stratabound Deposits - Galena, marcasite, iron-poor sphalerite, and rare pyrite infill cavities within the Lower Sequence sediments of the carbonate/clastic lithofacies and rarely are associated with the Upper Sequence clastics. Galena and sphalerite occur as euhedral to anhedral crystals whereas marcasite typically has a botryoidal splay shape. Generally, galena is found overlying the marcasite, and sphalerite is commonly overlying marcasite. All three minerals may line the inside walls of a cavity. An example of geopetal sphalerite crystals within a worm tube was noted, and suggests the

FIGURE 75: Calcite pseudomorphs of lenticular gypsum (grey-white in photograph). Originally, the gypsum grew within micrite (dark colour in photograph), but was altered to carbonate by late-stage phreatic fluids. The arrow indicates a preserved crystal termination. Photomicrograph in plain light. Scale bar is 375 micrometres.

FIGURE 76: Prismatic calcite pseudomorphs of possible anhydrite. The arrows describe the splay orientation. The alteration from sulphate to carbonate is considered to have occurred during late stage diagenesis. Photomicrograph with cross-polarized light. Scale bar is 230 micrometres.

FIGURE 77: Sutured crystal boundaries of barite replacing part of a fauna/cement structure. Photomicrograph with cross-polarized light. Scale bar is 230 micrometres.

FIGURE 78: Calcite/marcasite veinlet cutting Table Point lithology. The sulphide is always in botryoidal splays lining the sides of the veinlet. Hammer for scale.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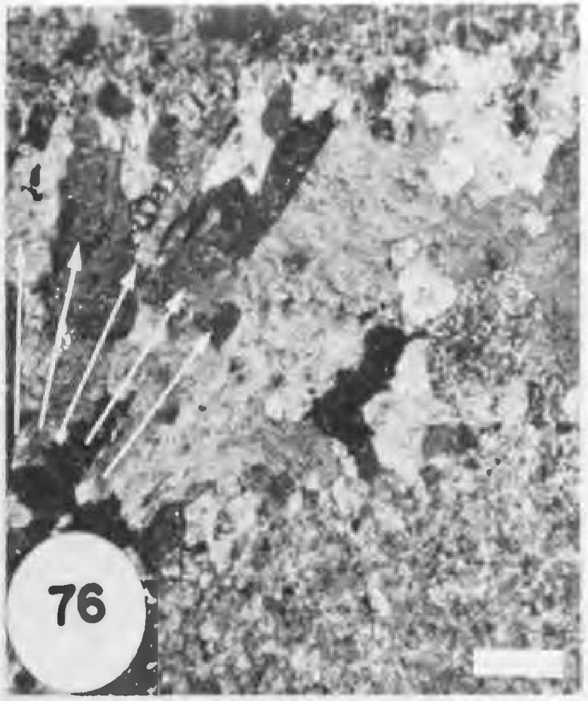
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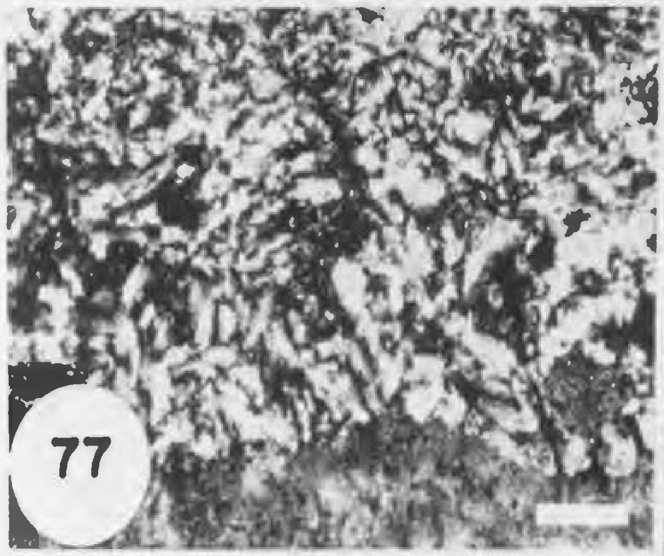
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passive settling of crystals from a solution. Large pyrite cubes were found in Bellman's Cove associated with gossan zones. Pyrite is generally rare in other localities. Late stage iron-rich and iron-poor calcite occurs in contact with all sulphide minerals and is the last precipitate within the cavities. Replacement of late stage calcite by marcasite or pyrite occurs rarely and is associated with Upper Sequence clastics in the carbonate/clastic lithofacies.

The superposition of sulphates on sulphides is common in deposits where the two types of minerals occur. Contemporaneous deposition is interpreted where adjacent examples of this relationship and its reverse are found. A superposition of marcasite-sphalerite-galena occurs within the sulphide assemblage. This relationship is similar to the order of precipitation of sulphides from a fluid controlled by Eh and solubility potential (Barnes, 1979). The large pyrite cubes at Bellman's Cove appear more related to precipitation from fluids moving along later fault zones, and thus are not considered part of the above sequence.

If the solubility sequence of sulphides is extended, sulphates (barite to celestite) precipitate after galena (Barnes, 1979). Although no sequence of precipitation was noted between barite and celestite in the study area, barite commonly overlies sulphides.

7.3. Controls of Mineralization

7.3.1. Stratabound Deposits

Factors which appear to control the style and distribution of mineralization in these deposits are: (i) faults; (ii) texture of the host sediment; (iii) basement topographic relief; and (iv) the distribution and diagenetic environment of the host strata and the mineralization source.

(i) Faults - Several north-south oriented faults cut the Ordovician and Upper Mississippian sediment in the northeastern part of the peninsula. In Bellman's Cove, Lead Cove, and Mistaken Cove, gossans are associated with these faults. Faults cutting the Upper Mississippian strata, or Ordovician strata, elsewhere on the peninsula have no similar associated gossans. It is within these gossan zones that the large pyrite cubes occur.

In Lead Cove, and Mistaken Cove, mineralization appears to pre-date the faulting. Faulted mineralized blocks of limestone are surrounded by non-mineralized fault breccia. In other mineralized localities to the west, no faults are apparent, though mineralization is just as pervasive.

(ii) Texture of the Host Sediments - Stratabound deposits are found within rubbly, relatively porous limestones, and sandstones of the Lower Sequence, and rarely within the Upper Sequence sandstones even though they are almost as porous. These deposits do not occur within the terrigenous red-bed lithologies along the south or southwest coast, though locally, barite was found replacing late stage calcite cement. At the time of mineralization, it is interpreted that intergranular pores within the intermound limestone and sandstone sediments, as well as the intramound pores, provided good porosity and permeability.

The porosity of these sediments is in marked contrast with the relatively impermeable Table Head and St. George Group carbonates which underlie the Upper Mississippian sediments. Fluids penetrating the region would preferentially travel through the Upper Mississippian sediments. Mineralization within these sediments may locally penetrate the Ordovician strata via cracks within the contact walls (e.g., Aguathuna "Island"). Apart from this minor variation, the only mineralization occurring within the Ordovician sediments, related to this time period, are sulphide vein deposits.

(iii) Basement Palaeotopographic Relief - The karst topography developed on the Ordovician prior to deposition of Upper Mississippian sediments has been previously discussed in detail (Chapter 2). It is sufficient to say that fluids travelling down-gradient would be preferentially channeled into buried karst valleys due to the low permeability of the Ordovician rocks, and the lower piezeometric gradient within the valleys caused by the palaeorelief of the Ordovician surface. The fluids would probably travel along or near the base of the Upper Mississippian–Ordovician contact.

(iv) Distribution and Diagenetic Environment of Host Rock and Mineralization Source - Two observations can be made with respect to the stratabound deposits on the peninsula in conjunction with relating a mineralization source rock or area to the host strata. First, relatively thick deposits of sandy gypsum are adjacent to, or in the vicinity of, the stratabound mineralization, and occur at a somewhat higher elevation. Second, stratabound deposits only occur in a marine/fluvial sediments and never in the terrigenous red-beds along the south or southwestern coasts.

Gypsum strata would provide an abundant and adequate source of sulphate to be complexed with barium and strontium, and reduced/complexed with lead, iron and zinc. An equally abundant, and adequate, medium within which which the complexes can be transported from source to host strata, is a groundwater system. Other factors which suggest that this model may be correct are: (i) it is interpreted that much of the mineralization in these deposits is pre-faulting; (ii) the palaeorelief of the Ordovician surface is sufficient to provide effective flow gradients; and (iii) the buried karst valleys are effective channelways for groundwater which would travel through the Upper Mississippian sediments due to the contrast in porosity with the Ordovician strata. The observation of the gypsum-mineralization relationship as outlined above would explain the paucity of mineralization in Big Cove; that is, no gypsum source is available. In the northeastern part of the peninsula, the present distribution of gypsum is restricted to the Boswarlos-Piccadilly region. The gypsum may have been more areally extensive, or its drainage system, such that the coves farther to the east were affected by the sulphate-laden waters.

The second observation, that stratabound deposits only occur in the marine/fluvial sediments, suggests some kind of control associated with a meteoric-marine interaction. Though the host strata would have to be immersed within the phreatic zone during mineralization, a marine basin may have still existed to the north of the region. The recognized sulphide-sulphate solubility ordering found within the sediments, however, would tend to indicate that Eh and solubility potential were more important than a meteoric-marine interaction.

Although the mechanism for transport and mineralization of the limestones and sandstones of the Lower Sequence has been discussed, the source for the cations (Pb, Zn, Fe, Ba, and Sr) is more problematic. The barium and strontium may be supplied by the removal of strontium from the limestones during their diagenesis. The source for the other cations may be the source rock of the terrigenous clastics in the red-beds, and the Upper Sequence terrigenous sandstones which cover or are adjacent to the Lower Sequence sediments.

7.3.2. Vein Deposits

The controls of mineralization for this style of mineralization is interpreted to be tectonic. The source of the fluids within the vein deposits could be verified by sulphur and lead isotope studies.

This is beyond the scope of this study. However, a brief discussion dealing with the problem is given.

If the veins are interpreted to be related to Alleghenian faulting, then it is possible that the fluids were derived in some manner from Grenville basement underlying the Cambro-Ordovician strata on the peninsula. Gravity anomaly maps (Zietz et al., 1980) indicate a near surface gavity anomaly underlying most of the peninsula. As Grenville basement outcrops south of Stephenville, it is interpreted that the anomaly is basement.

7.4. Summary

The model used here to explain the stratabound mineral deposits is similar to models used for barite and celestite deposits of equivalent age in Nova Scotia (Felderhof, 1978). It is suggested that four mineralizing events took place during and after the deposition and burial of the potential host strata:

(i) primary synsedimentary mineralization of gypsum and anhydrite;

(ii) sulphide and sulphate mineralization from groundwater controlled by host strata porosity, Eh and the solubility, and possibly some meteoric-marine interaction;

(iii) locally restricted replacement of strata by barite and celestite;

(iv) faulting and associated mineralization locally overprinting a pre-tectonic mineralization; veins occur, within the Ordovician and Upper Mississippian lithologies.

Later vadose alteration of the sulphide and sulphates would dissolve and/or redistribute the elements from their original sites.

CHAPTER 8

DIAGENESIS OF THE CARBONATE/CLASTIC LITHOFACIES (and Speleothems)

8.1. Introduction

Diagenetic textures in the carbonate/clastic lithofacies, and speleothem cements, which coat and/or infill fissures in the Ordovician limestone, are described and divided temporally into three paragenetic stages (Early, Middle, and Late). The textures include early and late cements, fabric specific dissolution features, several styles of neomorphism, desulpherization, dolomitization and mineralization. Thin section petrography, iron and calcite staining techniques (Evamy, 1969), electron microprobe analyses, and cathodoluminescence were used to outline the diagenetic textures. The first part of this chapter contains descriptions of the diagenetic textures; this is followed by their interpretation, and a discussion.

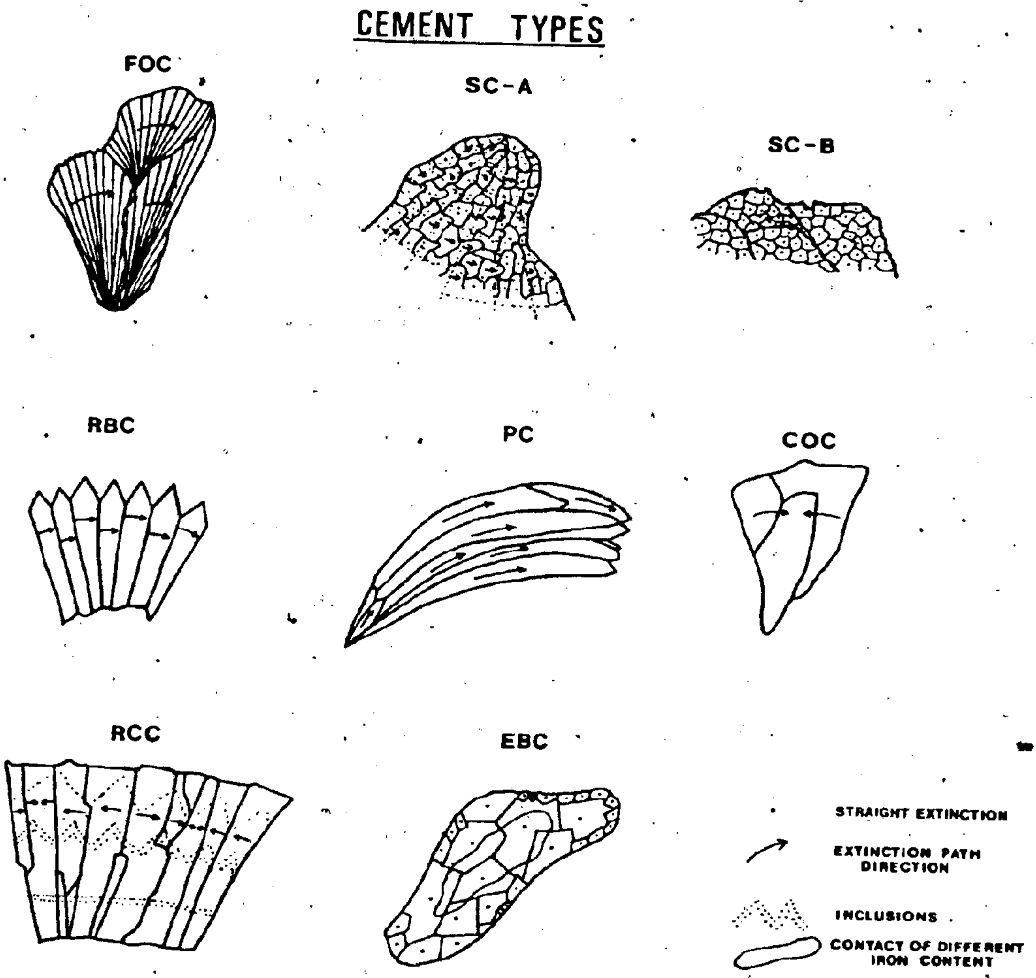
8.2. Cements

Six types of cements are recognized (Fig. 79). The first two, fascicular-optic calcite and spherulitic calcite, are restricted to the marine carbonates. Three cements are confined to speleothem deposits: radial columnar calcite, plumose calcite, and radial bladed calcite. The sixth cement, equant blocky calcite, is found throughout all lithofacies. All cements but radial bladed and equant blocky calcite appear as neomorphic alterations of an original precursor with relict internal fabric preserved in some cases.

(i) Fascicular-Optic Calcite (FOC) - Single to multi-generation fascicular-optic calcite (Kendall, 1977) acts as an inter- and intragranular cement. It is particularly conspicuous coating bryozoans, algae, and worm tubes, to form complex fauna/cement structures in bioherms. This cement is the neomorphic replacement of a fibrous to acicular precursor, with radially divergent relic fibres (Kendall, 1977). In Port au Port examples, relic fibres, or inclusions defining original fibres, are commonly preserved (Fig. 79). The neomorphic alteration of an aggregate of fibres yields a fan shape. The fans are usually elongate, often with consertal to sutured boundaries, vary in length from 100 to 1000 micrometres, and expand with length from 100 up to 500 micrometers. Under crossed-polarized light, each fan displays sweeping extinction that terminates at the contact with an adjacent fan. The ends of a fan may be sharp and well defined (Fig. 80A) or ragged (Fig. 94), terminating in fibres of unequal length. Where many fans are stacked together, a compound-lens effect is produced by the similar oriented extinction patterns (Fig. 80B).

Peloids, Spirorbis caperatus, foraminifera, thin micritic laminae, and dispersed micrite are found within the cement where it forms a fauna/cement structure. The micrite laminae separate single to multiple generations of cement precipitation that are concentric around faunal elements (Fig. 80C). Fascicular-optic calcite is also found infilling or coating other bryozoans, ostracodes, brachiopods

FIGURE 79:


CEMENT TYPES
FOC
SC-A
SC-B
RBC
PC
COC
RCC
EBC
STRAIGHT EXTINCTION
EXTINCTION PATH DIRECTION
INCLUSIONS
CONTACT OF DIFFERENT IRON CONTENT

and pelecypods not associated with the fauna/cement structures, interlaminated with multigeneration sediment, as well as occluding interpreted cavities in zebra rock found in Big Cove Creek. As described in Chapter 3, zebra rock is composed of interlaminated biomicrite and calcite spar. The latter is composed of fascicular-optic calcite as fan-shaped masses infilling horizontal cavities (Fig. 81). Associated with the FOC cement is equant blocky calcite similar in morphology to the late stage cement (see below).

Microprobe analyses indicate that the cement generally has between 0.3 to 0.6 mole percent magnesium carbonate, but may contain as much as 1.0 percent. No detectable strontium and usually less than 0.5 percent of iron oxide are present. This type of calcite does not luminesce.

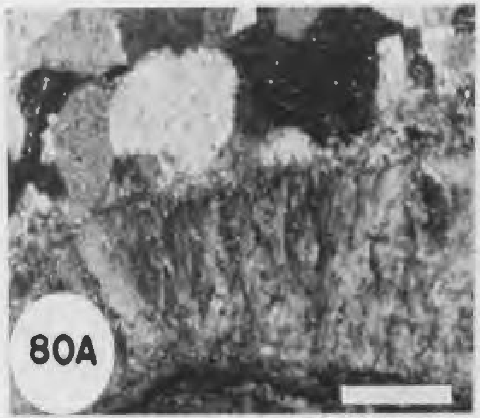
(ii) <u>Spherulitic Calcite (SC-A and SC-B)</u> - <u>SC-A</u> - Calcite fan-shaped masses, composed of equant blocky pseudospar (Folk, 1965), herein called spherulitic calcite, and exhibiting discontinuous laminae perpendicular and parallel to fan elongation, are locally very abundant in one mound at Aguathuna Creek (Fig. 79). Fans are commonly one millimetre in length by one millimetre at greatest width. The largest fan was 4 millimetres in length, with a maximum width of 2.5 millimetres. Laminations (dusty and/or fluid inclusions) cut across the pseudospar which develops an interlocking mosaic of generally elongate crystals, 50 to 250 micrometres in length and 50 to 125 micrometres in width. The crystals exhibit straight to faint sweeping extinction and are radially divergent

FIGURE 80A: Fans of fascicular-optic calcite, possible magnesium calcite cement, with sharp terminations. Overlain by late stage calcite cement. Photomicrograph with cross-polarized light. Scale bar is 500 micrometres.

FIGURE 80B: An array of fascicular-optic calcite fans, with apices oriented towards a sediment core (bottom of photograph). The cement with encorporated matrix (above the scale bar) is of the same mineralogy but does not display fan morphology. Photomicrograph with cross-polarized light. Scale bar is 2.0 millimetres.

FIGURE 80C: Fascicular-optic calcite fans forming isopachous rims. Each cement generation is separated by a micrite laminae (arrow). The pseudospar (above arrow) associated with the possible magnesium calcite cement may be altered aragonite cement (see FIGURES 82 and 85). Photomicrograph with cross-polarized light. Scale bar is 2.0 millimetres.

FIGURE 81: Zebra rock showing laminae of biomicrite separated by fascicular-optic calcite, geopetal micrite, and blocky calcite. Splays of the early cement on the ceiling and floor of the palaeocavities extend downward and upward respectively. Arrows point to the downward extent of sweeping extinction from the early cement into the blocky calcite. Sharp boundaries between the fascicular-optic calcite and blocky calcite also occur. Moldic porosity within the biomicrite is common. White specks in the biomicrite are quartz and feldspar grains, with rare dolomite rhombohedra. Photomicrograph with cross-polarized light. Scale bar is 500 micrometres.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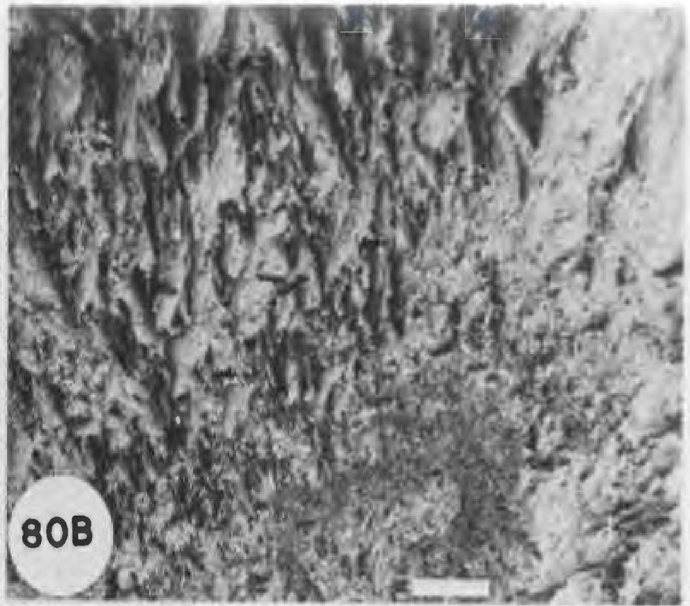
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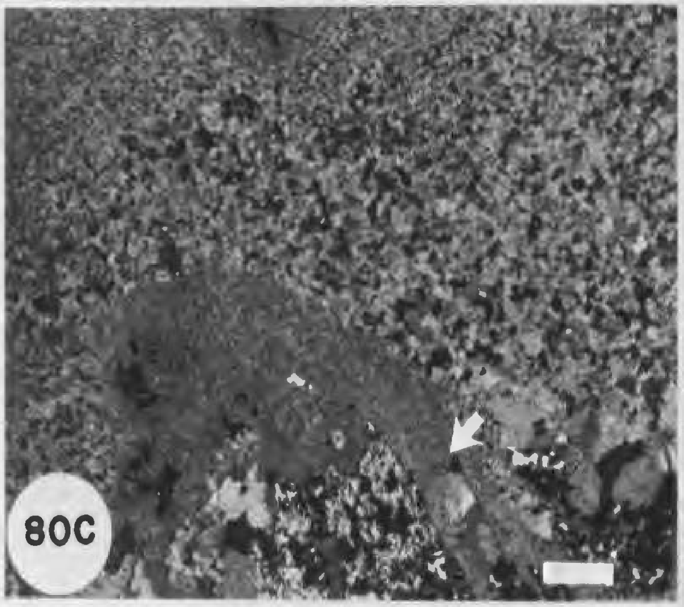
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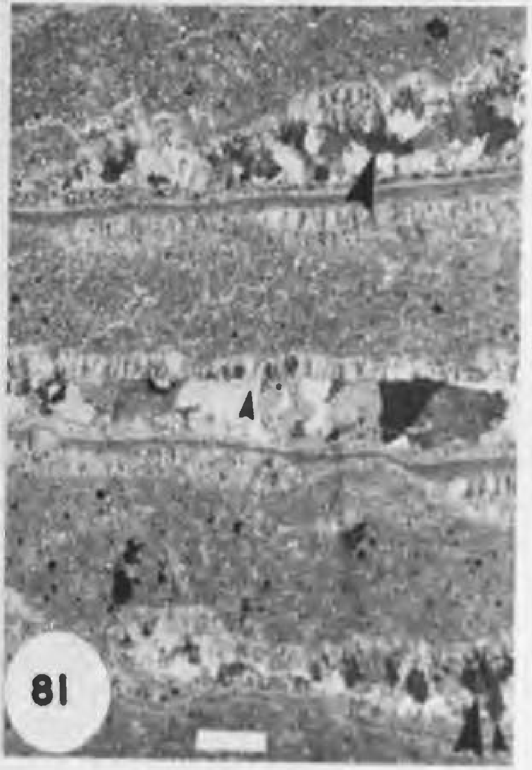
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from the apex of the fan. Fans are attached to a micrite substrate or to other fans. The contact of two fans is a thin micritic laminae similar to that in FOC cement. In one instance, a laminae of FOC cement was found coating an outer edge of an SC-A fan, and the contact between the two was also defined by a similar looking thin micritic laminae (Fig. 82). Free terminations of SC-A calcite are also micritic and may exhibit feathery to chisel-shaped edges. No inclusions of fauna or other allochems within the fans were noted, though dispersed micrite is common. The fans contain between 1.0 and 1.5 percent magnesium carbonate, no detectable strontium, and less than 0.2 percent iron oxide. This type of calcite also does not luminesce.

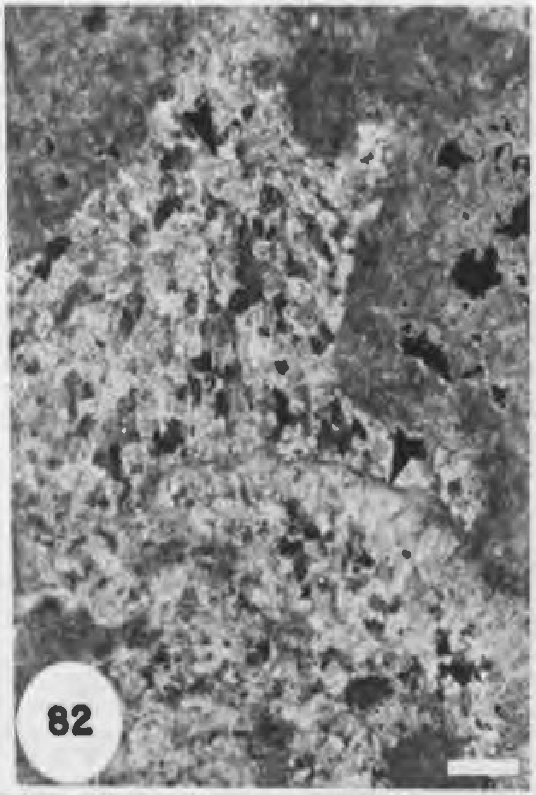
<u>SC-B</u> - This type of calcite cement is common in mounds, and well developed in the grey micritic limestone of the Upper Sequence in Aguathuna Creek. In the latter locality, well formed botryoids, of blocky equant pseudospar defined by micrite laminae often exhibit feathery and chisel shaped edges (Figs. 79, 83, 84). The blocky calcite texture with associated micrite laminae is common in fauna/cement structures. The laminae, in this case, however, rarely outline botryoidal morphology and the pseudospar occurs in much more irregular shapes (Fig. 85). Pseudospar crystals are equant, vaguely radially divergent when found in botryoids, and are 10 to 300 micrometres in diameter. Crystal boundaries within the pseudospar are sharp and irregular. Cathodoluminescence indicates the presence of inclusions, not seen in plain light, aligned in a radially divergent pattern from the apex of the botryoids. These terminate at the micrite laminae on which another botryoid is developed.

FIGURE 82: Typical spherulitic calcite, interpreted as being possible aragonite cement. The fan is directed downwards infilling a cavity within a micritic-rich mound. The upper arrow indicates faint horizontal and vertical laminations (inclusions define primary textures). The lower arrow points to a micritic contact between this type of cement and an isopachous rim of fascicular-optic calcite cement. Photomicrograph with cross-polarized light. Scale bar is 460 micrometres.

FIGURE 83: Botryoids of spherulitic calcite with peloid inclusions and well developed micritic contacts between botryoids. Arrows point to patches of coarser pseudospar indicating extent of alteration from the interpreted aragonite to pseudospar. Photomicrograph with cross-polarized light. Scale bar is 500 micrometres.

FIGURE 84: Detail of micritic laminae from FIGURE 83. Black arrow points to poorly developed square chisel-shaped laminae terminations. Note apparent boring? in large peloid (white arrow). Photomicrograph with plain light. Scale bar is 500 micrometres.

FIGURE 85: Irregular to botryoidal bodies of altered cement, with inclusions of peloids. Note large patches of coarse pseudospar similar to those in FIGURE 83. Extreme alteration may yield very coarse blocky calcite. Photomicrograph with cross-polarized light. Scale bar is 500 micrometres.



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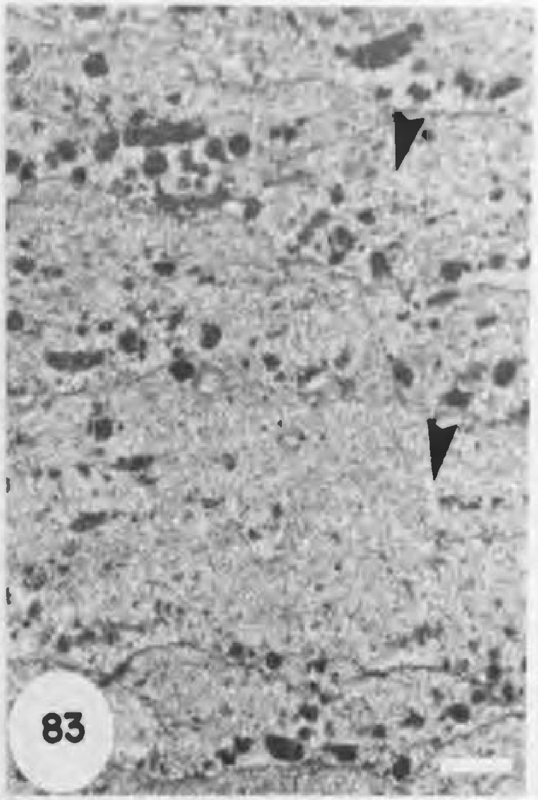

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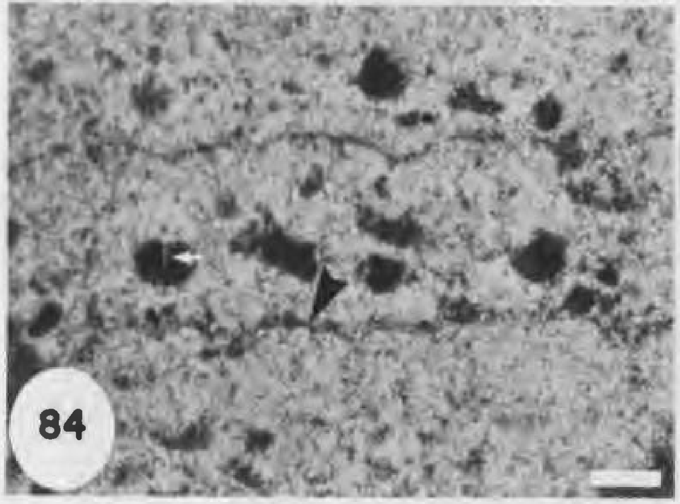

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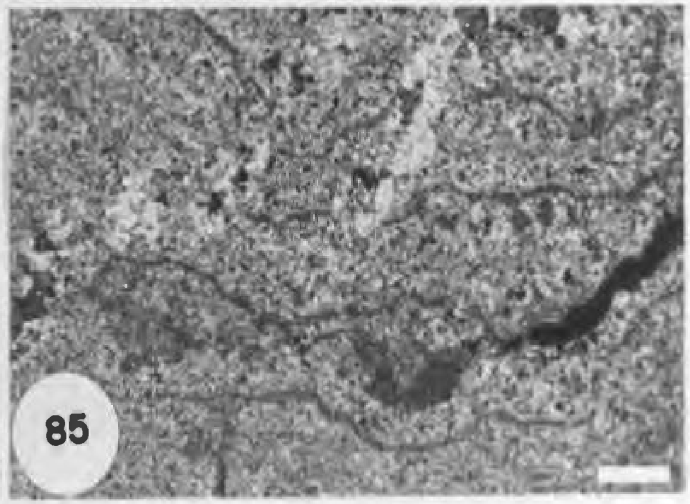

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Within the mounds, irregular shaped "bodies" of spherulitic calcite are sometimes vertically stacked normal to the substrate (either fauna or FOC cement), but are more often nongeostrophic (Fig. 86). In the micritic limestone at Aguathuna Creek, all botryoids are oriented normal to the bedding. This cement type contains less than 1.0 mole percent magnesium carbonate, no detectable strontium, less than 0.2 percent iron oxide, and is non-luminescent.

(iii) Radial Columnar Calcite (RCC) - This cement is found as stalactites in Pratt's Cave. The crystals, neomorphic after a previous speleothem fabric vary up to 3.0 mm in length, and 0.1 to 0.55 micrometres in width. Some crystals have sharp re-entrants as described by Kendall and Broughton (1978) but are generally well defined and collumnar in shape (Figs. 79 and 87). A single laminae of this calcite may have several ill-defined aggregates of radially divergent crystals, each aggregate having a preferred direction of extinction. As a result, converging extinction is found at the junction of adjacent crystal aggregates. In some cases, convergence occurs within a single crystal. The crystals cut across primary structures of the speleothem (crystal terminations and laminae defined by dusty inclusions). Alternating iron content parallel to primary growth is apparent by staining. These cements have no detectable strontium, less than 1.0 mole percent magnesium carbonate, and strongly luminesce. Iron oxide content varies from 0.0 to 0.65 percent in the iron "rich" zones.

(iv) Plumose Calcite (PC) - This cement is a peculiar and localized neomorphic replacement of an original speleothem fabric. Several curved crystals form plume-shaped masses up to 1500 micrometres in length and up to 500 micrometres at greatest width (Fig. 79). Inclusions and sweeping extinction follow the curvature of the crystals. Several of these plumes adjacent to one another give the appearance of a feather headband (Fig. 88). Larger crystals (Type COC; Fig. 79) with subcrystals, are elongate to more equant in shape and have an extinction pattern that converges at the centre of the large crystal. These cements fabrics are related to the PC cement and may be some variation in neomorphic alteration within the cement. The original speleothem structure appears to both control, and be cut by, the neomorphic calcite. This type of calcite does not luminesce.

(v) Radial Bladed Calcite (RBC) - This cement is found as speleothems at Sheaves Cove and Pratt's Cave. Aggregates of up to ten crystals are found as isopachous layers rimming earlier druse. The blades are 50 to 500 micrometres in length, and 20 to 50 micrometres at greatest width (Figs. 79 and 89). There is a sweeping extinction pattern within the individual crystals. Inclusions of micrite range from numerous to few throughout the cement. The mineralogy of alternating laminae vary from calcite to dolomite.

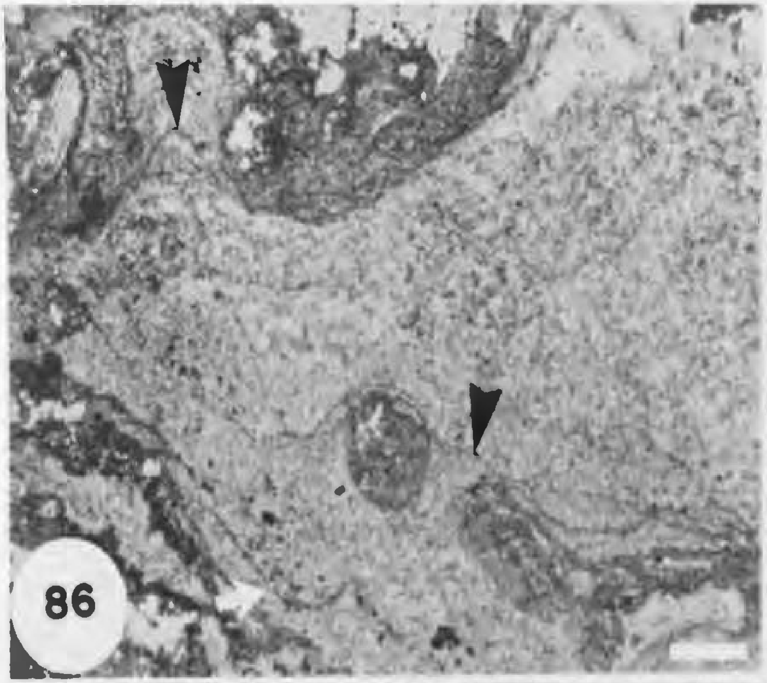
(vi) Equant Blocky Calcite (EBC) - Equant blocky fine to coarsely crystalline calcite spar acts as a late stage inter- and intragranular pore-filling cement (Fig. 79). Within some of the Upper

FIGURE 86: Non-geostrophic to geostrophic altered cement and laminae (arrows). White arrow points to cement bodies, defined by micrite laminae, which are inverted with respect to those in the middle or top of the photograph. Photomicrograph in plain light. Scale bar is 500 micrometres.

FIGURE 87: Typical radial columnar calcite from stalactites in Pratt's Cave. Photomicrograph with cross-polarized light. Scale bar is 360 micrometres.

FIGURE 88: Plumose calcite. Localized speleothem cement texture. Photomicrograph with cross-polarized light. Scale bar is 250 micrometres.

FIGURE 89: Radial bladed calcite. Associated with speleothem flowstone. Photomicrograph with cross-polarized light. Scale bar is 250 micrometres.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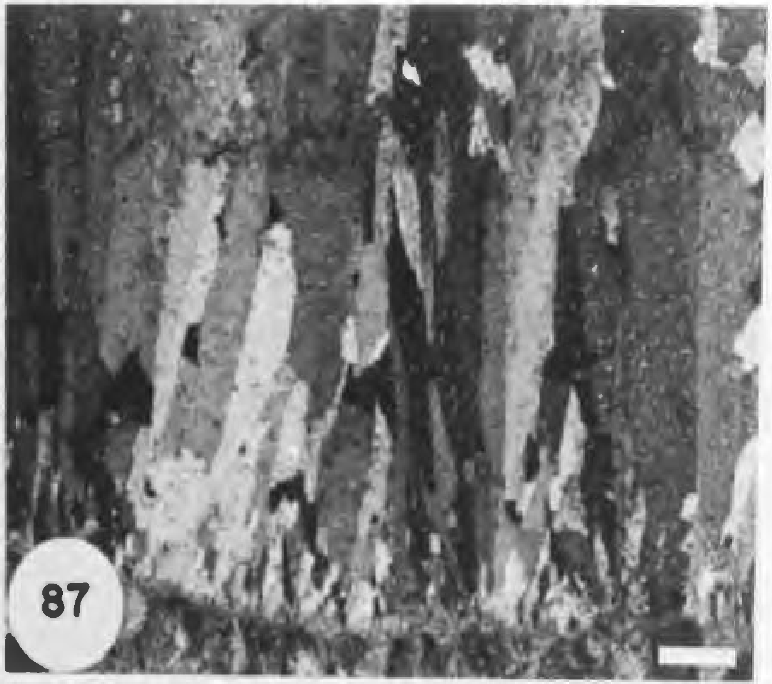
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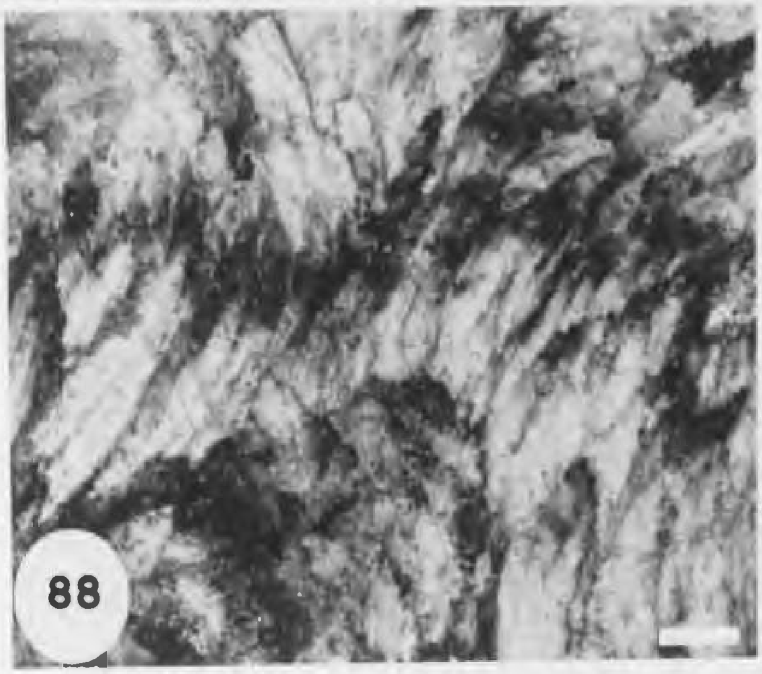
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Sequence sandstone, as well as the terrigenous clastics associated with the red-beds on the south shore, intergranular pore space is infilled with iron-rich blocky calcite cement followed by iron-free calcite. In the carbonates of the Lower Sequence, and some clastics of the Upper Sequence and red-bed lithology, this iron sequence is commonly reversed. Typically, however, no iron is present at all. Late-stage veinlets which locally cut Lower Sequence limestones consist of iron-poor blocky calcite.

Within a pore, there is usually an increase in crystal size toward the centre, with an isopachous to discontinuous laminae of equant and/or slightly bladed spar rimming the substrate wall. Crystals range in size from microns to several centimetres. The highest iron content in any of the blocky calcite observed is 0.6 percent. These cements brightly luminesce and up to four stages of precipitation may be found in a single cement-filled pore.

8.3. Allochems

Within the carbonates, various allochems exhibit different styles of preservation:

(a) brachiopods, annelida (Spirorbis caperatus), bryozoans, and ostracodes generally retain their fabric;

(b) the large worm? tubes are identical to the fabric of FOC cement and may be a result of cementation occurring along a membranous organic? tube within which the organism resided;

(c) gastropods are generally dissolved and replaced by EBC cement; only one gastropod possessing a micrite rim was found though the remainder of the shell had been completely dissolved;

(d) pelecypods are either completely dissolved and replaced by EBC cement, or retain their fabric;

(e) intraclasts of faecal mounds? or grapestone?, from the laminated limestone at Boswarlos, have a fine crystalline matrix surrounding the peloids within the intraclasts (Fig. 90); it is uncertain whether the matrix is neomorphic or cement spar.

8.4. Dissolution Features

Peloids, blue-green algal structures and gypsum are preferentially susceptable to dissolution. This process is visible in various stages of development, and when well developed produced moldic porosity. Micrite surrounding dissolution pores often displays a green colouration.

Rounded to lobate peloids associated with intermound packstones in the biohermal limestones are particularly susceptable to dissolution. Various degrees of dissolution are preserved with the most extreme producing good peloid moldic porosity (Fig. 91). In some peloids, a vague interior structure may occur resembling the micritic foraminifers found in related sediments.

Micrite laminae associated with the algal structures are commonly preferentially dissolved. Porosity is moldic as well, with affected structures producing concentric laminar vugs (Fig. 92). The surrounding rock, including both FOC and EBC cements, appear unaffected.

Round to irregular shaped thin micrite rims are infilled with EBC cement. In the laminated limestone of the sulphate/clastic lithofacies various stages of dissolution, including micrite rim development, followed by cement infill are found in the lithoclasts interpreted as eroded mounds of faecal pellets, or grapestones (Fig. 90).

Gypsum and barite crystals infilling fractures or primary voids are completely to partially dissolved. Remnant gypsum often has an associated finely crystalline alteration product (clay?) developed along the edges and along the cleavage traces. If fractures, originally containing gypsum, cut a micrite host sediment, a green colouration is noted in the micrite along the fracture edge.

8.5. Neomorphic Textures

8.5.1. Microspar

Microspar (Folk, 1965) is found: (i) adjacent to, and replacing micrite; (ii) within fauna/cement structures adjacent to pseudospar; (iii) partially replacing SC-type cement; and (iv) as "geopetal" sediment within cement-filled mound voids. In the mounds, the microspar exhibits an abrupt contact with the underlying material, either structure cement, or graded multigeneration sediment. Peloids and terrigenous clastic grains may be associated with this fabric although these inclusions are rare. Spar size is typically 10 to 40 micrometres in length, and less than 30 micrometres in width, with contacts curved to straight.

8.5.2. Pseudospar

Pseudospar (Folk, 1965) partly to completely replaces all cements, some micritic allochems, and portions of the fauna/cement structures. Two stages of neomorphism of the cements occur:

(i) Neomorphism 1 - With respect to replacement of cement types FOC and SC, the resultant fabric is an interlocking mosaic of equant to elongate crystals which may cross-cut the original cement texture (see above; and Fig. 93).

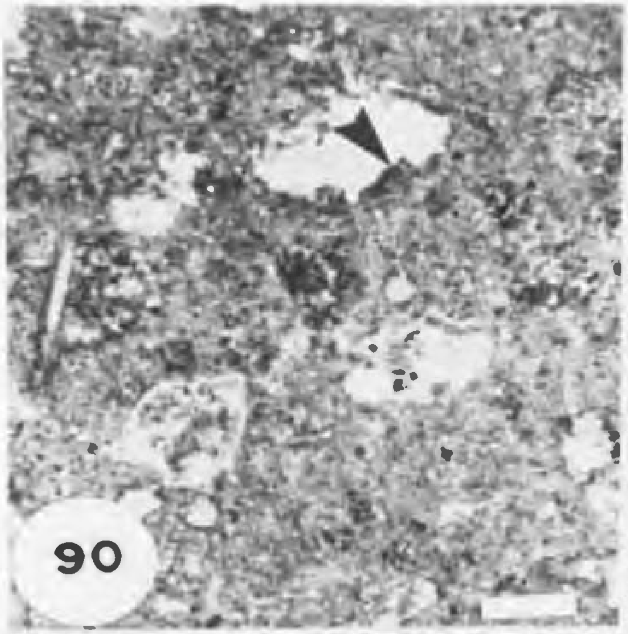
(ii) Neomorphism 2 - A second stage of neomorphic replacement is associated only with the FOC cement. This alteration produces coarse spar which has the appearance of EBC cement. Replacement occurs at the edges of the FOC cement fans, and extends towards the fan apex. The fans may be in contact with EBC cement (e.g., in mound cavities). This pseudospar texture is recognized by (a) relic fibres of the original FOC cement fans (Fig. 94), and (b) relic sweeping extinction extending from the FOC cement into the EBC-type pseudospar (Fig. 81). An extreme form of the replacement occurs in the zebra rock from Big Cove Creek. In this case, laminae of coarse pseudospar (EBC-

FIGURE 90: Dissolution of intraclasts and precipitation of late stage calcite cement within the molds (arrow). The outer rim of an intraclast is still preserved (arrow). Compaction of sediments has resulted in the fracturing of an ostracode test (lower left of photograph). Photomicrograph in plain light. Scale bar is 400 micrometres.

FIGURE 91: Peloid, and intraclast, moldic porosity. Photomicrograph with cross-polarized light. Scale bar is 500 micrometres.

FIGURE 92: Moldic porosity (left and centre of photograph) associated with blue-green algal thromobolite. Note that late stage cement (white) in the surrounding sediment is unaffected. Late stage diagenesis. Photomicrograph with cross-polarized light. Scale bar is 750 micrometres.

FIGURE 93: Algal moldic porosity (black in photograph) and juxtaposition of both possible magnesium calcite and aragonite cements, now altered to calcite. Photomicrograph with cross-polarized light. Scale bar is 450 micrometres.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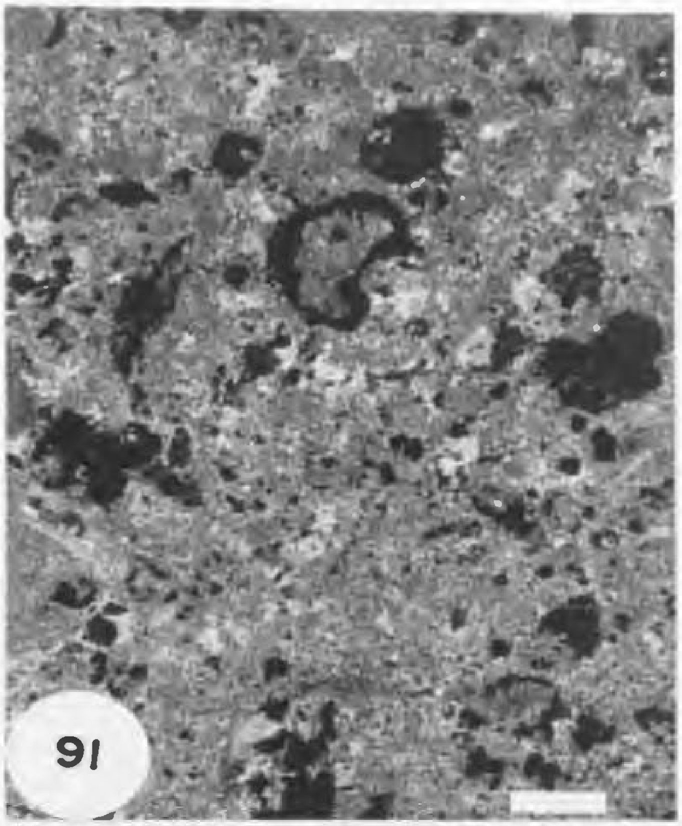
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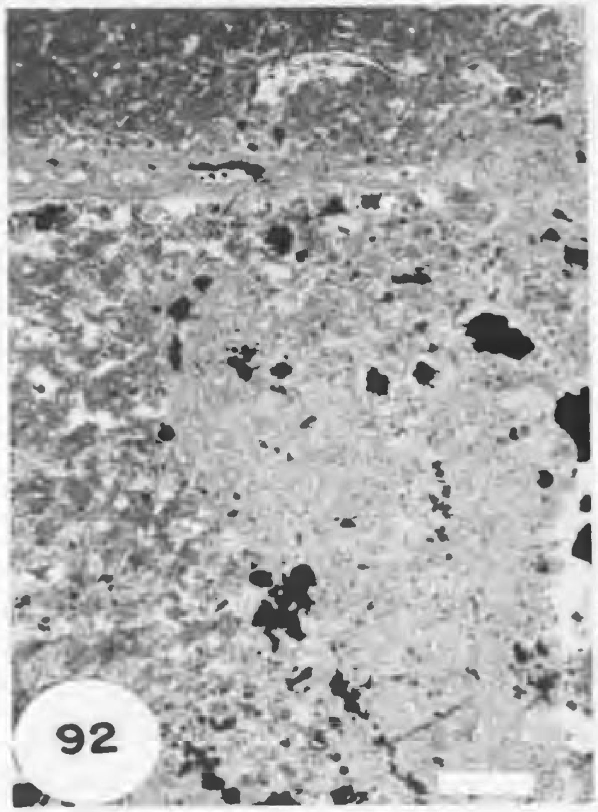
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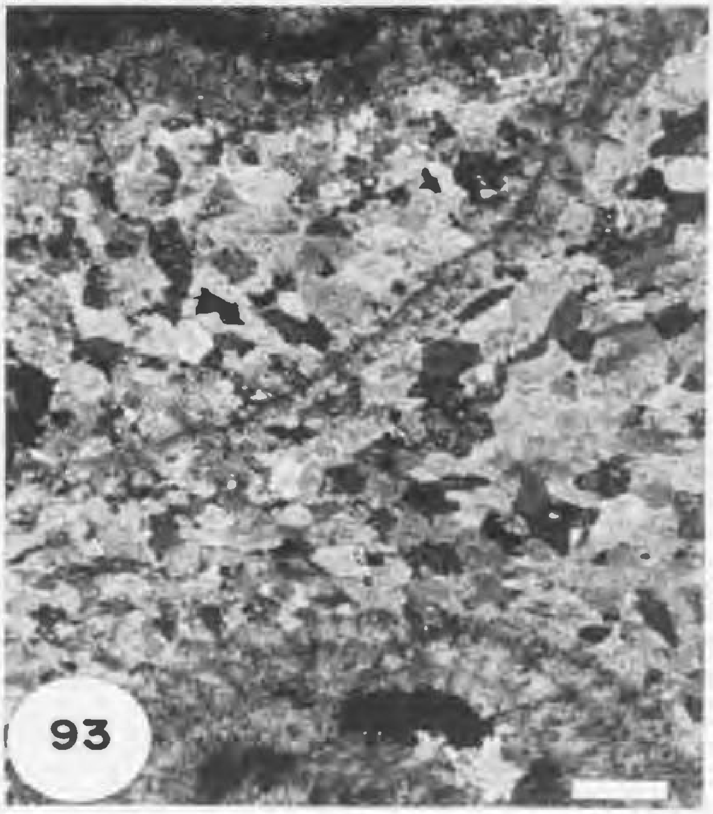
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type) have replaced cavity filling FOC cements fans. The laminae of the EBC-type pseudospar vary in thickness from 0 to 1000 micrometres. The replacement textures vary from well developed to non-existant along a single cavity fill (Fig. 95). Large sweeping extinction patterns within the second pseudospar are the clue that the replacement has occurred. Commonly, sharp boundaries between the two calcites may occur giving the appearance of EBC cement infilling a cavity that is lined by FOC cement (Fig. 81).

Fractures cut through the host biomicrite and FOC cement within the zebra rock. Where the fractures cut biomicrite only, they are infilled with well defined EBC cement. Along the same fractures, where the fracture cuts through the FOC cement fans, the fracture "infill" is clearly the EBC-type pseudospar (Fig. 96). It is interpreted that cavities developed within the biomicrite were infilled with the FOC cement. Fracturing was preferential along the original cavity orientation, and EBC fluids percolated along the fractures replacing FOC cement, or, precipitating EBC cement in fractures not associated with FOC cement.

8.5.3. Aggrading Neomorphism

As defined by Folk (1965), this term is used to describe the change from micrite through microspar to pseudospar. Although examples of this change are rarely well defined in the Port au Port Upper Mississippian strata, one well developed example is found in a micritic facies of the biostromal limestone (upper limestone unit of the Lower Sequence) at Lead Cove, immediately overlying the middle siliclastic unit. Here, microspar grades into local patches of pseudospar, 100 to 200 micrometres in diameter (Fig. 97). Iron sulphide blebs may be locally present in the pseudospar. This calcite texture has replaced lenticular gypsum.

8.6. Dolomitization

Two types of dolomite can be found, though both are rare. The first is the replacement of micrite by small beige-coloured rhombohedra 10 to 40 micrometres in diameter. Often broken reworked rhombohedra occur in packstones of the Lower Sequence (e.g., Big Cove). In the zebra rock, dolomite rhombohedra are found in micritic fragments of the host biomicrite, and surrounded by the FOC cement (Fig. 98).

The second type of dolomite is the complete replacement of cement, micrite and allochems. This occurs in small 2.0 to 3.0 millimetre patches with irregular edges (Fig. 99). This style of dolomitization was found only in the upper limestone unit of the Lower Sequence in Aguathuna "Island", and is associated temporally with barite/celestite replacement.

8.7. Desulfitization

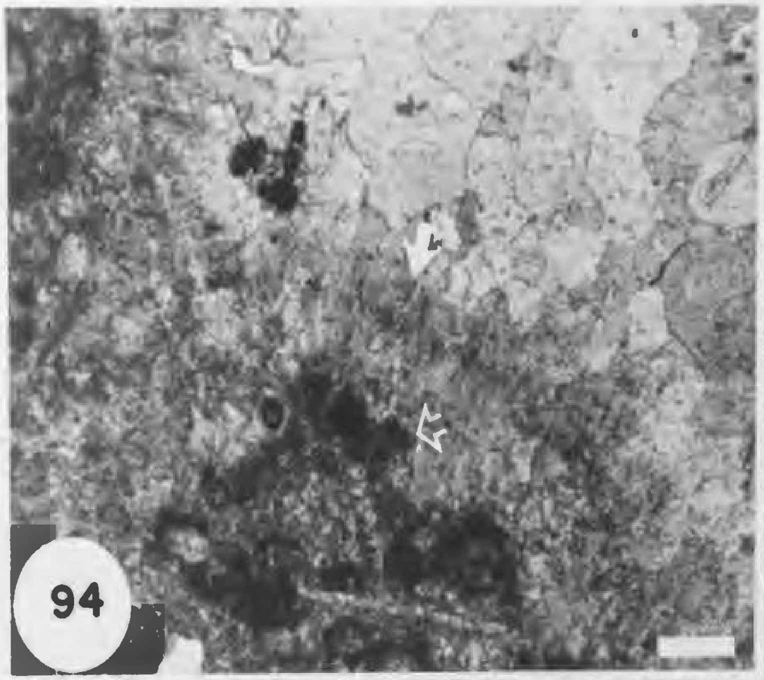
This term is used for the replacement of both gypsum and anhydrite crystals by calcite. Evidence of this is rare, but when discovered is well developed. Grey calcite nodules with a mammellose

FIGURE 94: Ragged terminations of fascicular-optic calcite (FOC) fans extending into coarse pseudospar. Note at solid arrow the pseudospar underlining the ragged terminations. The substrate to FOC cement appears to be peloids and/or clotted micrite (open arrow). Photomicrograph with cross-polarized light. Scale bar is 230 micrometres.

FIGURE 95: Zebra rock alteration. At arrows, fascicular-optic calcite cement is altered to pseudospar (white). Photomicrograph with cross-polarized light. Scale bar is 230 micrometres.

FIGURE 96: Late stage blocky calcite cement versus pseudospar in zebra rock. The left arrow points to late stage cement in contact with biomicrite. The right arrow indicates a point where fascicular-optic calcite is altered to pseudospar. Note that this occurs where a fracture through the biomicrite extends into the fascicular-optic calcite as well. Photomicrograph with cross-polarized light. Scale bar is 230 micrometres.

FIGURE 97: Aggrading neomorphism. Microspar, initially altering gypsum, grades into pseudospar (white). Black iron sulphide blebs are associated with calcite suggesting that alteration from gypsum to calcite occurred during late stage diagenesis. Photomicrograph in plain light. Scale bar is 230 micrometres.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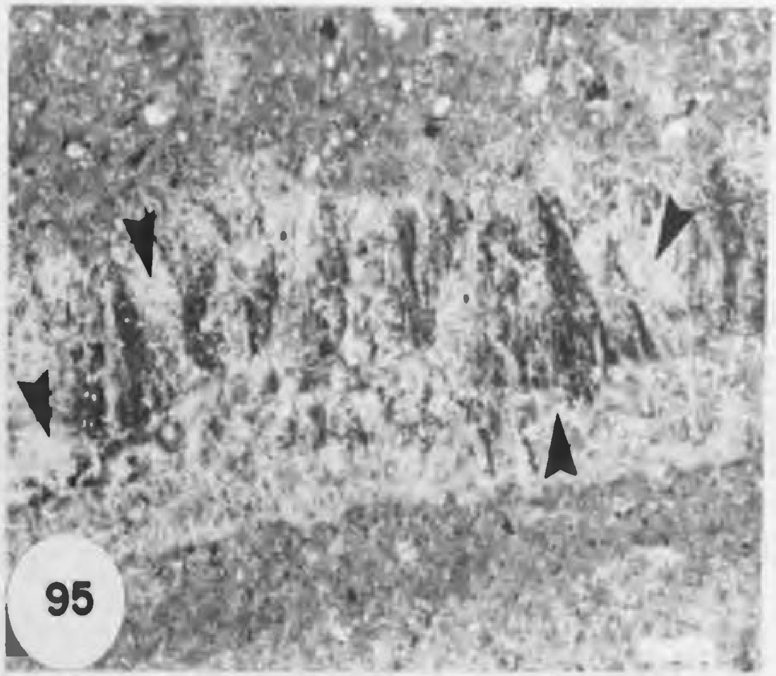
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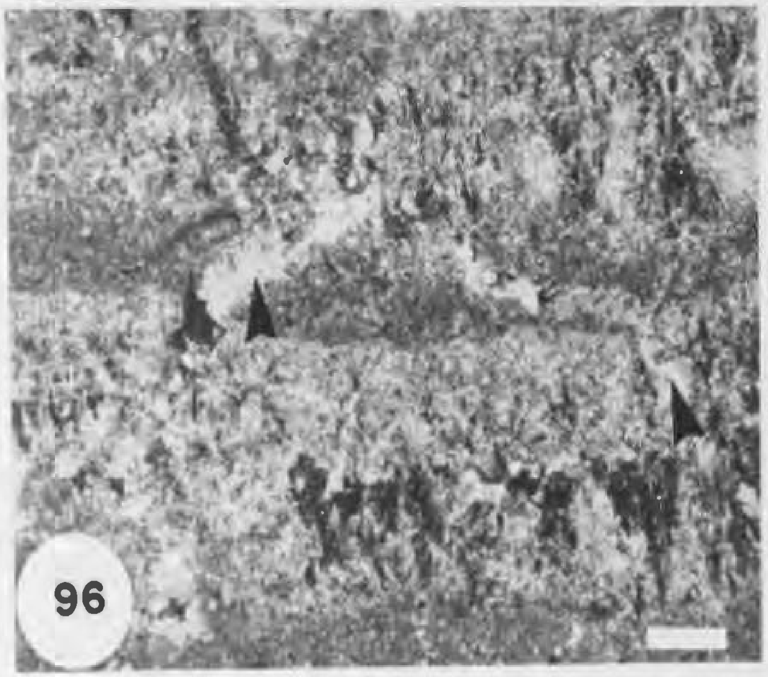
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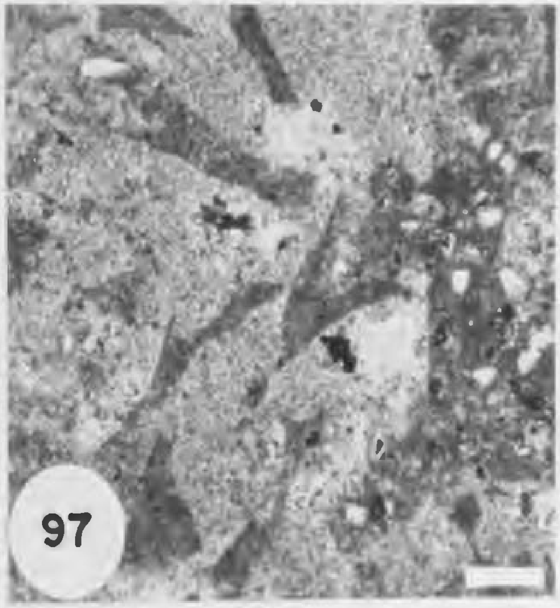
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surface texture have an internal nodular texture mimicing chickenwire gypsum (Fig. 100). These are found in the feldspathic arenites of the Upper Sequence in Lead Cove. The replacing calcite alternates from iron-free to iron-poor as illustrated by staining, and may show increasing crystal size towards the centre of each individual nodule in the chickenwire structure. This chickenwire texture is also found in some of the fauna/cement structures in the mounds but is not as well developed as above.

In the biostromal limestone unit of the Lower Sequence at Lead Cove, masses of lenticular gypsum within a micritic limestone host rock are replaced by microspar and pseudospar (Figs. 75 and 97).

A third type of desulfitization is found in primary vugs within the mounds. Pore-filling splays of prismatic anhydrite are replaced by calcite with the primary structure of the sulphate still retained (Fig. 76). Within the same vug, the replacing calcite acts as pore-filling EBC cement occluding the porosity.

8.8. Barite, Gypsum, and Marcasite Replacement

Examples of barite and gypsum replacing fragments, shells, and EBC cement are common in packstones and grainstones, as well as mounds, from Gillam's Cove, the upper limestone unit in Aguathuna "Island" and in Aguathuna East. Barite replaces cement in some red conglomerates in the Ship Cove area, and in the grey breccias of the

Upper Sequence in Aguathuna Creek. Rare marcasite is found replacing cement in some red-bed sandstones and conglomerates along the south coast.

8.9. Other Diagenetic Features

Other features that complete the diagenetic sequence are the following:

(i) Fracturing of allochems due to compaction; this is found both before and after FOC cement rims the allochems. Often brachiopods and ostracodes lined with this cement are found broken and the remaining porosity is filled with EBC cement.

(ii) Fractures cutting through both fauna/cement structures and associated intrastructure sediments, and intermound packstones and grainstones, are filled with EBC cement and/or sulphide/sulphate mineralization (Fig. 101).

(iii) Veinlets of iron-poor calcite (recognized by staining) cross-cut sediment, early and late stage cements, and mineralization; sulphates and barite may occur locally within these veinlets.

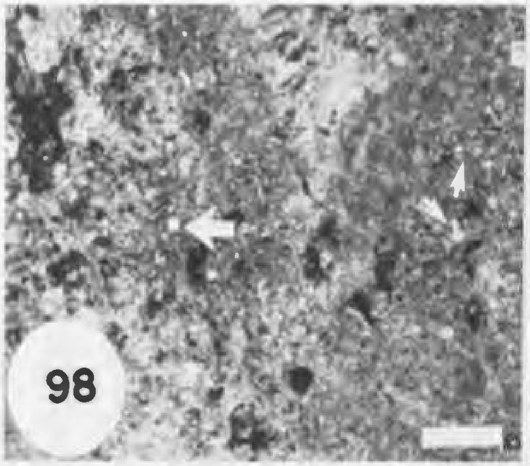
(iv) Four stages of mineralization are recognized: (i) precipitation of anhydrite and/or gypsum in primary vugs and muds; (ii) sulphide and sulphates deposited with

FIGURE 98: Dolomite rhombohedra (arrows) within biomicrite. Only one well formed dolomite rhombohedron is present (large arrow). Photomicrograph with cross-polarized light. Scale bar is 230 micrometres.

FIGURE 99: Massive dolomite replacing both late stage calcite cement and sediment (including allochems)-see arrows. Photomicrograph with cross polarized light. Scale bar is 230 micrometres.

FIGURE 100: Relic chickenwire gypsum. The sulphate is replaced by late stage calcite. Photomicrograph with cross-polarized light. Scale bar is 600 micrometres.

FIGURE 101: Fracturing of biohermal limestone, with the fractures and remaining porosity infilled with late stage calcite cement. Photomicrograph with plain light. Scale bar is 500 micrometres.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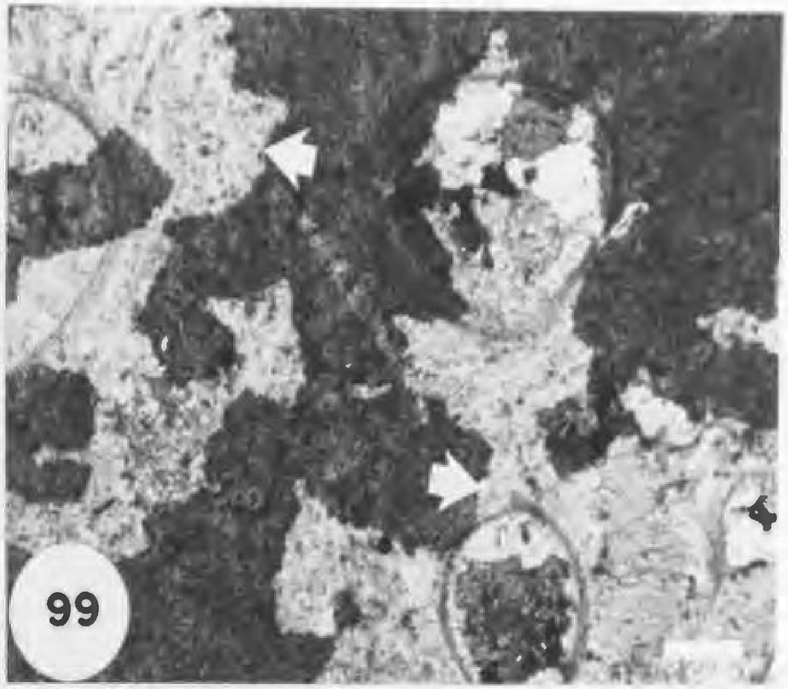
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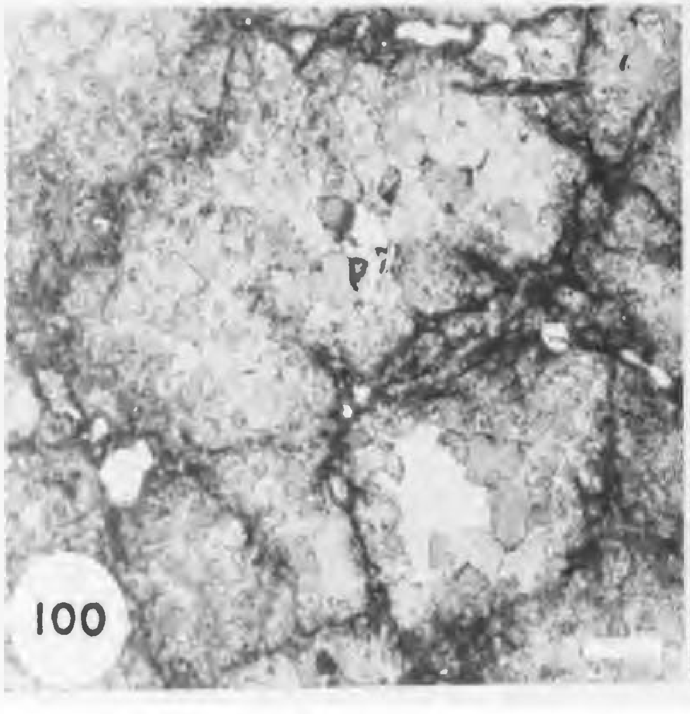
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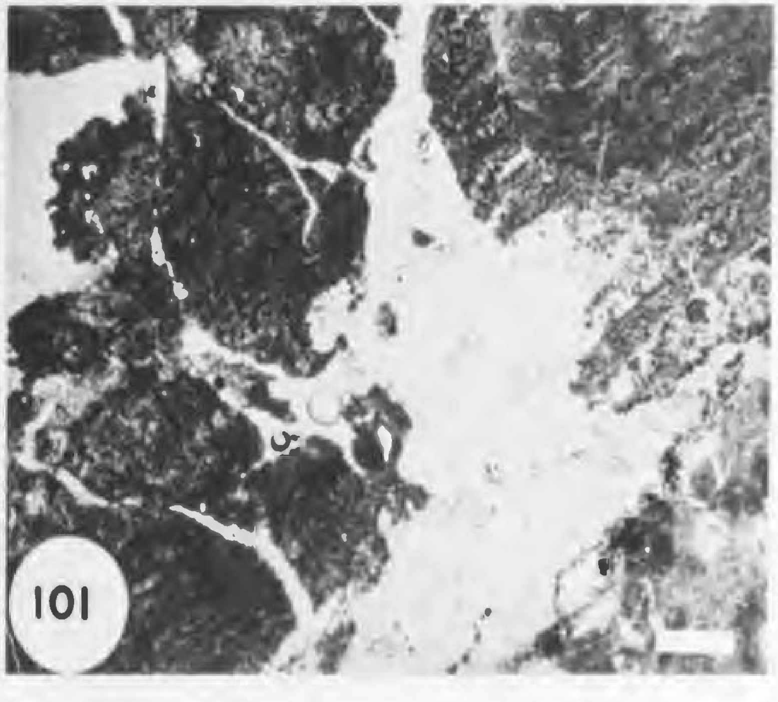
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EBC cement; (iii) barite, celestite and gypsum, with local accumulations of marcasite replacing cemented sediments; and (iv) veinlets with minor and sporadically distributed sulphate mineralization, locally concentrated near faults; associated with faults is pyrite mineralization.

8.10. Discussion

8.10.1. Introduction

The recognition of pervasive synsedimentary cementation in the submarine environment is well documented for both modern and ancient reefs and mounds (e.g., Krebs, 1969; Land and Goreau, 1970; Bricker (ed.), 1971; Ginsburg and James, 1976; James *et al*., 1976; Davies, 1977; Mazullo and Cys, 1979; and James and Ginsburg, 1979). Associated multigeneration sediments and cement is also recorded for both Holocene and Palaeozoic reefs (e.g., James *et al*., 1976; Davies, 1977; and others).

This pervasive cementation and related sedimentation comprises a major part of the carbonate/clastic lithofacies on the Port au Port Peninsula. Complex neomorphic textures, however, commonly overprint this early fabric. Evidence of possible vadose fabrics consist only of fabric-specific dissolution, and are interpreted as occurring in the latest stage of diagenesis and are probably still active at present.

Although microprobe data indicates that all structures interpreted as cements, allochems, and micrite found in the biohermal limestone, are now low magnesium carbonate with less than 1.5 percent magnesium carbonate, their original mineralogic precursor can be deduced by comparison of fabrics with known or previously interpreted examples published in the literature. The following discussion of fabrics will be dealt with according to the different stages of diagenesis (Early, Middle, and Late); a compilation of these stages and their defining parameters is given in Figure 102.

8.10.2. Early Diagenesis

The most abundant cements found in the mound facies and intermound sediments are fascicular-optic calcite, interpreted to be originally a magnesium calcite cement, and spherulitic calcite which is interpreted to be aragonite in origin.

(i) Possible Mg-Calcite Cements - Fascicular-optic calcite recognized in the Port au Port samples is similar to that described by Kendall (1977; pg. 1058, Figs. 1A, B, and E; and pg. 1059, Fig. 2). He stated that the original mineralogy could be either calcite or aragonite, indicating that fabric alone was an insufficient criterion. The cement acts as an inter- and intragranular cement and incorporates and coats marine organisms. Overlying the cement laminae, with abrupt contact, is sediment exhibiting marine organisms as well. Thus, it is interpreted that the cement is of marine origin.

DIAGENETIC SEQUENCE IN THE CARBONATE/CLASTIC LITHOFACIES

```
                                                    LATE
                      EARLY      MIDDLE      1     2     3     4
Parameters
Early cements         xxxxx x x
Sedimentation         xxxxxxxxx
Micritization         xxxxxxxxx
Compaction            xxxxxxxxx
Mineralization:
(a) sulphate             x xxxx             xxxxxxxxxxx x x
(b) sulphide                                xxxxxxxxxxx x x
Neomorphism 1                  xxxxxxxxxxx
Neomorphism 2                               xxxxxx
Fracturing                     x x xxxxxxx
Stylolitization                x x xxxxxxx
Late stage cement                           xxxxxx
Desulfitization                             xxxxxx
Dolomitization                                    xxxxxx
Veinlets                                                xxxxx
Dissolution                    xxxxxx x                      xxxxxxx
                      |--------|----------------------------|------|
                      submarine               phreatic       vadose
```

FIGURE 102: Interpreted diagenetic sequence for the carbonate/clastic lithofacies.

Early neomorphic alteration of the fibrous precursor is similar to the alteration exhibited by the skeletal clasts known to be of calcite mineralogy (e.g., brachiopods, ostracodes, <u>Spirorbis caperatus</u>, and bryozoans). Their fabric, as in the fascicular-optic calcite, is wholly or partially retained.

Laminated crusts of modern magnesium calcite cements (Land and Goreau, 1970; pg. 460, Fig. 5) look very similar to crusts of the FOC cement enveloping bryozoans in the mounds at Big Cove (Fig. 32) and Aguathuna "Island". The presence of micrite laminae, peloids, and/or dispersed micrite within, and separating the thicknesses of the FOC cement suggests episodic to slow sedimentation during growth of the cement. The presence of <u>Spirorbis</u> <u>caperatus</u> encrusting, and engulfed by, the cement suggests that the cement provided a hard substrate for these organisms.

The overall morphology, internal fabric and sediment-cement relationship of this cement is similar to described high Mg-calcite crusts in modern and ancient reefs or mounds. The lack of luminescence associated with this cement supports its interpretation as an early marine cement (Myers, 1974). On the basis of these criteria, the cement is interpreted to be an early diagenetic, possibly high Mg-calcite cement.

(ii) <u>Possible Aragonite Cements</u> - Two cement types SC-A and -B are interpreted to have an aragonitic precursor. SC-A is very similar in gross morphology and crystallinity to cement fans described by Mazullo and Cys (1979). They describe relic ray-crystals oriented radially divergent within the cement fans, with portions of the crystals engulfed by composite (pseudospar) crystals, which are also radially divergent. In other words, the composite crystal cut across the original fabric. Sweeping extinction of each composite crystal is caused by the addition of individual extinctions of the included ray-crystals.

In Port au Port examples, relic fibres are not preserved but defined by inclusions (either dust or fluid) aligned as radially divergent lineations from the base of a fan. Perpendicular to these lineations are other discontinuous laminae which may be breaks in fan growth. The pseudospar that includes portions of the lineations and laminae is similar in morphology to the composite crystals of Mazullo and Cys (1979). The pseudospar exhibits faint sweeping extinction, though distribution of these is sporadic within a fan. The faint extinctions may represent relic and poorly preserved "ray-crystals" within the pseudospar.

Mazullo and Cys (1979) suggest an aragonitic precursor for their fans. In the Port au Port examples the fans have a different style of neomorphism than the fascicular-optic calcite. This is well depicted in one sample where the latter type of cement encrusts SC-A cement (Fig. 82). Isolated fans or botryoidal laminae of aragonite are described in modern strata (e.g., Ginsburg and James, 1976). The fans in the Port au Port example are found in groups of two or three or, commonly isolated, attached to and infilling small cavities. They are never in an isopachous fringing attitude as is the interpreted Mg-calcite cement. Based on the above comparisons, the fans are considered to have had an original aragonite mineralogy.

A related type of calcite, the SC-B cement, is found in vertically to horizontally stacked botryoids in the minor micritic limestone in Aguathuna Creek. This fabric is similar to fabrics described by Davies (1977; pg. 14, Fig. 5A) for aragonite botryoids in intermound sediments associated with Permo-Pennsylvanian reefs in the Canadian Arctic. He shows chemically and petrographically that the botryoids were probably composed of fibrous radially divergent aragonite crystals which may be altered in various stages to equant pseudospar. With the alteration, the strontium content decreases.

As in his example, the Aguathuna Creek limestone has internal sediment of peloids and micrite suggesting continual to sporadic sedimentation during cement growth. Some of the sediment infills depressions between botryoids indicating that the cement surface was a relatively hard substrate. Cathodoluminescence shows the presence of inclusions, not seen in plain light, which are aligned in radially divergent lineations converging at the base of each botryoid. These cement types are also non-luminescent again suggestive of marine deposition (Myers, 1974). The tops of the botryoids, defined by micrite laminae, often show vague chisel-ends to fibrous fabrics not unlike textures interpreted as evidence for aragonite by Loucks and Folk (1976). Thus, this type of cement is also interpreted to be an early diagenetic aragonite cement.

In the mound facies, pseudospar similar to SC-type calcite occurs in irregular isolated to stacked "bodies", defined by bounding micrite laminae. This micrite laminae is similar to the laminae associated with aragonite cements described above. Most laminae can be traced between structures or are built up from some base. Small botryoids, 60 to 100 micrometres long, some with chisel to feathery edges, may be associated with these buildups enhancing the interpretation that these irregular bodies are aragonite cement as well. Davies (1977) suggested that the micrite laminae within his samples may be of an organic origin. No evidence of organics (algae, etc.) associated with the micrite in the laminae in the Port au Port examples was noted. It is suggested that the laminae represent breaks between cement growth, where vertically stacked botryoids or irregular cement bodies are formed, or a form of sutured boundary where growing edges of fans converge.

(iii) Other Early Diagenetic Features - One stage of mineralization is interpreted to have taken place early in the diagenetic history of these rocks: sulphate precipitation. Prismatic anhydrite occurs in well developed crystal splays infilling vugs, and lenticular gypsum is found formed in micritic muds. Both examples are calcitized by late stage phreatic fluids. Lenticular gypsum is found in modern environments, in unconsolidated muds down to depths of several metres in the sub-surface (Cody, 1979). This form of gypsum indicates both organic-rich muds, and alkaline fluids within the groundwater system (Cody, 1979).

The micritization of unknown particles, and some gastropods, took place within the marine environment during deposition of sediment. Compaction of allochems, producing broken fragments, occurred in the early stage of diagenesis both prior to, and after, cementation by Mg-calcite and aragonite.

The time of neomorphism of the original mineralogy and fabric in speleothem deposits is unclear in the Port au Port region. Dolomitization of some of the laminae within cave deposits can occur early due to changing Mg/Ca ratios in the cave waters (Thrailkill, 1967, 1971). Though Mg-rich calcite or dolomite may precipitate as a primary deposit in caves (Thrailkill, 1971), the crystal textures in the Port au Port samples suggest calcite (possibly high Mg-calcite), with dolomite forming as a secondary replacement. The bright luminescent quality of most of the speleothem deposits indicates that they were deposited under phreatic conditions (Myers, 1974).

Replacement of micrite by dolomite rhombohedra is considered to occur in the early stages of diagenesis. In the zebra rock, dolomite rhombohedra are found in a fragment of the host biomicrite surrounded by interpreted high magnesium calcite cement (Fig. 98). The cement infills horizontal cavities developed in the biomicrite. The cement also acts as intergranular cement in the biomicrite sandwiched between the palaeocavities. Thus, a possible syn-sedimentary to pre-cementation replacement of micrite by dolomite is considered. Packstones in Big Cove have fragmented rhombohedra. These are similar in texture to the rhombohedra in the zebra rock, though not necessarily derived from this source. This suggests erosion and redeposition within the Upper Mississippian marine environment.

8.10.3. Middle Stage Diagenesis

Dissolution of elements such as gastropods, some pelecypods, and unknowns producing micrite rims, took place as solutions passed through dissolving unstable aragonite. As no vadose textures are preserved (e.g., vadose cements), it is suggested that most dissolution took place under meteoric phreatic conditions. An important middle stage feature is the evidence of widespread fracturing of fauna/cement structures and inter- and intramound sediment. This fracturing is found both in outcrop localities which have obvious late faulting, as well as in outcrops where no faulting is evident. The competent nature of the intramound micrite suggests early lithification despite lack of visible Mg-calcite or aragonite cements. This suggests lithification of micrite prior to fracturing. Fracturing occurs prior to precipitation of late stage cement (EBC-type) but after all early cements. No fractures are lined with these latter cements. Therefore, the fracturing occurred prior to the phreatic environment.

Stylolites are associated with fracturing in the mounds, and may exhibit up to 20 millimetres relief. They preferentially affect the fauna/cement structures, and are not seen to cut late stage cement or fractures. Therefore, they developed as fracturing induced pressure in the well-lithified strata. The cause of the fracturing, and associated stylolites, is unclear. Buxton and Sibley (1981) note that well developed stylolites occur in lithified sediments with only 1500 metres of depth of burial. In the Port au Port example, as prograding fluvial and red-bed sedimentation built up the overlying thickness of sediments, fracturing may have been induced within the carbonates, which were already well lithified due to the early cementation.

The time of alteration of the early aragonite and Mg-calcite cements is interpreted to be middle stage as well. This is Neomorphism 1, referred to above. The lack of luminescence associated with the spar in the aragonite cements suggests that the cement was completely altered to low Mg-calcite by the time late stage phreatic fluids were moving. No solution moldic-reprecipitation alteration of the aragonite cement occurs. Initial alteration of the interpreted high Mg-calcite cements occurred prior to late stage diagenesis as well. However, during Neomorphism 2 (movement of phreatic fluids), the edges of the FOC fans (previously, the Mg-calcite cements) were neomorphosed to coarse pseudospar. Well developed FOC fans are most susceptible suggesting a possible crystallographic control for this second alteration event.

8.10.4. Late Stage Diagenesis

This stage of diagenesis can be divided into four parts: (i) cementation, mineralization, and Neomorphism 2; (ii) replacement of cemented sediment by dolomite, barite/celestite, and minor marcasite; (iii) ferroan calcite veinlets and minor mineralization associated with faulting; and (iv) dissolution forming moldic porosity.

(i) Equant blocky calcite infills any remaining pore spaces and fractures in all clastic and carbonate sediments in all three lithofacies on the Port au Port Peninsula. Luminescent studies show that the cements luminesce brightly, reflecting the amount of manganese and iron within the calcite lattice. In order for the calcite lattice to incorporate the cations, a reducing environment (e.g., phreatic fluids) is needed. At least four stages of cement precipitation within a given pore may be recognized. A detailed study of the cement stratigraphy in the different lithofacies was not attempted. The irregular nature in the alteration of iron contents within this cement between the Upper Sequence and Lower Sequence of the carbonate/clastic lithofacies suggests different stages of cement deposition. Mineralization of marcasite, minor pyrite, galena and sphalerite, as well as barite and rare gypsum is associated with the cement.

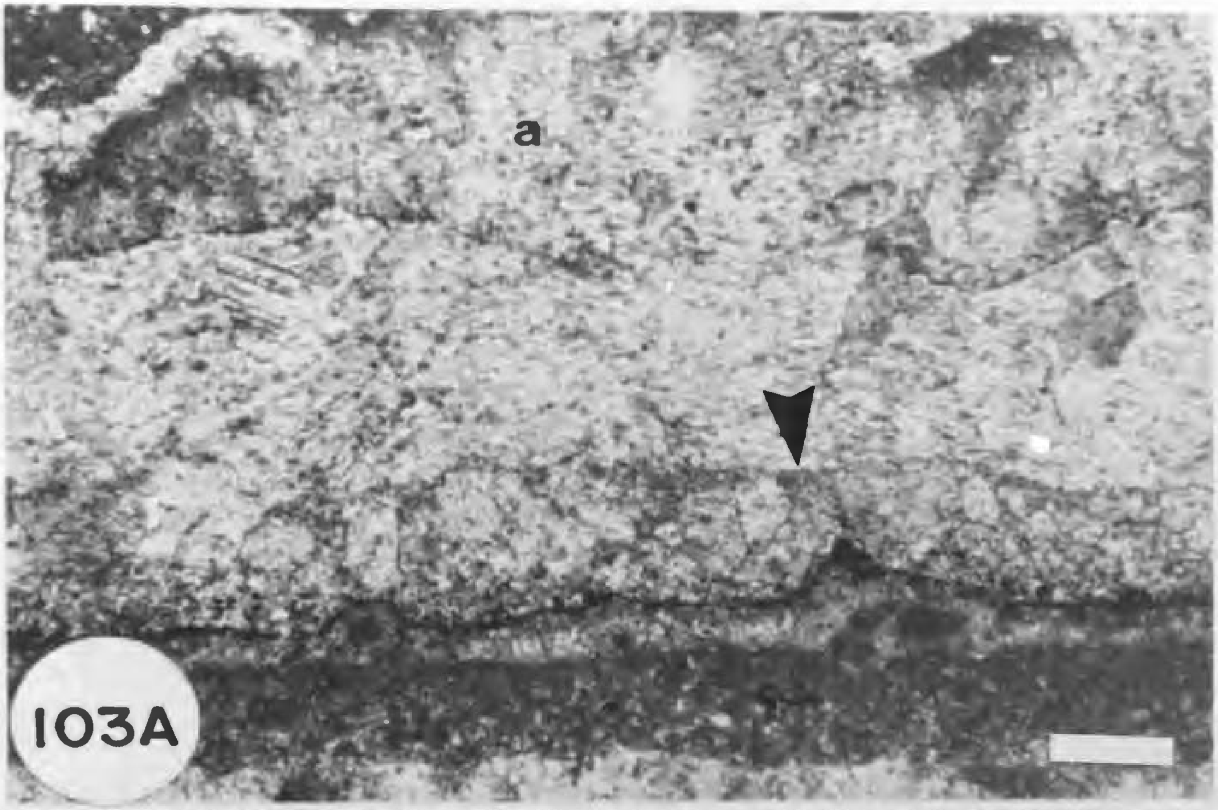
Desulfitization, and calcitization, of anhydrite and gypsum occurred during this stage. Calcite replacing the anhydrite in pores may extend laterally without break into EBC-type cement, which infills the remainder of the pore. Small blebs of iron sulphide, probably marcasite, are associated with the altered lenticular gypsum suggesting alteration by EBC mineralized fluids. Phreatic fluids can replace sulphate without a solution phase (West, 1964).

In the zebra rock of Big Cove Creek, partial alteration of the possible magnesium calcite cement to the coarse pseudospar occurred at this time as well. It is suggested that fluids migrated along fractures developed at the contacts between downward-directed coarse fans of FOC cement (that are interpreted to infill horizontal cavities within a biomicrite host) and the underlying mixture of this cement and sediment (peloids and micrite) in which rare fan development occurs (Fig. 103A,B). The fluids altered both edges of the crack, but appear to alter much more of the fan cement (due to a more ordered morphology of the cement?). Neomorphism of the underlying peloid/micrite/cement mixture produces microspar to fine-grained pseudospar with the included sediment. The density of the included sediment remains fairly constant if adjacent neomorphic and original fabrics are compared. Moving fluids may also have contributed to the sediment content.

The geopetal microspar which overlies graded sediment in mound pores and cavities is considered to be produced by neomorphism by phreatic fluids moving through the vugs. Commonly, the top layers of the multigenerated sediment may also be neomorphosed.

FIGURE 103A: Zebra rock. Alteration of fascicular-optic calcite cement to coarse pseudospar (a). Arrow points to contact of coarse pseudospar (possible replaced cement) and peloid/pseudospar (early geopetal sediment during growth of the marine fans?). Photomicrograph in plain light. Scale bar is 450 micrometres.

FIGURE 103B: Same view as in FIGURE 103A, but cross-polarized light. To the right of (a) and above (b), sweeping extinction extends into the pseudospar. Near (a), the extinction extends down to the contact indicated in FIGURE 103A. It is suggested that fractures developed along this junction between the cement splays and the possible geopetal sediment allowing late stage phreatic fluids to penetrate the rock. The fluids would then alter the early cement sporadically. Photomicrograph. Scale bar is 450 micrometres.



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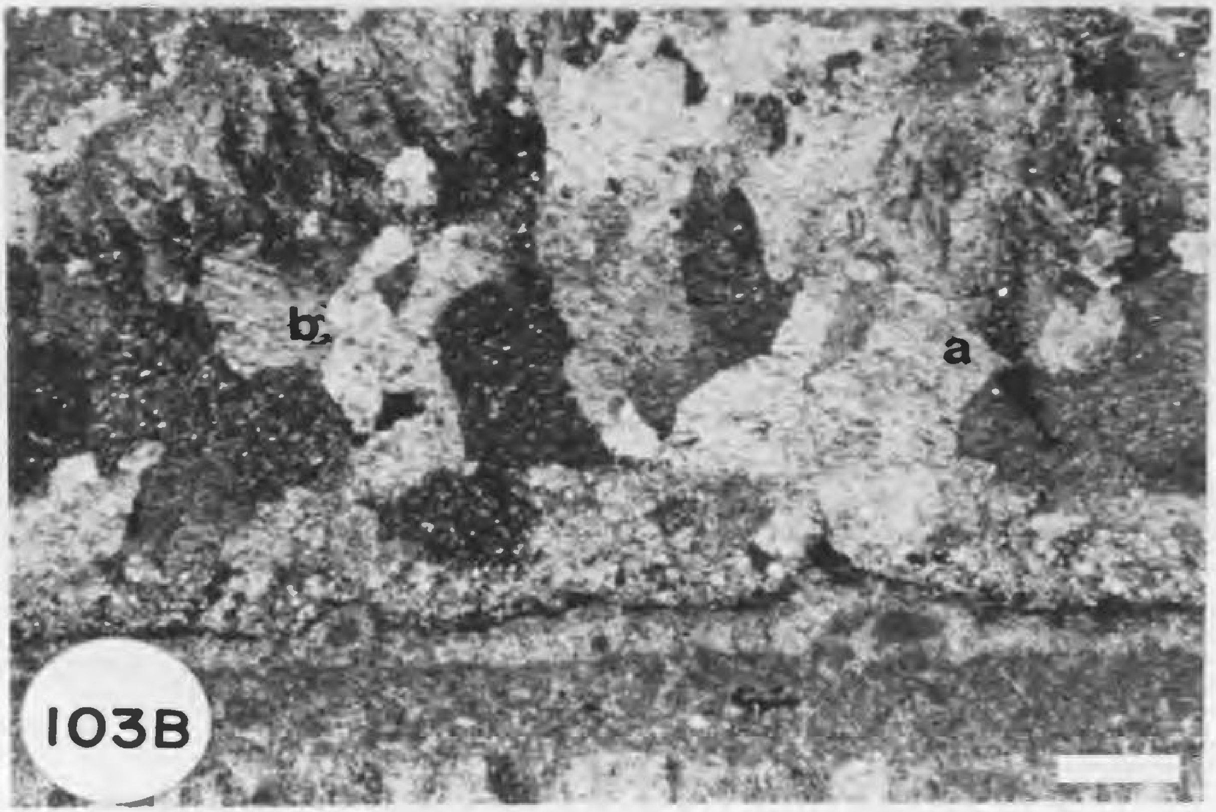

103B

(ii) After the late stage cement has produced a well-cemented rock, replacement of cement and allochems by dolomite, barite/celestite, and locally marcasite and/or pyrite may occur (e.g., Aguathuna "Island", Gillam's Cove). The presence of magnesium and the $SO_4^=$ radical within replacing fluids suggests that the evaporites are acting as source region for the fluids.

(iii) The third part of the late stage diagenesis occurred after late cementation, but its relation with (ii) is unclear. Ferroan calcite veinlets cross-cut strata, mineralization, and late stage cement. Poorly developed barite may be included in the veinlets. This may be reactivated barite, as most of the veinlets are unmineralized. Within the fault zones, minor pyrite occurs.

(iv) The last stage of diagenesis is taking place today. Preferential dissolution, sporadic in distribution, of certain peloids, micritic laminae associated with algal structures, and gypsum, leaves strata extremely porous and rubbly. This dissolution is due to modern karstification of the Upper Mississippian strata, though this is primarily confined to the soil/rock interface. It is evident that the karst effects decrease with depth. The gypsum is unstable in the present vadose environment as evident from the karst topography in the gypsum cliffs at Romaines Brook. A curious problem associated with the dissolution process is, why is it confined in the carbonates to the micritic structures, and what is the cause of the green colouration associated with affected micrite?

8.11. Summary

The diagenetic sequence discussed above is shown diagrammatically in Figure 102. Not all features can be found at any one cove, or, in any one hand specimen. In summary, the diagenesis of the carbonate/clastic lithofacies involved a progression from marine cementation and sedimentation, to fracturing (by the overburden of terrestrial sediments?) and postburial cementation and mineralization in the phreatic zone. Intervals of neomorphism continued from middle to late stages, and include the alteration of original aragonite, and Mg-calcite cements, to composite crystal and fascicular-optic calcite, respectively, during the Middle Stage.

Alteration of fascicular-optic calcite to pseudospar, which mimics late stage calcite cement, and alteration of micrite to local patches of microspar and pseudospar occurred during Late Stage diagenesis. The ferroan calcite veinlets interpreted to be associated with faulting that deform some of the Upper Mississippian sediments, imposes a control on the conclusion of late stage cementation. The veinlets cross-cut late stage mineralization and cement. This cement is interpreted to have lithified both the Upper and Lower Sequence of the carbonate/clastic lithofacies and probably the overlying red-beds. Therefore, all diagenesis, except for late dissolution and minor mineralization, has occurred prior to faulting. Unfortunately, this does not impose a control on the age of the faulting or the length of the Upper Sequence sedimentation.

The alteration of the original speleothem textures to their presently preserved textures would have taken place in a similar diagenetic environment as was present for the initial neomorphism of the marine cements (Neomorphism 1). The interpreted age for the speleothems is pre-Alleghenian; whether they were contemporaneous with, or formed before, the Upper Mississippian sediments is unknown.

CHAPTER 9

CONCLUSIONS

In Mississippian time, the Port au Port Peninsula was an uplifted ridge of early Palaeozoic carbonate strata which were first karsted and then gradually buried by coeval deposition of carbonates, evaporites, and terrigenous clastics which prograded out over adjacent marine basins. Post-Mississippian erosion has removed most of this cover and exhumed the karsted early Palaeozoic core with small preserved remnants of the once extensive Upper Mississippian cover fringing the ridge.

Two styles of karstification are preserved on the Ordovician carbonates. The first, a surface-solution phenomenon, formed on Table Point Formation carbonates, and a similar limestone lithology in the St. George Group, exhibits karst features which are predominantly solution grooves ranging from small (rillenkarran) to large (karst valleys). The second style, controlled by subsurface drainage, formed within the alternating dolomites and limestones of the St. George Group. Caves, and interpreted collapsed caves (now valleys), form the present day landscape. Speleothems of Early to Late Mississippian age are rare, but where present include drusy-calcite fissure fillings and cave precipitates. Modern karst affects the Upper Mississippian sediments producing moldic porosity and appears to have locally rejuvenated the Early Mississippian karst landscape.

Upper Mississippian sediments (Codroy Group), preferentially preserved in karst depressions and low lying areas of the peninsula, are subdivided into three lithofacies:

(1) terrigenous clastic facies (red sandstone, conglomerate, and breccia) deposited in an alluvial fan - braided stream environment and overlies both Table Point Formation, St. George Group (both Ordovician in age) and earlier Mississippian strata;

(2) sulphate/clastic facies (conglomerates, laminated micritic limestone, laminated sandy gypsum, and sandstone) deposited initially in a nearshore, shallow water hypersaline environment which later became brackish to fresh (sandstone), and overlies Humber Arm Supergroup (Ordovician) and thins onto Table Point Formation;

(3) carbonate/clastic facies (Lower Sequence: biohermal and biostromal limestone, and interbedded sandstone; Upper Sequence: sandstone conglomerate, breccia and minor micritic limestone) deposited initially in a near-shore marine environment fluctuating from hypersaline to brackish water conditions, followed by dominantly brackish to fresh water conditions (clastics), and overlies Table Point Formation and St. George Group.

Upper Mississippian seas along the northern and western margins of the Port au Port ridge supported an abundant community dominated by brachiopods, blue-green algae, bryozoans, pelecypods, ostracodes, and gastropods. Notably absent are crinoids/echinoids and true corals (only conularids occur); reduced to a few species and/or individuals are forams, conodonts and cephalopods. Detailed sampling of the macrofauna indicates that they are facies-controlled within the carbonate/clastic lithofacies. Fauna assigned to Upper Codroy strata by Hayes and Johnson (1938) and Bell (1948) occur below and/or are equivalent to Lower Codroy fauna. Few macrofauna occur in the sulphate/clastic lithofacies, and none occur in the terrigenous clastic lithofacies. Plants grew on the slopes of the exposed Port au Port ridge, as interbedded sandstones in both sulphate and carbonate/clastic lithofacies contain a well preserved spore assemblage. Plant debris is also associated with the sandstones but poorly preserved.

The Lower Sequence carbonates are composed of bryozoan/algal mounds. Intermound sediments include fossiliferous carbonate, black shaley limestone, and/or calcareous sandstone. The mounds are either isolated or are vertically and horizontally stacked to form bioherm complexes. Molluscs and ostracodes are predominate within the intermound sediments, whereas bryozoans, algae, brachiopods and worms are prevalent within the mounds. Most mounds have a well preserved bryozoan baffle which consists of individuals coated and joined together by synsedimentary marine cement. Multigenerations of graded sediment infilled the pores and cavities in this structure. Locally, restriction of pore waters within the mound allowed salinities to be raised to sufficient levels for precipitation of anhydrite/gypsum.

The diagenetic history of the carbonate/clastic lithofacies includes: (1) the precipitation of probable aragonite and magnesium calcite cements, in a marginal marine environment, followed by; (2) shallow burial by prograding fluvial and terrestrial sediments, resulting in; (3) fracturing and stylolitization of the lithified sediment. Within the remaining primary porosity and fractures, precipitation of (4) late stage phreatic cement, and associated sulphide/sulphate mineralization occurred in the phreatic zone. Sulphate mineralization also took place after this latter event replacing the late stage cement, as well as in early diagenesis during the deposition of the carbonate sediments.

The early isopachous magnesium calcite cements are neomorphosed to fascicular-optic calcite, and then locally altered by late stage phreatic fluids to a blocky equant pseudospar similar in texture to the late stage cement. Evidence of this secondary alteration is the extension of the sweeping extinction of the fascicular-optic calcite, and rare relic fibres (or inclusions) into the coarse pseudospar.

Calcite spar interpreted to once have been aragonite cement is preserved as fans, botryoids, and/or bodies of irregular shape, exhibiting micritic outlines some of which have poorly defined chisel-shaped terminations. These structures are always altered to equant or slightly elongate pseudospar and never form isopachous rims. In both cement types, incorporated sediment and encrusting worm tubes suggest that during sedimentation the cement structures were rigid features.

Late stage calcite cement is composed of coarsely crystalline ferroan to non-ferroan calcite, and is the last cement precipitate in all lithofacies. No consistent pattern in the order of the iron content is distinguishable but non-ferroan calcite is the most common.

Subsequent to the preceding diagenesis, faulting, interpreted as occurring during Alleghenian deformation, formed graben structures within some karst valleys. Minor sulphide mineralization may be associated. These faults are thought to have developed along palaeolineaments initially formed during the Acadian Orogeny.

Three significant observations during this study have important implications for the Atlantic Carboniferous basin: (1) facies-controlled fauna, and abundant "marine" fauna in marginal marine conditions; (2) coeval deposition in markedly different environments in a small region; and (3) the occurrence of mounds in the marine sediments.

(1) Macrofauna, and probably microfauna, are facies-controlled casting doubt upon current biostratigraphic zonations for the Upper Mississippian in Atlantic Canada. It is suggested that miospores,

unaffected by marine conditions, would be more suitable for detailed chronostratigraphic evaluations. The presence of brachiopods and bryozoans in interpreted hypersaline to brackish environments adds to the growing realization that these fauna are not restricted to normal marine conditions.

(2) The lateral equivalence of markedly different Upper Mississippian environments as defined on the Port au Port Peninsula has profound significance in areas elsewhere in the Atlantic Carboniferous basin where outcrop exposure, or control, is poor. Extensive deposits of gypsum, thin associated limestone units, and fluvial to alluvial red-bed sequences are characteristic of the Late Mississippian in Nova Scotia, New Brunswick, and Newfoundland. Using the stratigraphic relationships of the Port au Port Peninsula as an example, the appreciation of complex lateral facies changes would be critical in piecing together the vertical stratigraphic sequence.

(3) The occurrence of carbonate mounds in the Late Mississippian in the Port au Port are~~a is~~ part of a worldwide phenomenon during the Early Carboniferous. Their lithology (with well preserved baffle structure) and sedimentary facies (nearshore, marginal marine), however, is in marked contrast to the Waulsortian-type mounds described in the United States and Europe (dominantly shelf-edge, open marine). It is unknown whether mounds exist in the offshore Mississippian sediments in the Port au Port area; the presence of a rocky karsted shoreline may have provided unique energy and environmental conditions.

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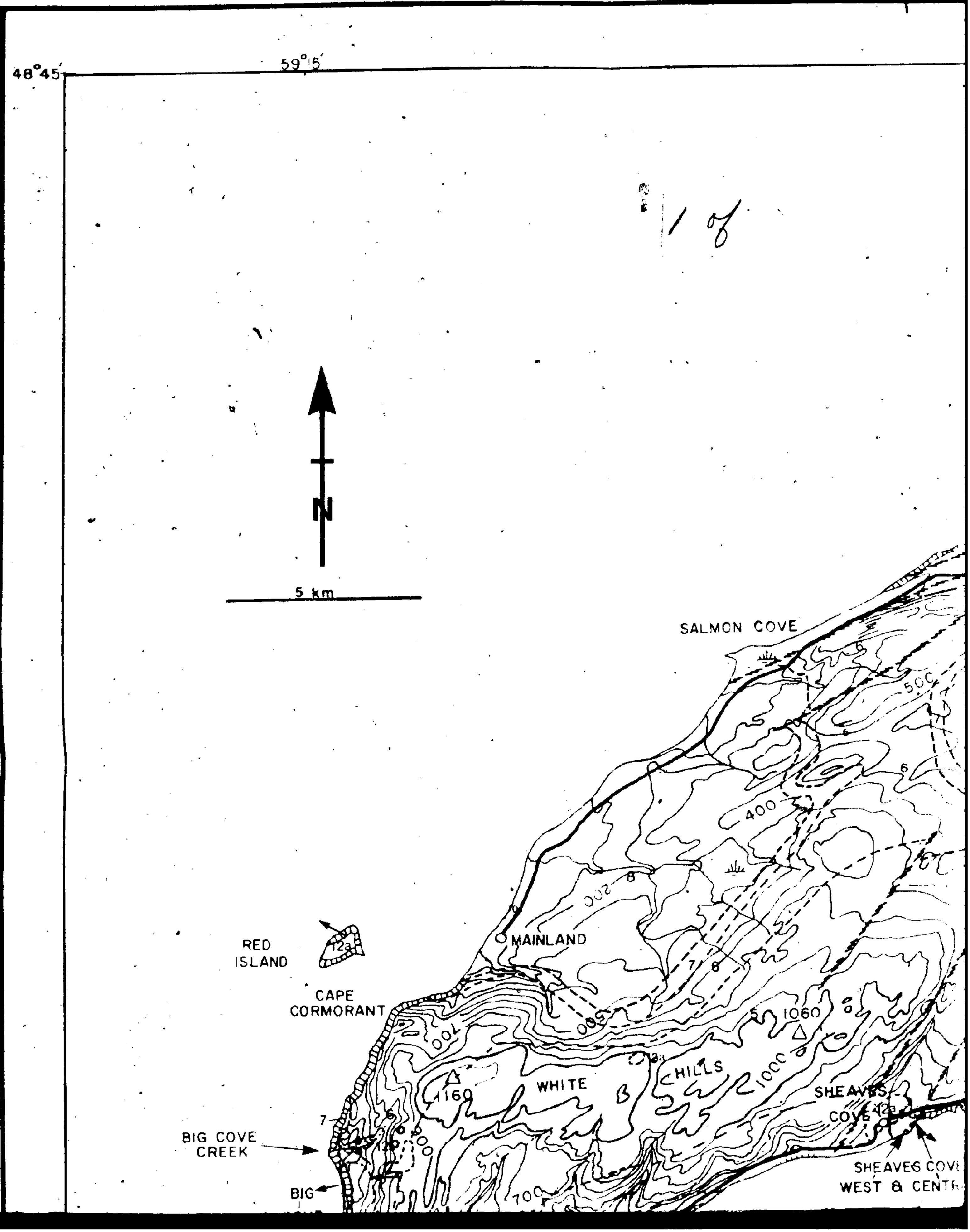

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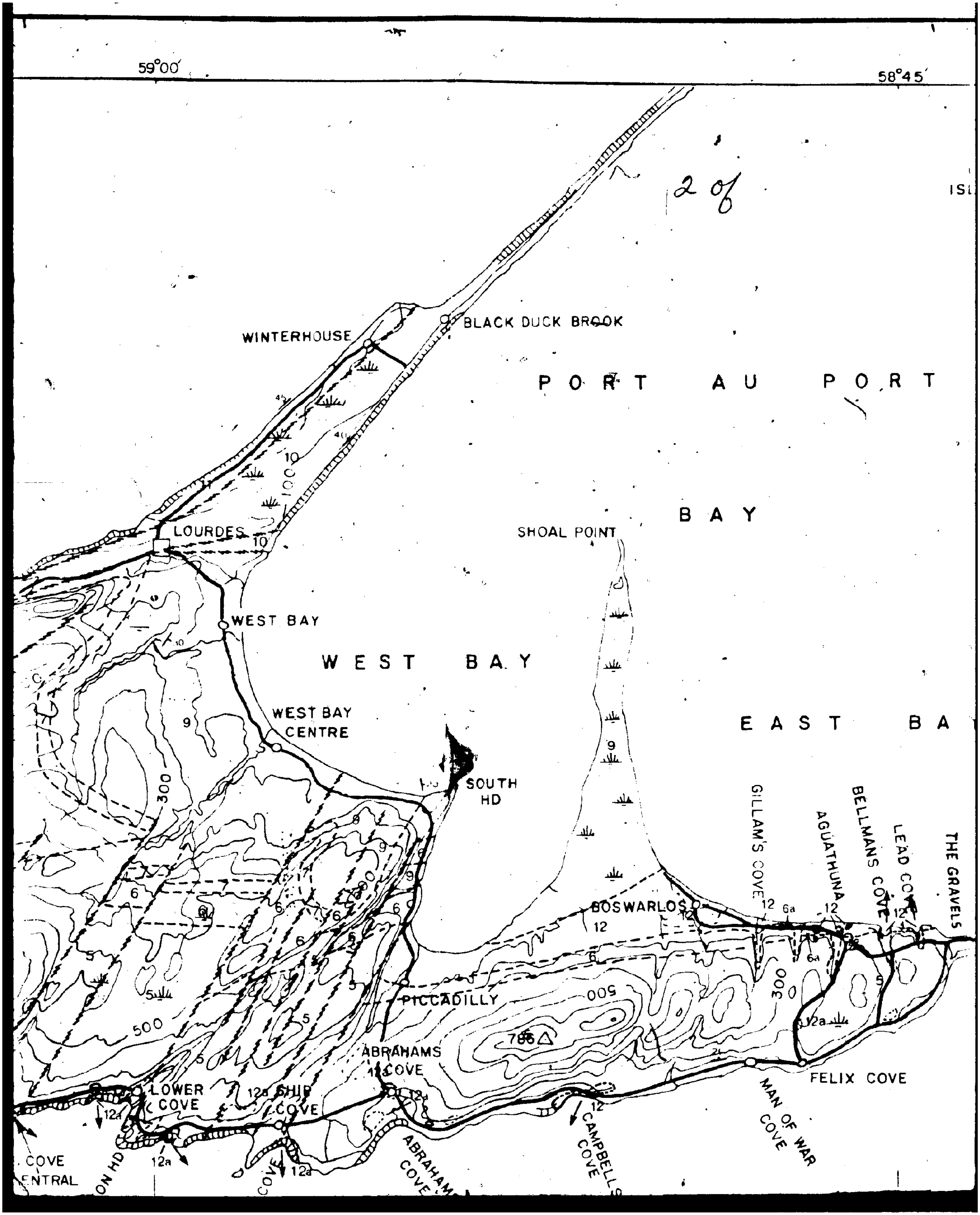
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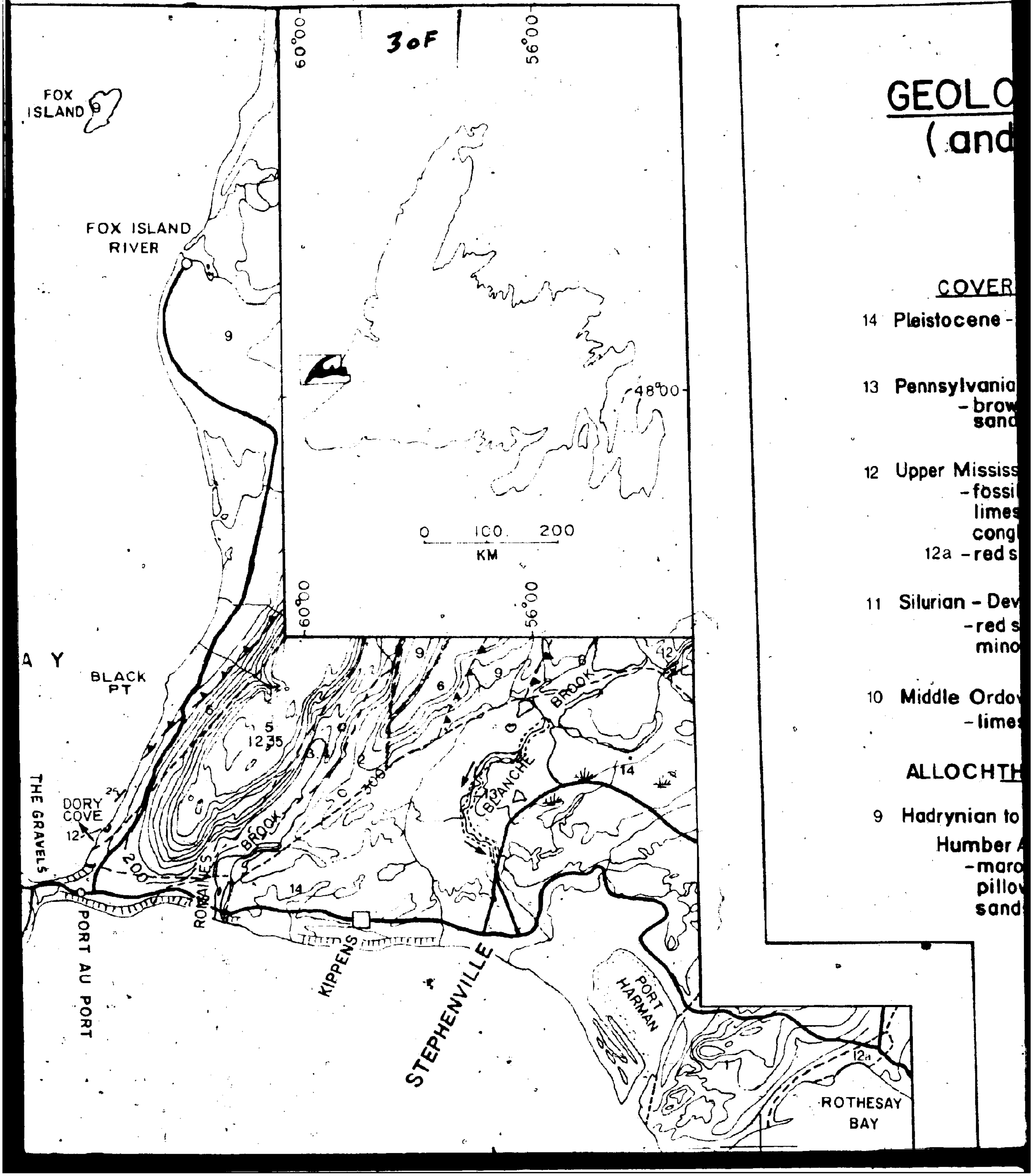

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LOGY OF THE PORT AU PORT PENINSULA
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LEGEND

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and conglomerates

anian- Barachois Group
brown and green fossiliferous
sandstones

ississippian - Codroy Group
fossiliferous sandstones and
limestones, gypsum, and
onglomerates
ed sandstones and conglomerates

- Devonian - Clam Bank Formation
ed sandstones, grey shale, and
inor limestone

rdovician - Long Point Group
imestone, sandstone, and shale

HTHONOUS ROCKS

n to Middle Ordovician -
ber Arm Supergroup
aroon and green shales, basalts,
illow lava, tuff, agglomerate,
andstone, chert, limestone

AUTOCHTHONOUS ROCKS

Middle Ordovician -
8 Mainland sandstone
-green-grey micaceous and quartz
sandstones, shale

Table Head Group
7 Cape Cormorant Formation
-lime megabreccias, terrigenoclastic
and calcareous sandstones,
siltstones and shales

6a Table Cove Formation
-limestones and grey- black
calcareous shales

6 Table Point Formation
grey hackly limestones

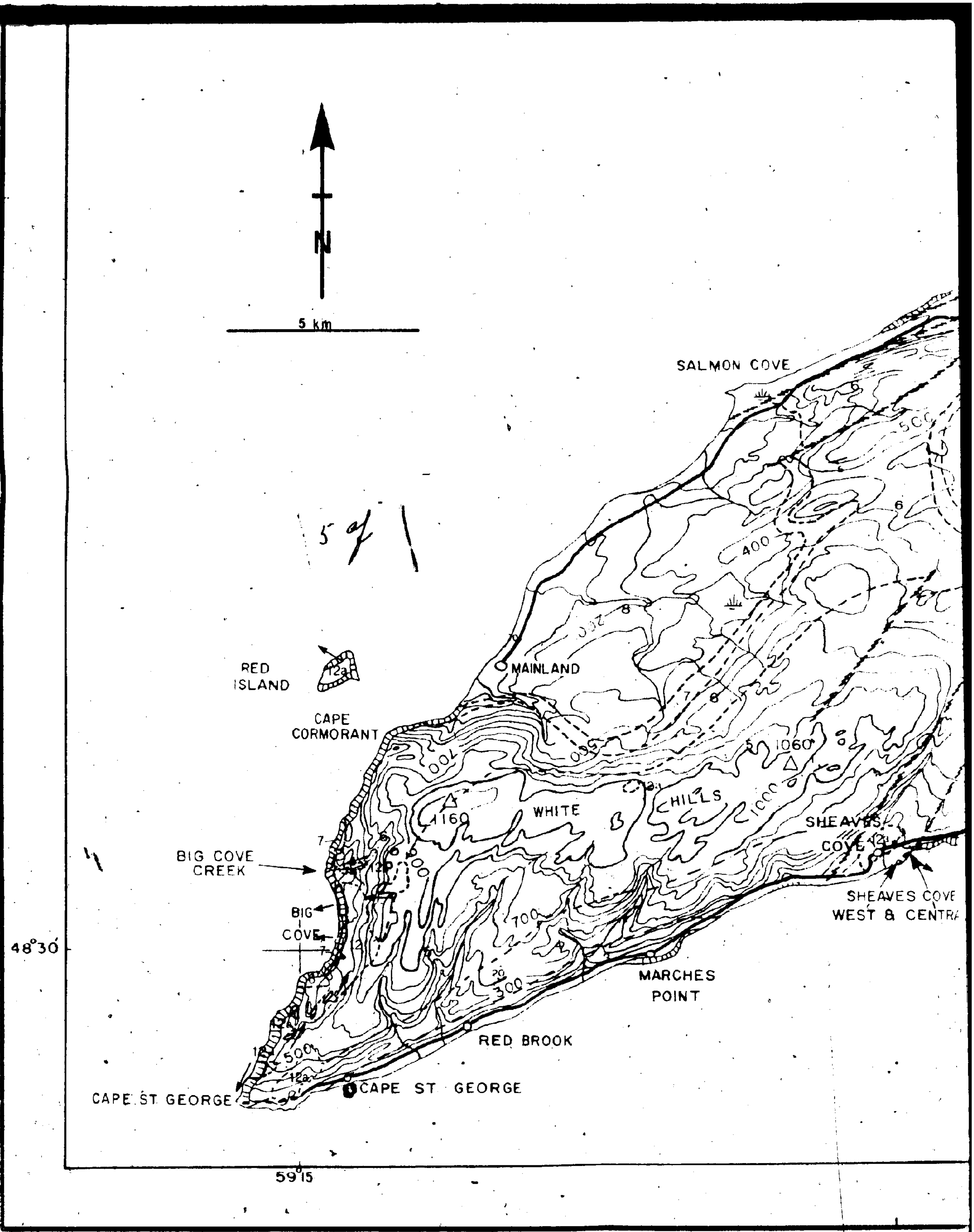
Lower Ordovician
5 St. George Group
-limestone, dolomite, and shale

Cambrian
4 Petit Jardin Formation
-shale, limestone, and dolomite

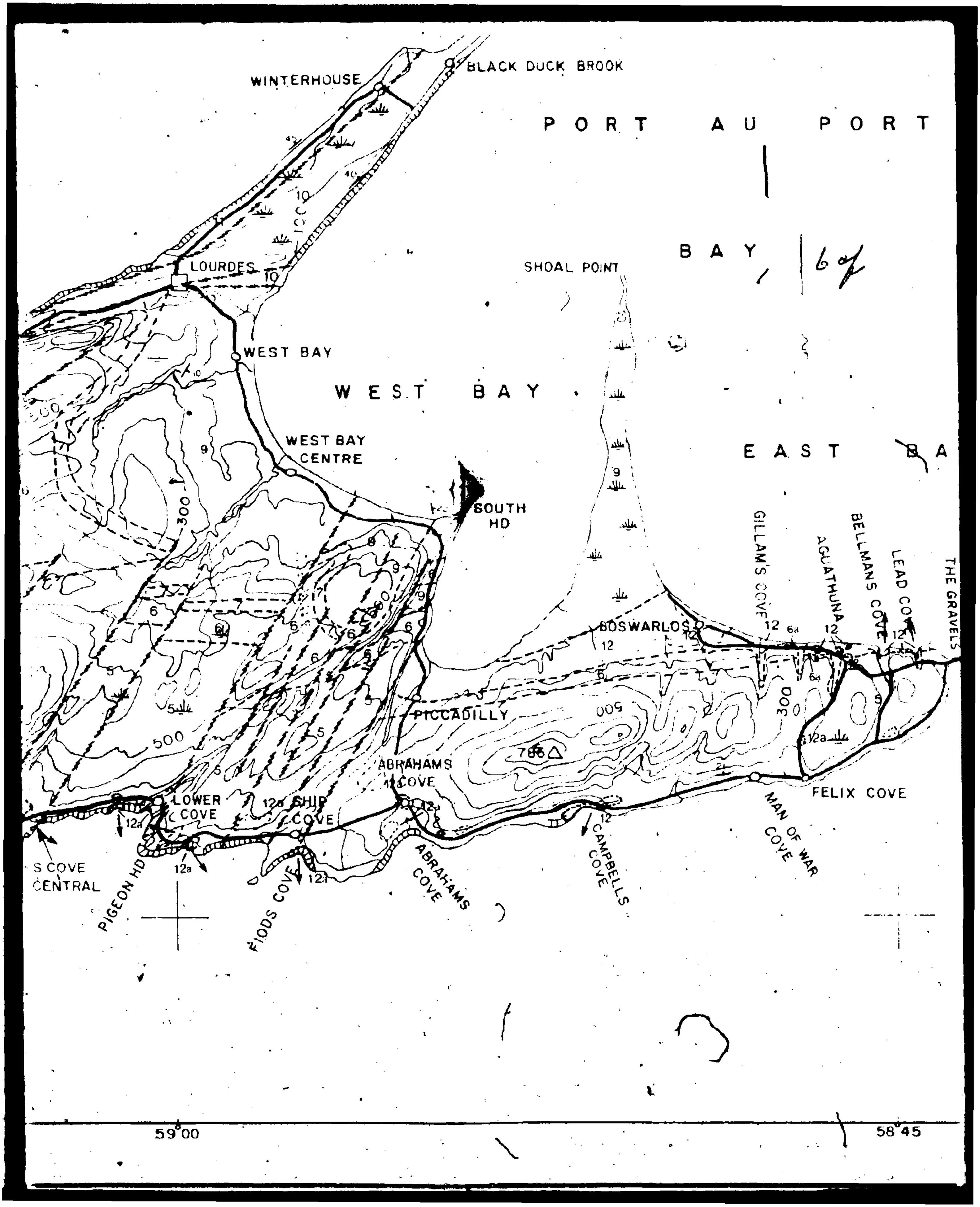
3 March Point Formation
-sandstone, shale, and limestone

2 Kippens Formation
-shale, limestone, and dolomite

Precambrian
1 Indian Head Range Complex
-gneissic granitic and basic intrusives


N
5 km
SALMON COVE
500
6
400
8
200
MAINLAND
RED ISLAND
12a
CAPE CORMORANT
700
500
7
6
5
1060
1000
WHITE
HILLS
1160
SHEAVES COVE
12a
SHEAVES COVE WEST & CENTRA
BIG COVE CREEK
12b
800
7
BIG COVE
700
48°30′
20
300
MARCHES POINT
RED BROOK
500
12a
CAPE ST GEORGE
CAPE ST GEORGE
59°15′

5 of


BLACK DUCK BROOK
WINTERHOUSE
PORT AU PORT
BAY
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SHOAL POINT
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GILLAM'S COVE
AGUATHUNA
BELLMANS COVE
LEAD COVE
THE GRAVELS
BOSWARLOS
PICCADILLY
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785
ABRAHAMS COVE
LOWER COVE
SHIP COVE
FELIX COVE
MAN OF WAR COVE
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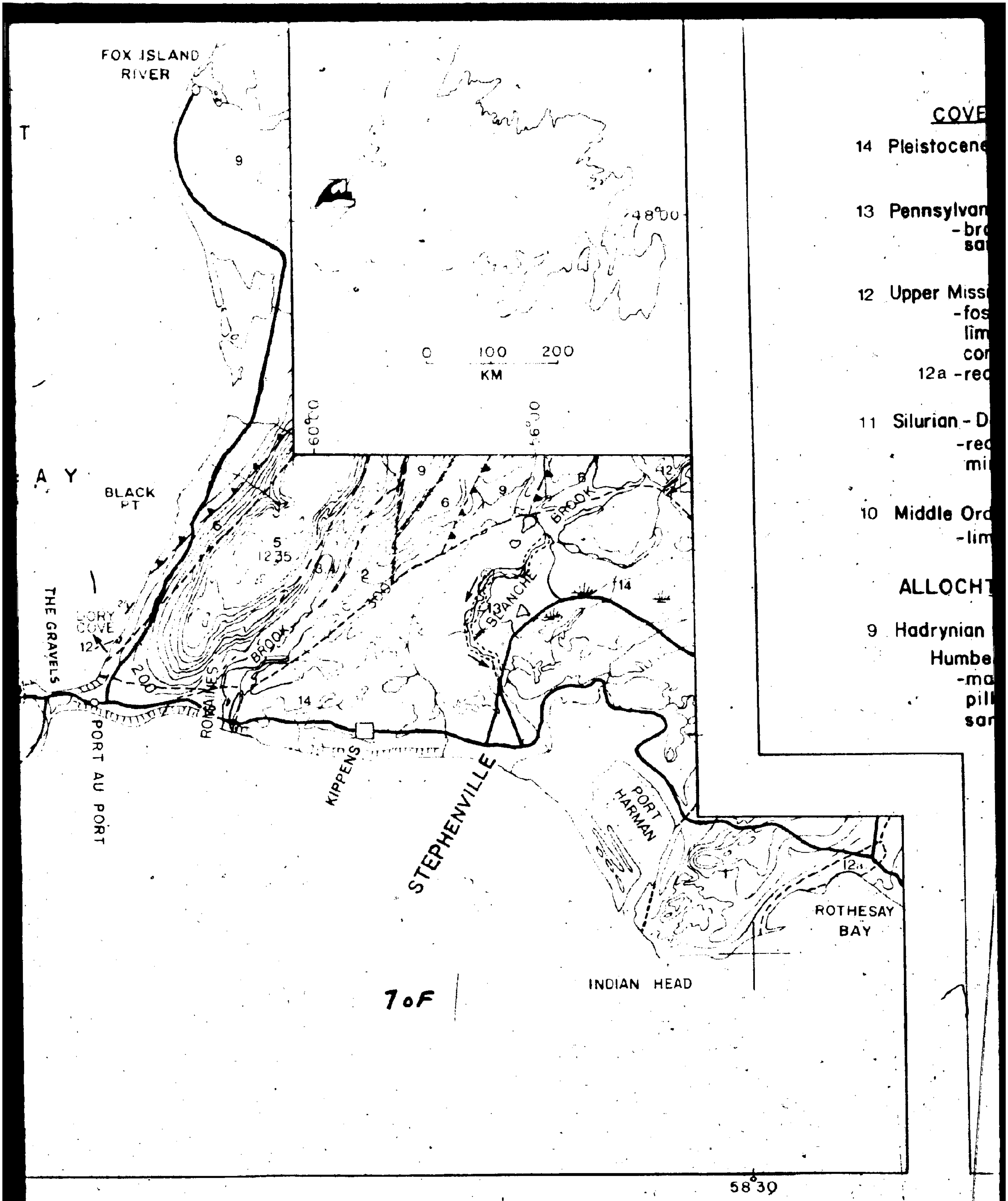
S COVE CENTRAL
59°00
58°45

6 of


FOX ISLAND RIVER
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9
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BROOK
BROOK
SEAL
SEANCHE
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14
THE GRAVELS
LORY COVE
12
200
ROMAINES
PORT AU PORT
14
KIPPENS
STEPHENVILLE
PORT HARMAN
12a
ROTHESAY BAY
INDIAN HEAD
58°30
COVE
14 Pleistocene
13 Pennsylvan
-bro
sa
12 Upper Missi
-fos
lim
con
12a -rec
11 Silurian - D
-rec
mi
10 Middle Ord
-lim
ALLOCHT
9 Hadrynian
Humbe
-ma
pill
sar

7oF

LEGEND

COVER ROCKS

tocene - glacial outwash sands
and conglomerates

sylvanian - Barachois Group
-brown and green fossiliferous sandstones

r Mississippian - Codroy Group
-fossiliferous sandstones and limestones, gypsum, and conglomerates

a -red sandstones and conglomerates

an - Devonian - Clam Bank Formation
-red sandstones, grey shale, and minor limestone

le Ordovician - Long Point Group
-limestone, sandstone, and shale

OCHTHONOUS ROCKS

ynian to Middle Ordovician -
Humber Arm Supergroup
-maroon and green shales, basalts, pillow lava, tuff, agglomerate, sandstone, chert, limestone

8of8

AUTOCHTHONOUS ROCKS

Middle Ordovician -

8 Mainland sandstone
-green-grey micaceous and quartz sandstones, shale

Table Head Group

7 Cape Cormorant Formation
-lime megabreccias, terrigenoclastic and calcareous sandstones, siltstones and shales

6a **Table Cove Formation**
-limestones and grey-black calcareous shales

6 **Table Point Formation**
grey hackly limestones

Lower Ordovician

5 St. George Group
-limestone, dolomite, and shale

Cambrian

4 Petit Jardin Formation
-shale, limestone, and dolomite

3 March Point Formation
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2 Kippens Formation
-shale, limestone, and dolomite

Precambrian

1 Indian Head Range Complex
-gneissic granitic and basic intrusives

SYMBOLS

×, ⌒, ◌ distribution of units: isolated, visible contact, covered contact

▼▼▼▼ thrust fault

- - - high angle fault

——► palaeocurrent direction of the Carboniferous strata

45 ⅄ bedding attitude

COMPILED FROM WILLIAMS (1981), KLAPPA et Al (1980) SCHILLEREFF and WILLIAMS (1979) and this report

GEOLOGY OF NORTHEASTERN PORT AU PORT PENIN

12 CODROY GROUP

TERRIGENOUS CLASTIC LITHOFACIES

a - red sandstones

1 of

CARBONATE/CLASTIC LITHOFACIES

b - Lower Sequence

(biohermal limestones, green sandstones and breccias, an biostromal limestone)

c - Upper Sequence

(green and red sandstones, conglomerates, grey limestone breccias, and minor limestone)

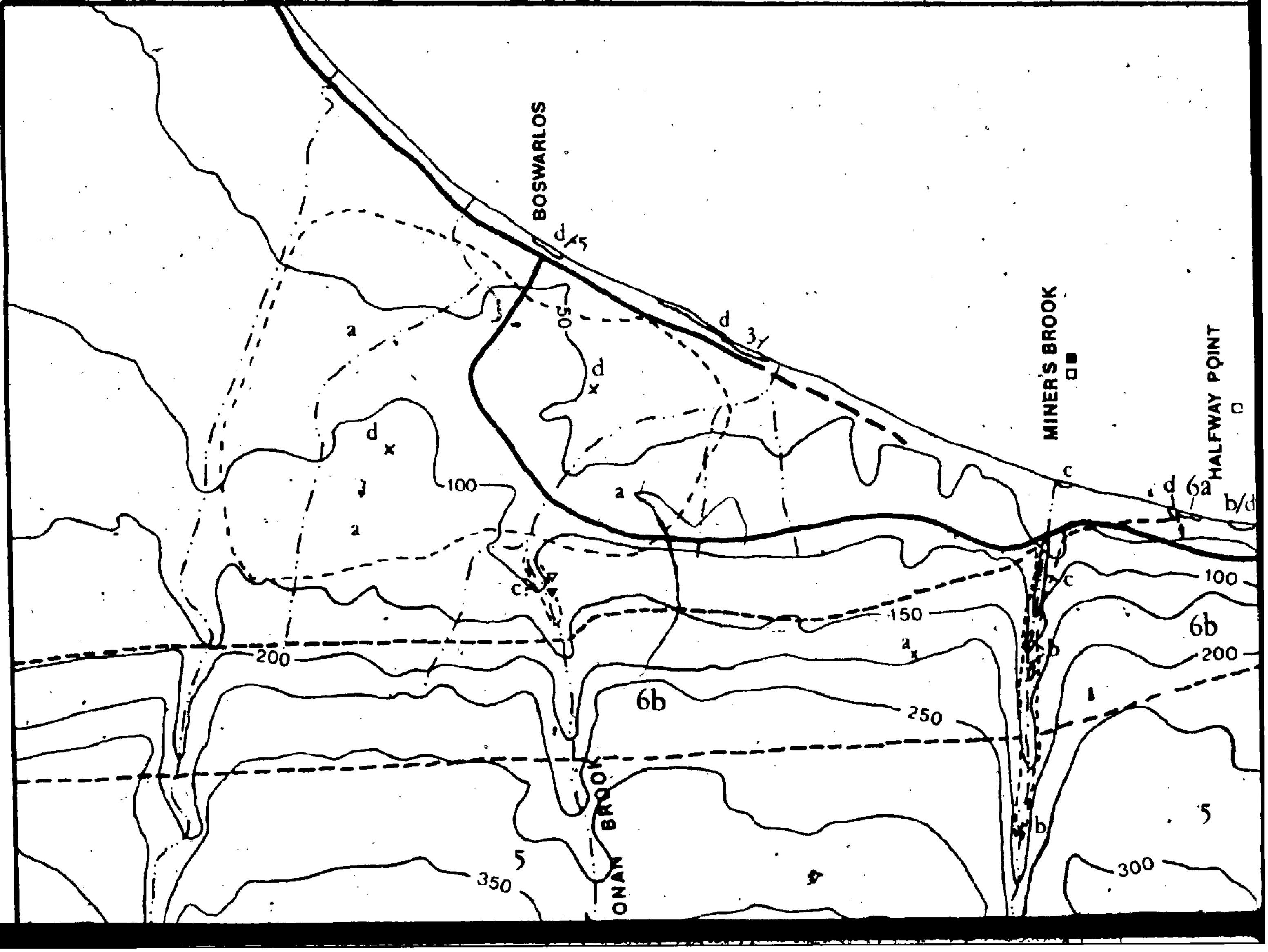
SULPHATE/CL

d - 1

6 TABLE HEAD GROUP

6a - Table Cove Formation; 6b - Table Point Formatio

5 ST. GEORGE GROUP



INSULA

CLASTIC LITHOFACIES

- laminated limestone

2 of 1

SYMBOLS

OUTCROPS

✕ isolated
◌ covered assumed contacts
◯ known exposed contacts

MINERALIZATION

▽ barite
▼ celestite
■ galena
□ marcasite/pyrite
● sphalerite

FAULTS

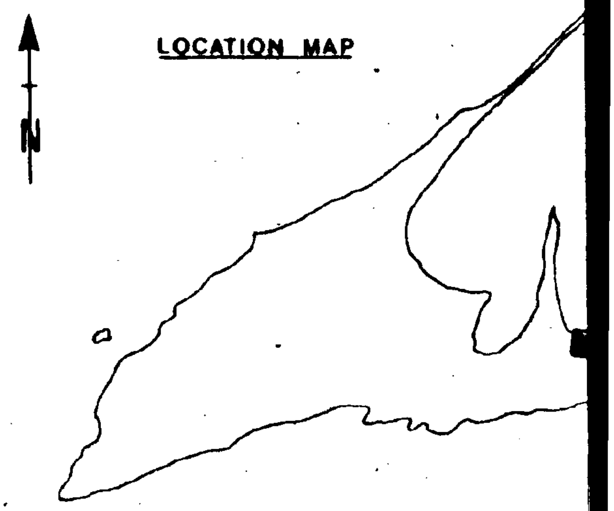
〰 defined

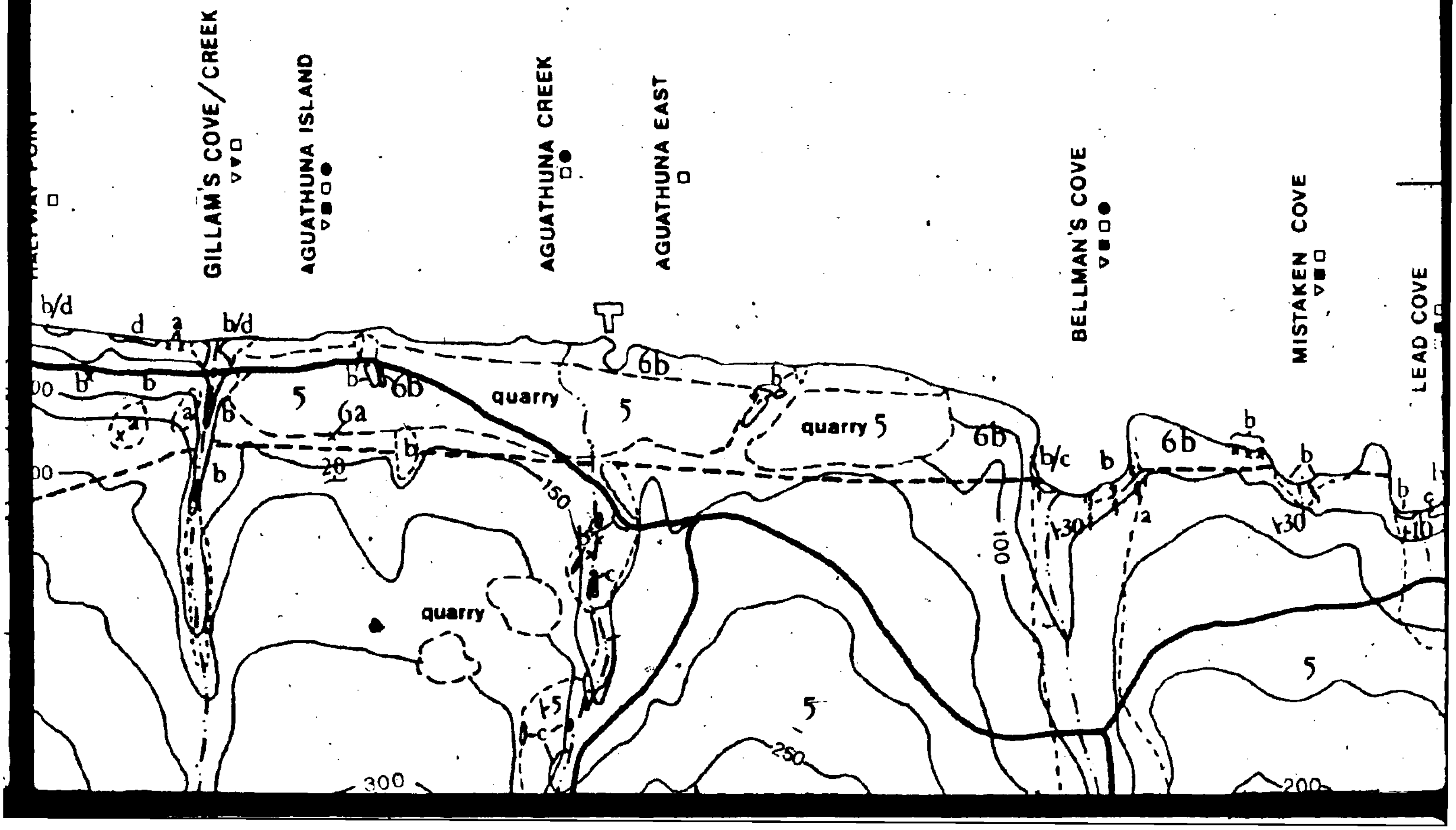
STRATA ATTITUDE

15 strike/dip

OTHER

50 contours (in feet)





SYMBOLS

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ered assumed contact
en exposed contacts

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casite/pyrite
alerite

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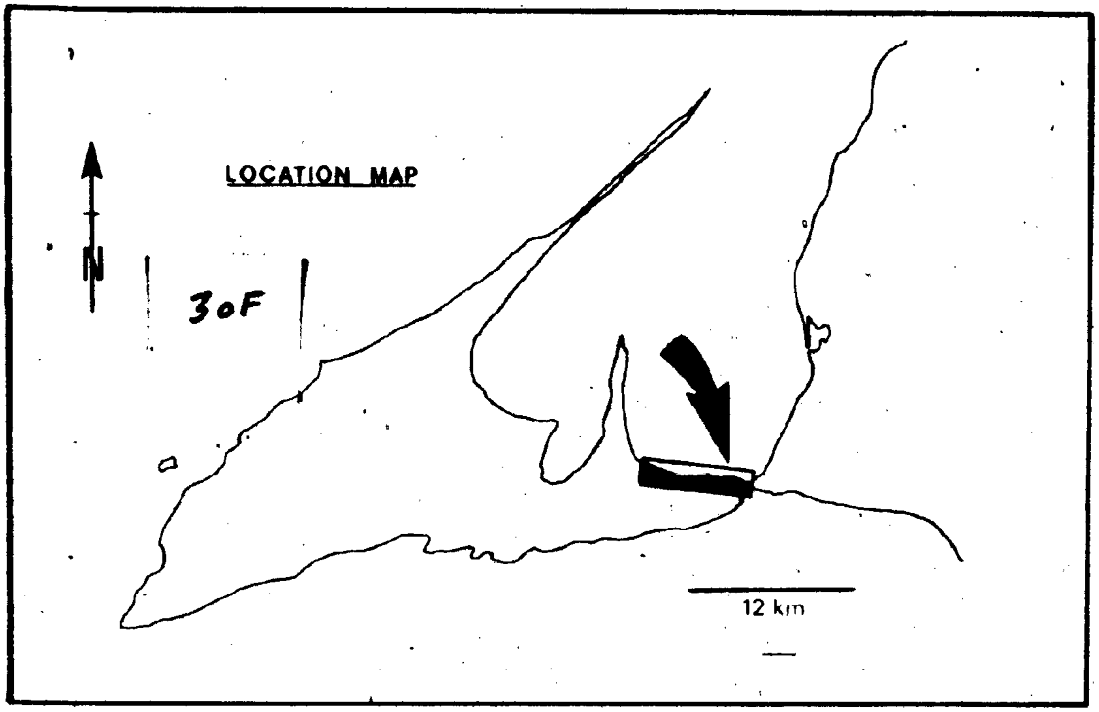
ITUDE
ike/dip

tours (in feet)



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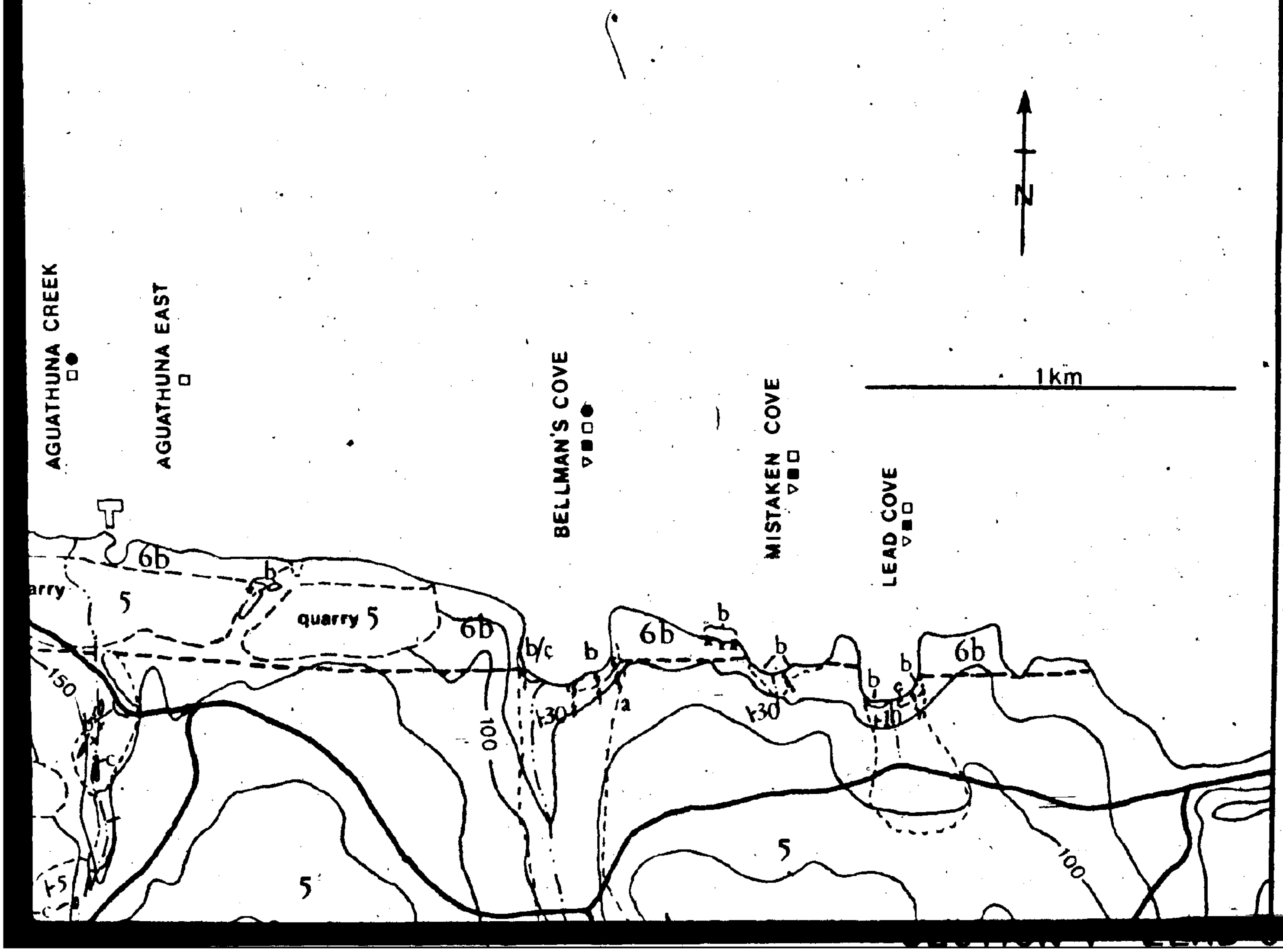

TERRIGENOUS CLASTIC LITHOFACIES

a - red sandstones

CARBONATE/CLASTIC LITHOFACIES

b - Lower Sequence

(biohermal limestones, green sandstones and breccias, an biostromal limestone)

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(green and red sandstones, conglomerates, grey limestone breccias, and minor limestone)

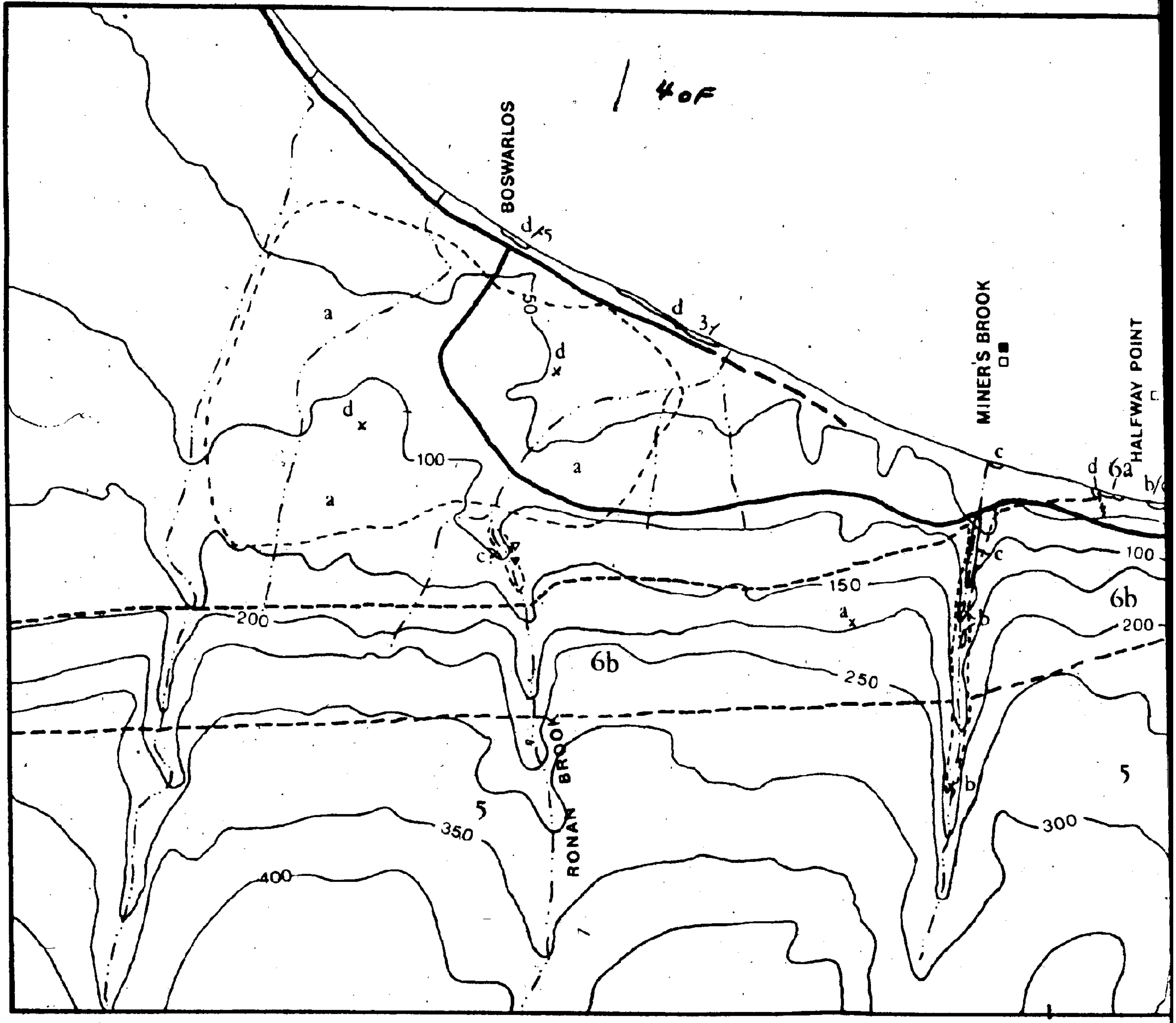
SULPHATE/

d -

6 TABLE HEAD GROUP

6a - Table Cove Formation , 6b - Table Point Formatio

5 ST. GEORGE GROUP



SULPHATE/CLASTIC LITHOFACIES

d - laminated limestone

X isolated
covered assumed contact
known exposed contacts

MINERALIZATION

▽ barite
▼ celestite
■ galena
□ marcasite/pyrite
● sphalerite

FAULTS

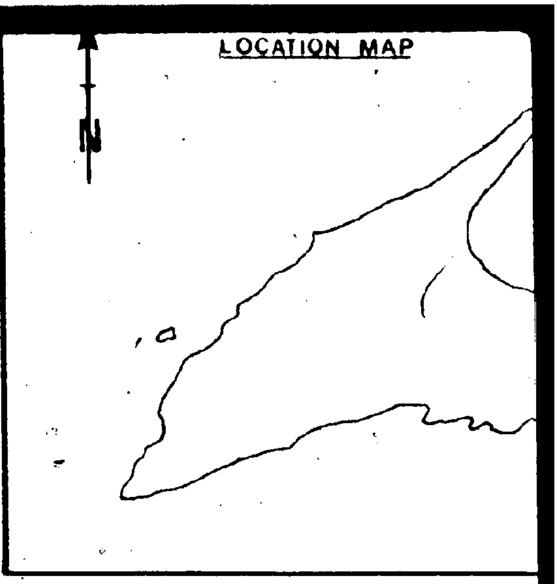
~~ defined

STRATA ATTITUDE

/15 strike/dip

OTHER

~50~ contours (in feet)



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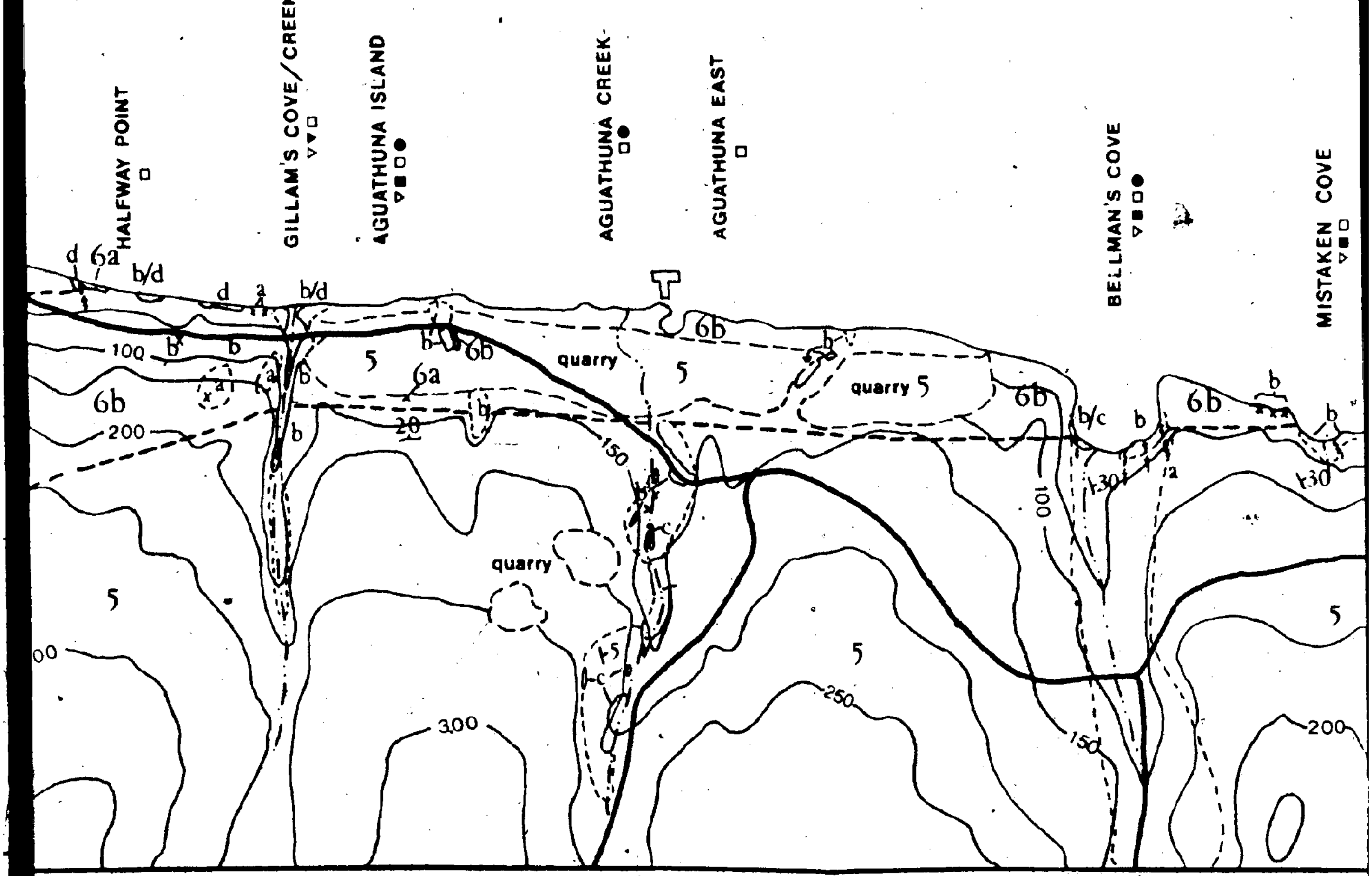

red assumed contact
wn exposed contacts

ATION
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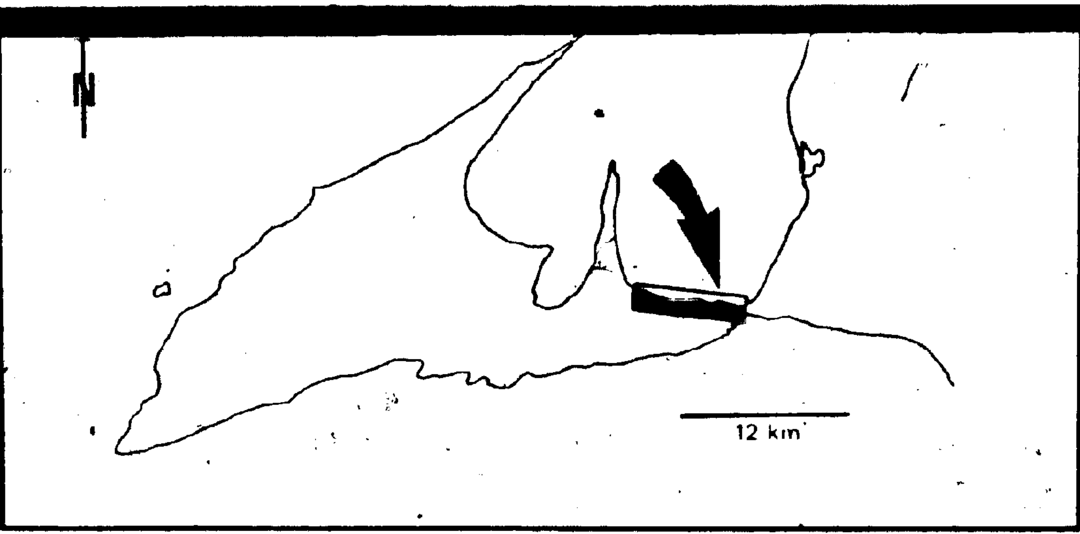
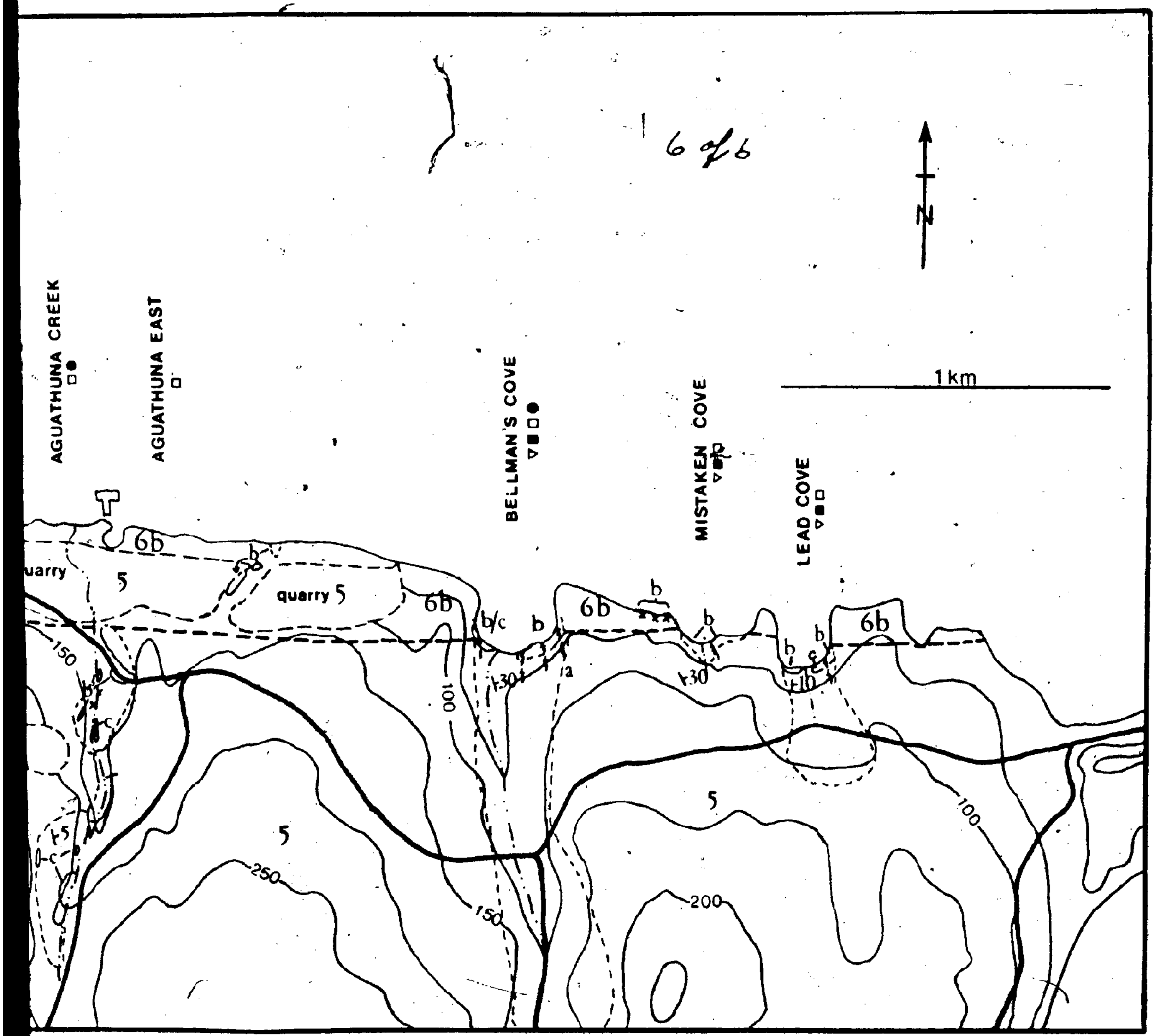
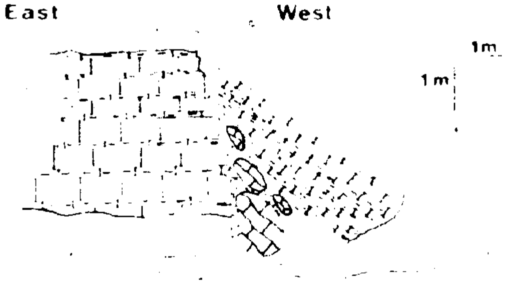




6 of 6

1 of

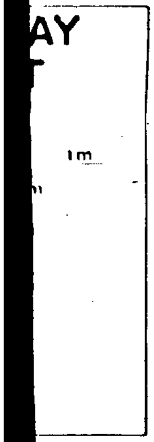
SECTION B - HALFWAY POINT

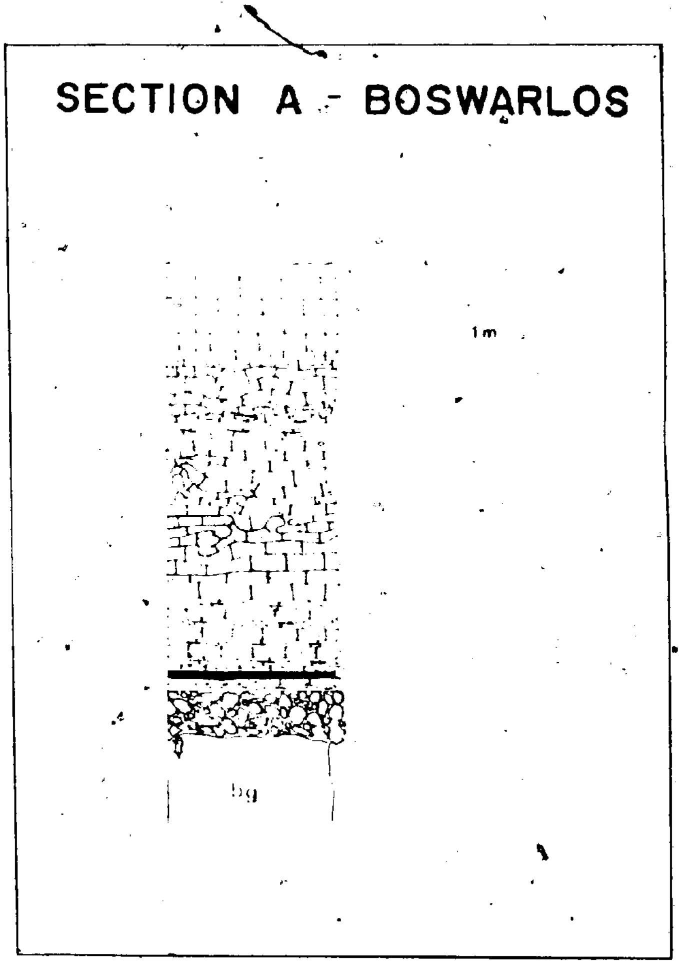


SECTION C - NORTH SHORE

GEOLOGY OF THE UPPER MISSISSI ALONG THE NORTHEAST COAST OF THE PORT AU PORT PENINSULA

2 of





SISSIPPIAN SEDIMENTS
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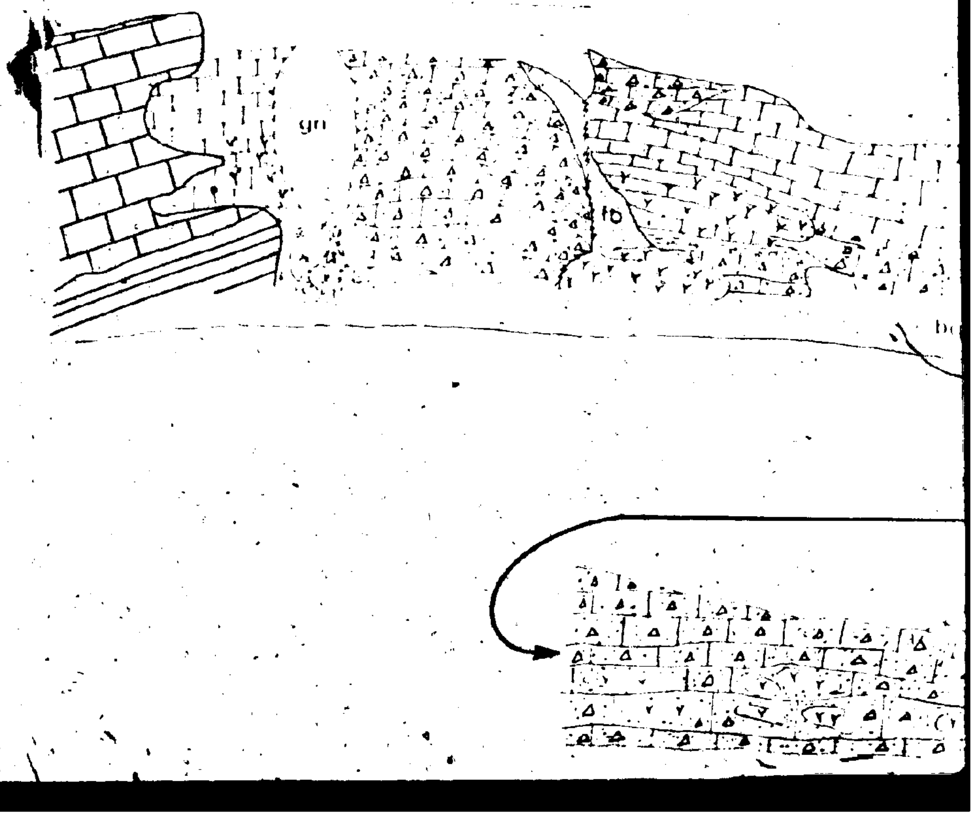
3 of

SECTION G - BELL

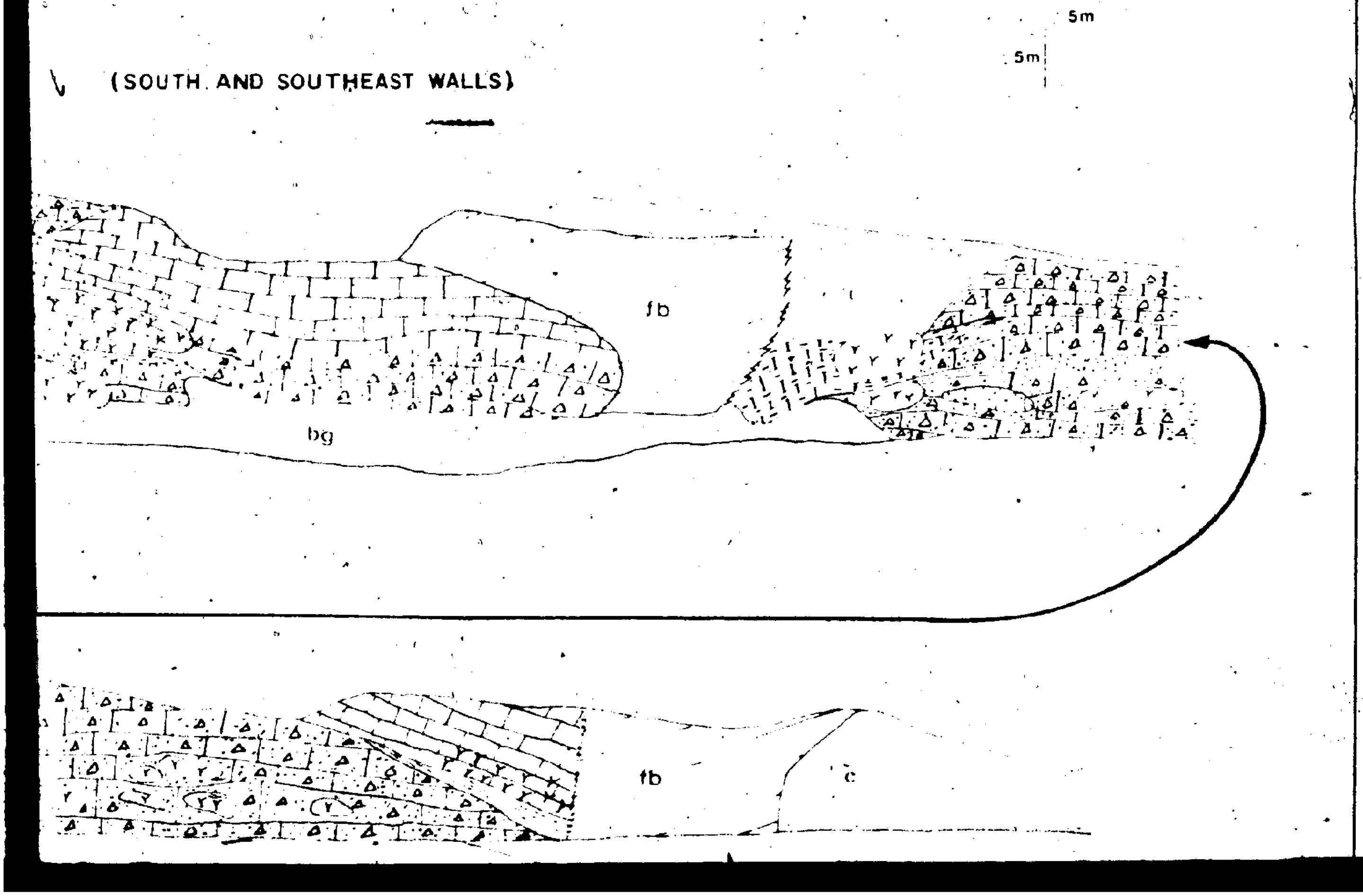
(SOUTH AND SOU

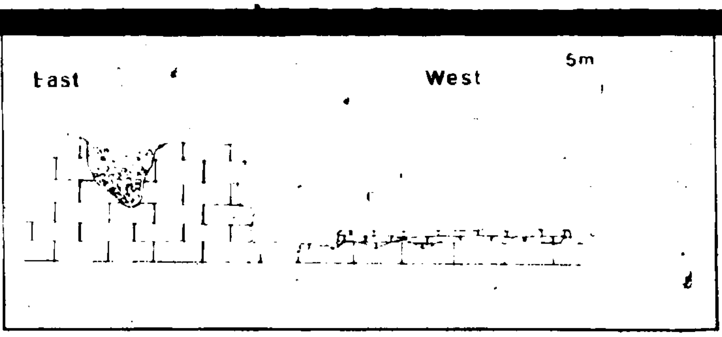


4oF

ION G - BELLMAN'S COVE

(SOUTH AND SOUTHEAST WALLS)

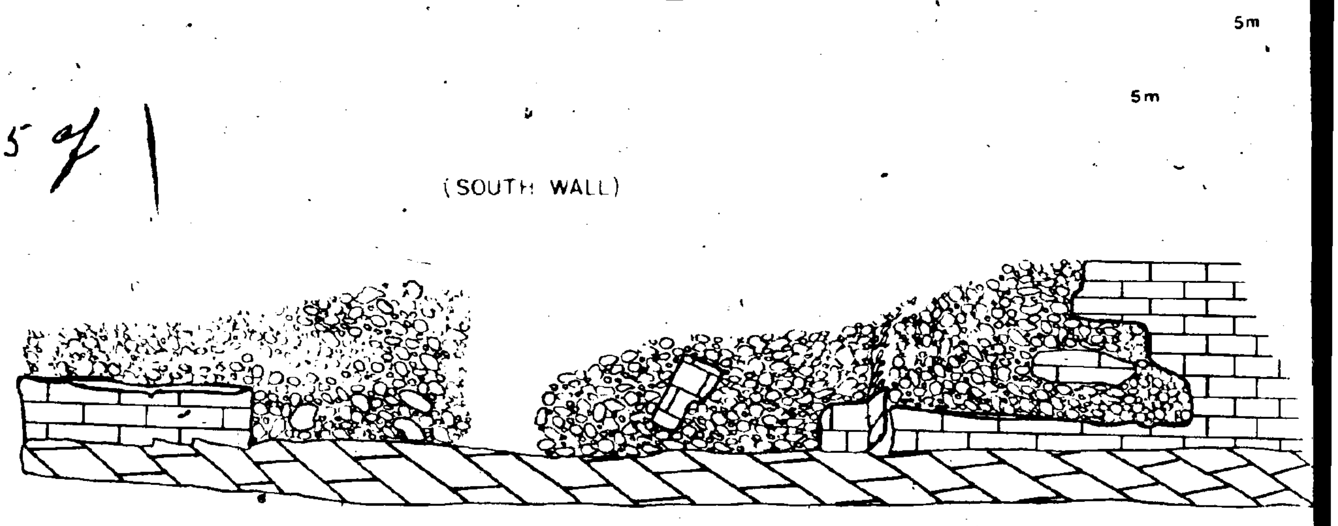




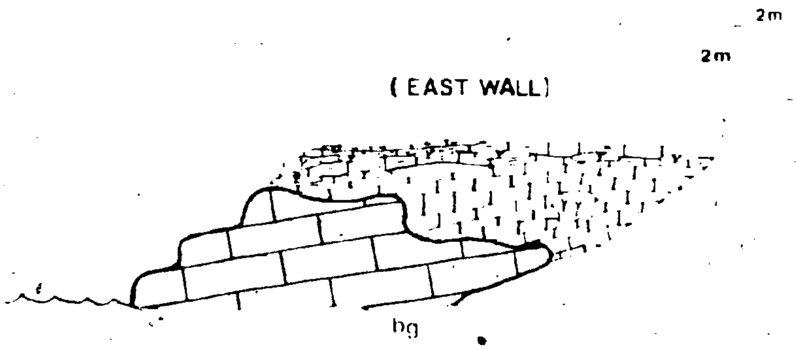
SECTION D - GILLAM'S COVE

5 7

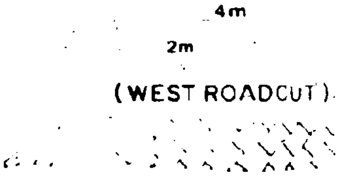
(SOUTH WALL)



(EAST WALL)

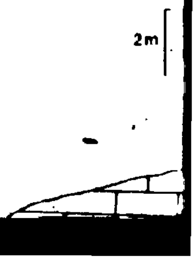


(WEST ROADCUT)

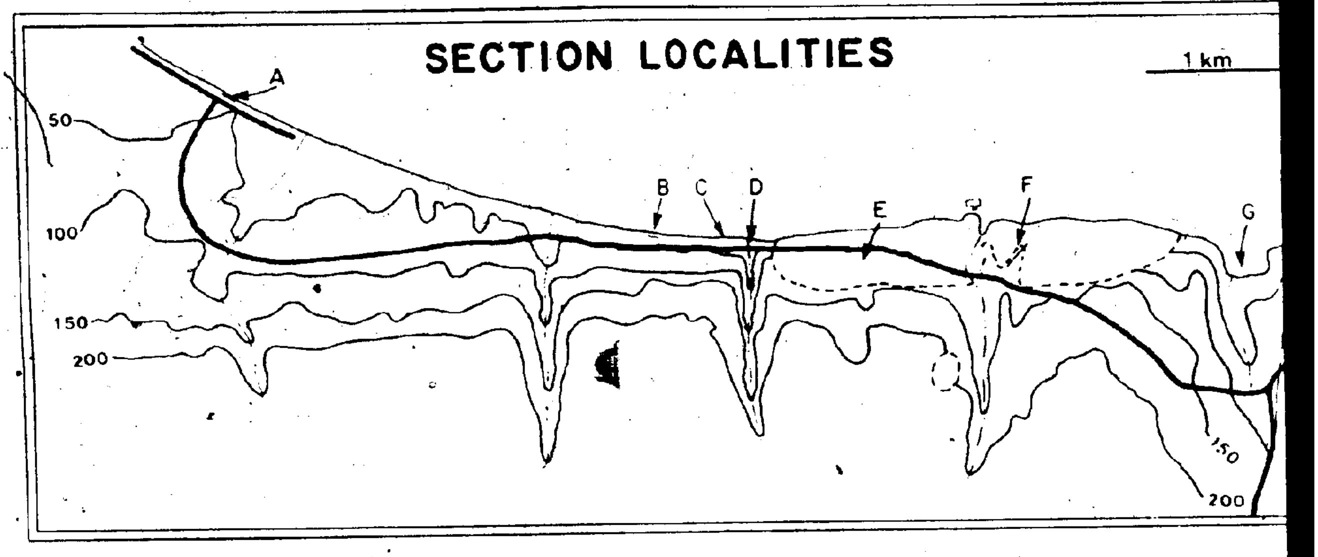


SECTION E - AGUATHUNA ISLAND

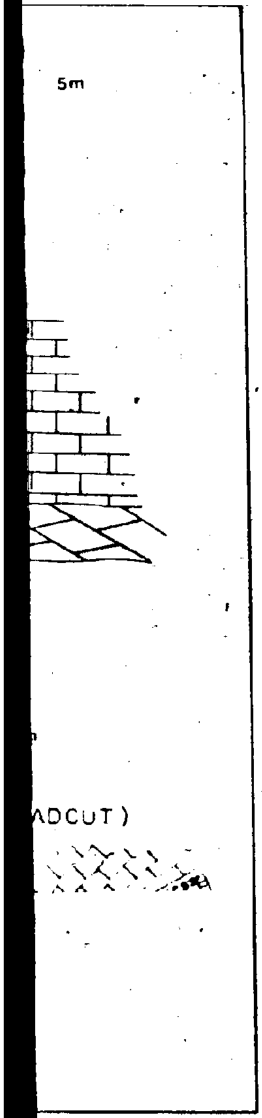
(SOUTH WALL)



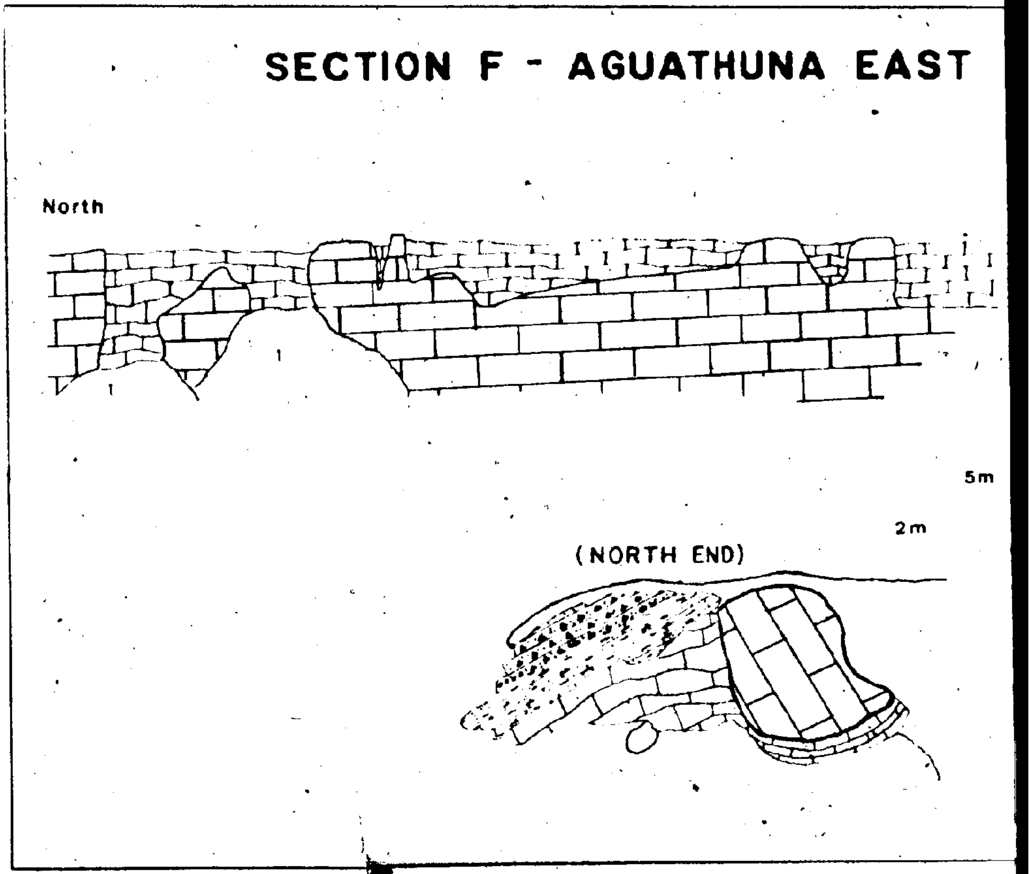
SECTION LOCALITIES

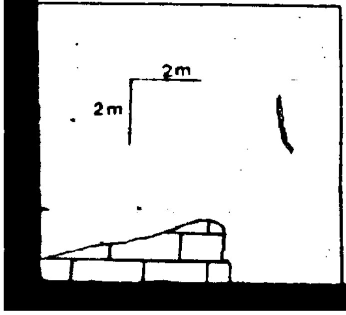


6 of 6

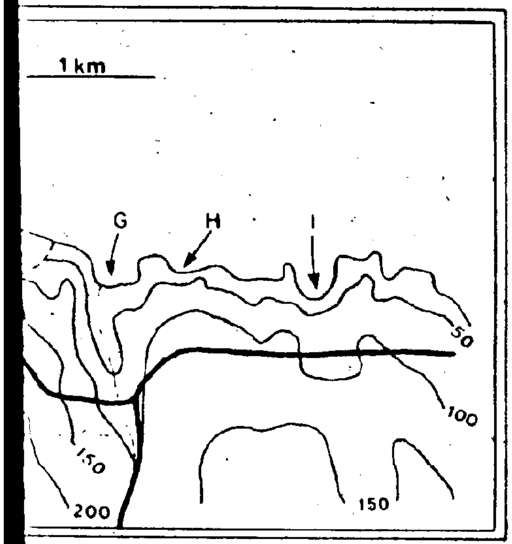


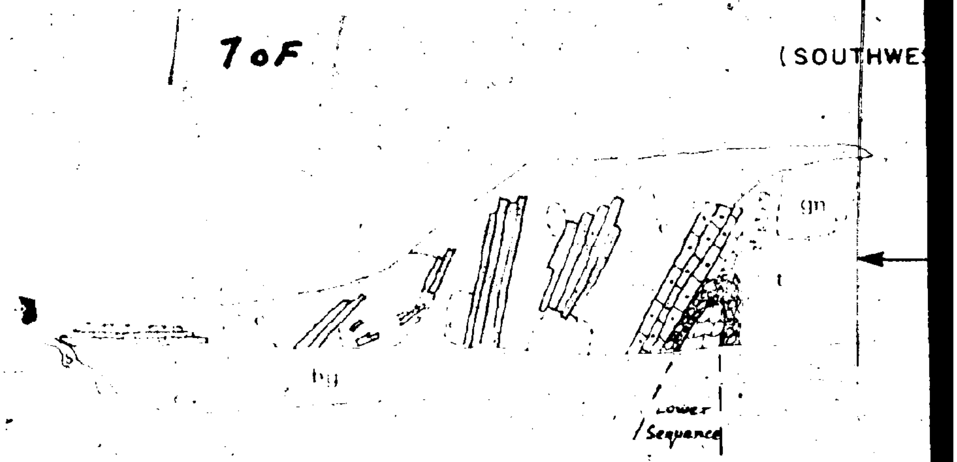
SECTION F - AGUATHUNA EAST





SECTION H - MISTAKEN CO





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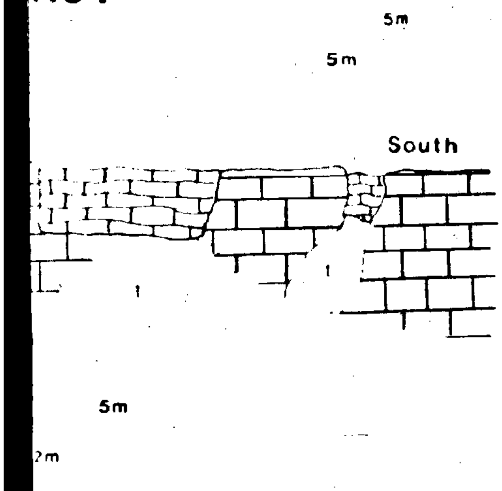
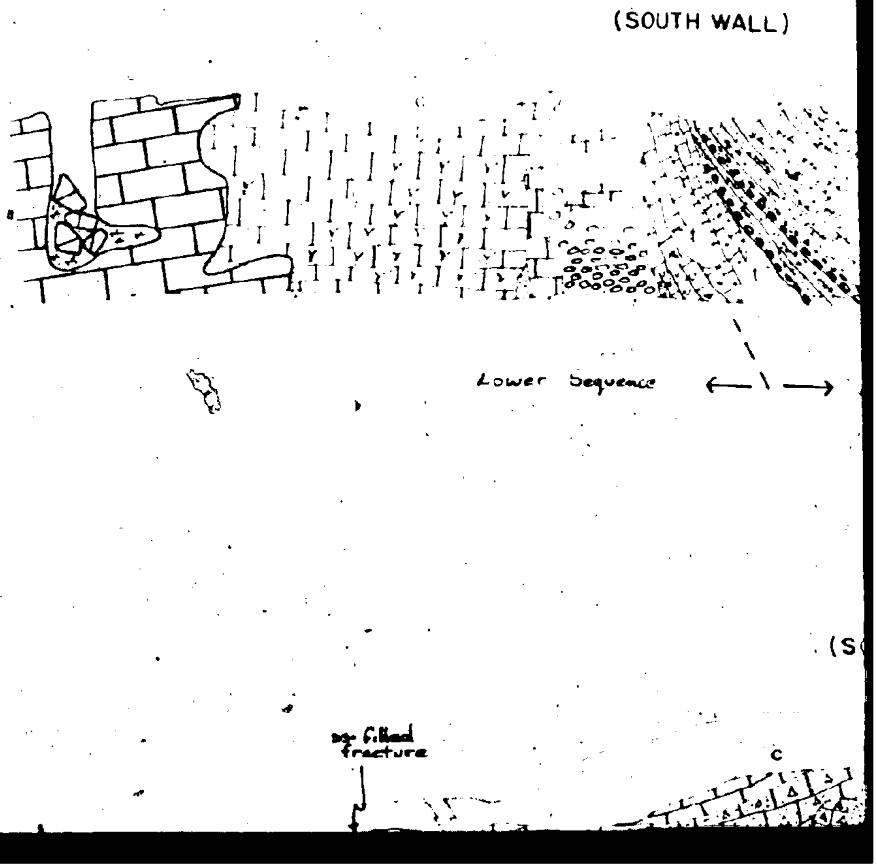


SECTION I - LEAD C



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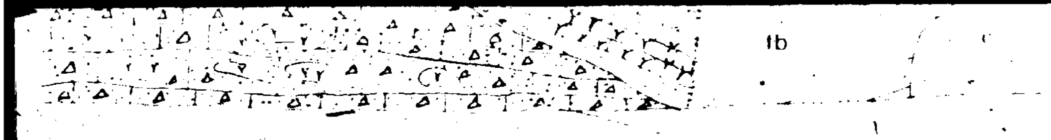

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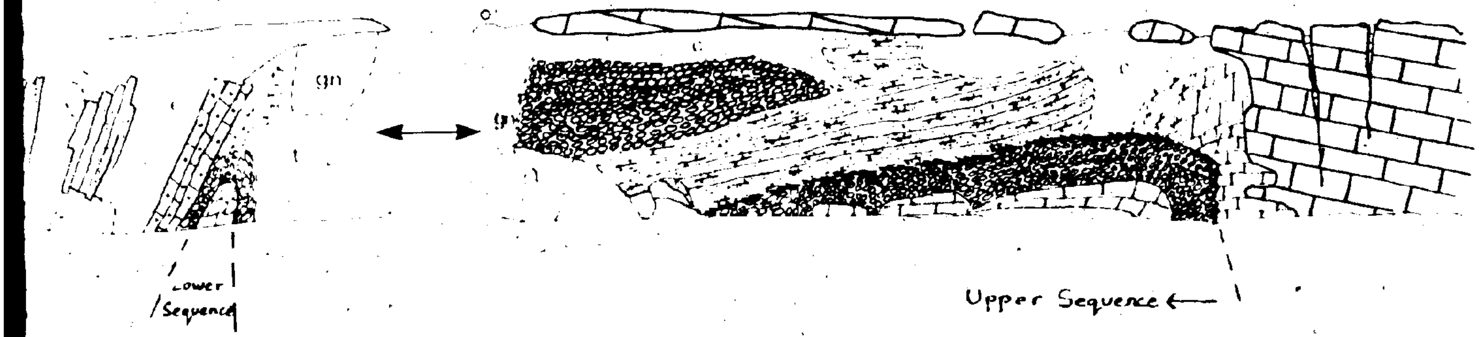
(SOUTHWEST AND WEST WALLS)

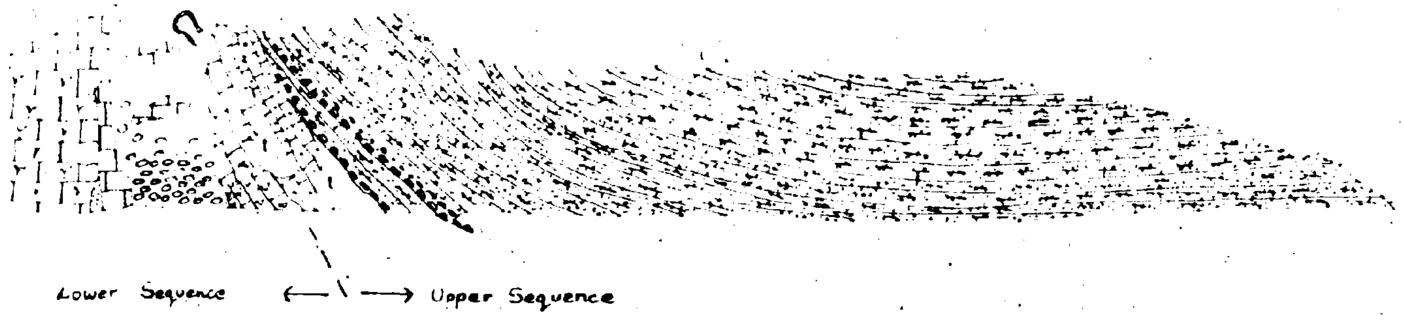


SECTION I - LEAD COVE

(SOUTH WALL)

5m

5m

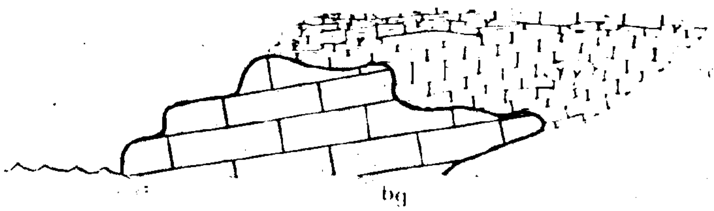


(SOUTHWEST WALL)

2m

2m

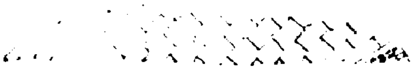
(EAST WALL)



4m

2m

(WEST ROADCUT)

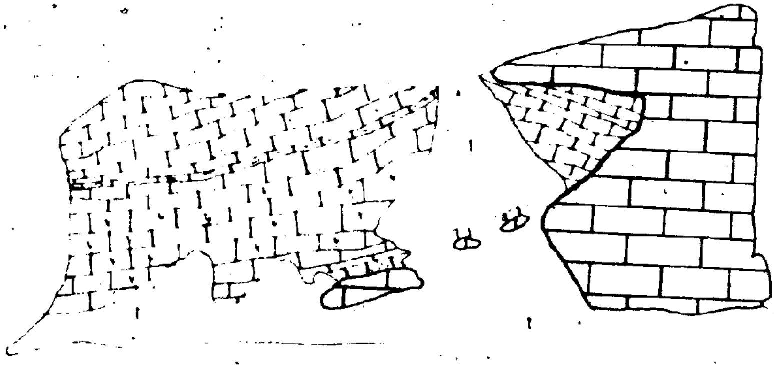


SECTION E - AGUATHUNA ISLAND

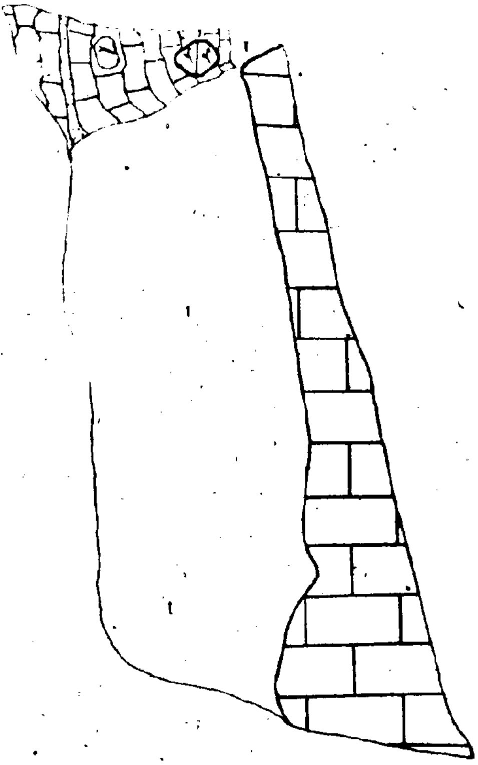
2m

2m

(SOUTH WALL)



(PLAN VIEW)



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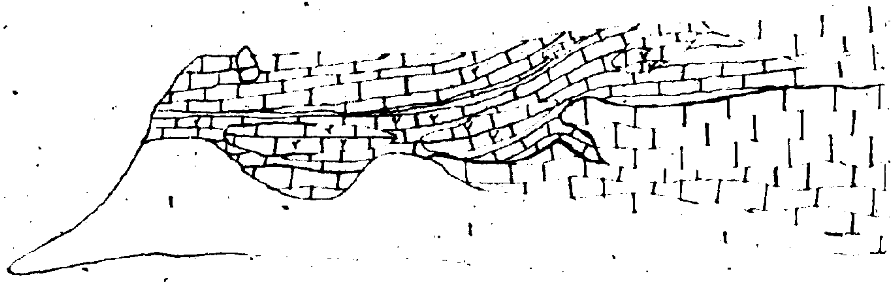
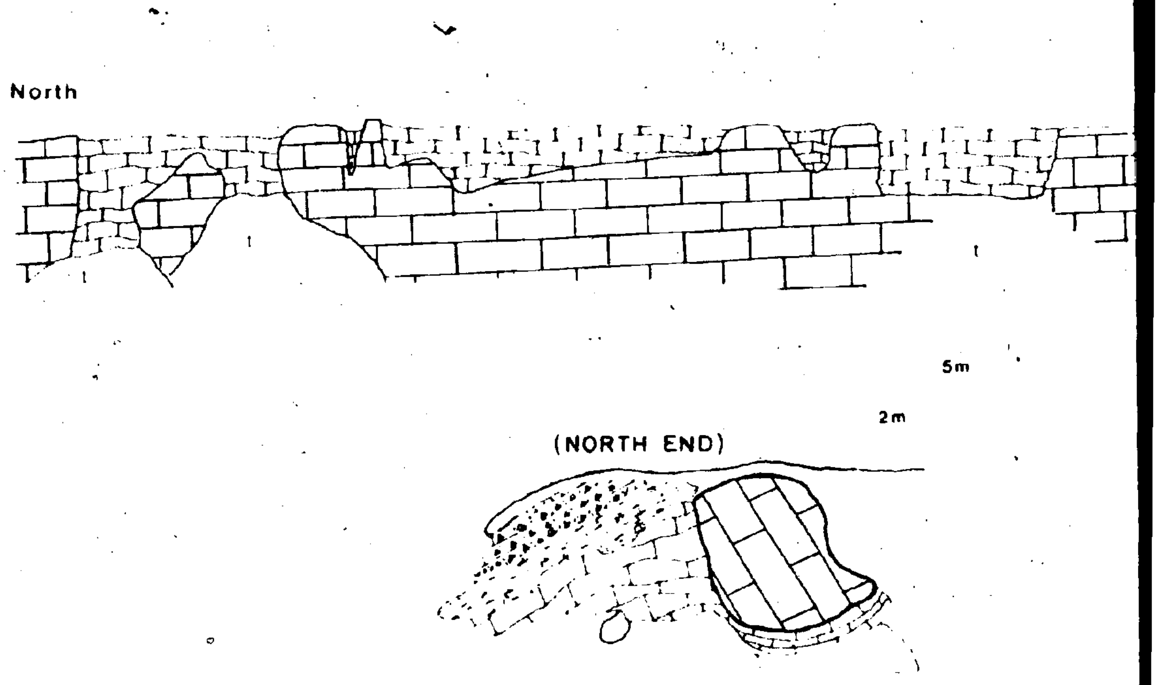
(WEST WALL)

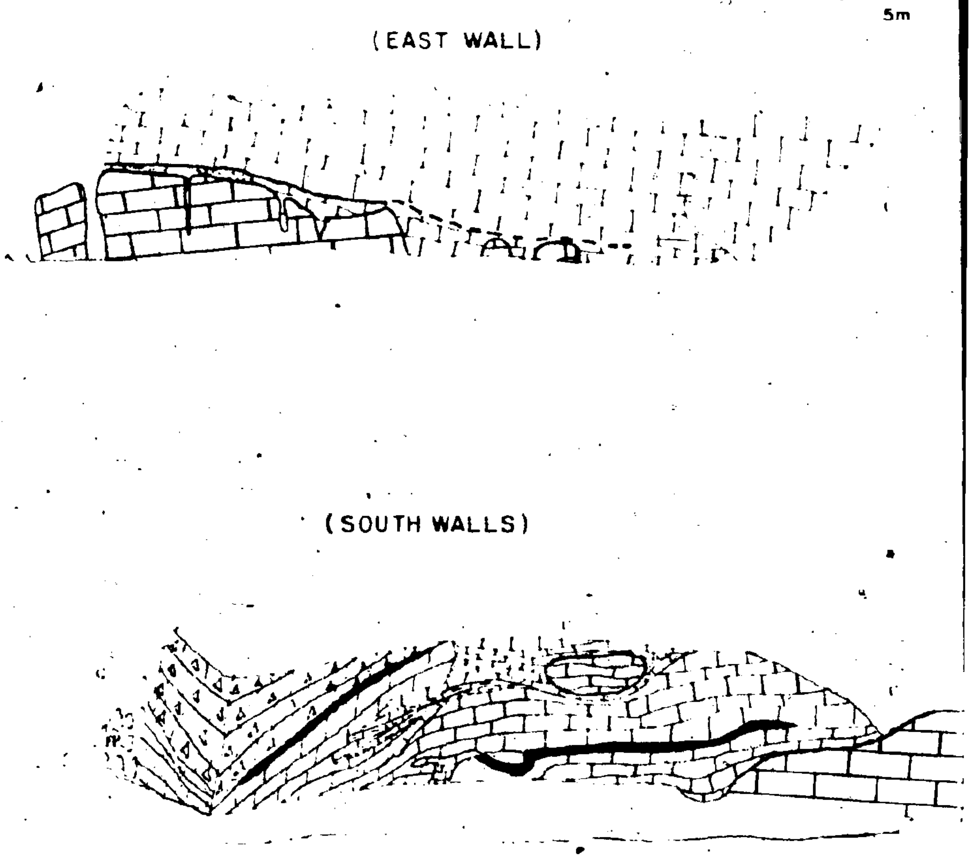


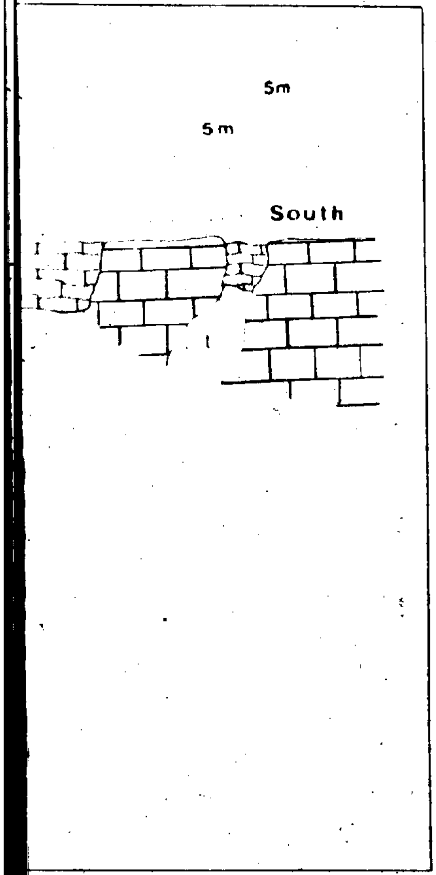
SECTION F - AGUATHUNA EAST

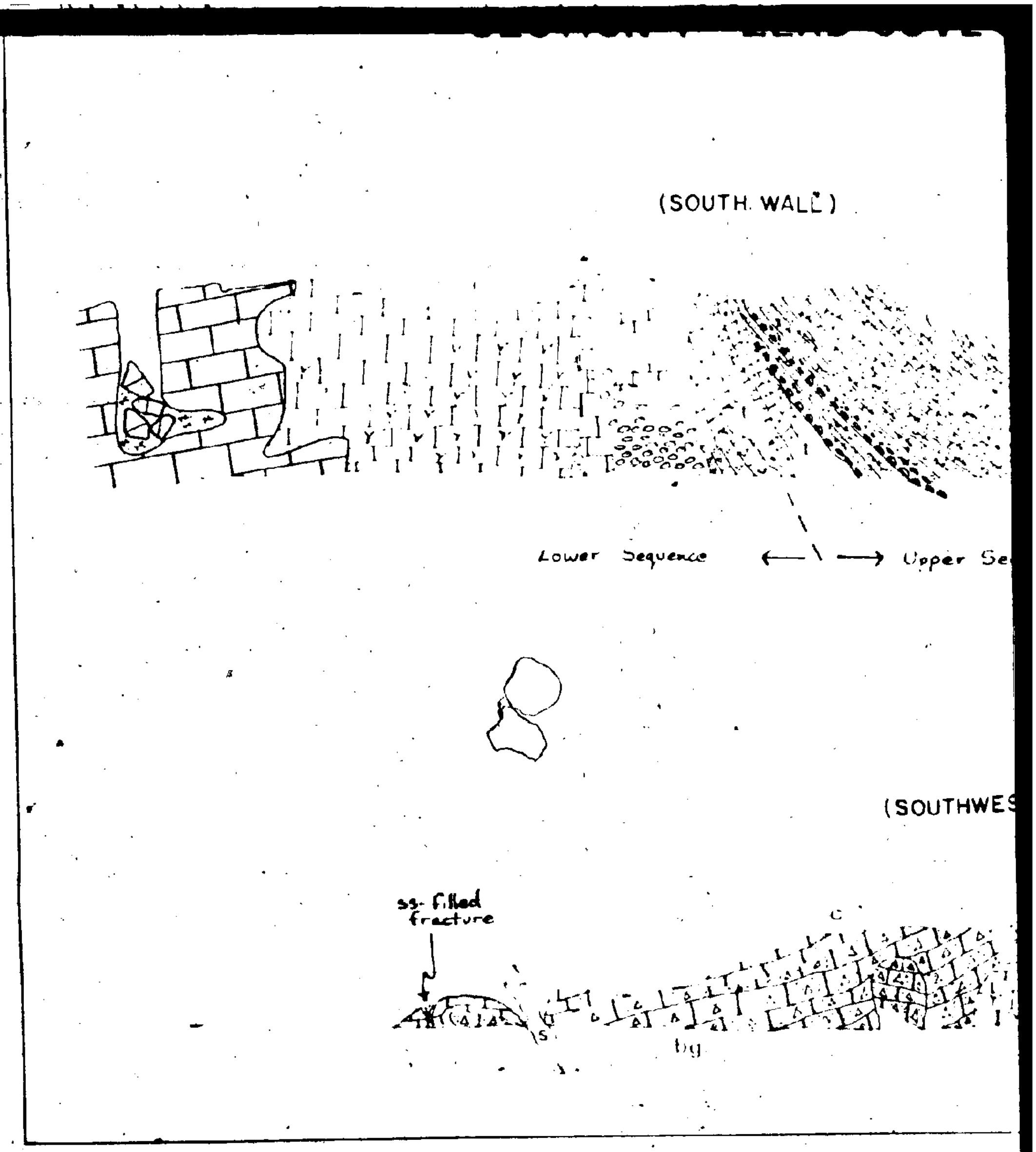


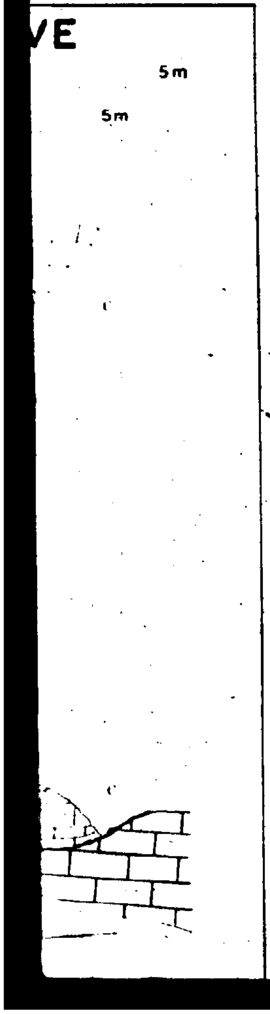
10 OF 1

SECTION H - MISTAKEN COVE









11 of 1

LEGE

- ▨ Limestone pebble to cobble conglomerate.
- ▨ Calcareous, mica-rich, plant-bearing sandstone.
- ▨ Sandy limestone breccia.
- ▨ Cobble to boulder conglomerate, with sandy lenses
- ▤ Micritic limestone
- ▤ Very fossili limestone (b limestone)
- ▤ Argillaceous limestone
- ▤ Arenaceous, micritic li
- ▬ Black shaley limestone

SECTION I - LEAD COVE

(SOUTH WALL)

(SOUTHWEST WALL)

12 of 12

LEGEND

- ▦ Limestone pebble to cobble conglomerate.
- ▤ Calcareous, mica-rich, plant-bearing sandstone.
- ▦ Sandy limestone breccia.
- ▦ Cobble to boulder conglomerate, with sandy lenses.
- ▦ Micritic limestone
- ▦ Very fossiliferous limestone (bioalgal limestone)
- ▦ Argillaceous limestone
- ▦ Arenaceous, micritic limestone
- ▬ Black shaley limestone
- ▦ Table Point Limestone
- ▦ Table Cove Limestone
- ▦ St. George Group Carbonates
- ▦ Bryozoan/Algal Mounds
- Y Y Y Bryozoan occurrances

c - cover
t - talus
bg - beach gravel
fb - fault breccia

50 contours, in feet