FACIES ANATOMY OF A LOWER
CAMBRIAN ARCHAEOCYATHID
BIOSTROME COMPLEX,
SOUTHERN LABRADOR

STEVEN HUGHES

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NL-339 (3/77)

FACIES ANATOMY OF A LOWER CAMBRIAN
ARCHAEOCYATHID BIOSTROME COMPLEX,
SOUTHERN LABRADOR

by

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

Department of Geology
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July 1979

St. John's   Newfoundland

ABSTRACT

An archaeocyathid-rich biostrome complex in the
middle of the Forteau Formation (Lower Cambrian) of south-
ern Labrador, is divisible into two facies: (1) Oolite
Sand Facies, and (2) Biostrome Facies. Stratigraphic and
sedimentologic analysis of eight selected areas indicates
that the Biostrome Facies was deposited seaward of the
Oolite Sand Facies and that the paleoslope sloped towards
the south or south-east. The highly irregular nature of the
contact between the two facies suggests that salients and
recesses occurred within the Oolite Sand Facies and that
the Biostrome Facies was deposited on shallow swales within
recesses.

Seven lithologies make up the Oolite Sand Facies:
skeletal grainstone, oolitic grainstone, mixed oolitic
grainstone, mixed peloid packstone, mixed oncolitic grain-
stone, intraclast grainstone, dolostone and dolomitic silt-
stone. These lithologies are considered to form an oolite
shoal complex consisting of an active shoal, stable sand
channels, storm-affected supra-tidal islands, and leeward
oolite shoal spillover lobes.

The Biostrome Facies was deposited seaward of, and on
shallow swales between, the oolite shoals. This facies
consists of five distinct units : Dolomite Mound Unit (BD),
Red Mound Unit (BR), Nodular Mound Unit (BN), Oolite
Bioherm Unit (BB), and Grey Mound Unit (BG). Each unit
consists of two lithofacies : (1) skeletal calcarenite, which

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does not vary between units, and (2) moundstone, a new non-genetic rock-type applied to mounds or bioherms of uncertain origin. Five different moundstone lithofacies occur, all of which contain archaeocyathids and sometimes calcareous algae, in a mudstone matrix. The moundstones form mounds, biostromes, and rarely bioherms, all flanked by skeletal calcarenites. Dolomitic Moundstones (BD-1) and Nodular Moundstones (BN-1) formed in relatively deep water, seaward of Red Moundstone (BR-1) which accumulated in lateral contact with the active oolite shoal. Grey Moundstone (BG-1) and Archaeocyathid Bioherms (BB-2) accumulated on shallow, protected swales between oolite shoals. The Archaeocyathid Bioherm lithofacies is flanked by 'quiet-water' oolitic calcarenites (BB-1).

Diagenetic processes which modified the original depositional texture of the moundstones and calcarenites include: bioerosion, dissolution and cementation, neomorphism, dolomitization, silicification, pressure solution (stylolitization), and fracturing. Diagenetic fabrics were formed by these processes operating in a number of diagenetic environments. Micritization, macroborings and facies specific cementation were formed by processes operating in the submarine diagenetic environment. Selective dolomitization occurred in a zone of mixing between meteoric phreatic and marine phreatic waters. Minor dissolution and widespread cementation occurred in the

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vadose zone. Fabrics formed in the phreatic environment include extensive stylolitization, dissolution, fracturing, pore-fill cementation, and aggrading neomorphism which includes a transitional micrite-microspar-pseudospar fabric affecting archaeocyathid skeletons. Widespread dolomitization and rare silicification and stylolitization occurred in a late, unspecified diagenetic environment.

The autecology of archaeocyathids, calcareous algae, stromatolites, a new, primitive 'coelenterate', brachiopods, trilobites, hyolithids, echinoderms, and agmata (Salterella), is reviewed and three faunal/floral assemblages are recognised: (1) mound-flanking Skeletal Calcarenite faunal assemblage, consisting predominantly of echinoderms with brachiopods, trilobites, hyolithids and Salterella, (2) mound-dwelling assemblage, consisting predominantly of archaeocyathids and calcareous algae with brachiopods, trilobites, coelenterate, sponges, hyolithids and the ichnogenus Trypanites, (3) coelobitic (cavity dwelling) assemblage, found mainly beneath retilaminiform archaeocyathids and consisting of pendant calcareous algae, foraminifera, encrusting archaeocyathids, Archaeotrypa, sponges, trilobites, and worms.

ACKNOWLEDGEMENTS

Finally, to my wife Elizabeth, who was a great help in the preparation of this thesis and whose patience and encouragement saw it through to its completion, my deepest thanks.

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CHAPTER I: INTRODUCTION

AIMS

Fossil reefs, constructed by different groups of organisms at different times in geologic history, illustrate a wide variety of form and structure (Wilson, 1975). The earliest skeletal reefs are formed by an extinct metazoan, archaeocyathida (Hill, 1972), but such reefs are poorly known and have been rarely described (See Appendix I).

Some of the best exposures of Lower Cambrian archaeo-cyathid-rich reefs outside of the U.S.S.R. occur in southern Labrador. Here, in the Forteau Formation, two separate archaeocyathid-rich horizons have been recognised (James and Fong, 1976), a lower series of bioherms called the 'patch-reef series' (James and Kobluk, 1978) and an upper biostrome complex. The purpose of this study is to document the biostrome complex, specifically to:-

    (1)   Map the lithofacies of the biostrome.

    (2)   Document the paleontological and sedimentolo-
           gical aspects of the biostrome and associated
           facies to interpret the environment of deposition.

    (3)   Outline the diagenetic evolution of the carbon-
           ate rocks.

    (4)   Determine certain aspects of the paleoecology.

STUDY AREA
Physiography

The study area, southern Labrador, forms the north coast of the Strait of Belle Isle (Fig. 1), at a latitude of approximately $51^{\circ}30'$ and a longitude of $57^{\circ}00'$.

Flat topped hills, bounded by terraced cliffs and wide river valleys form the coastal area and give way inland to rugged Precambrian terrain. The physiography reflects the lithology of the bed-rock and the occurrence of faults. High, steep sea-cliffs such as those between Bradore and L'Anse au Loup (Fig.4), are formed of Lower Cambrian sandstones (Bradore Formation). These cliffs also form the sides of the major river valleys. The sandstone cliffs give way to a more rolling topography, formed by Lower Cambrian limestone, siltstones and shales of the Forteau Formation, which rises to a maximum elevation of 843 ft. (255 m) above sea-level northwest of Forteau.

Well-developed terracing, formed by differential erosion (Schuchert and Dunbar, 1934) occurs when the Bradore Formation and Forteau Formation are continuously exposed, as to the west of Schooner Cove.

Four major river valleys run parallel to each other in a N.W.-S.E. direction. These U-shaped valleys, containing rivers draining into the sea at Blanc Sablon, Forteau, L'Anse au Loup, and L'Anse au Diable, cut down into the underlying Precambrian crystalline basement. The upland drainage pattern is almost completely controlled by faulting (see below).
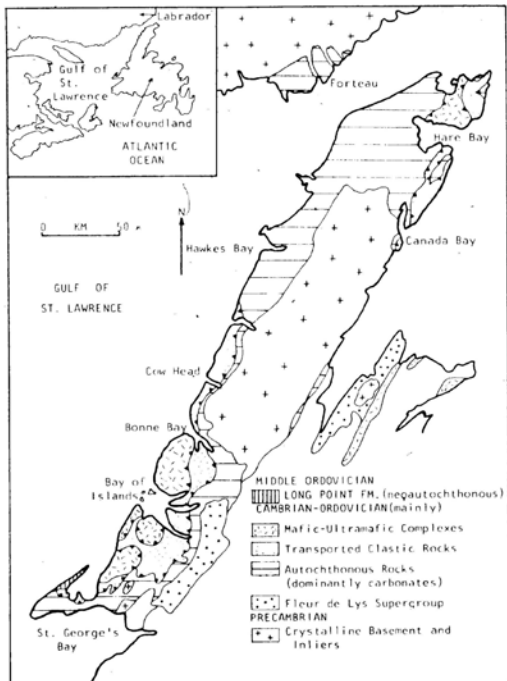
Fig.1: Major geological elements of western Newfoundland
and southern Labrador (based on Williams, 1975).

The legend of the figure reads:

MIDDLE ORDOVICIAN
▦ LONG POINT FM.(neoautochthonous)
CAMBRIAN-ORDOVICIAN(mainly)
Mafic-Ultramafic Complexes
Transported Clastic Rocks
Autochthonous Rocks
(dominantly carbonates)
Fleur de Lys Supergroup
PRECAMBRIAN
Crystalline Basement and
Inliers

Map labels: Labrador, Gulf of St. Lawrence, Newfoundland, ATLANTIC OCEAN, Forteau, Hare Bay, Hawkes Bay, Canada Bay, GULF OF ST. LAWRENCE, Cow Head, Bonne Bay, Bay of Islands, St. George's Bay

0   KM   50   N

Geologic setting

The rocks under study occur in the upper part of the
Forteau Formation, as exposed in southern Labrador and Quebec.
Similar rocks also occur in western Newfoundland and these
were examined briefly for comparative purposes.

Tectonically, the study area lies west of the western
limit of Appalachian deformation but may be considered as the
undeformed equivalents of the Lomond Zone (Zone A) of Williams,
Kennedy and Neale (1974) now renamed the Humber Zone (Will-
iams, 1976). This zone, lying in western Newfoundland (Fig.1),
represents the Lower Paleozoic stable continental margin, parts
of which were destroyed by westward transport and subsequent
emplacement of oceanic crust (ophiolites) and other allochth-
onous rocks in Middle Ordovician time (Williams, 1975).

The sedimentary succession (Fig.2) overlies a Precamb-
rian complex of gneisses and schists of Grenville age cut by
900 m.y. granites (Williams et al., 1974). Local developments
of plateau basalts, such as the Lighthouse Cove Formation of
Belle Isle (Williams and Stevens, 1969), are seen in places
to directly overlie Precambrian basement. Most of the sedi-
mentary sequence consists of an eastward thickening, Lower
Paleozoic, partly clastic but dominantly carbonate succession
(Logan, 1863; Schuchert and Dunbar, 1934; Whittington and
Kindle, 1969; Cumming, in press) which can be traced laterally
along the length of the Appalachian-Caledonian orogen as far south
as Alabama (Palmer, 1971; Williams and Stevens, 1974), and
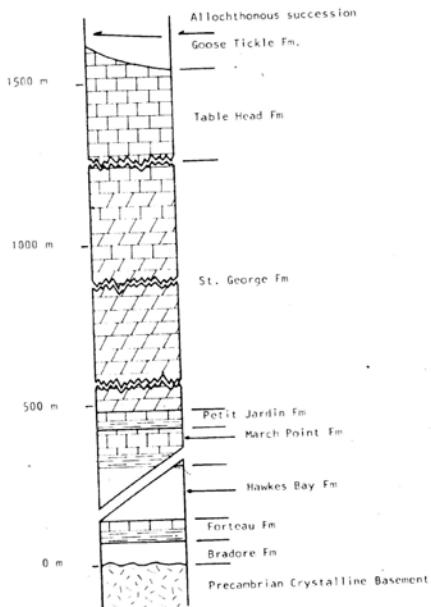
Fig.2: Generalized stratigraphic section of the autochthonous sequence of western Newfoundland (Humber Zone). Modified after Swett and Smit (1972, Fig.1).

northwards into Greenland, Scotland, and Spitzbergen (Harland, 1969; Swett and Smit, 1972).

The **sequence in** Newfoundland (Fig.2) has been described as two unequal siliciclastic-carbonate megacycles (Levesque, James and Stevens, 1977). The lower cycle is much thinner and of considerably shorter duration, being entirely Lower Cambrian in age, compared with the much thicker upper cycle which ranges from Lower Cambrian to Middle Ordovician. In each case, the cycle commences with a siliciclastic unit, (the Bradore Formation and Hawke Bay Formation, respectively), which grade up into a dominantly limestone sequence (Forteau Formation in the lower cycle, and the St. George and Table Head Formations in the upper cycle).

Conformably overlying the Table Head Formation (Middle Ordovician is part of a westward transgressing flysch wedge (Goose Tickle Formation) that abruptly terminates the carbonate succession (Williams et al., 1974) and is the highest autochthonous unit seen in W. Newfoundland. The rest of the sequence in the Humber Zone consists of an allochthonous succession of westerly transported rocks, emplaced as structural slices. Sedimentary rocks, including a coarse limestone breccia, are interpreted as being eastern contempories of the authochthonous succession, and occur in the lower structural slices, while the higher slices are interpreted as ophiolite suites (Williams, 1975).

The youngest Ordovician stratum seen in this zone is the neoauthochthonous Long Point Group (Bergström, Riva and Kay, 1974); a series of biohermal limestones, shales, minor sandstones, and red-beds, of Upper Champlanian-Lower Cincinnatian age, (Fahraeus, 1973; Bergström et al; 1974) which were deposited disconformably(?) onto the allochthon (Stevens, 1970).

Detailed Lower Cambrian stratigraphy of southern
Labrador

The area studied in southern Labrador comprises only the basal two-thirds of the thinner, lower megacycle (James and Kobluk, 1978), represented by rocks of the Labrador Group (Schuchert and Dunbar, 1934). The Labrador Group is represented by the Bradore Formation and the lower half of the Forteau Formation, the rest having been removed by erosion (Fig.3). These rocks outcrop over a 40 km coastal belt from east of Lourdes de Blanc Sablon in Quebec, north-eastwards to West St. Modeste in Labrador (Figs. 8 and 72). Outcrop is continuous in cliff-section except where the major river valleys drain to the sea. Inland the rocks are exposed variably for a maximum distance of 15 km where they are faulted out against Precambrian basement. Outliers occur to the north of the major fault, but are inaccessible by foot.

As the strata in the area are generally flat-lying, the only structural complications result from high angle normal faults of small displacement which are very common. Two sets of faults can be distinguished (see Fig. 72, in pocket) (1)
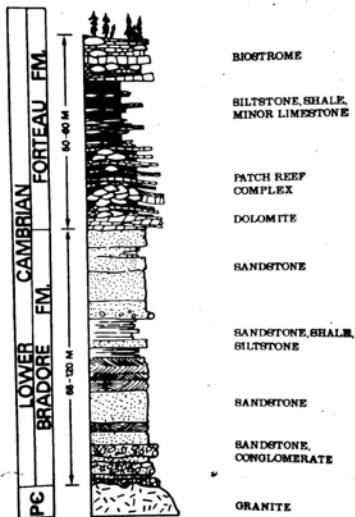
Fig. 4: Generalized stratigraphic section of the Lower-Cambrian
         sequence in southern Labrador (after James and Lobluk,
         1976).

those trending N.E.-S.W., (2) those trending E.N.E.-W.S.W.
No age relationships can be deciphered between the two sets.
A small number of faults have anomalous trends: a N.-S. fault
runs through L'Anse au Clair, and two minor N.W.-S.E. faults
occur on the Pointe Amour peninsula. Upland drainage is con-
trolled by faulting with all streams following the trend of
the faults. The major river valleys flow along Precamb-
rian basement and drain to the south-east. It is not known
whether the location of these rivers is fault controlled or
glacially controlled.

Bradore Formation

The Bradore Formation (Schuchert and Dunbar, 1934)
(Fig. 4) unconformably overlies the Precambrian Grenville base-
ment complex. The contact is a paleosub-aerial surface (James
and Kobluk, 1978; Cumming, in press) and can be seen at the
base of the cliff to the east of Blanc Sablon. The basal
15 m consists of thin conglomerates and red arkosic sandstones
with a bimodal and bipolar current-bedding distribution (Swett
and Smit, 1972) characteristic of tidal sand bodies (Reineck
and Singh, 1975). The upper 55 m is a more mature arkose
to orthoquartzite. The most obvious structure in these sedi-
ments are many vertical tubes interpreted as water-escape
structures (Cumming, in press) but widely accepted as bur-
rows and called <u>Skolithus linearis</u>. Other trace fossils,
including <u>Monocraterion</u>, <u>Dolophichnus</u>, and <u>Lingulichnus</u>, also
occur in the Bradore Formation (Pemberton, James and Kobluk,

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Fig. 4: Sandstone cliffs of the Bradore
         Formation exposed to the east of
         L'Anse au Loup.

1977; Pemberton and Kobluk, 1978). The only body fossils reported from the sandstone are broken brachiopod shells, believed to be obollelids (Balsam, 1973).

The maximum thickness of the Bradore Formation was given as 285 ft. (86 m) by Schuchert and Dunbar (1934). Cumming (in press) recognises a thickening towards the north-east (West St. Modeste) where he records a thickness of 400 ft. (121 m).

The Bradore Formation occurs in western Newfoundland but is always incomplete. Equivalent strata in western Newfoundland include the Cloud Mountains Formation, (Betz, 1939) in Canada Bay, and the Bradore Formation on Belle Isle (Williams and Stevens, 1969). Swett and Smit (1972) suggest correlatives in Scotland (Eriboll Sandstone), and also East-Central Greenland (Kløftelv Formation).

Forteau Formation

The Bradore Formation is conformably overlain by the Forteau Formation (Schuchert and Dunbar, 1934). These sediments record the first occurrence of carbonate rocks during the evolution of the Lower Paleozoic continental shelf. Only the basal 185 ft. (56 m) occurs in Labrador but the maximum, complete thickness in the Highlands of St. John is 386 ft. (117 m) (Schuchert and Dunbar, 1934).

The sequence (Fig.3) commences with a basal dolomite and shale unit, 3-4 m thick. This is overlain by an archaeocyathid patch-reef complex (Fig.5) which has an average thickness of

Fig.5: Patch-reef facies of the Forteau Formation east of Fox Cove. A patch-reef (centre) is flanked on either side by bedded skeletal calcarenite.

Fig.6: Shales and siltstones of the open-shelf facies, Forteau Formation, exposed in a quarry near to Ten Mile Lake, western Newfoundland.

10 m and has been described by James and Kobluk (1978).
They recognise two laterally equivalent facies; a widespread,
laterally continous limestone and shale interbed sequence,
termed the 'open-shelf facies', and a complex mosaic of arch-
aeocyathid-rich bioherms and inter-bioherm sediments, termed
the 'patch-reef facies'.

The open-shelf sediments are cyclic, each cycle coarsening
upwards from shale into nodular limestone, into calcareous silt-
stone or silty limestone with a maximum thickness of 2 m.

The patch-reef facies (Fig.5) consists predominantly of
archaeocyathids and calcareous algae in matrix of lime-mud.
These are flanked by off-reef skeletal calcarenites extending
out 2 to 6 m from the reef and grading into thin nodular lime-
stones (James and Kobluk, 1978).

The patch-reef complex is overlain by up to 20 m of
interbedded calcareous and dolomitic siltstones and shales
(James and Kobluk, 1978) which contain a rich and diverse
trace-fossil assemblage (Pemberton et al., 1977).

The upper part of the sequence in Labrador consists of
a complex of archaeocyathid-rich mounds, surrounded and inter-
calated with skeletal and/or oolitic calcarenites and lime
mudstone, up to 20 m thick (James and Fong, 1976) (Fig. 7).
These rocks are the subject of this thesis.

Traced eastwards into Newfoundland, the patch-reef comp-
lex of the Forteau Formation grades into black potassium-rich
shales (Fig.6) with minor limestones and siltstones (James and
Fong, 1976). The biostrome complex is present in St. Margarets

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Fig. 7: Archaeocyathid-rich, lime-mud mounds and bedded
calcarenites of the biostrome complex, Forteau
Formation, L'Anse Amour.

quarry but thins considerably further south in the Highlands
of St. John (Schuchert and Dunbar, 1934). To the north on
Belle Isle (Williams and Stevens, 1969) and to the south in
Bonne Bay (Schuchert and Dunbar, 1934), no archaeocyathids
have to date been reported from the Forteau Formation, the
sequences being largely argillaceous.

The age of the Forteau Formation in Labrador has been
determined using both trilobites and archaeocyathids. Using
trilobites, the formation falls into the Bonnia-Olenellus zone
and is correlatable with the Sekwi Formation (Upper Elankian)
of Fritz (1972). The occurrence of Antagmus sp. and Bonnia
columbensis suggests that the Forteau Formation falls into
the top of the Bonnia-Olenellus zone while on the basis of the
occurrence of Wanneria logani, it falls into the middle of
that zone.

Using archaeocyathids, the Forteau Formation is correla-
table with the Obrutchev horizon of the Elankian stage of the
Siberian platform (Rozanov and Debrenne, 1974).

It may be concluded therefore, using both dates, that
the Forteau Formation represents the topmost Lower Cambrian
and makes the reefs amongst the youngest archaeocyathid struct-
ures so far recorded (James and Kobluk, 1978).

AREAS SELECTED FOR DETAILED STUDY

As a precursor to detailed analysis of the biostrome complex, reconnaissance mapping of the area under study revealed that strata overlying the widespread siltstones and shales above the Lower patch-reef series, were either archaeocyathid-rich lime-mudstone or oolitic calcarenites (James and Fong, 1976). Examination of all available out-crops in southern Labrador suggests that these two litho-logies along with respective associated lithologies, com-prise two distinct facies, herein called: (1) Biostrome Facies (sensu stricto), (2) Oolite Sand Facies, (see Chapter 3).

Lithologic variation between and within the two fac-ies is such that ten areas were selected for detailed study (Fig. 8). Five of these areas are within the Bio-strome Facies, four are within the Oolite Facies, and one area combines both facies. The areas selected for detailed study are outlined below. The letter refers to the position of the outcrop on the location map (Fig. 8). (A) Blanc Sablon: This outcrop is the westernmost exposure of the Biostrome Facies and consists of a good vertical section which differs in lithofacies arrangement from the Pointe Amour peninsula. (B) Diversion Reef: This area, which in-cludes the transition between the Biostrome Facies and the

LOCATION OF SECTIONS

A   Blanc Sablon
B   Diversion Reef
C   Osprey Reef
D   Forteau
E   L'Anse Amour
F   Fox Cove
G   Schooner Cove
H   L'Anse au Loup
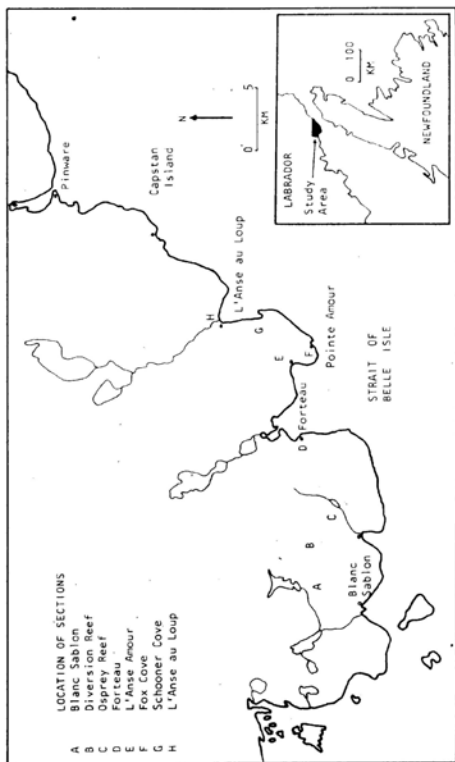
Fig. 8: Location map of southern Labrador.

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Oolite Sand Facies, is located approximately 4 km to the north of L'Anse au Clair. The exposures are found along a track but are often covered, giving incomplete sections. (C) Osprey Reef: This extensive cliff exposure, located to the north of the main road between L'Anse au Clair and Forteau, shows the transition between the two facies. (D) Forteau: This is the thickest, although poorly exposed, sequence within the Oolite Sand Facies and occurs in outcrops to the south of the main road to the west of Forteau. (E) L'Anse Amour: This cliff exposure gives a complete vertical section through the Biostrome Facies and extends laterally for almost 3 km. (F) Fox Cove: This is the only coastal exposure of the Biostrome Facies and is therefore the only location with good bedding plane exposure. (G) Schooner Cove: An almost complete section occurs in a sequence in which rocks of both facies are present. (H) L'Anse au Loup: Although very poorly exposed this is the easternmost outcrop of the Oolite Sand Facies that was studied.

The stratigraphy and facies relationships are documented in detail for each locality in the Appendices (A-H) and are discussed in the text.

FIELD METHODS

As the rocks under study constitute a biostromal facies with great lateral variation, just as much emphasis was placed

on lateral relationships within the biostrome as in the vertical succession. More often than not, lateral litho-logic changes **are** as sudden and as frequent as vertical changes.

Where outcrop allowed, photo-mosaics were taken of large exposures to record the lithofacies variation not observable close to the outcrop. Several small-scale maps were drawn to record the horizontal disposition of units in complex areas. About 220 samples were collected and lab-elled for laboratory examination.

TERMINOLOGY

Due to the many terms used to describe accumulations of fossil remains, and the often misleading or multiple def-initions of the individual terms, the following is a brief discussion with definitions of terminology used throughout this thesis. In addition, new terms are introduced where previous terminology is inadequate or non-existent.

The term biostrome has several definitions in the geo-logical literature (see review in Nelson, 1962). It is used in this thesis to describe a diverse suite of rocks, pred-ominantly organic accumulations which form a stratigraphic entity of considerable lateral extent, often measurable in kilometres (cf. Cumming, 1932). Sea-floor relief was pres-ent or absent but the unit probably did not form a wave-resistant structure.

This differs from a bioherm which is also an organic accumulation, with or without primary depositional relief, but is not a stratigraphic entity because it is surrounded by rocks of different lithology, and has limited lateral extent, measurable in metres. Bioherms do not form a wave-resistant structure (cf. Cloud, 1952).

A reef is an organic accumulation and does form a wave-resistant structure. Its geometry can be explained using the adjective forms of the terms bioherm and biostrome to qualify the word reef (cf. Nelson, 1962).

The three most used limestone classifications (Folk, 1959; 1962; Dunham, 1962; Embry and Klovan, 1971) were each, in their own way found to be inadequate to describe the rocks under study.

Embry and Klovan (1971) recognised the inadequacy of both Folk's and Dunham's classifications regarding 'reef-like' accumulations (see discussion in Embry and Klovan, 1971; p.733), but retained the useful grain-size discrimination of Folk (1962), and the textural classification of Dunham (1962) in their own classification (Embry and Klovan, 1971; p.734-737) which is widely used today (James, 1978).

Using Dunham's (1962) classification for the allochthon-ous group of rocks (mudstone, wackestone, packestone, and grainstone), Embry and Klovan introduced a new size fraction of particles larger than 2.0 mm and subsequently added two new names for rocks containing more than 10% of the greater

than 2.0 mm size fraction. The two rock-types are distinguishable on textural terms, in keeping with Dunham, into, floatstone where the large particles are matrix-supported; and rudstone, where the large particles are self-supporting. Embry and Klovan also subdivided the autochthonous organic build-ups into three distinct rock-types, the criteria used being the way in which organisms bound sediment. These rocks are: framestone (organisms constructing a rigid framework and trapping sediment), bindstone (organisms encrusting and binding sediment), and bafflestone (organisms acting as baffles and trapping sediment).

Problems arise with this classification, however, when it is applied to the rocks under study because it is often difficult to clearly differentiate between these three rock-types in the field. The interpretation of bafflestone is particularly difficult and normally requires excellent exposure in three dimensions and considerable interpretation by the worker, as noted by Embry and Klovan (1971, p.737).

For the purpose of this study, a new non-genetic rock-type is proposed; MOUNDSTONE. This is defined as an autochthonous assemblage of skeletons and matrix sediment, commonly mudstone, (but may also be wackestone or packestone) which together have an external geometry of a mound, biostrome, bioherm or reef. This rock-type has no genetic implications and is used only to describe lithologies of an authochthonous nature where the process of sediment trapping is

obviously not baffling, binding, or a framework, or when
the process of formation is in doubt. Moundstone may
therefore include rocks that were formed by the post-mortem
disintegration and subsequent accumulation of the mud frac-
tion, similar to the mud accumulation of Rodriquez Bank,
Florida (Turmel and Swanson, 1976), which is a process not
considered by Embry and Klovan (1971). When the process
of sediment accumulation is clear cut, however, then the
classification of Embry and Klovan (1971) is used.

Calcarenite sand bodies vary widely in their shape. On
a large scale, measurable in tens of metres, four basic
morphologies are distinguished (Fig. 9). These morphologies
are: (1) Wedge: This usually has a flat base, tapering
from a maximum thickness at one end to a minimum thickness
and eventual disappearance at the other end. The contact
with moundstone is interdigitatory although vertical in a
broad sense. The calcarenite may be horizontally bedded or
may drape off the moundstone at angles of up to 16 degrees.
(2) Lens: This is usually flat-topped and flat-based
over much of its extent, but thins towards the contact with
the moundstone. Lateral extent is in the order of tens of
metres and the thickness generally less than 2 m. Contact
with the moundstone may be horizontal or draped. (3)
Tabular lens: This is usually flat-topped and flat-based
and normally more than 1 m thick. It differs from a normal
lens in that the contact with moundstone is vertical (although
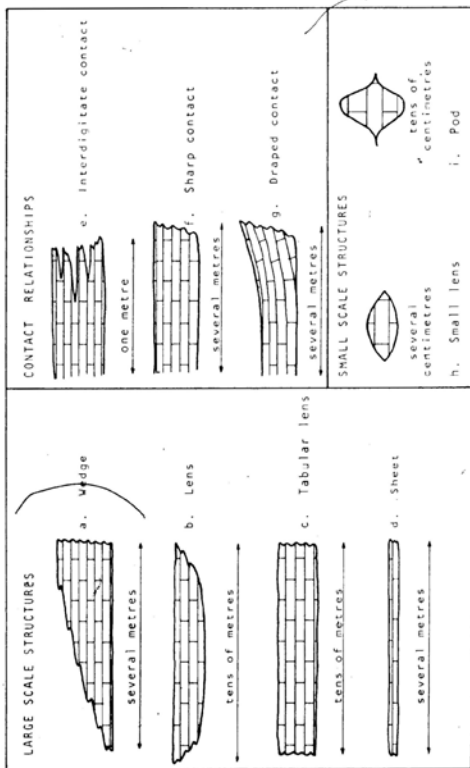
Fig. 9: Sketch illustrating the different geometries of skeletal calcarenite bodies.

LARGE SCALE STRUCTURES

a. Wedge — several metres

b. Lens — tens of metres

c. Tabular lens — tens of metres

d. Sheet — several metres

CONTACT RELATIONSHIPS

e. Interdigitate contact — one metre

f. Sharp contact — several metres

g. Draped contact — several metres

SMALL SCALE STRUCTURES

h. Small lens — several centimetres

i. Pod — tens of centimetres

interdigitory) and no thinning occurs towards the moundstone.

(4) Sheet: A thin bed that persists over several metres,
and tapers out laterally.

On a small scale (measurable in centimetres), two mor-
phologies are recognised. (1) Small lens, where the
length of the body is greater than the thickness. (2) Pod,
where the height of the body is equal to, or greater than
the thickness.

As identification of archaeocyathid taxa is difficult
to achieve in the field (Hill, 1972), emphasis was placed
on skeletal morphology of the organisms, which shows con-
siderable variation. The basic, undifferentiated archaeo-
cyathid skeleton is a cup (Hill, 1972), and where it is
possible to see the shape of the cup, then the following
morphotypes are recognised (Fig. 10): (1) Stick (Fig.
10a), the cup has parallel sides throughout the entire
height, which is many times greater than the diameter, it
is circular in cross-section and may lack an intervallum.
This form was later identified as either Archaeocyathus
atlanticus or Metaldetes simpliporous, (F. Debrenne, pers.
comm., 1978). (2) Cone (Fig. 10b-c). This form is ess-
entially an inverted cone expanding vertically from a basal
apex. It is circular in cross-section. Two categories are
recognised: narrow cones (Fig. 10b), where the angle of the
sides of the cup from the horizontal is more than 45 degrees

a. "colonial" stick-forms
Archaeocyathus atlanticus
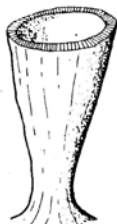
b. Narrow cone
Metaldetes profundus
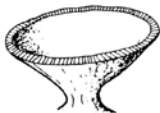
c. Wide cone
Metaldetes profundus

d. Bowl
Metaldetes profundus
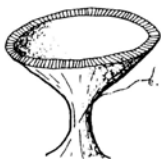
e. Funnel
Metaldetes profundus
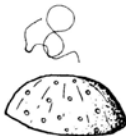
f. Retilaminiform
Retilamina amourensis

Fig. 10: Sketch illustrating the different
archaeocyathid morphotypes.

and wide cones (Fig. 10c), where the angle is less than 45 degrees. In the latter category (although very difficult to observe), if there is no apex, then the morphotype is a bowl (Fig. 10d). If the apex of the cone is elongated over a considerable distance with sides parallel to one another, then a funnel is recognised (Fig. 10e). All the archaeocyathids in the cone category were later identified as *Metaldetes profundus* (F. Debrenne, pers. comm., 1978). (3) *Retilaminiform* (Fig. 10f). This is a new archaeocyathid morphotype and genus, *Retilamina amourensis* (Debrenne and James, in prep.), which is dome-shaped to sheet-like in form (see description in Chapter V: Paleoecology; Archaeocyath-ids).

A new organism, found in the Biostrome Facies, is of uncertain zoological affinities but has been tentatively identified as a primitive skeletal coelenterate. This organism is under study by Kobluk and Sorauf (in prep.) and for the purpose of this thesis it is referred to as a coel-enterate.

Relative abundance of organisms is given as follows: Absent, 0% of rock volume; Rare, 0-5%; Present, 5-10%; Common, 10-25%; Abundant, 25-50%; Very Abundant, more than 50%.

PETROGRAPHY

Introduction

Samples from the two facies were slabbed and approximately 150 thin-sections were prepared from representative portions of the slab. The thin-sections were stained with Alizarin Red-S and potassium ferricyanide to differentiate between calcite and dolomite, and to determine the distribution of ferrous iron in the samples (Dickson, 1966; Davies and Till, 1968).

Estimates of percentage of components were made visually as was the approximation of the degree of sorting (poor, moderate, good). The grain size is standardized as follows: mud/micrite (less than 4u), silt (4-100 u), fine sand (100-250 u), medium sand (0.25-0.5mm), coarse sand (0.5-2.0 mm), granule (2-4 mm), pebble (more than 4 mm).

Sedimentary and biogenic structures were noted in the field. Most of the biogenic structures (burrows, etc.) appear to be dolomitized (mottled) and are referred to as bioturbation, the percentage of which was estimated visually.

Components

The major components can be divided into skeletal and non-skeletal categories. Skeletal components occur in various states of preservation, most of which are characteristic for each individual taxon, and are used, along with skeletal morphology, for petrographic identification. Echinoderm plates, trilobite carapaces, _Salterella_ cones, Foraminifera, calcareous algae (_Renalcis_, renalcid, and

<u>Girvanella</u>), non-calcareous brachiopods, and most arch-
aeocyathid skeletons have retained most of their original
skeletal structures and are identified by these along with
their characteristic morphologies. Some archaeocyathid
skeletons have undergone aggrading neomorphism and sometimes
dolomitization (see Chapter IV, Diagenesis) but are still
recognisable by their skeletal morphology. On the other
hand, hyolithid cones and calcareous brachiopods (the maj-
ority of brachiopods present) have all been leached and the
voids later filled by a calcite cement. Identification of
these components is more difficult in this case and mor-
phology alone must be relied on.

Non-skeletal components, because of their wide var-
iety of forms and hence terminology, are described below.

Mud matrix

The original mud-sized matrix has nearly always been
neomorphosed to microspar (up to 25 u). Relict patches
of micrite (less than 4 u) are rarely seen, usually in
shelter cavities or between clumps of calcareous algae.

Ooids

Ooids are the most common non-skeletal component in
the Oolite Sand Facies but also occur in Oolitic Calcaren-
ites of the Biostrome Facies. They are preserved in a
variety of ways including; a radial-concentric fabric, a
pseudospar fabric, and a dolomite fabric. These fabrics are

described in detail below (Chapter IV, Diagenesis).

Composite grains (grapestone)

In the rocks under study composite grains consist predominantly of ooids and echinoderm plates. They are often an important constituent in Oolitic Calcarenites of the Biostrome Facies and occur sporadically in the oolitic and oncolitic grainstones of the Oolite Sand Facies. They are smaller in the oolitic grainstones (750 u) and consist of 2 or 3 ooids embedded in micrite, both in the interstices and around the margin of the grain. They are both larger and more common in the oncolitic grainstone and the Oolitic Calcarenites of the Biostrome Facies. Some of the components are truncated at the margins of the composite grain which is subsequently rimmed with micrite. The composite grains commonly form the nuclei of the oncolites. Following the terminology commonly used (Illing, 1954; Purdy, 1963; Winland and Mathews, 1974;), the composite grains in the rocks under study are probably grapestones.

Peloids

The term peloid embraces all grains constructed of an aggregate of cryptocrystalline carbonate, irrespective of origin (McKee and Gutschick, 1969), thus avoiding genetic implications. It is thought however, that elongate ellipsoidal peloids may represent fecal pellets (Bathurst, 1971). In this study, the only peloids, except for the occasional micritized ooid or skeleton, are very well-sorted, small

(130 x 85 u), elongated ellipsoids, suggesting a common
origin; probably fecal.

Rarely, the peloids are replaced by a single calcite
crystal, and more commonly are replaced by dolomite, in the
form of either a single rhomb or several smaller rhombs
(cf. ooids).

Oncolites and encrusted grains

Oncolites, occurring only in the Oolitic Sand Facies,
range in size from 7 mm to a maximum of 35 mm, and have a
nucleus which is either a single skeletal fragment or a
composite grain. The nuclei are then encrusted with tubules
of the blue-green alga Girvanella along with entrapped
quartz grains and small skeletal fragments. The oncolites
are not deformed and have even laminae around the nucleus
(type SS-C of Logan, Rezak and Ginsburg, 1964). They show
evidence of more than one period of growth with a maximum
of three being observed.

Encrusted grains are defined in this study as grains
that are coated on one side only by Girvanella. They never
make up more than 5% of the rock volume.

Algal intraclasts

The only observed intraclasts consist of Girvanella
tubules with microspar filling the interstices, and range in
size from single filaments up to clasts 6 mm long. They
vary in morphology from elongated clasts with ragged margins
and a high proportion of microspar, to perfectly rounded

balls with lesser amounts of microspar. They differ from
oncolites in that they do not posses a nucleus.

Quartz silt

Quartz grains occur only in the silt grade as sub-
angular to sub-rounded grains making up to 50% of some of
the dolomitic siltstone, and occurring in small proportions
throughout the sequence.

CHAPTER III: SEDIMENTOLOGY

LATERAL DISTRIBUTION OF FACIES

Reconnaissance mapping of the study area revealed that the biostrome complex consists of two laterally equivalent facies (see Fig. 72, in pocket): (1) The "Biostrome Facies" consists of a series of archaeocyathid-rich, lime-mud mounds and flanking skeletal calcarenites. (2) An "Oolite Sand Facies" consists of a series of cross-bedded oolitic grainstones, mixed component grainstones, dolostones, and skeletal calcarenites.

That the two facies are lateral equivalents with respect to each other is not in doubt. With the exception of the section of Schooner Cove (Appendix G), all of the outcrops examined in the area consist of lithologies of either the Biostrome Facies or the Oolite Sand Facies. The transition between the two facies can be seen in the large cliff outcrop at Osprey Reef (Appendix C) where the Biostrome Facies passes laterally into cross-bedded oolites of the Oolite Sand Facies (see Fig. 73, in pocket). At Diversion Reef (Appendix B), the Biostrome Facies passes northwards into Salterella-rich oolites, burrowed oolites, dolostones, and calcarenites of the Oolite Sand Facies. The only section where the two facies are interbedded is at Schooner Cove (Appendix G) where archaeocyathid-rich mounds of the Biostrome Facies are inter-bedded with oolitic and oncolitic grainstones of the Oolite Sand Facies.

BIOSTROME FACIES

Introduction

The Biostrome Facies is a complex assemblage of lithologies between 15 and 20 m thick, that occur over a wide area. Using the data from measured sections it is possible to subdivide the Biostrome Facies into several distinct lithological entities. The facies is first divided into UNITS, which are defined as laterally continuous strata bounded by sharp upper and lower contacts. Each unit may contain diverse lithologies but as a whole is regarded as a stratigraphic entity over a large area and can be used in local mapping (but not reconnaissance mapping). Within each unit, LITHOFACIES can be recognised and defined as discrete rock assemblages that are lateral equivalents to one another within a unit. Each lithofacies may contain up to three discrete lithologies which are noted in the description of the lithofacies (see below). The various lithounits are designated as follows:- the Biostrome Facies is designated by an upper case B. Each unit is given identifying upper case letters. Lithofacies are given numbers.

Using this scheme, the Biostrome Facies can be subdivided into five distinct units. Within each of these units, 2 or 3 laterally equivalent lithofacies can be recognised which may contain up to three discrete lithologies.

<u>Generalized Section</u>

A generalized vertical section of the Biostrome Facies is outlined here, and in Figure 11. This is used as a basis for describing the various lithounits. This section is a synthesis of the measured sections described in appendices A-H.

The base of the Biostrome Facies is taken as the first occurrence of moundstone or skeletal calcarenite overlying the siltstones and shales of the open-shelf facies. In most cases, Dolomitic Moundstone (BD-1), with laterally equivalent Black Shales (BD-2) and Skeletal Calcarenites (BD-3) form the basal unit. Sharp lateral contacts occur between archaeocyathid moundstone with dolomite pods, and calcarenite bodies. For contrast, black shales and siltstones grade laterally into both moundstones and calcarenite. This unit is characterized by the large dolomite pods, by interbedded shales, and by a fauna and flora of relatively low density and diversity.

The Dolomite Mound Unit is terminated by a thin but laterally extensive sheet of skeletal calcarenite which is overlain by the Red Mound Unit (BR). This unit consists of archaeocyathid-rich Red Moundstone (BR-1) and flanking Skeletal Calcarenite (BR-2). This unit differs from the underlying Dolomite Mound Unit by its red colour and a fauna and flora of very high density and diversity.

The Red Mound Unit grades upwards into the Nodular Mound Unit (BN) which consists of a black to dark-grey
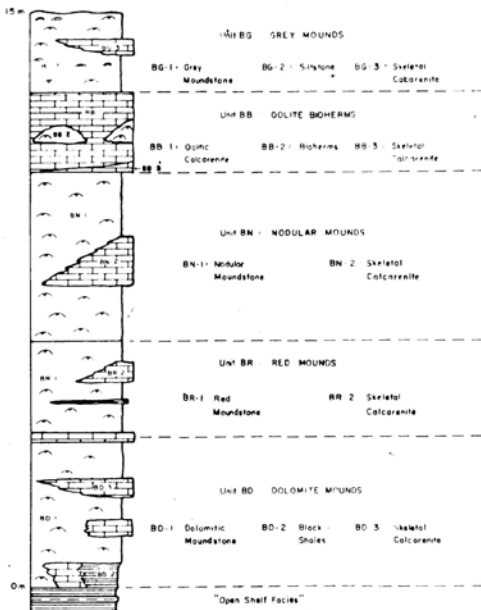
Fig. 11: Generalized section of the Biostrome Facies illustrating the division into five units and five various lithofacies.

Nodular Moundstone (BN-1) with wide-cone archaeocyathids and laterally equivalent Skeletal Calcarenites (BN-2). This unit is characterized by the nodular appearance of the beds and a fauna of low density and diversity.

A sharp contact separates the Nodular Mound Unit from the overlying Oolite Bioherm Unit (BB). Oolitic Calcarenite (packestone to grainstone) is the dominant lithology (BB-1) but contained within the oolites are small Archaeocyathid Bioherms (BB-2).

The topmost unit seen in Labrador is the Grey Mound Unit (BG), which overlies the Oolite Bioherm Unit. This Unit consists of Grey Moundstone (BG-1) flanked by Skeletal Calcarenites (BG-3), and rare Siltstone (BG-2). It is characterized by a grey colour, the abundance of calcareous algae, and the presence of stromatolites.

Description of Lithounits

Five distinct units are recognised within the Biostrome Facies in southern Labrador. Within these five units the two most common lithofacies are: (1) Moundstone, and (2) Skeletal Calcarenite. Siltstone and shale also occur in some of the units but only in minor amounts. The skeletal calcarenite lithofacies are similar in composition throughout the five units so this lithofacies is described only once. On the other hand, the composition of the moundstone varies greatly from unit to unit and these differences are highlighted

in the individual descriptions.

Lithofacies Skeletal Calcarenite: (BD-3, BR-2, BN-2, BG-3, BB-3)

The skeletal calcarenite consists of a white to light-brown resistant wackestone to packestone (common) to grain-stone to archaeocyathid floatstone with a packestone matrix (Fig. 12). The calcarenite is composed mostly of echinoderm debris with disarticulated, but unbroken, inarticulate brachiopod shells, and to a lesser extent trilobites and hyolithids. Large archaeocyathid fragments are common adjacent to the moundstones but are rare away from it. Pockets, up to 20 cm thick, consist almost entirely of in-articulate brachiopod shells and are relatively common. Mud matrix comprises from 0-35% of the rock volume.

The calcarenites are massively bedded and for the most part contain no diagnostic physical sedimentary structures. Minor cross-bedding occurs adjacent to the mounds where the calcarenites often dip off the moundstone at angles up to 15 degrees. The cross-bedding always dips away from the mound. (Fig. 25). Other physical sedimentary structures are rare, occurring only locally where they are generally restricted to one horizon (e.g. mega-ripples and ripple-marks in the Dolomite Mound Unit at Fox Cove (Fig. 13 and 14). Stylolites are common throughout.

Fig.12: Bedding-plane exposure of skeletal calcarenite
which flanks Dolomitic Moundstone (BD-1) at Fox
Cove. The small, white areas (bottom, right) are
archaeocyathid fragments.
Scale is 30 cm long.

Fig.13: Bedding-plane exposure of mega-ripples in skele-
tal calcarenite (BD-2) at Fox Cove.
Hammer is 25 cm long.

Fig.14: Bedding-plane exposure of rippled skeletal cal-
carenite (BD-2) at Fox Cove.
Scale is 30 cm long.

Fig.15: Dolomitic Moundstone lithofacies (BD-1) at Fox
Cove. A pod of dolomite (D) is surrounded by
nodular moundstone.
Notebook is 20 cm long.

The skeletal calcarenites occur in a variety of geom-
etries including wedges, tabular lenses, lenses, sheets and
channels. They also occur as small lenses within several
of the moundstone lithofacies.

Unit BD: Dolomite Mound

This unit occurs in sections only on the Pointe Amour
peninsula at L'Anse Amour, Fox Cove and Schooner Cove but
is laterally persistent within the peninsula. It is also
exposed in the cliff-section at St. Margaret's quarry in
western Newfoundland. The rocks are characterized by the
presence of pods and small lenses of dolomite.

Three laterally equivalent lithofacies occur within
this unit; archaeocyathid moundstone characterized by large
pods and small lenses of dolomite (BD-1), coarse skeletal
calcarenite (BD-3), relatively minor occurrences of black
shale (BD-2).

Lithofacies BD-1: Dolomitic Moundstone

This lithofacies is a light-to dark-grey or green
archaeocyathid rich moundstone with a mudstone (common) to
packestone (rare) matrix and weathers grey to green to brown
with a pitted appearance. The skeletal fraction is dominated
by archaeocyathids, most of which are upright. Other skele-
tal components include the coelenterate which is only loc-
ally abundant and is often absent altogether. Subordinate
skeletal components include inarticulate brachiopods and
trilobites. Detrital quartz silt is very common in this
lithofacies.

Stylolites, often delineated by dolomite, are prevalent throughout the moundstone giving it a nodular appearance. A very coarsely crystalline pink calcite commonly fills voids.

Small (several centimetres), skeletal calcarenite lenses contribute approximately 15% by volume to the lithofacies and may have orginally contributed more as their margins are also marked by stylolites.

One of the diagnostic features of the Dolomitic Moundstone lithofacies is the occurrence of large (tens of centimetres) pods of finely crystalline dark-green to light-grey dolomite, which weather light to dark brown and buff (Fig.15). The relatively large pods or lenses attain a maximum size of 2.0 x 1.5 m and every gradation is seen in the geometry from a laterally expanded lens to a laterally compressed pod. The contact with the surrounding moundstone is always stylolitized and it is probably because of the intense development of stylolites in the moundstone and absence of them in the dolomite that causes the moundstone to have the appearance of being "wrapped around" the dolomite pods. Several pods show, in weathered cross-section only, distinct laminations and evidence of organic activity in the form of vertical and inclined burrows (Fig.16). Skeletal particles are, however, rare as only one or two upright archaeocyathid cups were found along with the rare skeletal calcarenite lenses.

Lithofacies BD-2: Black Shales

This lithofacies consists of fissile, black shales which grade laterally and vertically into fine siltstones with occasional small lenses of skeletal calcarenite. The shales are of small lateral extent passing laterally, over a few metres, into both skeletal calcarenite and moundstone. The contact between calcarenite and shale is transitional through silts, but the contact between shales and moundstone (seen only at Fox Cove) shows the shales to be draping off the moundstone at angles up to 30 degrees. Small-scale ripples rarely occur in the shales and both skeletal and ichnofauna are absent.

Lithofacies BD-3: Skeletal Calcarenite

Skeletal calcarenites in the Dolomite Mound Unit occur as wedges of limited lateral extent, tabular lenses, and sheets, both extending for tens of metres.

Unit BR: Red Mound

This widespread unit occurs at Blanc Sablon, Osprey Reef, L'Anse Amour and Fox Cove and is distinguished by its red colour and high faunal and floral density and diversity. Although laterally persistent, the unit is often relatively thin and always variable, attaining substantial thickness (more than 15 m) only at Osprey Reef.

Two laterally equivalent lithofacies are distinguishable within the unit: an archaeocyathid rich, red moundstone (BR-1); and laterally equivalent medium to coarse-grained calcarenite (BR-2).

Lithofacies BR-1: Red Moundstone

This lithofacies is a red archaeocyathid moundstone with a mudstone, to rarely packestone matrix containing minor detrital quartz silt and skeletal material (up to 15%). The rock weathers dark red to green, and has a distinctive nodular appearance because of intense stylolitization (Fig. 17). No sedimentary structures are present. The skeletal component is dominated by upright archaeocyathids, with narrow cones predominating over stick forms. Retilamini-forms are common and wide cones are rare. Brachiopods are common but trilobites are rare. The coelenterate occurs throughout and calcareous algae is abundant. A coarsely crystalline pink calcite commonly fills primary cavities.

About 10% of the lithofacies consists of small lenses of skeletal calcarenite which are always bounded by stylo-lites.

Lithofacies BR-2: Skeletal calcarenite

Skeletal calcarenites occur in the Red Mound Unit as wedges of small extent, and as a complex lithofacies mosaic at Osprey Reef (see Appendix C and Fig. 73).

Unit BN: Nodular Mound

This unit is found only on the Pointe Amour peninsula at L'Anse Amour and Fox Cove. It is distinguished by the way that it weathers which gives it a nodular, rubbly, dark-coloured, apparently featureless appearance; and by the relatively low density of archaeocyathids (Fig. 18).

Fig.16: Weathered exposure of a dolomite pod (in BD-1 at Fox Cove) showing laminations and burrows. Scale is in centimetres.

Fig.17: Archaeocyathid-rich, nodular Red Moundstone (BR-1) at Fox Cove. Scale is 30 cm long.

Again two laterally equivalent lithofacies are recognised within this unit; an archaeocyathid-bearing nodular moundstone, and a coarse-grained skeletal calcarenite.

Lithofacies BN-1: Nodular Moundstone

This lithofacies consist of black to dark-grey nodular moundstone with a mudstone and quartz silt (up to 15%) matrix, and weathers dark brown to black with a rubbly appearance. Skeletal elements include rare to common, upright or toppled archaeocyathids with funnel shapes more common than stick forms or cones. Subordinate fauna consists of unbroken, disarticulated inarticulate brachiopods, rare coelenterates and Girvanella, and skeletal debris. The bedding is nodular because of the profusion of styllolites.

Skeletal calcarenite lenses within the moundstone comprise between 10-50% of the volume of the rock and a green to black lime-shale comprises approximately 5% of the total volume.

Lithofacies BN-2: Skeletal Calcarenite

Skeletal calcarenite occurs only as wedges with a maximum lateral extent of 20 m.

Unit BB: Oolite Bioherm

This unit occurs only in sections measured on the Pointe Amour peninsula at L'Anse Amour, Fox Cove, and Schooner Cove. Three lithofacies are recognised, an archaeocyathid moundstone with a mudstone matrix forming small bioherms (BB-2), oolitic calcarenite (packestones-grainstones) (BB-1),

and skeletal calcarenite (BB-3). The unit is distinguished
by the presence of oolitic grainstones, the dominance of
calcarenite over moundstone, and the occurrence of mound-
stone in small, discrete bioherms.

Lithofacies BB-1: Oolitic Calcarenite

This lithofacies consists of a diverse suite of oolitic
packestones and grainstones (Fig. 18). The lithofacies
includes clean oolitic grainstones; a common occurrence
of oolitic packestones (15% mud matrix) with irregu-
larly coated ooids, grapestones, oolitically coated grains,
and local developments of skeletal stromatolites; a very
coarse-grained skeletal oolitic grainstone where ooids
occur with brachiopods, trilobites, occasional archaeo-
cyathid cups and Salterella cones.

The size of the ooids varies greatly and fining up-
wards sequences occur, reflected in both the size of the
ooids and the proportion of skeletal material. No other
sedimentary structures occur although sharp contacts with-
in the sequence are common. Selective dolomitization of
ooids occurs and stylolites are present.

Lithofacies BB-2: Archaeocyathid Bioherms

Red to grey to green archaeocyathid moundstone bio-
herms with a mudstone to packestone matrix occur locally
throughout the unit. The bioherms have a flat to slightly
convex base and are strongly convex at the top. The maximum
thickness is at the centre of the structure and tapers away

on both sides until the structure pinches out altogether.
The contact with the oolites is interdigitatory. No sedi-
mentary structures are observed. Retilaminiform archaeo-
cyathids are abundant at the base occurring with calcar-
eous algae but are replaced upwards by narrow cone archaeo-
cyathids with thick walls, and sticks. Brachiopods,
trilobites and calcareous algae are present. Skeletal
debris forms up to 20% by volume of the matrix. Stylo-
lites are present.

Lithofacies BB-3: Skeletal Calcarenite

Skeletal calcarenites in the Oolite Bioherm Unit occur
as laterally impersistent lenses extending laterally for
up to tens of metres.

Unit BG: Grey Mound

This unit occurs in sections measured at Blanc Sablon,
L'Anse Amour and Fox Cove, where it forms the highest beds
seen. It is distinguished by a predominantly light-to
dark-grey colour, the abundance of calcareous algae, and
the occurrence of non-skeletal and skeletal stromatolites.
Compared with other units it is relatively poorly exposed
so the lateral extent and equivalent rock-types are poorly
known. Three laterally equivalent lithofacies can be rec-
ognised, however, an algal/archaeocyathid grey moundstone
(BG-1), medium to coarse-grained skeletal calcarenite (BG-3),
and calcareous siltstone (BG-2).

Lithofacies BG-1: Grey Moundstone

This algal-archaeocyathid moundstone is light-grey in colour and has a mudstone matrix, containing up to 30% quartz silt, and weathers light-to dark-grey with a pitted surface (Fig. 19). Bedding and other sedimentary structures are absent. Archaeocyathids are rare to abundant, both upright and overturned, and are generally smaller in size than in other units. Cones, stick-forms, and retilamini-forms are present. Brachiopods are present, calcareous algae and both skeletal (Girvanella) and non-skeletal stromato-lites are widespread. Stylolites, although present, are not as common as in the other units.

Lithofacies BG-2: Siltstone

This lithofacies consists of a fine-grained, slightly calcareous siltstone which occurs only at the base of the unit in one outcrop, as the lateral equivalent to the skele-tal calcarenite and in turn the moundstone. The contact between the silt and the calcarenite is transitional, one grading into the other over a short distance (less than 10 m). The siltstone is laminated and shows ripple-laminations as well as interference ripple-marks. No skeletal fauna is ob-served but there is a profuse ichnofauna with well preserved burrows, tracks and trails. This siltstone is very similar to that found in the open-shelf facies underlying the bio-strome complex.

Lithofacies BG-3: Skeletal Calcarenite

The skeletal calcarenite of the Grey Mound Unit occurs

Fig.18: Cliff-section of Nodular Moundstone (BN-1) over-
lain sharply by bedded Oolitic Calcarenites (BB-1)
at Fox Cove.

Fig.19: Cliff-section exposure of Grey Moundstone (BG-1)
and flanking skeletal calcarenites (BG-2) at
Blanc Sablon. Range pole is graduated in 20 cm
increments.

as small wedges, tabular lenses, and as a channel-like
structure at Blanc Sablon which is described in detail in
Appendix A.

OOLITE SAND FACIES: DESCRIPTION OF LITHOLOGIES

Introduction

In contrast to the Biostrome Facies, the Oolite Sand
Facies is very poorly exposed and in only three areas can
sections be measured (see Appendices C, D, H). Using the
data from these sections, augmented by petrographic analy-
sis, a total of seven lithologies can be recognised; (1)
Skeletal grainstone, (2) Oolitic grainstone, (3) Mixed
oolitic grainstone, (4) Mixed peloid packestone, (5)
Mixed oncolitic grainstone, (6) Intraclast grainstone,
(7) Dolostone-dolomitic siltstone.

Lithologies are named using the most abundant comp-
onent, and depositional texture (after Dunham, 1962; Embry
and Klovan, 1971) but other features were also taken into
account in their description, e.g. sorting, grain size, and
physical and biogenic structures. The lithologies are sum-
marized in Table I and are described below.

Lithologies

(1). Skeletal grainstone

The skeletal grainstones are poorly to moderately sorted
and range in size from silt through to granule grade. The
skeletal components, in order of decreasing importance are;
echinoderm plates, Salterella cones, trilobite carapaces,

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TABLE 1: Summary of composition and structures of lithologies in the Oolite Sand Facies

		Lithologies in the Oolite Sand Facies	Skeletal Grainstone	Oolitic Grainstone	Mixed Oolitic Grainstone	Mixed Peloid Packstone	Mixed Oncolitic Grainstone	Intraclast Grainstone	Dolomite Dolomitic Siltstone
STRUCTURES	PHYSICAL	Bioturbation							
		Cross-bedding							
		Ripple Lamination							
		Lamination							
COMPONENTS	SKELETAL	Girvanella	(2-5)			(2)	(20-30)	(65)	
		Salterella	0-40	0-5		20	10-20		
		Hyolithids	0-5			2	5-20		
		Trilobites	0-10	0-5	5	5	0-5		2-15
		Brachiopods	0-10		5				0-10
		Echinoderms	25-55	2-20	7	15	15		0-5
	NON-SKELETAL	Algal Intraclasts						65	
		Encrusted grains	0-5			2		5	
		Oncolites					20-30		
		Silt	0-5	0-5		3	0-5		0-50
		Grapestones		0-2			0-5		
		Peloids	0-10		0-40	40	0-10		
		Ooids	0-15	75-90	45-80	2	5-30		
GRAIN SIZE		Crystalline							
		Pebble							
		Granule							
	Sand	Coarse							
		Medium							
		Fine							
		Silt							
		Mud							
SORTING		Good							
		Moderate							
		Poor							

KEY
- - - Range
··· Average
0-100 Percentage of component by visual estimate

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hyolithid shells, brachiopod shells, and tubules of the
blue-green algae _Girvanella_. Less than 15% of the com-
ponents are non-skeletal allochems; ooids, peloids, quartz
silt, and encrusted grains. The sediments are generally
bioturbated with dolomite mottle occupying up to 20% of the
rock. This calcarenite differs from the skeletal calcaren-
ite of the Biostrome Facies in that it is bioturbated, often
contains _Salterella_ cones, encrusted grains, a wider variety
of allochems, and contains no mud fraction.

(2). _Oolitic grainstone_

The oolite grainstones are well-sorted and consist pre-
dominantly of coarse, sand-grade ooids (up to 90% of
components), with minor amounts of non-skeletal components,
quartz silt, and composite grains. In some samples skeletal
components, mainly echinoderm plates, trilobites, and _Salt-
erella_, make up to 20% of the total components. Planar cross-
bedding is common (Fig. 20).

(3). _Mixed oolitic grainstone_

The mixed oolitic grainstone is a moderately sorted,
medium to coarse-grained, sand-size grainstone consisting
mainly of ooids (40-80%), but with large proportions of
other components, in this case peloids and skeletal material
(echinoderms, trilobites, and brachiopods).

(4). _Mixed peloid packstone_

The mixed peloid packstone is a poor to moderately
sorted (mud to granule-size grade) packstone with peloids
forming the main component (40%), but with a large skeletal
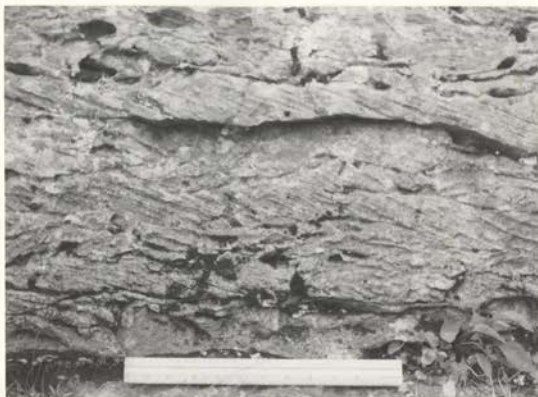
Fig.20: Cross-bedded oolitic calcarenites of the Oolite
        Sand Facies, Osprey Reef.
        Scale is 30 cm long.
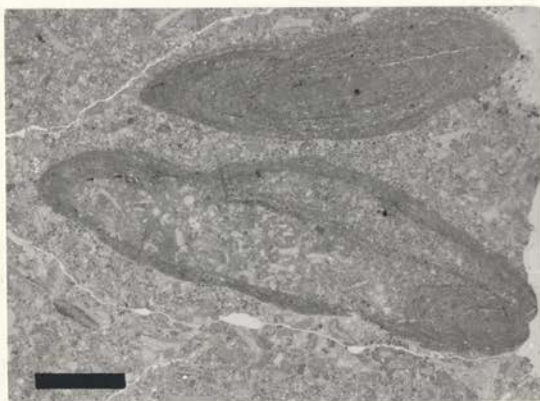
Fig. 21:Photomicrograph (plane light) of the mixed oncolite
        grainstone lithology showing two large oncolites
        (one with three periods of growth) in a grainstone
        matrix of ooids, peloids, echinoderm plates and
        other skeletal material.
        Scale bar is 5 mm.

content (40%) of <u>Salterella</u> cones, echinoderm plates, trilo-
bites, hyolithids and <u>Girvanella</u>. About 10% of the rock
consists of dolomitic mottling (probably bioturbation).

(5). <u>Mixed oncolitic grainstone</u>

The mixed oncolitic grainstone is a poorly sorted,
silt to pebble grain-size grainstone composed of <u>Girvanella</u>
oncolites, with lesser, but significant proportions of
ooids, peloids, quartz silt, and composite grains (Fig. 21).
Skeletal components include <u>Salterella</u>, echinoderms, hyo-
lithids, and trilobites. Up to 20% of the rock-volume is
dolomite mottling (bioturbation).

(6). <u>Intraclast grainstone</u>

The intraclast grainstone is a poorly sorted, silt to
pebble grade grainstone consisting almost entirely of algal
intraclasts, either as rounded balls or as elongated clasts
with ragged edges (Fig. 22). The intraclasts consist of
<u>Girvanella</u> tubules with no apparent nuclei. Skeletal
(unidentified) grains encrusted with <u>Girvanella</u> contribute
less than 5%. One-third of the rock-volume consists of
very coarse spar which fills in the primary porosity, and
geopetal microspar.

(7). <u>Dolostone-dolomitic siltstone</u>

This lithology ranges from 100% crystalline dolomite
with a very sucrosic texture, to a dolomitic siltstone con-
sisting of 50% crystalline dolomite and 50% detrital quartz
silt. Skeletal components occur sporadically but are always
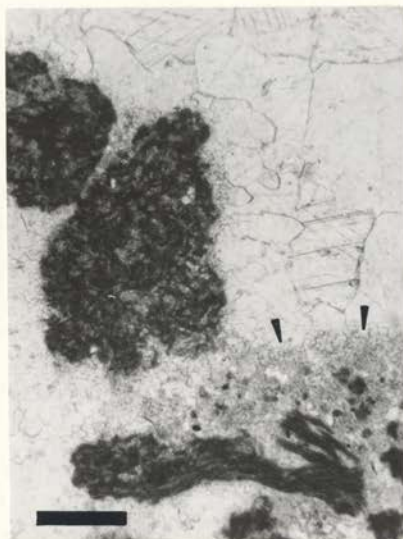
Fig.22: Photomicrograph (plane light) of the
intraclast grainstone lithology show-
ing both rounded and elongate, ragged
clasts, both consisting entirely of
Girvanella tubules. Note geopetal
sediment (arrowed) above ragged clast
and the abundance of pore-fill cement.
Scale bar is 0.45 mm.

partially dolomitized. Sedimentary structures include horizontal, parallel, and ripple lamination. About 10% of the rock is bioturbated.

DISCUSSION

Correlation

Geologic mapping of the area studied indicates that the Biostrome Facies and the Oolite Sand Facies are lateral equivalents and represent two completely different sedimentary regimes which occurred simultaneously at the time of deposition (see Fig. 72, in pocket). Contacts between the two facies are either abrupt and can be walked out along strike (as at Osprey Reef, Appendix C; and Diversion Reef, Appendix B) or are inter-digitatory (as at Schooner Cove, Appendix G) with rocks characteristic of each facies alternating in a vertical sequence. In other measured sections, using the top of the open-shelf facies as a datum, the sequences consist wholly of either the Biostrome Facies or the Oolite Sand Facies.

Within each facies lithologic correlation is extremely difficult due to the lateral variation of lithofacies and lithologies. This is exemplified in the Oolite Sand Facies at Diversion Reef (Appendix B) where incomplete exposure and lateral variation of lithologies make correlation impossible. Such variation indicates that rapid lateral changes in environmental conditions occurred in the sedimentary regime at the time of deposition. It has been established,

however, that the Oolite Sand Facies consists of seven
distinct but gradational litholigies, each characteristic
of the environment in which it was deposited so the gen-
eral picture of the sedimentary environment can be formu-
lated. Differences between the five units of the Biostrome
Facies are real, although slight, but could be used for
detailed mapping only because of the rapid lateral changes.
All the units are similar in terms of texture (they are all
moundstones), most have identical flanking skeletal cal-
carenites, and all contain archaeocyathids. The major
differences between the units are colour of sediment, den-
sity & diversity of organisms, morphologies of archaeo-
cyathids, and diversity of calcareous algae.

The Dolomitic Moundstone (BD-1) is characterized by
the presence of dolomite pods at certain localities. There
is a relatively low density and diversity of organisms while
calcareous algae is absent.

The Red Moundstone lithofacies (BR-1) differs greatly
from the Dolomitic Moundstone by being red in colour, having
the highest density and diversity of organisms, and contain-
ing abundant calcareous algae.

The Nodular Moundstone lithofacies (BN-1) is very simi-
lar to the Dolomitic Moundstone but has more shales and a
lower density and diversity of organisms.

The Grey Moundstone lithofacies (BG-1) is character-
ized by its grey colour and by the abundance of calcareous
algae and both skeletal and non-skeletal stromatolites.

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The Archaeocyathid Bioherm lithofacies (BB-2) is internally similar to the Red Moundstone but differs by forming discrete bioherms within Oolitic Calcarenites (BB-1).

On a broad scale, the five units were probably deposited in a similar environment with slight differences in parameters (depth, light, energy, etc.) producing the characteristic features of the units.

The units within the Biostrome Facies can be correlated locally on the Pointe Amour peninsula between L'Anse Amour, Fox Cove, and to a certain extent Schooner Cove. This gives an indication of the true biostromal nature of the facies. On a larger scale, however, lateral variation of measured sections prevents precise correlation, but taking the top of the open-shelf facies as a datum, it is considered that the sections are contemporaneous.

The lateral distribution of the Red Mound Unit (BR), the most widespread of the five units, illustrates the problems of correlation and emphasizes the lateral variation within the Biostrome Facies. At Blanc Sablon (Appendix A), Red Moundstone is only 1.30 m thick and is both underlain and overlain by rocks of the Grey Mound Unit (BG). About 8 km to the east at Osprey Reef (Appendix C), the Red Mound Unit exceeds 15 m in thickness and occurs in lateral contact with the Oolite Sand Facies. A further 10 km to the east the Red Moundstone is 2.30 m thick at Fox Cove (Appendix F) where it is underlain by Dolomitic Moundstone

(BD-1) and overlain by Nodular Moundstone (BN-1). Less
than 5 km to the north-east at Schooner Cove, however,
the Red Mound Unit does not occur at all, possibly replaced
by rocks of the Oolite Sand Facies.

Other units; the Dolomite Mound (BD), Nodular Mound
(BN), and Oolite Bioherm (BB), are restricted to, but later-
ally persistent within, the Pointe Amour peninsula. Most
of the section at Blanc Sablon consists of rocks of the
Grey Mound Unit. This unit is only seen at the top of the
section at Fox Cove and L'Anse Amour and is inter-bedded
between oolitic calcarenites at Schooner Cove. This further
illustrates the difficulty of both local and large scale
correlation within the Biostrome Facies.

Depositional Environment of the Oolite Sand Facies

Each of the seven lithologies documented in the Oolite
Sand Facies have diagnostic features which are used to form-
ulate an appropriate environment of deposition. The litho-
logies described earlier are discussed in turn below.

(1) Skeletal grainstone

The grainstone texture of this lithology and the worn
and often broken nature of the components suggests an en-
vironment of constant wave or current action where mud is
removed by winnowing (Wilson, 1975). The skeletal content
of the calcarenites suggests a shallow, sub-tidal origin of
the components (Heckel, 1972). Such sediments are accumula-
ting today in the Persian Gulf and the Bahamas in a position

seaward of oolite tidal shoals (Heckel, 1972; Purser, 1973;
N. James, pers. comm.). The stratigraphic occurrence of
the skeletal grainstone with oolites in the rocks under
study would support a shallow, sub-tidal, agitated environ-
ment seaward of an oolite sand shoal.

(2) Oolitic grainstone

By comparison with modern occurrences of well-formed
(uniformly coated) ooids, the oolitic grainstones are
interpreted to have formed in well-agitated inter-tidal
or shallow sub-tidal environments (Bathurst, 1971). The
occurrence of herring-bone cross-bedding at Osprey Reef
(Appendix C) indicates current reversal and infers an
inter-tidal origin (Reineck and Singh, 1975) although meas-
urement of current direction from all cross-beds at Osprey
Reef indicates a polymodal direction (Fig. 23). The ool-
itic grainstones are considered, therefore, to have formed
in inter-tidal or shallow sub-tidal, high energy oolite
tidal shoals, similar to environments described from the
Bahamas (Ball, 1967; Bathurst, 1971) and the Persian Gulf
(Loreau and Purser, 1973).

(3) Mixed oolitic grainstone and (4) Mixed peloid
     packestone

No sedimentary structures were observed in either of
these lithologies so analogy with modern environments must
be relied on to interpret the depositional environment.
Skeletal, peloid calcarenites are accumulating in inter-tidal

n = 17
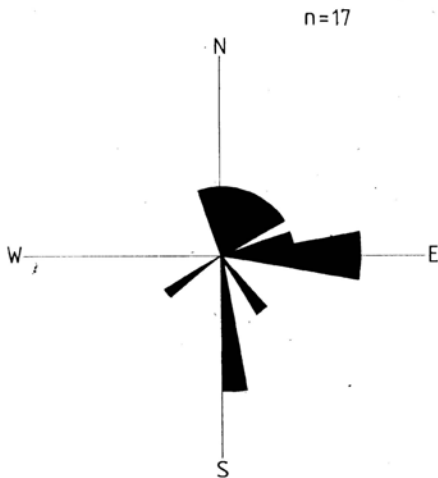
Fig. 23: Rose diagram of inferred paleocurrent
directions from cross-bedded oolites,
Osprey Reef.

zones within oolite bars or in shallow, protected sub-tidal
zones behind tidal oolite shoals along the Trucial Coast
of the Persian Gulf (Loreau, and Purser, 1973; Purser and
Evans, 1973). As there is no indication of inter-tidal
structures and the skeletal components suggest a sub-tidal
origin, the shallow, protected sub-tidal environment behind
an oolite shoal is preferred. The mixed oolitic grainstone
can be considered gradational with the mixed peloid grain-
stone and formed in a similar environment although closer
to the actual source of ooids.

(5) Mixed oncolitic grainstone

Diagnostic components in this lithology are composite
grains (grapestone), and oncolites. Grapestones occur in
areas of uneven turbulence (alternating intervals of cement-
ation and agitation), low sedimentation rates and high water
circulation rates (Winland and Mathews, 1974). Oncolites
form in a variety of environments, some favouring high-energy
and continual motion (Ginsburg, 1960; Logan et al., 1964),
some shallow-water and moderately high-energy (Wilson, 1975).
They are also found in sheltered, inter-tidal areas and in
stable sand channels between mobile oolite shoals (Bathurst,
1971). As several of the oncolites show periodic growth,
with grapestones forming the nuclei, a high-energy, continual
motion environment is not favoured. A shallow, sub-tidal,
medium-high energy environment with slow deposition and
fluctuating turbulence is favoured. This environment may

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occur in stable sand channels between oolite shoals (Bath-
urst, 1971).

(6) Intraclast grainstone

The fragmented (ragged) to rounded nature of the
Girvanella clasts suggests that they have been ripped up
from a nearby source, probably an algal (Girvanella) mat,
and redeposited. The degree of roundness may reflect
different lengths of time in the transport regime. The
geopetal microspar may have been secondarily introduced
(vadose silt?) as it occurs in leached skeletons now filled
with cement, implying that the skeleton was leached before
deposition of the silt. The intraclast grainstone may
therefore, be a storm deposit, formed in an environment
usually above sea-level and only submerged during storm
flooding. The rapid deposition would explain why all of
the clasts are not rounded in what would appear to be a high
energy deposit (a grainstone texture).

(7) Dolostone-dolomitic siltstone

The environment of deposition of this lithology is
also not clear. The occurrence of dolostones in a facies
which is, for the greater part, undolomitized may suggest
that dolomitization was early, possibly penecontemporaneous
with deposition. Recent penecontemporaneous dolomite is
recorded from the supratidal environment, forming inches
above the high-tide level (Shinn et al., 1965). The dolo-
stones under study are, for the most part, structureless but

are sometimes laminated, burrowed, and rarely ripple-
laminated. Recent supra-tidal dolomite crusts are simi-
lar, being for the most part structureless with occasional
laminations, burrows, and mud cracks, (Shinn et al., 1965).
No mud cracks were observed in the dolostones but this may
have been due to the badly weathered nature of the outcrop.
The dolostones are considered, therefore, to have formed
in a dominantly supra-tidal environment which was period-
ically submerged (during storms?) to accommodate the quartz
silt, and produce rare ripple laminations.

The seven lithologies described and discussed can all
be attributed to formation within an oolite shoal complex,
and can be compared to modern day environments, particularly
in the Persian Gulf (Loreau and Purser, 1973; Purser and
Evans 1973). Lack of outcrop prevents detailed discussion
of the geometry of the oolite shoal although a general model
can be presented.

Cross-bedded oolitic grainstones formed under optimum,
high-energy conditions for ooid growth, probably in the
inter-tidal or shallow sub-tidal environments. In between
individual shoals, mixed oncolite grainstone accumulated
slowly in stable sand channels. The oolite shoals built up
sufficiently to become emerged above the high-tide level
where supra-tidal dolomite formation occurred. This envir-
onment, on the crest of the shoals, was periodically inundated
by storm floods, possibly also producing the intraclast
grainstone. Winnowed, skeletal grainstones occurred seaward

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of the oolite shoal in a medium-energy, shallow, sub-
tidal environment, where a wide variety of organisms flour-
ished in well-aerated waters. In quieter areas, behind the
oolite shoals the mixed oolitic grainstones and mixed pel-
oid packestones accumulated as oolite shoal spillover with
mixed oolitic grainstones occurring closer to the shoal.

Depositional Environment of the Biostrome Facies

Essentially, two major lithofacies occur within the
Biostrome Facies; skeletal calcarenite, and moundstone.
Variation is considerable within the moundstone but the
calcarenites which flank the mounds are essentially the
same and indicate that the variation in environmental para-
meters which controlled the distribution of organisms which
contribute sediment to the calcarenite lithofacies was not
great.

Diagnostic characteristics of a particular depositional
environment are lacking in the calcarenties. They probably
formed under sub-tidal conditions, almost certainly quiet-
water as there is a lack of fragmentation or wear of the
skeletal components, and there is a mud content of up to
30% which was not winnowed out. This is the opposite situa-
tion to the skeletal calcarenite of the Oolite Sand Facies
which is a grainstone and often has fragmented and worn
skeletal components. This suggests that the skeletal cal-
carenite of the Biostrome Facies accumulated in a lower energy,
more protected environment, possibly below the wave base.

For the most part, the skeletal calcarenites are massive
bedded and do not contain any sedimentary structures. Where
sedimentary structures do occur they are restricted to a
single horizon as at Fox Cove (Appendix F) where mega-ripples
(with wavelengths of more than 1 m) can be traced in a
single bed for more than 300 m (Figs. 13 and 70). Mega-
ripples are generally indicative of very high-energy
(Reineck and Singh, 1975), but as this is the only indica-
tion of high-energy, the mega-rippled horizon is inter-
preted as storm generated. The fact that the mega-ripples
are preserved and have not been reworked is a possible in-
dication of the prevailing low energy conditions. Ripple
marks (symmetrical, asymmetrical and interference) are
often associated with calcarenites and siltstones at the
base of the Biostrome Facies adjacent to the contact with
the open-shelf facies (e.g. Blanc Sablon, Appendix A; Fox
Cove, Appendix F; L'Anse Amour, Appendix E), but the occur-
rences are regarded as indicative of the sedimentary re-
gime of the open-shelf facies and that the contact between
the two is really transitional.

The origin of the ooids in the Oolitic Calcarenite
lithofacies (BB-1) merits special attention. A proport-
ion (20-30%) of the ooids show a high degree of asymmetry
of the oolitic layers about the nucleus (Fig. 24), and some-
times the nucleus protrudes through incomplete coatings.
The incomplete coatings abut the nucleus so are not the re-

sult of abrasion, and although the coatings have a scal-
loped appearance, it is the result of differential growth
of the layers.

Ooids are generally considered to be generated in a
high-energy environment (Bathurst, 1971). The irregular
ooids, however, are similar to those formed today in a low-
energy environment in the Lauguna Madre, Texas and described
as 'quiet-water' ooids (Freeman, 1962). The mud content
(approximately 15% of rock volume) of these oolitic pack-
estones, and the absence of sedimentary structures indica-
tive of high-energy conditions, supports the origin of these
ooids in a relatively quiet-water environment. The occur-
rence of small, archaeocyathid bioherms and small, skele-
tal (_Girvanella_) stromatolites embedded within the 'quiet-
water' ooids suggest normal marine conditions as regards
circulation, salinity, etc. The presence of normal ooids,
however, suggests that an active oolite shoal was close by
and probably acted as a source for the majority of ooids,
some of which then grew irregular coatings in the lower-energy
environment.

The skeletal calcarenite lithofacies throughout most
of the five units is interpreted therefore as having formed
under normal marine, relatively quiet-water conditions, but
probably shallow-water enough to be affected by storms.

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As the archaeocyathid mounds are always found in lat-
eral contact with the skeletal calcarenites, then a simi-
lar environment (low-energy, shallow marine) is interpreted
for the mounds as well. Supporting evidence for relatively
quiet water conditions is the high percentage of upright
archaeocyathids in all of the moundstone lithofacies and
supporting shallow water is the occurrence of calcareous
algae in some of the moundstones. The dominance of sus-
pension feeders (archaeocyathids, echinoderms, brachiopods,
etc.) and presence of silt-grade quartz in both the mound-
stones and calcarenites suggests however, that the water
was continuously turbulent to some degree, with currents
powerful enough to keep silt in suspension. It is poss-
ible, however, that the silt may have been of windblown
origin.

The draping (up to 15 degrees) of the skeletal calcar-
enite beds off the mounds implies that the mounds formed
topographic highs on the sea-floor although field observa-
tions suggest that this relief was in the order of only
one or two metres. The elevation of the mounds (not always
seen) may have been induced by the baffling of mud by
archaeocyathids, or early cementation of the mounds, or a
combination of both.

Differences between the five moundstone lithofacies
are sufficient for more precise environments of deposition
to be suggested. These differences, along with stratigraph-
ical evidence can be used to suggest a paleogeographical model.

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The Dolomite Mound Unit (BD) is restricted to the
Pointe Amour peninsula and consists of low elevation,
but laterally extensive mounds flanked by skeletal cal-
carenites (Fig. 25), and rarely shales. The mounds are
devoid of calcareous algae and have a low density and div-
ersity of archaeocyathids and other organisms. The absence
of calcareous algae, which is commonly associated with
archaeocyathids elsewhere in the sequence, may suggest
deposition below the photic zone. The exact depth of
deposition is not known, but the occurrence of calcarenites
interpreted as storm-induced deposits interbedded with cal-
carenites indicating prevailing low-energy conditions sug-
gests that deposition probably occurred below wave-base,
but in water shallow enough to be affected by storms. The
dolomite pods are interpreted as being initially small
areas of mud occurring within, but differing from, the mound
sediments (see discussion in Chapter IV, Diagenesis). The
muds supported a different fauna (as evidence by trace fos-
sils which do not occur in the moundstones) and probably
occurred in shallow, protected depressions within the arch-
aeocyathid mounds. The Dolomite Unit contains shales, has
a high silt content, and overlies and is in part laterally
equivalent to the siltstones and shales of the open-shelf
facies. It probably represents the initial stage of the
development of the biostrome complex. The widespread Red
Mound Unit (BR) consists of a complex lithofacies mosaic

Fig.24: Photomicrgraph (plane light) of irregularly coated
ooids in the Oolitic Calcarenite (BB-1). Note in-
complete coatings which give the scalloped appear-
ance of ooids. Scale bar is 0.45 mm.

Fig.25: Contact relationships between Skeletal Calcarenite
(BD-2) and Dolomitic Moundstone (BD-1) at Fox Cove.
Skeletal calcarenite thins towards, and is replaced
laterally by, moundstone. Structurally, the strata
are flat-lying but the calcarenite drapes off the
moundstone at about 12°. Note minor cross-bedding
(arrowed) associated with the angle of drape.
Scale (centre left) is 30 cm.

of laterally restricted (tens of metres), low elevation
mounds and flanking skeletal calcarenites. Calcareous
algae, and to a lesser extent non-skeletal stromatolites,
are abundant in the Red Moundstone (BR-1) implying deposi-
tion within the photic zone. The high density and diversity
of archaeocyathids and other organisms suggests a well-
aerated environment. The thickest development of the Red
Mound Unit occurs at Osprey Reef (Appendix C) where it is
in lateral contact with cross-bedded oolites. The channel-
ing of the moundstones by skeletal calcarenites (Fig. 26),
along with their association with cross-bedded oolites
would suggest that deposition of the Red Mound Unit was
under relatively high-energy conditions, possibly within
the surf zone.

The red colour of the moundstones poses a problem as
marine red beds are rare in the stratigraphic record. In
order for them to be preserved, either continuous oxidiz-
ing conditions are needed during deposition, or rapid burial
must occur before reduction takes place (Heckel, 1972).
In view of the shallow water, well-oxygenated,high-energy
environment of the Red Moundstone lithofacies, it is more
likely that the sediments remained in a continously oxidiz-
ing condition during deposition and burial.

The Nodular Mound Unit (BN) is restricted to the Pointe Amour
peninsula and consists of indistinct, but laterally exten-
sive, low relief mounds flanked by wedges of skeletal cal-

Fig.26: Red Moundstone (BR-1) channeled by Skeletal
Calcarenite (BR-2) at Osprey Reef. Note irreg-
ular outline of erosive contact, and truncation
of archaeocyathid skeleton (arrowed) in the
moundstone.
Scale is in centimetres.

carenite at L'Anse Amour (Appendix E). At Fox Cove (App-
endix F) however, smaller but still indistinct mounds are
recognised by; an increase in the density of archaeo-
cyathids, an increase in the proportion of skeletal calcar-
enite, and an absence of shales. These mounds are surround-
ed by minor shales and nodular mudstones which support a
sparse fauna. On the whole, the Nodular Moundstone litho-
facies (BN-1) resembles the Dolomitic Moundstone (BD-1).
There is an absence of stromatolites and calcareous algae
(except for rare skeletal components coated with _Girvan-_
ella which may be transported). The density and diversity
of archaeocyathids and other organisms is similarly low.
The Nodular Mound Unit (BN), therefore, occupies a similar
environment as the Dolomite Mound Unit (BD); both deposited
in a relatively deep-water (below the photic zone and wave-
base), quiet environment.

The locally developed moundstones of the Oolite Bio-
herm Unit (BB) are internally similar to those of the Red
Moundstone lithofacies (BR-1), with abundant calcareous
algae, and with a high density and diversity of archaeo-
cyathids and other organisms. Geometrically, however, the
Archaeocyathid Bioherm lithofacies (BB-2) forms small,
discrete, strongly convex mounds or bioherms which are flan-
ked by 'quiet-water' oolitic calcarenites (see above). The
exact depositional environment of this unit can only be
speculated because of the peculiar nature of the sediments.

It is suggested, however, that the sediments were deposited
in a shallow (within the photic zone), clear, relatively
quiet environment with, perhaps, periodic moderate turbu-
lence which formed the irregular coated ooids. This en-
vironment is likely to be found in a shallow swale between
ooid shoals where a mix of the characteristics of both
the Biostrome Facies and the Oolite Sand Facies would
occur.

The most characteristic feature of the Grey Moundstone
lithofacies (BG-1) is the common occurrence of skeletal
(Girvanella) and non-skeletal stromatolites. Small, digit-
ate, non-skeletal stromatolites (Fig. 27) (SH-V type of
Logan et al., 1964) occur at Blanc Sablon (Appendix A)
where archaeocyathids are rare or absent. Skeletal (Girv-
anella) stromatolites (Fig. 28) (LLH-C type of Logan et al.,
1964) occur at the top of the sequence at L'Anse Amour
(Appendix E) and may indicate temporary inter-tidal con-
ditions. For the most part, the Grey Moundstones form low
relief, laterally extensive (tens of metres) mounds which
contain abundant archaeocyathids and calcareous algae, and
which are flanked by skeletal calcarenites consisting of
fossils representing a normal, sub-tidal fauna, which show
no signs of transport or wear. This would indicate that
the Grey Mound Unit was deposited in a predominantly shallow
sub-tidal low-energy environment which possibly shallowed
periodically into the inter-tidal zone. The lateral contact

Fig.27: Photomicrograph (plane light) of non-skeletal stromatolites (type SH-V) in the Grey Moundstone lithofacies (BG-1) at Blanc Sablon. Note archaeocyathid (Archaeocyathus) at bottom left. Scale bar is 4.5 mm.

Fig.28: Skeletal (<u>Girvanella</u>) stromatolites (type LLH-C) in the Grey Moundstone lithofacies (BG-1) at L'Anse Amour. Scale is in centimetres.

of the Grey Mound Unit with the spillover part of the oolite
shoal at Diversion Reef (Appendix B), and the vertical
association of the same two units at Schooner Cove (App-
endix G) suggests that the Grey Mound Unit occupied a pos-
ition behind the active part of the oolite shoal and con-
sequently favoured a protected environment often adjacent
to the spillover part of the oolite shoal.

Statigraphy

Mapping of the major facies indicates that the Oolite
Sand Facies was deposited to the north or north-west of
the Biostrome Facies and that the contact between the two
facies is highly irregular. The map (Fig. 72, in pocket)
indicates that salients of the Oolite Sand Facies existed
to the west of Forteau and around the bay of L'Anse au Loup,
with corresponding recesses to the north of Blanc Sablon
and on the Pointe Amour peninsula (with the exception of
Schooner Cove).

The distribution of Biostrome Facies units suggests
that the maximum development of the deeper-water units
(BD and BN) occupy positions further away from the Oolite
Sand Facies in a south-east direction while shallow-water
units (BR and BG) occur with their maximum development
adjacent to Oolite Sand Facies and occupy a position to the
north-west of the deeper-water units. This would indicate
that the paleoslope was trending towards the south-east
and that the Biostrome Facies was deposited seaward of the

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Oolite Sand Facies.

Figure 29 illustrates a simplification of the facies and units relationships interpreted from the measured section (Appendices A-H) and uses Fox Cove as the reference section. Deeper-water units (BD and BN) occur only on the Pointe Amour peninsula. In the measured sections at Fox Cove (Appendix F) and L'Anse Amour (Appendix E), the Dolomite Mound Unit (BD) and the Nodular Mound Unit (BN) are separated vertically by a thin bed of Red Moundstone (BR-1). This relationship suggests that the Dolomite Mound and Nodular Mound Units were deeper-water, lateral equivalents of the Red Mound Unit which was deposited seaward, and thickens towards a contact with the Oolite Sand Facies (see Fig. 29). The lower part of the sequence at Fox Cove and L'Anse Amour can be interpreted as a gradual shallowing and then deepening episode. The Dolomite Mound Unit (BD) was initially deposited as a lateral equivalent to, and then overlay, the siltstones and shales of the open-shelf facies. The Dolomite Mound Unit then shallowed sufficiently for the deposition of the calcareous algae-rich Red Mound Unit to be deposited. This event was short-lived, however, as the deeper-water Nodular Mound Unit overlies the Red Mound Unit. The remainder of the sequence consists of shallow-water units; Oolite Bioherm (BB) and Grey Mound (BG) Units. These are separated from the underlying Nodular Mound Unit by a planar erosion surface. The occurrence of these shallow-

Fig. 29: Schematic synthesis of correlation and facies relationships in the biostrome complex of the Forteau Formation of southern Labrador (not to scale).

water units on the Pointe Amour peninsula may represent a
general regression in the area.

The measured section on the north-east side of the
Pointe Amour peninsula, at Schooner Cove (Appendix G) is
the only sequence where rocks of the Biostrome Facies and
Oolite Sand Facies are intercalated. The Dolomite Mound
Unit (BD) again overlies the open-shelf Facies but is now
overlain itself by skeletal calcarenite which becomes ooli-
tic towards the top. This is probably the lateral equiva-
lent of the Red Mound Unit at Fox Cove. The remainder of
the sequence consists of the shallow-water Grey Mound Unit
(BG) intercalated with rocks characteristic of the spill-
over area of the oolite sand shoal. The corresponding beds
at Fox Cove would be the deeper-water Nodular Mound Unit
(BN). At the top of section archaeocyathid bioherms are em-
bedded in 'quiet-water' oolites. Most of the succession
at Schooner Cove would seem to represent lateral shifting
of shallow-water deposits. Such lateral shifting is sug-
gested as the sequence at Fox Cove and L'Anse Amour has the
Grey Mound Unit (BG) overlying the Oolite Bioherm Unit (BB)
while 3 km to the north-east at Schooner Cove, the reverse
is seen.

The inland sections at Osprey Reef (Appendix C) and
Diversion Reef (Appendix B) are important as both sections
show lateral relationships between the Biostrome Facies
and the Oolite Sand Facies and are therefore useful in any

paleogeographic reconstruction. Basically, the section
at Osprey Reef shows the thickest development of Red
Mound Unit (BR) in lateral contact with cross-bedded oolites
representing an active oolite shoal. At Diversion Reef,
however, the Grey Mound Unit (BG) is in lateral contact
with mixed skeletal-peloid-oolitic-oncolitic calcarenites
and dolostones characteristic of the spillover area of an
oolite shoal. It is significant that the open-shelf facies
thickens considerably in the northern part of the section
at Diversion Reef (Fig. 65, Appendix B) indicating that
the Oolite Sand Facies as a whole is tapering northwards.
This suggests that the oolite shoal itself is merely a
lens, replaced to the south by the Biostrome Facies and to
the north by the open-shelf facies.

The most north-westerly measured section of the Bio-
strome Facies to the north of Blanc Sablon (Appendix A)
consists entirely of shallow-water deposits overlying
siltstones and shales of the open-shelf facies. The se-
quence consists of two beds of rocks of the Grey Mound Unit
(BG) separated by a thin bed of Red Moundstone (BR-1). This
sequence may possibly be correlated with the lower part of
the sequence at Fox Cove and L'Anse Amour where a thin bed
of Red Moundstone separates the deeper-water Dolomite Mound
Unit (BD) and the Nodular Mound Unit (BN). These success-
ions may have been caused by a temporary expansion of the
oolite sand shoal which caused the adjacent Red Mound Unit

to displace other units. In the case of Fox Cove, the deeper, seaward Units (BD, BN) were replaced; while at Blanc Sablon, the shallow-water Grey Mound Unit was displaced. The lack of rocks representing the Oolite Sand Facies in the area around Blanc Sablon indicates that this area was a recess in the oolite shoal, but the shallow-water nature of the rocks may indicate that they were deposited between two oolite shoals (see Fig. 30).

The sequence at Forteau (Appendix D) and L'Anse au Loup (Appendix H) consists entirely of rocks of the Oolite Sand Facies. Both sequences can be considered to be caused by lateral shifting of facies within the spillover area of the oolite shoal.

Paleogeography

Because of the rapid lateral and vertical changes in lithology experienced in most of the outcrops, any paleogeographical model must be an oversimplification of the true distribution of lithofacies. Bearing in mind that lateral shifting of the shallow-water facies was probably considerable, the model presented (Fig. 30) gives an indication of the facies distribution at one particular time. Stratigraphic evidence suggests that the Biostrome Facies was deposited seaward and south-east of the Oolite Sand Facies. The Oolite Sand Facies consisted of rocks constituting an oolite shoal which can be divided into; an active oolite shoal of cross-bedded oolitic grainstones deposited
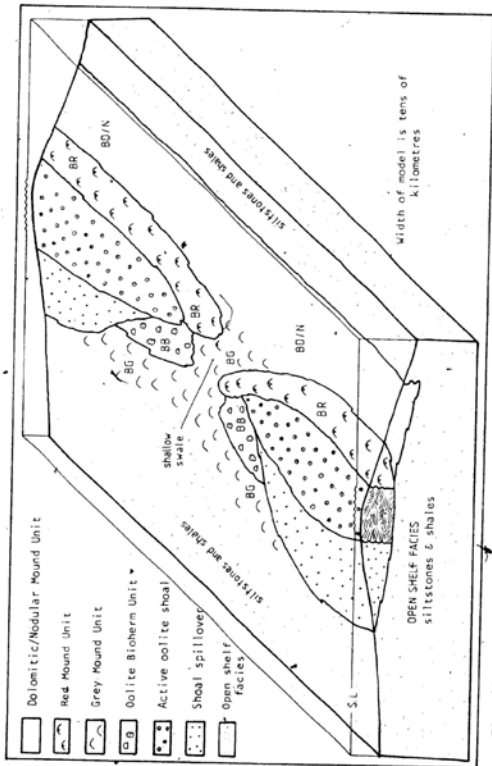
Fig. 30: Schematic model of sedimentation for the biostrome complex of the Forteau Formation of southern Labrador.

Legend:
- Dolomitic/Nodular Mound Unit
- Red Mound Unit
- Grey Mound Unit
- Oolite Bioherm Unit
- Active oolite shoal
- Shoal spillover
- Open shelf facies

Labels within figure: BD/N, BR, BG, BB, shallow swale, OPEN SHELF FACIES siltstones & shales, siltstones and shales, Width of model is tens of kilometres, SL

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in a shallow-water, high-energy environment, and a shoal spillover which was deposited in quieter-water behind the active oolite shoal. Seaward, but in contact with the active oolite shoal, was deposited the Red Mound Unit (BR) in shallow-water, high-energy conditions. In slightly deeper-water (below the shallow photic zone), sediments of the Dolomite Mound Unit (BD) and Nodular Mound Unit (BN) accumulated and probably passed seaward into silt-stones and shales (N. James, pers. comm). Facies mapping indicates that the contact between the Oolite Sand Facies and the Biostrome Facies is highly irregular and suggests that salients, recesses, and possibly breaks occurred be-tween shoals. In some shallow swales between oolite shoals, archaeocyathid bioherms accumulated, flanked by 'quiet-water' oolites (Uniy BB), with the ooids initially derived from the adjacent shoals. Also on the shallow swales, but generally occupying positions behind the active oolite shoal but in lateral contact with the shoal spillover, the Grey Moundstone Unit (BG) was deposited. The development of extensive stromatolites in this unit suggests that inter-tidal conditions may have prevailed for some of the time.

Such a facies distribution has broad similarities with recent carbonate environments such as the Trucial Coast of the Persian Gulf (Purser and Godfrey, 1973), and Joulters Cay, Bahamas (N. James, pers. comm.). In both cases, organic reefs are accumulating seaward of an active oolite shoal

with spillover sediments accumulating behind. The model
has a close analogue with the Type 1: Downslope mud accu-
mulation, shelf margin profile of Wilson (1975).

CHAPTER IV: DIAGENESIS

INTRODUCTION

Diagenesis of the various calcarenite lithologies
in the Oolite Sand Facies and the flanking calcarenites
of the Biostrome Facies are described as one entity be-
cause the diagenetic processes which affected them are
essentially the same, differing only in minor detail. The
various moundstone lithologies of the five assigned units
also share a common diagenetic history, again only diff-
ering in detail, and so are described as a second entity.

The diagenetic features are also tabulated using the
sedimentological division so that comparisons of features
can be made within each unit of the Biostrome Facies
(Table II).

Several processes have modifed the original depositi-
tional texture of both the moundstones and the calcarenites;
bioerosion, cementation, neomorphism, dolomitization,
silicification, pressure solution, and fracturing. Each
of the processes is described in turn (where applicable)
for both moundstones and calcarenites.

DIAGENESIS OF THE MOUNDSTONE LITHOFACIES

Bioerosion

Evidence of microboring organisms (such as micritic
tubules or envelopes) is absent from the moundstone com-
ponents although macroborings are relatively common in
several of the units (Figs. 31 and 32). The macroborings
are cylindrical tubes with a diameter of between 0.5 mm

TABLE II. Distribution of diagenetic fabrics within the five units.

LITHOLOGY — Unit	Lithofacies	DOLOMITE MOUND (DD)	RED MICRO (RM)	NODULAR MOUND (NN)	GREY MOUND (MG)	OOLITE BIOHERM (ND)
		Mound / Calc.	Mound / Calc.	Mound / Calc.	Mound / Calc.	Mound / Calc.
BIOEROSION — microborings		- / -	- / -	- / -	- / -	- / C
BIOEROSION — macroborings		A / -	C / -	- / -	- / -	C / -
CEMENTATION — cloudy fibrous		A / -	A / -	R / -	A / -	A / -
CEMENTATION — syntaxial		- / C	- / A	- / C	- / A	- / C
CEMENTATION — scalenohedron		A / C	A / C	C / C	A / C	A / C
CEMENTATION — ferroan pore-fill		C / R	A / R	R / C	C / -	C / R
NEOMORPHISM — ... of mud to microspar		A / A	A / A	A / A	A / A	A / A
NEOMORPHISM — ... of archaeocyathids		C / -	C / -	C / -	C / -	C / -
NEOMORPHISM — ... of cement fabrics		- / R	R / -	- / R	- / R	R / -
DOLOMITIZATION — ... of matrix		A / -	R / C	A / C	C / C	C / -
DOLOMITIZATION — ... of skeletons		- / -	- / R	- / R	- / R	R / -
DOLOMITIZATION — Two stages visible		- / -	- / -	- / -	C / C	C / -
STYLOLITIZATION — Irregular, anastomosing		A / C	A / C	A / C	R / C	- / C
STYLOLITIZATION — Peaked, low-amplitude		- / C	- / C	- / C	- / C	- / C
STYLOLITIZATION — Horse-tail		- / -	C / -	A / -	- / -	R / -
STYLOLITIZATION — Nodular-bedding		C / -	A / -	A / -	A / -	- / -
STYLOLITIZATION — Fracturing		- / -	A / -	C / -	C / -	- / R

KEY
- Absent
R Rare
C Common
A Abundant

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Fig.31: Bedding-plane exposure of Dolomitic Mound-
stone (BD-1) at Fox Cove showing archaeocyathids
(<u>Metaldetes</u>) and lime-mud matrix, both penetrated
by macroborings (small, dark dots) of the ichno-
fossil <u>Trypanites</u>.
Scale bar is in centimetres.
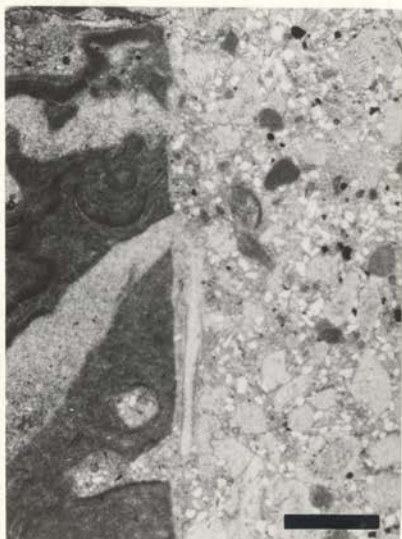
Fig.32: Photomicrograph (plane light) of
         archaeocyathid skeleton (left)
         truncated by the macroboring
         ichnofossil _Trypanites_. The
         vacant boring has since been in-
         filling with skeletal debris
         (right).
         Scale bar is 0.45 mm.

and 2 mm, and a length of between 2.5 mm and 3.5 mm. As
such these traces can be assigned to the morphogenus
Trypanites (Magdefrau). They penetrate archaeocyathid
skeletons, clumps of renalcid algae, and the matrix of
the rock, which is either cut cleanly, implying lithifica-
tion, or is pushed aside. The borings have been subse-
quently filled with either the surrounding matrix, (Fig.
32) or with cloudy, fibrous calcite cement (Fig. 48).

Cementation

The amount of obvious cementation is dependent on
the available pore-space and varies greatly between units,
in some cases occurring only in intra-skeletal pores of
archaeocyathid skeletons.

Two categories of cements are recognised within the
moundstone: (1) Rim-cements, which fringe particles;
(2) Pore-fill cements, which fill that part of the pore
not already occluded by rim-cement.

Rim-cements

Three different rim-cements can be distinguished with-
in the moundstone: (1) a cloudy fibrous cement (common),
(2) a clear scalenohedron cement (common), (3) a micrite
cement (rare?).

The cloudy fibrous cement is non-ferroan but rich in
inclusions which give it a brown colour. It occurs as the
first cement precipitated in a radial fibrous habit with
sweeping extinction in the following places: in the intra-

skeletal pores of archaeocyathid skeletons (Fig. 34); be-
tween, and encrusting bases of pendant coelobitic organ-
isms (Fig. 33); in between heads of small digitate stroma-
tolites; interlayered with internal sediments; lining the
floors of cavities. It is also found as blocky, equant
crystal rinds within internal sediment in the cavities,
around skeletons within the sediment, and lining the floors
of cavities. Broken, equant fragments of this cement also
occur as part of the internal sediment (Fig. 35).

The clear, scalenohedron calcite cement is also non-
ferroan and varies from equant, blocky crystals, to blades,
to a fibrous fabric. Correspondingly, the axial ratio
varies from 2:1, to an average of 3/4:1, to 8:1. The cem-
ent occurs chiefly in skeletons of archaeocyathids where it
is either the first cement precipitated (Fig. 36), or is
precipitated on top of cloudy fibrous cement (never the
reverse), in which case the bases of the individual crystals
are in optical continuity with the cement substrate. Pores
are often occluded with this cement. It also succeeds
cloudy fibrous cement encrusted onto the base of the coelo-
bitic organisms in cavities beneath retilaminiform archaeo-
cyathids and sometimes occluded with blades of this cement.

A possible micrite cement is precipitated between clumps
of pendant renalcid algae in cavities but is probably much
more widespread (see discussion).

Fig.33: Photomicrograph (plane light) of a
         cavity beneath Retilamina. The under-
         side of the skeleton of Retilamina (top)
         has a thick development of cloudy fibrous
         cement (C). Both the fracture (Z) and the
         remaining cavity (F) are occluded by
         iron-rich pore-fill cement. Note
         internal sediment forming the floor of the
         cavity.
         Scale bar is 0.45 mm.
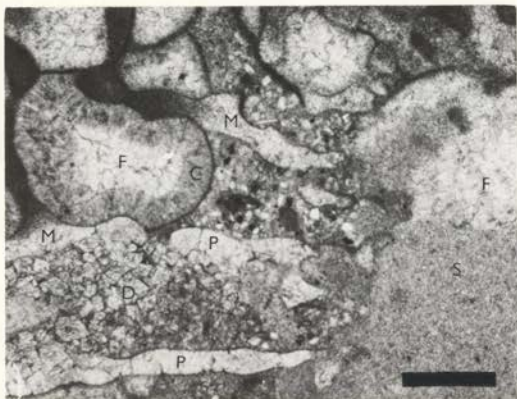
Fig.34: Photomicrograph (plane light) of archaeocyathid
skeleton. Original microgranular skeleton (black)
has undergone aggrading neomorphism to microspar
(M) and pseudospar (P). The central cavity (right)
has been partially filled with internal sediment
(S). Intra-skeletal pores often have thick rinds
of cloudy fibrous cement (C) and are occluded,
along with the remaining space in the central
cavity by iron-rich pore-fill cement (F). Some
of the intra-skeletal sediment has been dolomi-
tized. (D).
Scale bar is 0.45 mm.
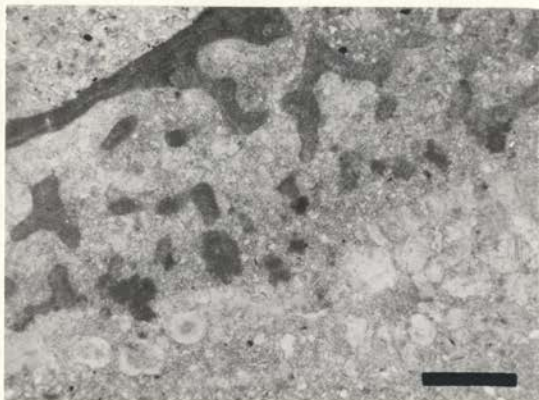
Fig.35: Photomicrograph (plane light) of part of a
skeleton of _Retilamina_ (dark area). Beneath
Retilamina is a matrix consisting mostly of
broken fragments of cloudy blocky cement.
Scale bar is 0.45 mm.
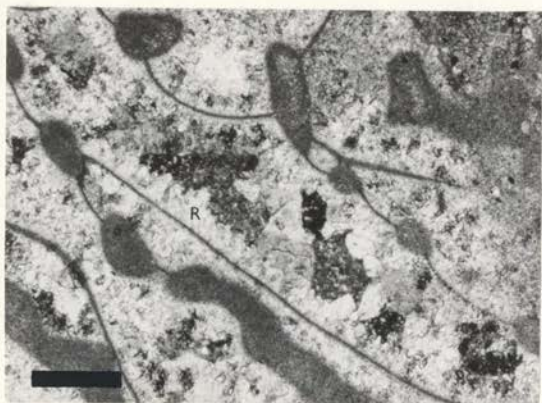
Fig.36: Photomicrograph (cross-polarized light) of an
archaeocyathid skeleton. Intra-skeletal por-
osity is occluded by a rim of clear, iron-poor
scalenohedron calcite cement (R) followed by
iron-rich pore-fill cement.
Scale bar is 0.4 mm.

Pore-fill cements

Pores within archaeocyathid skeletons, syndeposition-
al cavities, and solution cavities not already occluded by
rim-cements, and all fractures are filled with ferroan,
pink, often coarsely crystalline calcite (Figs. 33, 34
and 36). Solution of many aragonitic skeletons (brach-
iopods, hyolithids, etc.) probably occurred coeval with or just
prior to the precipitation of this cement as the cavities
thus formed are always filled with ferroan cement (rarely
the rim-cements).

Neomorphism

Three different neomorphic fabrics are recognised in
the moundstone lithofacies: (1) aggrading neomorphism of
mud matrix to microspar, (2) aggrading neomorphism of
archaeocyathid skeletons to microspar and pseudospar,
(3). recrystallization of cement fabrics to pseudospar.

Most of the mud-sized matrix of the moundstones has
undergone aggrading neomorphism from micrite to homogeneous
microspar (25u). Rare patches of relict micrite exist,
normally between clumps of coelobite organisms in cavities.

The microgranular (calcite) skeleton of archaeocyathids
has commonly undergone aggrading neomorphism from its orig-
inal form to microspar with relict patches of the micro-
granular fabric enclosed within it. The microspar has then
been aggraded to clear crystals of ferroan pseudospar, which
strongly resembles a pore-fill cement, but is regarded as

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neomorphic as the complete transition from microgranular calcite to pseudospar is often observed (Fig. 37).

The recrystallization of the radial cloudy fibrous calcite cement to a blocky, cloudy pseudospar fabric rarely occurs.

Dolomitization

The most extensive dolomitic fabrics form the large dolomite pods (Fig. 15) in the Dolomite Moundstone lithofacies (BD-1). The dolomite rhombs are euhedral and form a homogeneous, idiotopic texture. Individual crystals are iron-rich, with an average size of 25u. Small isolated patches of skeletal calcarenite and archaeocyathids are enclosed by the dolomite, and isolated rhombs occur throughout the calcarenite.

Partial, patchy dolomitization is common throughout the moundstone. The dolomite is again homogeneous, euhedral, idiotopic, and iron-rich with crystals averaging between 30-60u in size but ranging from 25-200u. A later, coarser dolomite occurs rarely with rhombs averaging 185-200u. Both stages post-date fracturing of the rock, so occur relatively late in the diagenetic history.

Although pervasive, the dolomitization often leaves echinoderm plates undolomitized except for corroded margins, but sometimes preferentially selects archaeocyathid skeletons, particularly those already neomorphosed to pseudospar.

Dolomite rhombs also occur as styloreactates.
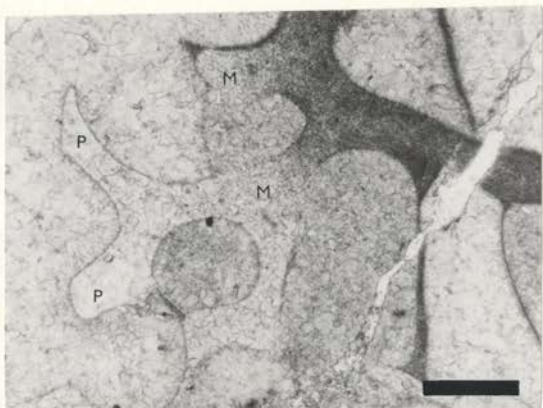
Fig.37: Photomicrograph (plane light) illustrating the
aggrading neomorphism of an archaeocyathid
skeleton. The original microgranular skeleton
(dark area) has been aggraded to microspar (M)
and pseudospar (P).
Scale bar is 0.3 mm.

Stylolitization

Abundant stylolites occur as two types; (1). Irregular, anastomosing swarms of non-sutured seams (Wanless, in press), where the seams are gently undulating, often divide and rejoin, and are associated with thick stylocumulates, (2). Horse-tail stylolites, defined as "wispy, subparallel microstylolites that converge into a single residual seam" (Mossop, 1972).

Within the units, stylolites vary in density from absent to abundant, and when abundant give a stylonodular appearance to the rock.

Quartz silt, clay minerals, and heavy minerals generally occur as stylocumulates, and dolomite rhombs grow as styloreactates.

Fracturing

Fractures vary in density from absent to common, and although they can be up to 3 mm wide, are generally much smaller. Fracturing occurred after the precipitation of rim-cement and was probably coeval with the precipitation of the equant ferroan pore-fill cement which always occludes the fractures (Fig. 33).

DIAGENESIS OF THE CALCARENITES

Bioerosion

Evidence of the activity of microborers is indicated by the presence of micritic envelopes (Bathurst, 1966) around components and by the rarer occurrence of totally micritized peloids which, because of their size and shape, are not

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fecal pellets.

In this study, microborings are commonly found in ech-
inoderm plates, <u>Salterella</u> cones, hyolithids, and ooids in
the skeletal, oolitic, mixed oolitic, and oncolitic grain-
stones of the Oolite Sand Facies and are restricted to the
Oolitic Calcarenites (BB-1) in the Biostrome Facies. In all
situations, microborings are preserved as micritic tubules are
well-preserved enough to be attributed to the blue-green
algae <u>Girvanella</u> (Fig. 50).

Micrite in the envelope has often been dolomitized and
has rarely been neomorphosed to microspar.

Cementation

Two categories of cement occur in the calcarenites:
(1) Rim-cements which fringe the particles, and (2)
Pore-fill cements of precipitated calcite which occlude that
part of the pore not occluded by the rim-cements.

Rim-cements

A total of 5 different, but sometimes gradational, cal-
cite rim-cements can be distinguished within the calcaren-
ites. Syntaxial overgrowths and bladed scalenohedra are
common while radial-fibrous, blocky scalenohedra, and micrite
are rarer.

Syntaxial cements occur most commonly on, and within,
echinoderm plates, either filling the pores in the plates or
enlarging their margins by syntaxial overgrowth (Fig. 50).

This cement occurs in all lithologies containing echinoderm plates but is not seen on plates possessing micritic envelopes which apparently inhibit any syntaxial overgrowth (Fig. 50). A second type of syntaxial cement is precipitated as non-ferroan bladed scalenohedra between 75u and 300u long with an axial ratio of 5:1, precipitated in optical continuity on to concave lower surfaces of trilobites in mixed peloid and mixed oncolitic grainstones of the Oolite Sand Facies (Fig. 38). The origin of this fabric as cement is not unequivocal, however, and a neomorphic origin cannot be ruled out (see below).

A clear, non-ferroan scalenohedron cement of bladed habit with pyramidal terminations (often iron-rich) to the individual crystals which range between 200u and 500u long with an axial ratio of 3 to 5:1, is often nucleated as the first cement. This cement is found on ooids and peloids in the skeletal grainstones; beneath trilobites in the mixed oolitic grainstones; on peloids and ooids in the oolitic grainstones. It also occurs on trilobites, brachiopods, archaeocyathids, and ooids in the calcarenites of the Biostrome Facies.

The less common radial-fibrous cement occurs as needles or elongated blades, 30-40u long with an axial ratio of 7:1 on ooids in the oolitic calcarenites of both facies.

Blocky spar consists of sub-equant crystals (axial ratio less than 2:1) between 30u and 100u in size. It occurs on

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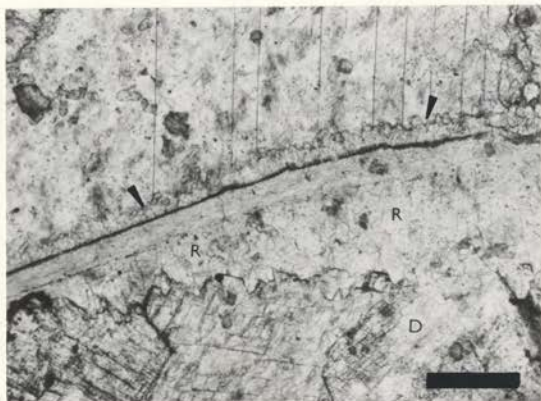
Fig.38: Photomicrograph (plane light) of a trilobite
carapace illustrating gravitational cement.
On top of the carapace a thin rim of clear,
blocky, calcite cement has been precipitated
(arrowed) while on the undersurface, a much
thicker rim of clear, bladed, calcite cement
(R) occurs. Iron-rich, pore-fill cement occ-
ludes the pore-space above the trilobite while
large, iron-rich dolomite rhombs (D) occur
beneath the bladed calcite cement.
Scale bar is 0.15 mm.

the top surface of trilobite carapaces which have bladed
cements on concave lower surfaces (Fig. 38), and occurs as
100u crystals on micritized peloids and ooids in the mixed
oncolitic grainstones. It is well displayed in the intra-
clast grainstone forming a rim of 40u crystals around algal
intraclasts which are not in direct contact with microspar.

A presumed micrite cement occurs within the rare
composite grains in the oolitic grainstones and mixed on-
colitic grainstones of the Oolite Sand Facies.

Pore-fill cements

The same ferroan, coarsely crystalline pore-fill cem-
ent that occurs in the moundstones also occurs in most of
the calcarenite lithotypes. It is absent, however, from
lithologies consisting entirely of echinoderm plates but
contributes up to 40% of the rock volume in the intraclast
grainstone of the Oolite Sand Facies (Fig. 22).

Neomorphism

Neomorphic fabrics occur throughout the calcarenites
in varying amounts and are represented by aggrading neomor-
phism of micrite mud to microspar and formation of microspar
and pseudospar in archaeocyathids. Both of these fabrics
are identical to those described from the moundstones.
Other neomorphic fabrics include the formation of pseudospar
and pseudo-radial microspar in ooids; syntaxial neomorphic
rims and blades on echinoderms plates and trilobites, res-
pectively; and a complete recrystallization fabric.

Ooids in the oolitic calcarenites are neomorphosed in
one of two ways. Commonly the radial-concentric structure
of ooids has been aggraded to a single crystal of clear,
ferroan pseudospar with a "ghost" relict nucleus of an ech-
inoderm fragment (non-ferroan). The margins of the ooids are
nearly always composed of a dark layer, possibly organic, of
varying thickness (Fig.39). Rarely, and only observed in
the oolite calcarenites of the Biostrome Facies, the radial-
concentric structure of the ooids has been neomorphosed to
microspar which displays a pseudo-radial fabric due to the
elongation of some of the crystals normal to the surface of
the nucleus of the ooid.

Some of the syntaxial overgrowths observed on echino-
derm plates and trilobite carapaces may be of neomorphic
origin as they embay the mud (micro-spar) matrix which is
probably of primary origin as the texture of the sediment
in some places is a wackestone, implying that the original
components had to be mud-supported. In one instance, bladed
syntaxial crystals develop on the underside of a two walled
skeleton and replace the interior of the shell as well as
the lower skeletal wall and subsequently embay echinoderm
plates. This may suggest a neomorphic origin of some of
the bladed cement fabrics described above.

A total recrystallization fabric occurs in some of the
oolitic and mixed oolitic grainstones close to the contact
with the Biostrome Facies at Osprey Reef. The fabric dev-
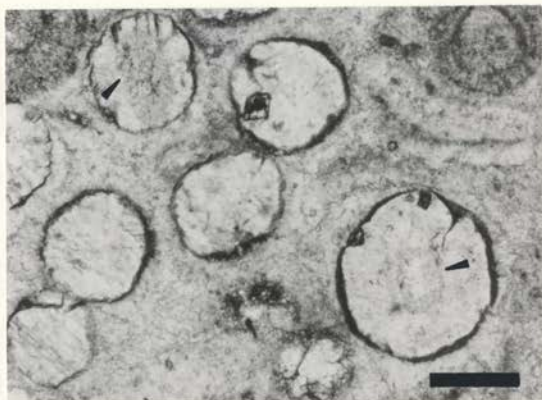
Fig.39: Photomicrograph (plane light) of neomorphosed
ooids. The original radial-concentric structure
of the ooids has been replaced by a single cry-
stal of iron-rich pseudospar. Note the relict
"ghost" nucleus (arrowed) in some of the ooids,
and the black rim on all of the ooids.
Scale bar is 0.3 mm.

eloped here is a mosaic of dolomitized ooids (where dolomite
rhombs have overgrown the margin of the ooid), and medium
to finely crystalline pseudospar.

Dolomitization

Dolomitization is prevalent in the calcarenites in a
number of forms including selective dolomitization of prev-
iously neomorphosed archaeocyathid skeletons and of indiv-
idual ooids, a dolomite mottling fabric, and total dolomit-
ization.

Archaeocyathid skeletons (in the Biostrome Facies cal-
carenites), that have previously been neomorphosed have
often undergone selective dolomitization with large (250u)
ferroan dolomite rhombs replacing the pseudospar.

Dolomitized ooids are common in both facies. Three
basic types of dolomitized ooids occur in the Oolite Sand
Facies ooids. The first type occurs when the ooid is
replaced by a single crystal of ferroan dolomite of aver-
age size 300u which is generally confined to the original
boundaries of the ooid but occasionally transgresses that
boundary (Fig. 40). The second type occurs when the ooid
is replaced by several smaller (60u) crystals of ferroan
dolomite (Fig. 41). This type of dolomitization also occurs
in the Biostrome Facies ooids. The third type consists of
a mosaic of numerous, very small (20-25u) rhombs of ferroan
dolomite. In the latter two cases, the nucleus is rarely
preserved as a corroded echinoderm plate.
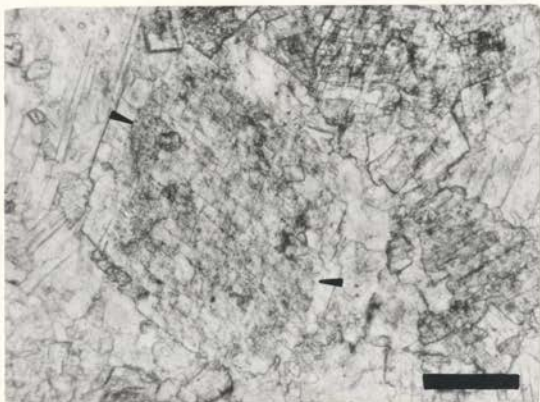
Fig.40: Photomicrograph (plane light) of dolomitized
ooids. The original ooid can be seen as a
vague, dusty relict (arrowed) in the centre of
the large dolomite rhomb. The ooid has been
replaced by the single rhomb of dolomite which
continued to grow beyong the margins of the ooid.
Scale bar is 0.15 mm.

A dolomite mottling texture can often be attributed
to preferential dolomitization of areas of bioturbation
or burrowing (Fig. 42), but in other cases this pervasive
texture is not obviously related to any particular factor.
Distinct dolomitized burrows often have ill-defined margins
which extend into the encompassing sediment. The dolomite
forms as iron-rich equant rhombs in an idiotopic texture
although individual rhombs are often smaller at the centre
of the burrows (15-25u) than at the margins (30-74u). Simi-
lar size ranges and textures are seen in the pervasive
dolomite mottles. In both cases, isolated skeletal com-
ponents (echinoderm plates and trilobites) are surrounded
by dolomite rhombs, but have corroded margins. The mott-
ling is seen in all lithotypes except the oolitic, mixed
oolitic, and intraclast grainstones. Two stages of dolom-
itization can be distinguished in the calcarenites which
flank Grey Moundstone (BG-1). Both stages consist of
euhedral, idiotopic, iron-rich rhombs, differentiated by
their crystal size; the first stage averaging 150u, and the
later stage 600u which commonly occurs in original sydep-
ositional cavities.

Dolostones and dolomitic siltstones are common within
the Oolite Sand Facies. The dolostones can be divided into
fabrics which retain their original components and textures
as "ghost" relics, and fabrics where no original components
or textures are preserved.

The original texture is best displayed by dolomitized
oncolitic grainstones at the top of the section to the west
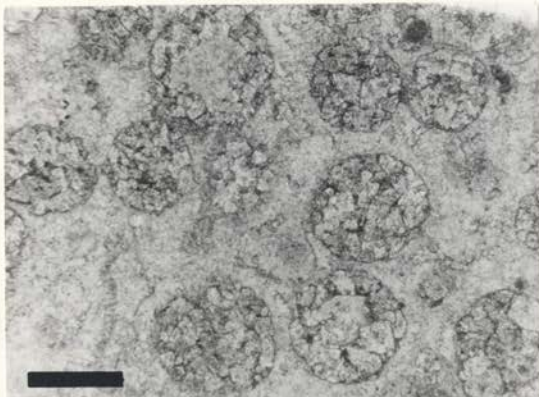
Fig.41: Photomicrograph (plane light) of dolomitized
ooids. The original ooids have been replaced
by several rhombs of iron-rich dolomite. Note the
rim-cements around the ooid have remained unaltered.
Scale bar is 0.45 mm.
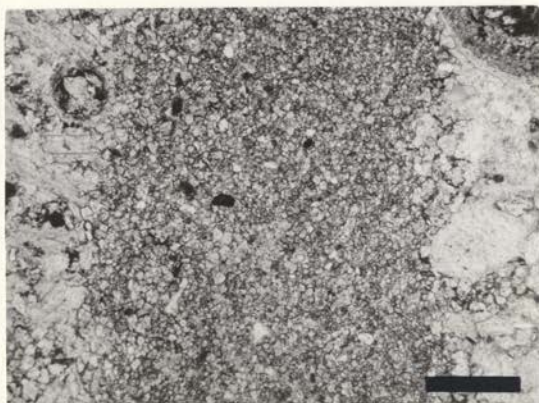
Fig.42: Photomicrograph (plane light) illustrating a
burrow in skeletal calcarenite of the Oolite
Sand Facies. The burrow (centre) has been
selectively dolomitized while the matrix remains
unaltered.
Scale bar is 0.45 mm.

of Forteau. The only grains left undolomitized are echinoderm plates, but even they have corroded margins. The dolomite 'matrix' consists of equant idiotopic (75-250u), Fe-rich rhombs. Components still identifiable in the 'matrix' include Salterella, whose cones have been replaced by clear, non ferroan rhombs (50-100u) with the matrix inside the conch consisting of smaller (25-75u), dusty rhombs. Oncolites now consist of a nucleus of finely crystalline, cloudy dolomite (50-75u), surrounded by clear, coarser, hypidiotopic dolomite rhombs (50-200u), and rimmed with medium size (50-125u), cloudy rhombs. A later stage ferroan, coarse (up to 2 mm) dolomite with strained crystals (curved twins and undulose extinction), partly replaces the earlier dolomite texture of some of the oncolites.

Dolostones with no preserved textures consist of euhedral rhombs in an idiotopic texture and may contain up to 50% quartz silt. Textures with both ferroan dolomite rhombs, surrounded by a mosaic of coarser crystals, probably represent original burrows.

Silicification

Silicification is uncommon, late stage and restricted to the Oolite Sand Facies where chert replaces internal matrix in Salterella cones and forms a fabric consisting of 30% dolomite rhombs and 70% chert. Very rarely, euhedral dolomite rhombs have been totally replaced by quartz.

Pressure solution

Pressure solution at grain contacts due to compaction is rare and is only seen in dolomitic siltstones of the Oolite Sand Facies where quartz grains are seen to embay one another. Stylolites are common in all of the calcarenites and two types can be distinguished: (1) Irregular, non-sutured seams (Wanless, in press). The seams are gently undulating, often divide and rejoin, and are associated with thick (up to 1 mm) stylocumulates consisting predominantly of quartz, clay minerals, and opaque minerals. (2) Clean, sutured seams (Wanless, in press). The seams are jagged of low amplitude and with thin stylocumulates. They trend mainly parallel to bedding, but are rarely normal to the bedding.

It is apparent by the concentration of quartz grains in the stylocumulate as compared to the rest of the sediment, and by the visible dissolution, in some cases of 90% of some ooids, that dissolution was considerable.

Stylolitization appears to have occurred at several times during the history of the rock as it predates pervasive dolomitization in the skeletal grainstones (common), post-dates dolomitization of dolostones (rare) as part of the rhombs have been dissolved, and post-dates dolomitization of the ooids in the mixed oolitic grainstone (rare).

Fracturing

Fractures are rare and consist of thin cracks (less than 65u). The event occurred after the precipitation of rim-cements, and was probably coeval with the precipitation of equant ferroan pore-fill cement which always occludes the fractures.

DIAGENESIS OF OOIDS

The diagenetic sequence of preservation and replacement of ooids is summarized diagramatically (Fig. 43). The order of replacement is always the same; the initial radial-concentric fabric consisting of a nucleus (echinoderm fragment) surrounded by a radiating cortex of calcite prisms interrupted in the outer two-thirds of the ooid by concentric lamellae of dark, possibly organic, material, is neomorphosed to a single, clear, ferroan pseudospar crystal (Fig.39). Micritization (micrite envelope or peloid) sometimes preceeds neomorphism. Partially neomorphosed ooids are only rarely encountered, possibly suggesting an efficient mechanism of replacement. Both neomorphosed ooids and radial-concentric ooids that did not undergo neomorphism were dolomitized in one of several ways. Commonly the ooid is replaced by a single, ferroan dolomite rhomb which occasionally overgrows the margin of the ooid (Fig.40). Several smaller (25-60u) ferroan dolomite rhombs often replace the pre-existing fabric (Fig.41) and sometimes overgrow the margin of the ooid. The
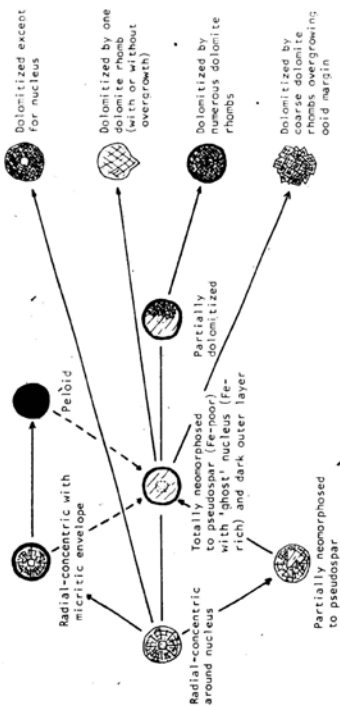
Fig. 43: Sketch illustrating the diagenesis of ooids.

Labels in figure:

Dolomitized except for nucleus

Dolomitized by one dolomite rhomb (with or without overgrowth)

Dolomitized by numerous dolomite rhombs

Dolomitized by coarse dolomite rhombs overgrowing ooid margin

Peloid

Radial-concentric with micritic envelope

Partially dolomitized

Totally neomorphosed to pseudospar (Fe-poor) with 'ghost' nucleus (Fe-rich) and dark outer layer

Radial-concentric around nucleus

Partially neomorphosed to pseudospar

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nucleus (echinoderm fragment) is rarely preserved in
dolomitized ooids and indicates that some of the
radial-concentric ooids were dolomitized without first
undergoing neomorphism. In most cases, both neomor-
phosed and dolomitized ooids are surrounded by a
concentric, marginal layer of dark possibly organic-
rich material (Fig.39). In all cases, rim-cements
precipitated onto the ooids remain unaltered unless
the margin of the ooid (and the cement) is overgrown
by dolomite rhombs.

DISCUSSION

Bioerosion

Bioerosion, in the form of micro-and macroborings
plays a significant role in the development of modern
day reefs (James, 1970; Bromley, 1978) by weakening
skeletal frameworks and producing sediment. Although
the activity of both microborers (represented by tubules,
micritic envelopes and peloids) and macroborers (rep-
resented by borings attributed to the morphogenus
Trypanites), is present, their contribution to the overall
fabric of the rock is minimal. The importance of the
macroborer Trypanites lies in the fact that it is the
oldest macroborer yet recorded (James, Kobluk and
Pemberton, 1977) and thus has important implications in
the evolution of macroboring organisms (Kobluk, James
and Pemberton, 1978).

Cementation

Rim-cements

The several types of rim-cements, including
micrite, were probably precipitated in a number of
diagenetic environments. With the absence of
characteristic criteria however, it is often difficult
to pin-point the precise location of precipitation
of some of the cements, particularly as it is unwise
to rely on the cement fabric alone which is more often
than not seen to be precipitated in more than one
environment (Schroeder, 1973).

The cloudy fibrous cement is interpreted as being
submarine in origin for a number of reasons. It is
facies specific, occurring only in the moundstones and
never in the flanking calcarenites. Facies specificity
of cements is known only in submarine environments (James,
Ginsburg, Marszalek and Choquette, 1976). Where present it is
always the first rim-cement precipitated but may be over-
lain by others. The cement is interlayered with internal
sediment inside cavities and loose, detached blocks of
cement occur within sediment, implying that cementation
and sedimentation were contemporary. The fabric of the
cement is fibrous and inclusion-rich, a common character-
istic of recent synsedimentary cements (Bricker, 1971;
p. 47). Lastly the cloudy fibrous cement is penetrated
by borings whose vacant cylinders are also often occluded
with this cement. The penetration of cements by borings

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is often used to denote a submarine origin for cement
(e.g. Purser, 1969; James and Kobluk, 1978).

A volumetrically important rim-cement is the
syntaxial overgrowth on echinoderm plates. This type of
cement has been interpreted in other rocks to be of
submarine origin (Purser, 1969), of vadose origin
(Talbot, 1971), or phreatic origin (Evamy and Shearman,
1965). The non-ferroan nature of this cement in the
rocks under study, which have a high iron content
(James and Kobluk, 1978) suggests that iron was in a
ferric state, above the water table and in contact with
air so was unable to be accommodated into the crystal
lattice. The syntaxial cements were, therefore probably
precipitated from meteoric waters in the vadose zone
(cf. Talbot, 1971).

The vadose diagenetic environment was probably
the site of a considerable amount of rim-cementation.
The blocky and bladed spar cements are interpreted as
being of vadose origin as they show geostrophic growth
(Fig. 38) with bladed spar often occurring on the under-
side of shells growing downwards and achieving
considerable length, while on the upper surface of the
shell, blocky, equant spar of more restricted dimensions
has been precipitated. This denotes that the cement was
precipitated under the influence of gravity from meteoric
waters percolating down through the rock. This type of
geostrophic cementation is well documented from subaerial
environments (e.g. Taylor and Illing, 1969; Purser, 1969;

Muller, 1971) and is often known as gravitational or
stalactitic cement. The non-ferroan nature of these
cements also infers a subaerial, vadose environment
(Talbot, 1971).

The most difficult rim-cement to interpret is the
radial-fibrous/bladed fabric occurring on the ooids
in both Oolite Sand Facies and the Biostrome Facies.
The ooids are rimmed with a fibrous/bladed cement around
the entire circumference of the grain, but the cement
thickens away from grain contacts and into the pore
space. This implies that the initial pore space was
entirely filled with pore-water, a situation found in
saturated conditions below the water table, either in a
submarine or phreatic environment. Pore-waters in the
vadose environment are often restricted to grain contacts
and produce meniscus cements (Dunham, 1971). The
presence of several laterally restricted erosion surfaces
in the Oolitic Calcarenites (BB-1) of the Biostrome
Facies suggests that early lithification of the sediment
occurred and may indicate a submarine origin. The cement
fabric is also similar to cements previously attributed
to submarine environments (Purser, 1969).
Circumstantial evidence suggests therefore that the radial
fibrous cements around the ooids may be synsedimentary
and therefore submarine.

A synsedimentary (submarine) origin for a micrite
cement is indicated for both the moundstones and inter-
particle between grains in the grapestone of the Oolite

Sand Facies. Recent grapestones are reported to be cemented by the precipitation of aragonitic micrite (Bathurst, 1971) and probably occurred in the rocks under study. Early lithification of the moundstones is indicated as the mud matrix (now microspar) is cut clearly by macroborings (<u>Trypanites</u>) suggesting that a micrite cement may have been involved. Micrite cements of submarine origin are commonly recorded from Recent environments (Schroeder, 1973; James et al., 1976).

Pore-fill cement

Pore-fill cements of anhedral coarse pink calcite are interpreted as being deposited in the phreatic diagenetic environment. The cements are invariably ferroan implying that the iron was in a ferrous (reducing) state and able to be incorporated into the crystal lattice. This process occurs out of contact with air, below the water table in the phreatic zone (Evamy, 1969; Talbot, 1971; Bathurst, 1971). The large size of crystals relative to the vadose cements is also indicative of the phreatic zone (Land, 1970; Thorstenson, Mackenzie and Ristvet, 1972; Steinen, 1974).

Neomorphism.

The most common type of neomorphism is aggrading neomorphism of micrite to microspar, often reported from ancient rocks (Folk, 1975) and probably occurring in the phreatic environment (Bathurst, 1971) although there is

no direct evidence for this.

All of the examples of pseudospar in the rocks under study are ferroan which infers that the growth of pseudospar at the expense of the ooid fabric or archaeocyathid skeleton was influenced by the pore-water, almost certainly in the phreatic environment. This implies that the growth of neomorphic spar occurred in a wet environment, probably by the migration of a solution film in a system of pores between two crystal lattices (Bathurst, 1971) and incorporated iron in a ferrous state into the growing lattice from the pore fluid.

It is difficult to ascertain whether the transitional fabric, micrite-microspar-pseudospar observed in the archaeocyathid skeletons is the result of one or two events of neomorphism. But if one considers that the growth of neomorphic spar occurs by migration of a solution film between two crystal lattices with one crystal growing at the expense of another (wet boundary migration of Bathurst, 1971), then there must have been two stages of growth. The first stage, or "pulse" of wet boundary migration converted part of the micrite skeleton to microspar and then stopped; the second stage or "pulse" then converted the microspar to clear, ferroan pseudospar and then either stopped, or continued. If the process continued past the terminating point of the first pulse, then the micrite skeleton was not converted to pseudospar, but to microspar thus making the effects

of 2 pulses indistinguishable (Fig.44), although it
can be argued that the extent of pseudospar is equal to
the extent of neomorphism in the first pulse as pseudospar
only replaces microspar.

Aggrading neomorphism of some ooids also presents
interesting problems. Very often the 'ghost' nucleus of
the ooid, almost always an echinoderm plate, is present
and is always non-ferroan whereas the encircling crystal
of pseudospar is always of ferroan calcite though both
nucleus and pseudospar are optically a single crystal.
Unaltered ooids seen in thin-section generally consist
of 2 to 3 concentric layers of what appears to be
organic-rich material. What has happened therefore to
those layers during the growth of pseudospar? Although
little is known on the subject, it is generally believed
that organic material inhibits the precipitation of
calcite (Bathurst, 1971). Petrographic observations
suggest that the organic material has been pushed to the
margin of the ooid during the growth of pseudospar, as
there is an unusually thick rind of dark material in that
position (fig.34). The optical relationship between
the nucleus and the pseudospar suggests that the pseudospar
is a neomorphic syntaxial rim of an echinoderm plate.
But if this is so, why is the margin of the ooid never
breached by pseudospar? Such detailed problems are
beyond the scope of this study.

STAGE 1:   INITIAL MICROGRANULAR
          SKELETON

STAGE 2:   FIRST PULSE OF WET
BOUNDARY MIGRATION
Part of the original micro-
granular skeleton is aggraded
to microspar (4-40).

STAGE 3:   SECOND PULSE OF WET
BOUNDARY MIGRATION
More of the original micro-
granular skeleton is aggraded
to microspar. The microspar
formed in stage 2 is aggraded
to pseudospar

Fig. 44: Sketch illustrating aggrading neomorphism of
          archaeocyathid skeletons (based on fig. 38).

Dolomitization

The selective dolomitization of certain structures is a prime problem of the rocks under study. This phenomena, whether it is dolomite mottling, or the selective dolomitization of sedimentary structures is well documented in the rock record (Beales, 1953; Shinn, 1968; Kendall, 1977; Morrow, 1978), and is usually explained by sediment heterogeneity which allows dolomitic brines to selectively pass through the rock. This was probably the case with the rocks under study. The two features which are most often selectively dolomitized are the dolomite pods which occur in the Dolomitic Moundstone lithofacies (BD-1) and bioturbation (including burrowing) features common in the Oolite Sand Facies.

In the case of the dolomite pods, the sediment heterogeneity may have been caused by the early lithification of the moundstone relative to the pods. Evidence for synsedimentary cementation of the moundstone has already been presented (submarine cements and micrite cut by borings) and although the nature of the original sediment of the dolomite pods has been obliterated, several structures are still preserved. For example, on some weathered surfaces, horizontal laminations and trace fossils (burrows, track, and trails) are seen (Fig. 16). Neither laminations nor trace fossils occur within the moundstone suggesting that the two adjacent deposits

differed greatly in their original form, the moundstones
being lithified to some degree, and the pods remaining
as soft sediment. This would provide the necessary
heterogeneity for the dolomitic brines to preferentially
select the more permeable pods (cf. Kendall, 1977).

The dolomite mottling caused by the preferential
dolomitization of burrows and bioturbation fabrics
has been described several times from the rock record
(Kendall, 1977; Morrow, 1978). This fabric occurs in
the biotrubated sediments of the Oolite Sand Facies in
the rocks under study. Heterogeniety in the sediment
was established possibly because the bioturbated sediment
was more porous then the matrix and was therefore
selectively dolomitized (Morrow, 1978). As the matrix
is a grainstone, however, the reverse would probably
have been true as grainstones have very high initial
porosity (Dunham, 1962). The alternative is that the
matrix (grainstone) underwent early lithification
(vadose) relative to the bioturbated sediment remained
uncemented and hence more permeable and susceptible to
dolomitization by percolating brines (cf. Kendall, 1977).

If the mechanism of selective dolomitization was
by the percolation of brines though a permeable versus
non-permeable sediment then dolomitization must have
been relatively early, before lithification of the sediment.
Petrographic evidence suggests, however, that dolomitization,
was diagenetically late, i.e. post phreatic (last stage)

cementation and stylolitization; evidence contrary to the hypotheses. Field evidence on the other hand indicates that the dolomite pods were lithified prior to the intense stylolitization that affected the moundstones. Stylolites do not pass through the pods but give the impression that the moundstone is "wrapped around" the pods (Fig.15). This implies two things: (1). That the pods were lithified relatively early (pre-stylolitization); (2). The pods did not consist of calcite when they were lithified otherwise the stylolites would not have avoided them. A logical explanation therefore is that the pods were lithified by early dolomitization, the fabrics of which have since been masked by a later event of dolomitization. The early dolomitization may have acted as a centre of nucleation for the later dolomitization (incorporating several stages) which was however, more widespread, involving dolomitization of phreatic cements, pseudospar and occasionally other sediments.

The timing and environment of early dolomitization is not clear as the fabrics have been masked by later dolomitization. The dolomite was probably not formed in the submarine environment as this generally requires salinities between 4 and 6 times that of normal seawater and is usually associated with the elimination of calcium sulphate (Liebermann, 1967). There is no evidence of hypersaline conditions existing in the Forteau

Formation as the organisms are considered stenohaline (Heckel, 1972) and no evaporite deposits are present. The most likely environment for the early dolomitization is at the interface between meteoric phreatic water and marine phreatic water (zone of mixing), where carbon dioxide-rich meteoric waters infiltrate the sediments (selectively) and mix with sea-water and precipitate dolomite, (Land, 1973a,b).

Stylolitization and Fracturing

Two types of stylolites are seen to be facies specific in the biostrome complex. Clean, sutured seams, generally of low amplitude and often laterally persistent are restricted to the calcarenites. In the moundstones stylolites occur as anastomosing swarms of fine non-sutured seams, grading into horse-tail stylolites. The reason for the difference in stylolite type is probably related to the percentage of insolubles present in each lithology. The relatively high silt and clay content in the moundstones concentrates at stylolite seams where it eventually inhibits further solution by 'clogging up' the seam. This initiates solution in another, adjacent area, resulting in a mosaic of anastomosing solution seams which eventually leads to a nodular appearance in the rock. Coarse skeletal material, in this case archaeocyathids, are known to provide structural resistance to stylolitization and may define the position and size of a nodule (Wanless, in press). This is certainly the case in moundstones where stylolites are

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often seen to abut against archaeocyathid skeletons.

The calcarenites contain much less insoluble material and as a result solution is not inhibited along any seam allowing the development of clean sutured seams which are well-spaced and occur in much fewer numbers, than the non-sutured seams of the moundstones. However, where the silt and clay fraction is high in the calcarenites, anastomosing, non-sutured seams do occur.

Stylolitization co-occurs with fracturing and the precipitation of iron-rich pore-fill cement although it is evident that either stylolitization or fracturing is the dominant form of pressure release in any one thin-section studied. The abundant stylolitization is an obvious source of the iron-rich pore-fill cement in the phreatic environment.

Summary of Diagenetic History

Table III summarizes the diagenetic history and relates petrographic fabrics to diagenetic processes and environment. Fabrics are interpreted to have formed in submarine, mixed meteoric phreatic-marine phreatic, vadose phreatic, and a late unspecified diagenetic environment.

Submarine diagenesis was restricted to bioerosion (by both micro-organisms and metazoans) and facies specific cementation, lithifying the moundstones and cementing the ooid grainstones.

As the sediments were buried, selective dolomit-ization and lithification of pods and bioturbation

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TABLE III. Summary of diagenetic processes and fabrics.

ENVIRONMENT	PROCESS	FABRIC
SUBMARINE	Bioerosion	macroborings (Trypanites) microtubular (Girvanella) micritic envelopes peloids
	Cementation	micrite cloudy-fibrous cement radial fibrous cement on ooids
ZONE OF MIXING (meteoric phreatic-marine phreatic)	Dolomitization	selective dolomitization
VADOSE	Dissolution	rare solution cavities rare leaching of aragonite shells
	Cementation	syntaxial cement on echinoderm plates blocky spar cement bladed spar cement
PHREATIC	Fracturing	small factures
	Dissolution	rare cavities common leaching of arag- onite shells
	Stylolitization	stylolites nodular bedding
	Cementation	ferroan pore-fill cement
	Neomorphism	microspar pseudospar
UNSPECIFIED (Late diagenetic)	Dolomitization	dolomite
	Silicification	rare silica replacement
	Stylolitization	rare stylolites

fabrics occurred in the zone of mixing between
meteoric phreatic and marine phreatic waters (Land, 1973
a, b). Burial was probably not great as the sediments
were then uplifted into the vadose diagenetic
environment where rim-cementation occurred affecting
all lithologies. Minor dissolution must have occurred
at this time as rare small solution cavities and leached
aragonitic shells are rimmed with vadose cements.
Exposure to the vadose environment must have been for
a considerable time as the cements are quite well-
developed in an environment where diagenetic processes
are notoriously slow (Land, 1970; Steinen, 1974).

Burial into the phreatic environment caused
extensive fracturing, dissolution of aragonitic shells,
stylolitization, pore-fill cementation utilizing iron-
rich solutions released by stylolites, and neomorphism.
Burial was probably considerable to cause such
extensive pressure solution and fracturing from overburden.

A late, undated diagenetic event caused further
dolomitization, minor replacement by silica, and rare
stylolitization.

CHAPTER V: PALEOECOLOGY OF THE BIOSTROME FACIES

INTRODUCTION

This is a qualitative review of the distribution of organisms in the mounds and calcarenites, the roles that these organisms played, and the structure of each organism association with regard to trophic grouping.

Data was obtained from field observations and supplemented by thin-section study. Where outcrop was sufficient, metre square quadrants were marked off and the organisms counted, with particular attention being paid to the morphology, size, and preservation of archaeocyathids in the moundstone. Where outcrop was restricted, areas of varying sizes were counted and the area noted.

Information regarding the density of organisms in the mounds is biased because of the intense stylolitization that has masked the original disposition of the skeletons and has caused severe vertical dislocations of individual skeletons relative to each other. It is noticeable that the mud matrix was dissolved more than archaeocyathid skeletons as the stylolites often bend around skeletons or abut against them. In view of the stylolitization problem, the density of the distribution of organisms is considered a maximum figure and was probably less at the time of deposition.

The autecology (Ager, 1963) of the main organisms

which occur in the mounds and calcarenites of the
Biostrome Facies is described and discussed. The
synecology (Ager, 1963) describes three distinct faunal
assemblages: the mound assemblage, the calcarenite
assemblage, and a coelobitic (cavity dwelling) assemblage
which occurs in some of the mound lithofacies. The
mound and calcarenite assemblages are considered to be
original separate "communities" because; (1) There is
little evidence of transportation of skeletal elements
in either lithofacies, a great proportion of the mound
organisms are preserved in situ, and skeletal elements of
the calcarenites are mostly unbroken, although often
disarticulated (which is due to spontaneous disintegration
upon death). (2) The separation of organisms
between the mounds and calcarenites is too clear
to be fortuitous and must reflect the original distribution
of the organisms.

The relative distribution of the organisms in the
various moundstone and calcarenite lithofacies is tabulated
in Table IV and is discussed later.

AUTECOLOGY

Archaeocyathids

Archaeocyathids are the principal skeletal components
in the Biostrome Facies. Very little is known of their
paleoecology (Hill, 1972), but by counting, measuring,
and noting morphologies within the five lithofacies, it

TABLE IV. Distribution and relative abundance of organisms in the five units.

	DOLOMITE MOUND		RED MOUND		NODULAR MOUND		GREY MOUND		OOLITE BIOHERM	
	Mound	Calc.	Mound	Calc	Mound	Calc	Mound	Calc	Mound	calc
ARCHAEOCYATHIDS Cones/Sticks	A	SD	A	SD	C	--	A	SD	A	SD
Retilamina	--	--	A	--	R	--	A	--	C	--
TRILOBITES	R	P	P	C	R	C	P	P	P	C
BRACHIOPODS	P	C	C	C	--	C/A	P	P	P	P
COELENTERATE	A	--	C	--	P	--	--	--	--	--
RENALCID ALGAE	--	--	A	--	--	--	C/A	--	A	--
Epiphyton	--	--	R	--	--	--	R	--	R	--
Girvanella	--	--	C/A	--	P	--	C/A	--	C/A	P
NON-SKELETAL STOMATOLITES	R	--	P	--	--	--	A	--	--	--
Trypanites	A	--	C	--	--	--	P	--	--	--
SPONGE SPICULES	--	--	R	--	--	--	R	--	R	--
ECHINODERMS	SD	A	C	A	SD	P	SD	A	SD	A
HYOLITHIDS	--	P	P	P	R	P	--	R	--	P
Salterella	--	--	--	--	--	--	--	--	--	C/A
FORAMINIFERA	--	--	P	--	--	--	P	--	P	--
Archaeotrypa	--	--	R	--	--	--	--	--	--	--
BURROWS (?WORMS)	--	--	P	--	--	--	C	--	P	--
Bija	--	--	P	--	--	--	--	--	--	--

KEY
-- - Absent
R - Rare
P - Present
C - Common
A - Abundant
SD - Skeletal debris

was hoped to ascertain whether certain parameters could
be correlated with environment. Counts were made in four
of the five lithofacies. Because of the badly weathered
surfaces and stylonodular structure of the Nodular
Moundstone (BN-1) no count was possible although it was
noted that forms present appeared to be large diameter wide
cones, funnels, or bowls.

The diversity of archaeocyathid taxa in the Biostrome
Facies is very low, consisting predominantly of
Metaldetes profundus, Archaeocyathus atlanticus and a
new genus and morphotype, Retilamina amourensis (Debrenne
and James, in prep.). Retilamina is dome-shaped to sheet-
like, single-walled with a reticulate skeleton, and an
upper surface which has large pores. Secondary thickening
of the wall is common. Individuals can be up to several
centimetres long but the wall is only 1 - 2 mm thick
(Figs. 45 and 57).

When the relative proportion of stick-forms (M.
profundus and A. atlanticus) against cone-forms (M. profundus)
is plotted for each lithofacies, a trend is seen (see Fig.46).
The lower outcrops of Grey Moundstone at Blanc Sablon
consists of sticks and cones in a ratio of 8:1; the Red
Moundstone consists of sticks and cones in roughly equal
proportions, while the Dolomitic Moundstone has sticks
and cones in a ratio of 1:10. This gives a further
indication of the distinction between the five lithofacies
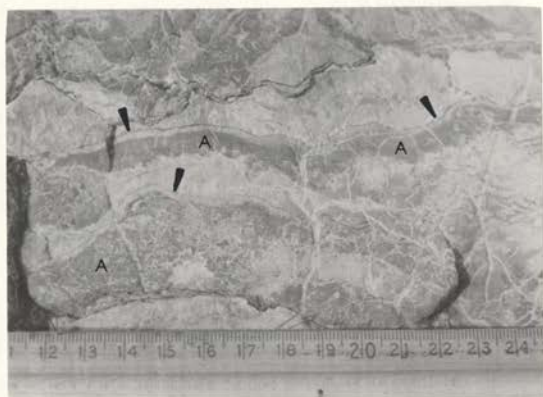
Fig.45: Cliff-section exposure of the Grey Moundstone
lithofacies (BG-1) at Diversion Reef. Laminar
Relilamina (arrowed) support a pendant growth
of calcareous algae (dark areas, labelled A)
beneath them. The lighter areas consist of
lime-mud matrix.
Scale is in centimetres.

X - Dolomitic Moundstone lithofacies(BD-1)
0 - Red Moundstone lithofaces (BR-1)
● - Archaeocyathid Bioherm lithofacies
       (BB-2)
+ - Grey Moundstone lithofacies (BG-1)
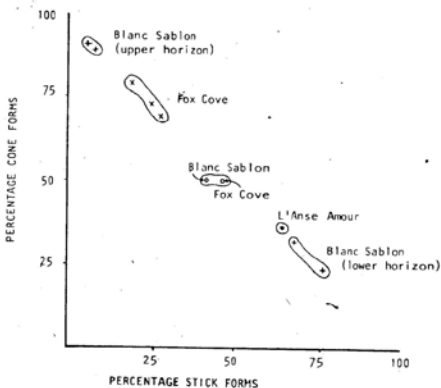
Fig. 46: Plot of relative percentage of cones versus sticks
         in various lithofacies.

although it is not clear at the moment what were the controlling factors in the distribution of archaeocyathid morphotypes between lithofacies. For the purpose of the synecology, however, archaeocyathids are considered as sessile, bethonic organisms feeding out of the water column, probably by filtering (Hill, 1964; Balsam, 1973).

Calcareous algae

Renalcis, renalcid algae, and Epiphyton

The calcareous algae Renalcis, Epiphyton, and a Renalcis-like organism (herein termed renalcid) are restricted to the mounds and have the same ecological function, so are described together. Preliminary notes on their affinities and previously described paleoecology are given seperately, however.

Renalcis (Vologdin) consists of hollow, inflated chambers with thick calcareous walls and can occur either as individual chambers or as botryoidal aggregates (Riding and Toomey, 1972)(Fig.47). Although this organism has a world-wide distribution and is quantitatively very important in Paleozoic reefs (Riding and Toomey, 1972; Wray, 1977) the biological affinities of Renalcis are still uncertain. Several authors believe that Renalcis is a foraminiferan(Elias, 1950; Riding, 1972; Riding and Brasier, 1975) on the basis that the size and morphology is consistent with Foraminifera, and that the chambers are an order of magnitude larger than those associated with

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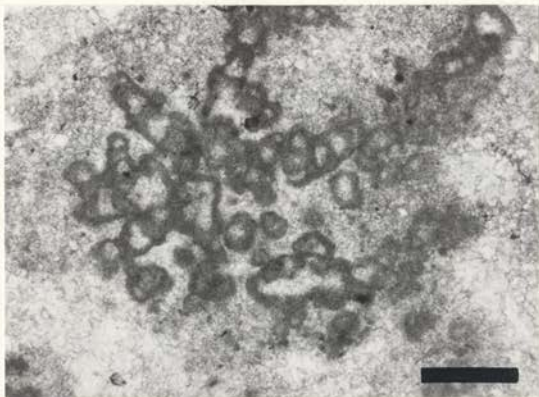
Fig.47: Photomicrograph (plane light) of a clump of chambered <u>Renalcis</u> occurring in the Red Mound-stone lithofacies (BR-1). Scale bar is 0.3mm.
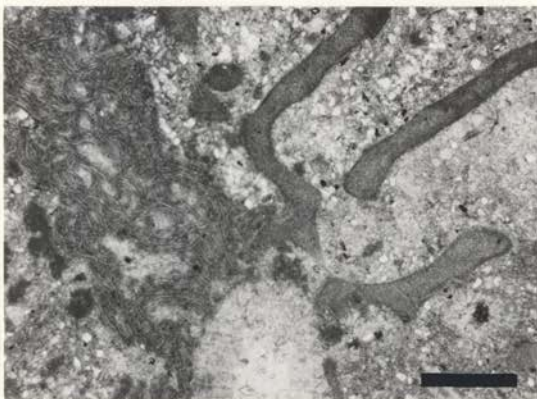
Fig.48: Photomicrograph (plane light) of tubules of <u>Girvanella</u> encrusting the central cavity of an overturned archaeocyathid (right). Note the penetration of <u>Girvanella</u> by the macro-boring ichnofossil <u>Trypanites</u> (bottom centre). Scale bar is 0.45 mm.

blue-green algae (see discussion in Riding and Brasier, 1975). They are therefore considered as a separate family (Renalcidae, n. fam.) of the Parathuramminacea (Riding and Brasier, 1975). On the other hand, they are often considered as blue-green algae (Korde, 1973; Hofmann, 1975) or at least problematic blue-green algae (Wray, 1977). A recent work (Brasier, 1977) illustrates well-preserved _Renalcis_ in oncolites from the Eilean Dubh Formation of the Durness Group (Lower Cambrian) in Scotland. Brasier (1977) describes the walls as consisting of a chain of minute coccoid cells with the packing of the cells reducing towards the central chamber. Brasier (1977) concludes that these resemble colonies of coccoid cyanophytes (blue-green algae) embedded in a gelatinous envelope, but concedes that _Renalcis_ may be an artificial or polygot genus (Brasier, 1977). In the light of this study, _Renalcis_ is considered here as a cyanophyte (blue-green algae).

Epiphyton (Bornemann) consists of densely branched calcareous thalli with no discernable internal structure and is generally less than one mm in overall dimensions (Riding and Toomey, 1972; Wray, 1977). It is placed in the Cyanophyta (as problematical blue-green algae) by Wray (1977) because of the resemblance to _Renalcis_, the lack of micro-structure in most specimens, and the non-definitive illustration of claimed microstructure.

Epiphyton is generally considered a member of the Rhodophyta
(Red algae) by most authors (Riding and Wray, 1972; Riding
and Toomey, 1972; Korde, 1973), based on the cellular
microstructure with cell-wall·pores and sporangia,
noted by Korde (in Wray,1977), and this interpretation
is followed in this study.

Epiphyton and *Renalcis* commonly occur in the Lower
Cambrian (Korde, 1973; Brasier, 1976; Zammareño, 1977;
James and Kobluk, 1978) sometimes forming algal mounds,
and also occurring in massive algal limestone (Zammareño,
1977). In Lower Ordovician mounds, *Epiphyton* and *Renalcis*
are mutually associated as sediment binders and
stabilizers by forming dense clusters in sediment
between and surrounding the mound forming organisms
Archaeoscyphia and *Calathium*, but preferring a firm sub-
strate (Riding and·Toomey, 1972). *Renalcis* also encrusts
other organisms but it is not certain whether *Epiphyton*
encrusts in the same fashion. Both *Renalcis* and *Para-
epiphyton* (later placed as junior synonym of *Epiphyton*
(Riding and Wray, 1972)) are regarded as good indicators
of reef facies in the Upper Devonian, where they occur
as encrusters, sediment stabilizers and binders (Wray,
1972).

Zhuravleva (1960, in Hill, 1972) claims that *Renalcis*
and *Epiphyton* are mutually exclusive, with *Renalcis* occurring
with archaeocyathids at depths down to 50 m and *Epiphyton*
occurring with archaeocyathids at depths between 50-100 m,

although Riding (1975) questions the association.

Following Kobluk and James (in prep.), an organism similar to both <u>Renalcis</u> and <u>Epiphyton</u> is referred to as renalcid algae. It resembles <u>Renalcis</u> in size, mode of growth, and occurrence but differs in being unchambered, more arborescent, and branching. It resembles <u>Epiphyton</u> in being branched, unchambered, and arborescent but differs in being larger (Figs. 57 and 58). The renalcid algae always occurs with <u>Renalcis</u>, so in the following text the two organisms are both referred to as renalcid algae unless stated otherwise.

The paleoecology of renalcid algae and <u>Epiphyton</u> is essentially the same in the Biostrome Facies of the Forteau Formation. They are all restricted to moundstone lithofacies and are completely absent from the flanking calcarenites. They are, however, totally absent from the Dolomitic Moundstone (BD-1) and the Nodular Moundstone (BN-1) but abundant in the other three moundstone lithofacies (BR-1, BG-1, BB-2). This pattern of occurrence is the same as the distribution of <u>Retilamina</u> with which the calcareous algae are always intimately associated (Figs. 45 and 57), although they do occur in other situations as well. In all occurrences, renalcid algae are the most common. <u>Epiphyton</u> is considered rare although this may be due to the difficulty in separating the organism within dense growths of renalcid algae.

The main habitat of calcareous algae is in cavities,

growing as pendants from the undersides of <u>Retilamina</u>
(Figs. 45 and 57) which forms the roof of the cavities.
These algae also commonly occur as thin (several
millimetres maximum) encrustations on the outside of
archaeocyathid cups and coelenterate skeletons but often
have geostrophic growth, with thickest accumulations on
the bases of skeletons.

The role of the calcareous algae in the mounds is
envisaged as being two-fold. They are the primary
producers (autotrophs) in the trophic structure in the
mounds, and also act as sediment stabilizers and binders
when they occur on the outside of skeletons (cf. Riding
and Toomey, 1972).

<u>Girvanella</u>

<u>Girvanella</u> (Nicholson and Etheridge) is a flexous,
tubular filament of uniform diameter, composed of
relatively thick calcareous walls and is generally accepted
as a member of the Cyanophyta (blue-green algae) (Wray,
1977), although it has also been considered as a Fora-
minifera, sponge, or green alga (see discussion in Riding,
1975). <u>Girvanella</u> has often been placed more precisely
into the family Oscillatoriaceae (e.g. Lauritzen and
Worsley, 1974), but probably represents the remains of
numerous taxa possibly belonging to several families of
blue-green algae (Riding, 1975; Wray, 1977), particularly
when it is considered that most of the features by which

extant blue-green algae are classified are lost during fossilization (Riding, 1975; 1977a).

The recorded geologic range of _Girvanella_ extends from the Cambrian to the Cretaceous (Riding, 1975), though extant forms are being documented (Riding, 1977a; Kobluk and Risk, 1977). Most of the fossil forms of _Girvanella_ are from marine sediments although freshwater forms from Cretaceous lacustrine limestones are known (Colin and Vachard, 1977). _Girvanella_ is often used as a shallow-water depth indicator but this may be suspect if _Girvanella_ is indeed representative of a number of taxa, each with its own tolerances (Riding, 1975). However, it has been cautiously suggested that the prostrate growth form of _Girvanella_ (Agathidia) compared with the erect growth form of the morphologically similar _Ortonella_ (Thamnidia) may indicate that _Girvanella_ inhabits high light availability areas (implying shallow-water) whereas the phototrophic growth of _Ortonella_ suggests physical confinement as regards light availability (and hence sometimes, but not always, deeper water) (Riding, 1977a).

Girvanella has been described from many environments and as performing many roles in its geologic history. It is commonly found as an encruster and binder in back-reef environments in the Silurian (Lauritzen and Worsley, 1974) and Devonian (Wray, 1972). It is documented as an

endolithic (boring) organism in the Lower Ordovician (Klement and Toomey, 1967), and occurs in clusters or 'nests' in the back-reef environment in the Silurian (Lauritzen and Worsley, 1974). _Girvanella_ is commonly the chief component in skeletal stromatolites (term after Riding, 1977b) in the Upper Cambrian (Ahr, 1971; Chafetz, 1973), where it also forms bioherms. In these bioherms _Girvanella_ has a dendritic growth form which baffles sediment by growing vertically in tangles of almost straight tubules to form a series of bushes up to five cm high which together constitute a bioherm (Ahr, 1971).

Girvanella occurs in the Biostrome Facies and also the Oolite Sand Facies in a variety of modes of life: (1) encrusting onto skeletons; (2) as skeletal stromatolites and oncolites; (3) in 'nests' or clusters; (4) as an endolith.

Encrusting _Girvanella_: The most common mode of occurrence for _Girvanella_ is as thin encrustations onto other skeletons, particularly archaeocyathids (Fig.48). This occurs in all of the moundstone lithofacies except the Dolomitic Moundstone (BD-1) and is particularly common in Red Moundstone (BR-1). More commonly, _Girvanella_ encrusts the top and sides of archaeocyathids but it also occurs as a coelobitic encruster on the undersides of _Retilamina_. _Girvanella_ occasionally encrusts the upper surface of trilobites in skeletal grainstone, mixed peloid

packestone and mixed oncolitic grainstone of the Oolite
Sand Facies.

   Girvanella as skeletal, stromatolites and oncolites:
The microstructure of some of the stromatolites in the
Grey Moundstone (BG-1) and the Oolite Bioherm lithofacies
(BB-1) consists of *Girvanella* tubules. At the top of
the section at L'Anse Amour, *Girvanella* stromalites
have a structure consisting of laterally linked
hemispheroids with close lateral linkage (LLH-C of
Logan et al., 1964). The microstructure consists of
prostrate *Girvanella* tubules which cumulatively form
vertical bush-like structures that possibly had the
ability to baffle sediment. The *Girvanella* stromatolites
embedded in Oolitic Calcarenites (BB-1) form small
ovoids in plan (diameter of several centimetres) and
have a structure of laterally linked hemispheroids with
spaced lateral linkage. This grades vertically (within
one cm) into laterally linked hemispheroids with close
lateral linkage (LLH-S/LLH-C of Logan et al., 1964). The
type LLH structure is interpreted from modern studies
to occur in the marine, intertidal mudflat environment,
mainly in protected re-entrant bays and behind barrier
islands and ridges where wave-action is usually slight
(Logan et al., 1964).

   Girvanella oncolites occur commonly in the mixed
oncolitic grainstones of the Oolite Sand Facies (Fig.49)
where they have a structure of concentrically stacked
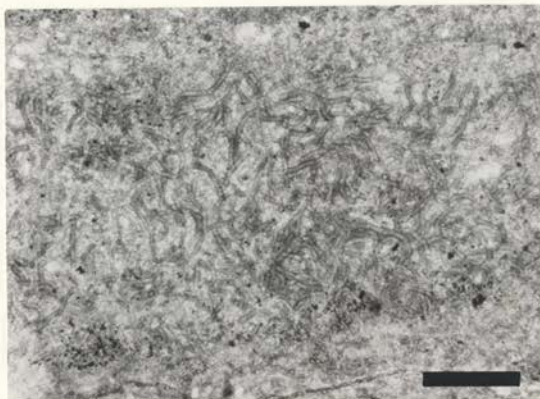
Fig.49: Photomicrograph (plane light) of <u>Girvanella</u>
occurring at the centre of an oncolite in the
mixed oncolite grainstone lithology. The on-
colite enlarged here is the same as that ill-
ustrated at the top of Fig.14.
Scale bar is 0.3mm.

spheroids (SS-C of Logan et al., 1964), normally around
a nucleus of a compound grain (grapestone). Up to three
periods of growth are indicated in some of the oncolites
(Fig.21). Type SS-C structures indicate continual
motion to achieve concentrically stacked spheroidal
laminations suggesting a high-energy environment for the
mixed oncolitic grainstone (Ginsburg, 1960; Logan et al.,
1964).

'Nests' or clusters of _Girvanella_: Rare occurrences
of spheroidal clusters of intertwined tubules of
Girvanella occur as aggregates up to several millimetres
across in some of the mounds. A similar morphology occurs
in the intraclast grainstone of the Oolite Sand Facies
(Fig.22) but these may be formed by transportation.

Girvanella as Endoliths: An isolated occurrence of
Girvanella as an endolithic organism is seen in the
mixed oncolitic grainstone of the Oolite Sand Facies
where one half of an echinoderm plate now consists
entirely of intertwined tubules of Girvanella while the
other half remains unaltered (Fig.50).

Non-Skeletal Stromatolites.

The only non-skeletal stromatolites (term after
Riding, 1977b) in the Biostrome Facies are small (less
than one cm high), vertical stacked hemispheroids with
a variable basal radius (type SH-V of Logan et al., 1964).
They commonly occur in groups in the Grey Moundstone
(BG-1) at Blanc Sablon (Fig.27) but occur rarely as
isolated stacks in the Dolomitic Moundstone (BD-1) and
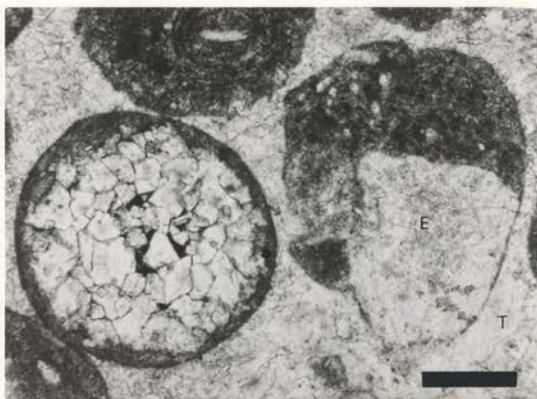
Fig.50: Photomicrograph (plane light) of the mixed on-
        colite grainstone lithology. The top part of
        the ?echinoderm fragment (E) has been micritized
        by the endolithic activity of _Girvanella_, tubules
        of which can still be seen. Note that syntaxial
        cement (T) occurs on parts of the fragment not
        bored into but is inhibited on the micritized
        part of the fragment. The ooid (left) has been
        dolomitized by numerous, small, dolomite
        rhombs. Note the dark outer layer of the ooid.
        Scale bar is 0.4 mm.

the Red Moundstone (BR-2) at Fox Cove.

Coelenterate.

A new, primitive coelenterate (?) occurs sporadically
in the Biostrome Facies. The skeleton, currently being
described by Kobluk and Sorauf (in prep.) consists of
highly branched fronds up to 10 cm long, each branch
tapering to a point (Figs. 51 and 52). The internal
structure is not visible as the original skeleton has
been dissolved and the resultant void filled with
cement (Fig.52).

The distribution of the coelenterate is very
irregular. It is very abundant in the northern outcrop
of the Dolomitic Moundstone (BD-1) at Fox Cove, but is
absent from equivalent strata 300 m to the south. It
also occurs in the Dolomitic Moundstone (BD-1) in the
cliffs at L'Anse Amour. It occurs throughout the Red
Moundstone (BR-1), particularly in a colonization assemblage
(see below), but is rare in the Nodular Moundstone (BN-1),
and is absent from the Grey Moundstone (BG-1) and Oolite
Bioherms (BB-2).

The role of the coelenterate in the mound structure
is uncertain. The branched morphology appears to grow
either horizontally along the sediment or downwards,
although an attachment point is not seen. Its morphology
suggests that it trapped sediment within its branches
which were also used as attachment points for pendant
calcareous algae.

Fig.51: Cliff-section of Dolomitic Moundstone (BD-1). A
frond of the coelenterate organism (X) lies
below three archaeocyathid (<u>Metaldetes</u>) cups.
Scale bar is in centimetres.
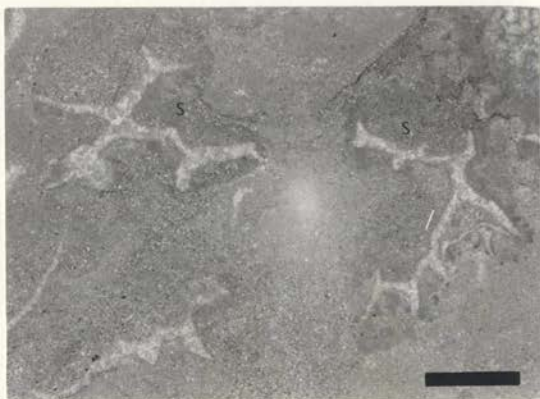
Fig.52: Photomicrograph (cross-polarized light) illustrating
skeletons of the coelenterate organism in Red
Moundstone (BR-1). The skeletons have been leached
and infilled by pore-fill cement. The matrix was
lime-mud (now microspar) with a proportion of
quartz silt. The dark sediment (S) surrounding some
of coelenterate fronds may be stromatolitic in
origin.
Scale bar is 2.5 mm.

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Brachiopods.

Early Cambrian brachiopods are a moderately large, quite complex (not primitive), diverse group of organisms which bear witness to a major phase of evolutionary radiation (Rudwick, 1970). Inarticulate brachiopods are more common than articulates in the Cambrian, particularly in the Lower Cambrian where five inarticulate superfamilies are known and only two articulate super-families. Schuchert and Dunbar (1934) list six species of brachiopods from the Forteau Formation but Fong (1967) and Balsan (1973) list only three: Obelella chromatica, Kutorgia cingulata (both inarticulate) and Nisusia oriens (an orthid articulate).

Ecologically, recent brachiopods can be described as bivalved, sessile benthonic, epifaunal (permanently attached), low-level filter-feeders (lophophorates). The feeding system of fossil brachiopods can be inter-preted to be functionally the same as extant forms (Rudwick, 1970) suggesting that fossil forms are ecologically similar to the living forms. The ingestation and digestion of inarticulates is essentially the same as the articulates, differing only in the expulsion of waste (articulates through the mouth, inarticulates through the anus) and the food is the same, both classes having the ability to assimilate dissolved substance plus bacteria, colloids, organic detritus and algae (Steele-Petrović, 1976). The food of fossil brachiopods was

probably the same as extant forms (Steele-Petrović, 1976). Brachiopods are attached to the substrate by a pedicle or by cementation (Rudwick, 1970), but the Lower Cambrian forms, particularly *Obelella*, had a pedicle attachment (Balsam, 1973).

Brachiopods are reported from "reef-like" environments throughout the Phanerozoic. Although a minor phylum today, they are present in modern reefs, but occupy a coelobitic habitat (Jackson, Goreau and Hartman, 1971; Logan, 1977), and only emerge from these cryptic environments with increasing depth (Logan, 1977). Inarticulate, acrotretide brachiopods show great diversity (17 genera) in the Ordovician Meiklejohn mounds of Nevada, reflecting the adaptation into numerous microhabitats (Rowell and Krause, 1972).

In the Biostrome Facies of the Forteau Formation, brachiopods, particularly *Obelella*, are found sporadically in both moundstones and calcarenites. In the moundstone, *Obelella* and rarely *Nisusia* occur as isolated individuals and are noticeably more common where there is an abundance of calcareous algae, especially in the Red Moundstone (BR-1). They may have attached themselves to calcareous algae as suggested from their occurrence in the Ordovician Meiklejohn mound (Rowell and Krause, 1972). There is no evidence for their attachment in this mode in the rocks under study, but this is not usual as the soft pedicle rots away upon death (Rudwick, 1970). They were not found in a coelobitic habitat.

Brachiopods are the chief skeletal component, along with echinoderms, of isolated pockets (small lenses) of skeletal calcarenite occurring within the Dolomitic Moundstone (BD-1), Red Moundstone (BR-1), and Nodular Moundstone (BN-1) and probably represent areas within the mounds favouring brachiopods and echinoderms.

Brachiopods are considerably more common in the flanking skeletal calcarenites where they occur as unbroken, disarticulated valves, either singly or in "nests" suggesting a gregarious mode of life. It is, however, important to differentiate between life and death assemblages. This is difficult with inarticulate brachiopods as the shells become disarticulated upon death (Ager, 1967). The individual, disarticulated valves of the "nests" are unbroken and show no other signs of wear suggesting that transport was minimal.

It is considered therefore, that brachiopods in the Biostrome Facies occurred as single individuals in the mounds possibly attached to calcareous algae, and occurred as both single individuals or in nests or pockets of calcarenite in the mounds and in the flanking calcarenites. In both cases they were low-level filter feeders.

Trilobites.

Lower Cambrian trilobites are a very complex and diverse group of organisms with 4 orders and 24 families (Harrington, 1959). In the Biostrome Facies the only

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genera recognised are <u>Bonnia</u> <u>sp.</u> (fam. Dorypygidae) and <u>Wanneria</u> <u>sp.</u> (fam. Olenellidae) although a third form, seen only in thin-section, may be another taxon.

In spite of the abundance of trilobites in the fossil record and the vast amount of taxonomic data on them, little is known of their paleoecology. It is possible however, that their mode of life may be deduced from their functional morphology (Bergström, 1973).

The main morphological features of <u>Bonnia</u> are: a wide rhachis (axis); a smooth exterior; a highly convex, isopygous body, particularly the cephalon; and small eyes. The wide rhachis allows plenty of room for appendages and muscles so that the animal had considerable power, useful for a swimmer, crawler, or burrower. The smooth exoskeleton would cut down the friction if the animal was a swimmer and would keep sediment from adhering to the skeleton if it was a burrower. The highly convex shape would be a restriction to a swimmer, but not to a burrower. The isopygous skeleton may suggest that the muscle power was evenly distributed, possibly allowing the animal to burrow backwards into the sediment as suggested for trilobites with similar morphologies to <u>Bonnia</u> (Bergström, 1973). It is likely therefore that <u>Bonnia</u> was a burrower, and as Bergström (1973) suggests for similar trilobites, the cephalon may have rested on the surface while the thorax and pygidium were inclined (not vertically) into the substrate. Burrows were not seen in the sediment studied but they are not often

preserved (Bergström, 1973; p.62). _Bonnia_ appears to be
restricted to the moundstone where it probably burrowed
and lived on food within the sediment. Many similar
trilobite morphologies have been found in reef-rocks of
the Middle and Upper Ordovician of Sweden (in Bergström,
1973).

Wanneria is characterized by a reticulate network
of raised lines on the skeleton which distinguish it
from _Olenellus_ in the field. Its main morphological
features are: an elongate, micropygous exoskeleton
which is nearly flat or with low convexity; large eyes;
long genal spines; a wide cephalon; and a narrow
pygidium (the axis tapers from cephalon to pygidium).
A tapering exoskeleton suggests that the muscles and
appendages were concentrated towards the front of the
animal, possibly indicating that the organism crawled
along the surface or burrowed head first. The long genal
spines and general spinose nature of the organism
precludes a burrowing or swimming habit, but not a
crawling habit. The large eyes suggest that the
animal either searched selectively for food or was prone
to attack from predators and used them for warning of
attacks. It is probable that _Wanneria_ was part of the
mobile benthos, possibly a scavenger or deposit feeder.
It was restricted in its distribution to the flanking
calcarenites.

The third trilobite, seen only in thin-section,

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(Fig.53) is very small (1 mm across) with a highly
convex carapace and occurs only within the internal
sediment of cavities. They are however, not spinose
as are the coelobitic trilobites of lower patch reefs
(Kobluk and James, in prep.). Not enough is known of
their morphology to infer a mode of life but they must
have lived either on or within (as burrowers) the
internal sediment, probably as scavengers or deposit
feeders.

Hyolithids

Hyolithids are extinct, operculate, bilaterally
symmetrical animals with a calcareous, ventrally
flattened, conical shell, and are of uncertain
affinities (Runnegar, Pojeta, Morris, Taylor, Taylor
and McClung, 1975). They are either considered a
separate phylum but related to the Mollusca or Sipunculoidea
(Runnegar et al., 1975) or are placed as separate class
in the phylum Mollusca (Yochelson, 1961; Marek and
Yochelson, 1976).

The hyolithid skeleton consists of three parts:
(1) An elongate cone (2) A close-fitting operculum
(3) Two narrow, dorsally curved appendages which project
from slots between the operculum and shell on opposite
sides of the organism. The arrangement of the muscle
scars suggest that the head could be protracted or
retracted, the operculum could open and close, and
appendages could be moved (Runnegar et al., 1975).

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Fig.53: Photomicrograph (plane light) of internal sedi-
ment in a cavity formed by _Retilamina_ in Red
Moundstone (BR-1). Sediment was lime-mud (now
microspar). Note small, highly convex, trilobite
carapaces. The lighter areas (now spar) were
probably small worm burrows.
Scale bar is 0.45 mm.
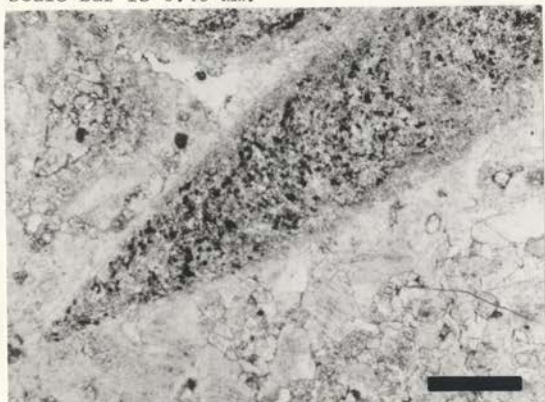
Fig.54: Photomicrograph (plane light) of a _Salterella_
cone in skeletal grainstone of the Oolite Sand
Facies.
Scale bar is 0.45 mm.

The function of the two appendages is controversial.
They may have been used as oars in a rowing action to
propel the organism along (Runnegar et al., 1975)
although there are no special muscles to suggest this
(Marek and Yochelson, 1976). Yochelson (1974) claims
that the appendages acted as stabilizers giving the animal
lateral stability. If movement of any kind involved
the appendages then it would have been slow and sporadic,
and of the order of a few millimetres at a time (Marek
and Yochelson, 1976). The presence of sediment in the
gut of well-preserved specimens suggests a deposit-
feeding mode of life (Runnegar et al., 1975) with a most
plausible food source of mixed detritus and micro-
organisms living on or within the sediment-water interface
(Marek and Yochelson, 1976). The food was most likely
collected by either a short proboscis that projected
ventrally between the operculum and cone (Runnegar et al.,
1975) or by tentacles, which would have also facilitated
movement (Marek and Yochelson, 1976).

Hyolithids occur in both the moundstones and
calcarenites, particularly the more muddy calcarenite
lithologies, where they were probably semi-sessile
omnivorous deposit feeders. Their distribution is
inverse to the distribution of preserved calcareous algae
suggesting that they are deposit feeders and not algal
browsers as suggested by Balsam (1973).

Echinoderms.

Four classes of primitive echinoders are recognised from the Lower Cambrian; Eocrinoidea (Blastozoa), Helicoplacoidea, Edrioasteroidea and Camptostromatoidea (all Echinozoa). This initial explosive radiation in the Lower Cambrian suggests that there was considerable Precambrian evolution of this group (Durham, 1964) which allowed diversification of the basic morphological design when the organisms colonized a new environment in the Lower Cambrian and adapted to a novel mode of life (Paul, 1977).

All of the Lower Cambrian classes were morphologically inefficient (Paul, 1977). They consisted of a flexible theca of imbricated plates, although the eocrinoids had a small oral surface of weakly tesselated plates. The relatively large theca and small exchange surfaces for oxygen and carbon dioxide suggests that respiration was inefficient (Paul, 1977). The large theca also indicates a large food requirement but with the small filter area available on Lower Cambrian echinoderms (see Paul, 1977; p. 138) then feeding must also have been very inefficient.

Paul (1977) regards all of the Lower Cambrian echinoderm classes as being filter-feeders but Sprinkle (1976) regards the camptostromatoids (only one genus known from the Lower Cambrian) as part of the mobile benthos or as shallow burrowing detritus feeders while eocrinoids are high-level filter feeders, and helicoplacoidea and edrioasteroids are low-level filter feeders.

The size of the food grooves in the food-gathering
brachioles and ambulacra of the eocrinoids suggests
that the food was microscopic plankton. The eocrinoids
were therefore microphagous high-level filter feeders
living in an upright position with a long attachment
appendage (holdfast) at the aboral end supporting a
globular calyx with mouth, ambulacral arms and food-
gathering concentrated at the summit (Sprinkle, 1973).
The eocrinoids were also gregarious, living in "gardens"
situated at favourable localities for feeding, attachment,
or reproduction (Sprinkle, 1973).

In the rocks under study, only disarticulated
plates of echinoderms are preserved so no taxa are
identifiable. This suggests that the echinoderms were
not rapidly buried as they possess skeletons which usually
disintegrate rapidly after death (Paul, 1977), so are only
preserved as whole skeletons upon rapid burial (Sprinkle,
1973). In the Biostrome Facies, the disarticulated plates
make up a very large proportion of the mound-flanking
skeletal calcarenites and are locally abundant in Red
Moundstone (BR-1) at Blanc Sablon, but are absent from
the rest of the moundstones except as skeletal debris
which was probably washed in. They do however, occur
in the small lenses of calcarenite which occur within
some of the mounds.

The echinoderms can therefore be said to be a
ubiquitous member of the sands flanking the archaeocyathid

mounds where they were probably high-level filter
feeders forming gardens, and also occurred in favourable
positions within the mound, along with other skeletal
fauna (brachiopods, trilobites, etc.), but were absent
or very rare from most of the mound.

Salterella

Salterella sp. (Fig.54) consists of a normally
radially symmetrical, simple cone of calcium carbonate,
which has grains, selected for size and shape, placed
layer by layer within it, and each layer of grains is
held in place by a thin layer of calcium carbonate. The
apical part of the cone is filled except for a central
tube of uniform diameter (Yochelson, 1977).

The affinities of Salterella are in doubt; Yochelson
(1977) places the genus, along with another closely
related genus Volborthella, in a new phylum, Agmata,
although Volborthella has also been ascribed to the phylum
Annelida (Glaessner, 1976).

Ecologically, Salterella has a functional morphology
which does not have a suitable ecological niche. It
has a geographical distribution throughout the Appalachians
but is apprently restricted to the top portion of the
Bonnia-Olenellus zone of the Lower Cambrian (Yochelson,
1970). Using sedimentological evidence, Salterella
inhabited environments which demonstrated a wide range
of energies but were predominantly shallow-water, with
depths between a few centimetres and a few metres (Yochelson,

1977). The presence of selected grains in the conch and absence of buoyancy structures rules out a pelagic or nektonic mode of life as their weight would have been too great. Glaessner (1976) draws the analogy between the closely related Volborthella and the sabellariid worms and suggests that Volborthella lived apex downward in the sediment with the top part exposed and was a filter-feeder which also picked silt-size grains out of the water-column as they drifted past. But Yochelson (1977) correctly points out that any current strong enough to carry silt would also be strong enough either to wash the small animal from the sea-floor or smother it completely. The mode of life has been compared to cerithid gastropods (Reinhardt and Wall, 1975). This is based on similarities of gross shell-shape and death assemblages. However, the functional morphology of the two animals differs too much for a direct comparison to be made. A mobile life-style is suggested, particularly as grains in the conch are often rare in the sediment matrix suggesting that the animal moved towards, and selected particular grains. Contrary to this hypothesis however, is the filling of the cone which would indicate that the organism may have lived apex down and that if Salterella was mobile then the conch would have to be dragged along (Yochelson, 1977). It seems likely therefore, that whatever mode of life was utilized by Salterella it was very inefficient.

Although common in the skeletal grainstone, mixed peloid packestone, and mixed oncolitic grainstone lithologies of the Oolite Sand Facies, _Salterella_ is absent from the moundstone and calcarenites of the Biostrome Facies, occurring only in the Oolitic Calcarenites (BB-1) which flank the Bioherms (BB-2) at Schooner Cove. In this lithofacies _Salterella_ is very abundant adjacent to the bioherms (within 2 m) but becomes rarer away from them, possibly suggesting a greater food source nearer to, and possibly derived from, the bioherms. It is envisaged therefore that the _Salterella_ was a very inefficient member of the mobile benthos, possibly a browser or deposit-feeder.

SYNECOLOGY

Mound-flanking Skeletal Calcarenite faunal assemblage

The term assemblage is prefered to community as this is only a qualitative description and the taxa involved are only identified on a very broad scale (never to the species level).

The assemblages are documented with a view to the role of the organisms in the assemblage and to their trophic grouping, so that a general, summary-like structure of the various assemblages can be presented forming a basis for future detailed analysis with tighter taxonomic control.

The skeletal composition of the flanking calcarenites is more or less the same for each lithofacies, consisting of five groups of organisms; echinoderms, brachiopods,

trilobites, hyolithids, and Salterella. Based on their
autecology, these organisms can be divided into sessile
epifauna and vagile epifauna (see Table V). The sessile
epifauna consists of echinoderms and brachiopods and
can be regarded as high and low-level filter suspension
feeders respectively thus partitioning the food supply.
The vagile epifauna consisting of trilobites, hyolithids,
and Salterella can be considered as sediment dependent
organisms; either deposit feeders of browsers. Volumetrically,
echinoderm plates form the bulk of the sediment with
brachiopods and trilobites the next most important;
hyolithids and particularly Salterella are rare. As
regards the structure of the assemblage, the preserved
trophic chain (Fig.55) is very simple lacking both
primary producers (autotrophs) and predators. Bearing
in mind that not all the organisms of the original
community will have been preserved (see discussion in
Stanton and Dodd, 1976), the dominance of filter-feeders
within the assemblage suggests that the environment was,
to some degree, turbid as the food supply to the
majority of organisms was in the water column.

Mound-dwelling faunal assemblage

The faunal assemblages which inhabit the mound
environment are generally more complex than the calcarenite
assemblage. There are differences in the diversity of
organisms between the five moundstone lithofacies, and
these are noted later. Because of these differences,
the most complex assemblage, that of the Red Moundstone

TABLE V. Role of organisms in the calcarenite
assemblage.

ORGANISM-NICHE RELATIONSHIP	TROPHIC GROUP
Sessile epifauna	
echinoderms	high-level filter suspension feeders
brachiopods	low-level filter suspension feeders
Vagile epifauna	
trilobites	deposit feeders
hyolithids	deposit feeders
Salterella	deposit feeder

RECUPERATORS   SEDIMENT   Trilobites
                             FEEDERS   Hyolithids
                                             Salterella

                      DETRITUS

CONSUMERS   WATER COLUMN   Echinoderms
                     FEEDERS   Brachiopods

INPUT   WATER-FLOW   Nutrients
                                              Oxygen
                                              Waste removal
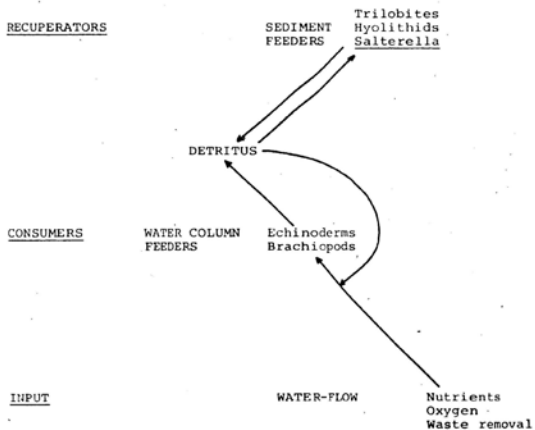
Fig.55:   Trophic structure of the calcarenite assemblage.

lithofacies (BR-1)), is described here.

In relation to the substrate, the mound-organisms can be divided into; sessile epifauna, mobile epifauna, and endoliths (see Table VI). A division of the sessile epifauna can be made into organisms which probably acted as sediment bafflers and organisms which acted as sediment trappers and binders (Table VI). A more complex trophic structure is represented in the mound where primary producers, consumers, and recuperators are well-represented (Fig.56).

The main difference between the mound and calcarenite assemblages are two-fold: (1) the presence of different kinds of high-level suspension feeders; (2) the presence of calcareous algae in the mound.

The mound assemblage is dominated by archaeocyathids and calcareous algae (renalcid algae, Epiphyton, and Girvanella) with less common brachiopods, coelenterate, trilobites, hyolithids, and sponges. The archaeocyathids are of very low diversity with only three species represented (Metaldetes profundus, Archaeocyathus atlanticus, and Retilamina amourensis) (Debrenne and James in prep.). The erect growth form of archaeocyathids may have served as sediment bafflers along with rare sponges, the coelenterate and possibly brachiopods. Although calcareous algae is most common in cavities, it also grew in clumps in the sediment and encrusted onto and within the archaeocyathid skeletons where it probably trapped

TABLE VI. Role of organisms in the mound
assemblage.

ORGANISM-NICHE RELATIONSHIP   TROPHIC GROUP

Sessile epifauna

(1)   Possible sediment bafflers

archaeocyathids   high-level suspension
                                    feeders

coelenterates   ?low/high-level
                                    suspension feeders

brachiopods   low-level filter
                                    suspension feeders

sponges   suspension feeders

(2)   Sediment trappers and binders

calcareous algae (outside   autotrophs
of cavities)

    Renalcis
    renalcid algae
    Girvanella
    Epiphyton

non-skeletal stromatolites   autotrophs

Vagile epifauna

Hyolithids   deposit feeders

?trilobites   deposit feeders

Infauna

trilobites   deposit feeders

Endoliths

Trypanites   ?

RECUPERATORS   SEDIMENT Hyolithids
                    FEEDERS Trilobites

DETRITUS

                               Archaeocyathids
                               ?Coelenterate
CONSUMERS   WATER COLUMN Brachiopods
                FEEDERS   Sponges

PRIMARY   Calcareous Algae
PRODUCERS   AUTOTROPHS Non-skeletal Stromatolites

                                Nutrients
INPUT   LIGHT   WATER-FLOW   Oxygen
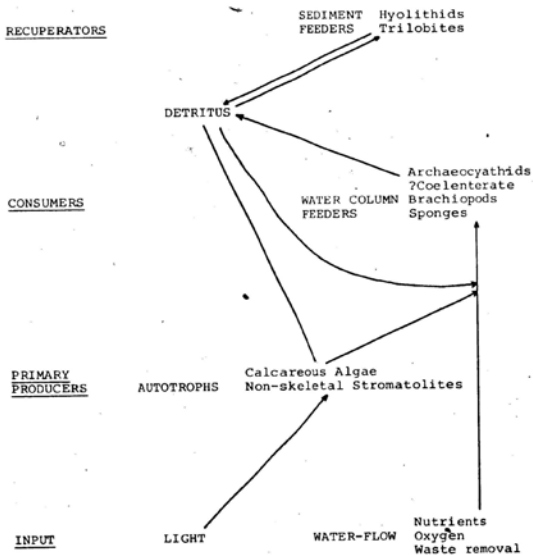   Waste removal

Fig. 56: Trophic structure of the mound assemblage.

and bound sediment. Semi-sessile hyolithids and burrowing
trilobites (cf. Bonnia) may have been deposit feeders.
Macroborers also played a role in the mound. The form
Trypanites, interpreted as a sipunculid worm (James et
al., 1977), is relatively common in most of the mounds
but as it is the only macroborer in the rocks, and
because of its relatively small size, the destruction
of the mounds is nowhere near as great as in that of
endolithic organisms in modern reefs (James 1970; Scoffin
and Garrett, 1974; Bromley, 1978).

The trophic structure of the mound, although more
complex than the calcarenite assemblage is still
relatively simple (Fig.56). Calcareous algae and non-
skeletal stromatolites acted as primary producers
(autotrophs) supplying nutrients for the partitioned
suspension feeders (consumers). Archaeocyathids,
sponges, and some coelenterates were high-level suspension
feeders while brachiopods, smaller coelenterates, and
possibly sipunculids (Trypanites) were low-level suspension
feeders. Both autotrophs and consumers contributed
nutrients to the sediment and in turn to the deposit
feeders, trilobites, and hyolithids. No predators are
recorded.

Coelobitic (cavity dwelling) assemblage

The dome-shaped nature of Retilamina amourensis forms
a natural, although small (several centimetres high and
wide) cavity which supports a relatively diverse coelobitic

assemblage, of similar structure to the cavity-dwelling
assemblages found in the 'patch-reef' series (Kobluk
and James, in prep.). Two substrate-niche relationships
are recognised: (1) Organisms which attach themselves
to the roof of the cavity; (2) Organisms which are
found in the internal sediment (see Table V11).

Those organisms which are attached to the roof of
the cavities include renalcid algae and rarely Epiphyton
which grew in pendants resembling bunches of grapes.
·Girvanella occasionally encrusted directly onto the
roof. Single-chambered and multi-chambered (cf.
Wetheredella) Foraminifera either attached themselves
directly onto the roof or were attached within clusters
of calcareous algae. Encrusting archaeocyathids
(Metaldetes sp.) were also either attached directly onto
the roof (Fig.57) or within clusters of calcareous algae.
The enigmatic forms Archaeotrypa and Bija were encrusted
directly onto the cavity roof (Fig.58). Both forms are
characterized by an irregular cellular structure of
tightly-packed rounded-polygonal cells, differing in that
Archaeotrypa was larger, has more regular walls, and a
skeleton that has always been leached and filled with
cement (Fig.58). Bija is considered either a coelent-
erate or an alga (Johnson, 1966). Archaeotrypa is also
of doubtful affinities, considered either a bryozoan, or
coelenterate (see discussion in Kobluk and James, in prep.).

Organisms inhabiting the internal sediment of the
cavities included small (one mm), highly convex, non-

TABLE VII. Role of organisms in the coelobite (cavity
dwelling) assemblage.

ORGANISM-NICHE RELATIONSHIP	TROPHIC GROUP
Attached (cavity roof encrusters)	

Calcareous algae
    Renalcis
    renalcid algae
    Girvanella
    Epiphyton
    Bija (if alga)
	autotrophs

foraminifera	suspension feeders
archaeocyathids	suspension feeders
Archaeotrypa	suspension feeder
Sediment dwellers	
trilobites (infaunal)	deposit feeders
?worms (infaunal)	deposit feeders
sponges (epifaunal)	suspension feeders
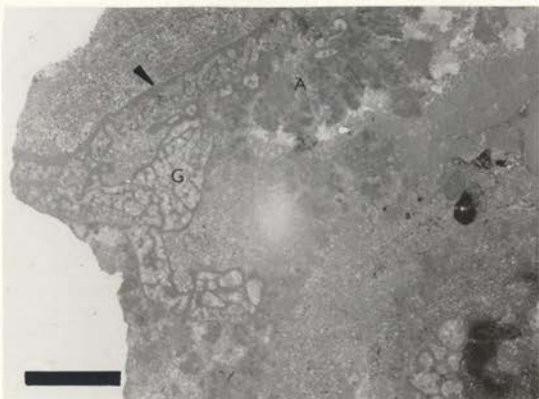
Fig.57: Photomicrograph (plane light) of <u>Retilamina</u>
         (arrowed) forming cavity. Encrusting archaeo-
         cyathid (G) and renalcid algae (A) are attached
         to the underside of <u>Retilamina</u> (the cavity roof)
         Scale bar is 3 mm.
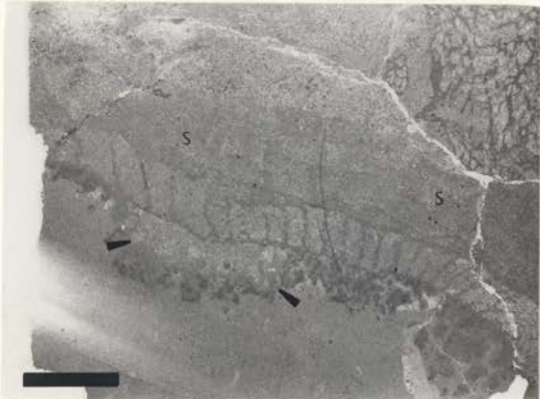
Fig.58: Photomicrograph (plane light) of an archaeo-
         cyathid forming a cavity. Renalcid algae and
         a leached (now spar) skeleton of <u>Archaeotrypa</u>
         (arrowed) encrust the underside of the archaeo-
         cyathid. Non-skeletal ?stromatolitic sediment
         (S) occurs on the top side of the archaeo-
         cyathid.
         Scale bar is 4 mm.

spinose trilobites (see Autecology: trilobites) which
were probably burrowers. They occur only in the
larger cavities. Sponge spicules (monaxon and triaxon)
occur sporadically in the internal sediment and sponges
may have inhabited the cavity. In cavities that are
large enough, the internal sediment often contains small,
cylindrical burrows, attributed, in the lower patch-
reef series, to worms (Kobluk and James, in prep.).

The trophic structure of the coelobite assemblage
is relatively complex (Fig.59). As primary producers
(calcareous algae) form the bulk of the biovolume, then
light must have been able to penetrate into the cavities.
Organisms dependent on the water column (suspension
feeders) include Foraminifera, archaeocyathids,
sponges, Archaeotrypa, and possibly Bija, and their
presence implies that there was a constant exchange of
water in and out of the cavity, bringing in nutrients and
oxygen and removing waste. The trilobites and worms
act as recuperators, either as scavengers or deposit feeders.

Vertical zonation in mounds

It has been established that more or less orderly
changes occur in a community through time, thus causing
a succession of communities preserved in the fossil
record as a vertical zonation (Walker and Alberstadt,
1975). Such vertical zonations are documented from
reefs from the Ordovician to Cretaceous (Nicol, 1962;
Alberstadt and Walker, 1973; Alberstadt, Walker and
Zurawski, 1974; Kauffmann, 1974; Walker and Alberstadt,

Fig. 59: Trophic structure of the coelobite (cavity dwelling) assemblage.

1975). Walker and Alberstadt (1975) recognise four
stages of development, each characterized by its own
community, in the development of vertical zonations in
ancient reefs. These stages are: (1) Stabilization
(pioneer) stage: This involves the stabilization of the
substrate, usually by the growth of echinoderms and the
accumulation of their debris; (2) Colonization stage:
This involves the initial colonization of the substrate
by reef-building organisms, normally by branching or
encrusting organisms. This stage is normally of short
duration, (3) Diversification stage: The increase in
niche space brought about by the colonization stage
leads to a rapid diversification, usually at high taxon-
omic levels, but is sometimes restricted within one
major taxon. This stage comprises the bulk of the reef.
(4) Domination stage: The final stage involves a
decrease in both the number of taxa and in the growth-
habits, often with the encrusting growth-habit dominating
to the exclusion of others. Walker and Alberstadt (1975)
claim that the first three stages; stabilization,
colonization, and diversification are due to intrinsic
factors, so that the succession is biologically accommodated.
The fourth stage, domination, may be due to extrinsic
factors, therefore physically induced and was maybe caused
by the reef growing into the surf-zone.

The mounds of the Biostrome Facies sometimes show
a distinct vertical zonation, correlatable with the

stabilization, colonization and diversification stages of Walker and Alberstadt (1975), but never show a domination stage. This may suggest that the Lower Cambrian mounds never grew into the surf-zone although sedimentological evidence possibly suggests otherwise.

The vertical zonation in the Biostrome Facies is best termed as a "recolonization process leading to diversification", and is best displayed at the base of the Red Moundstone (BR-1) at Fox Cove and at Osprey Reef. In all cases the succession appears to be the same (Fig.60); a development of moundstone is brought to an end by an influx of skeletal calcarenite which occurs as a thin (less than 20 cm) bed, sometimes with an erosive base suggesting an allochthonous source (possibly a storm-deposit). The calcarenite consists predominantly of echinoderm debris with trilobites, brachiopods, and hyolithids. This is a similar lithology as would be produced by the stabilization community of Walker and Alberstadt (1975). This thin calcarenite bed is then succeeded by an assemblage dominated by _Retilamina_ (Figs. 60 and 61) with minor occurrences of the coelenterate and stick-form archaeocyathids (_Archaeocyathus_ _atlanticus_). Associated with the _Retilamina_ is the coelobitic assemblage described above. All of the organisms in this assemblage occur in a lime-mud matrix, the mud probably being trapped by the closely packed _Retilamina_ and coelenterate fronds along with, in places, calcareous algae. This colonization assemblage is relatively thin
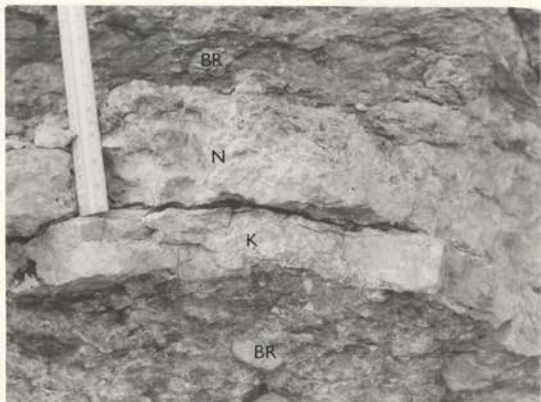
Fig.60: Cliff-section exposure of vertical zonation
of the Red Mound Unit at Osprey Reef.   Red
Moundstone (BR, bottom) is terminated by a
sheet of skeletal calcarenite (K). This is
overlain by the pioneer community (N) con-
sisting of mainly _Retilamina_ and calcareous
algae in a mudstone matrix. This passes
vertically into Red Moundstone (BR, top).
Scale is 25 cm long.

Fig.61: Bedding-plane exposure of the pioneer comm-
unity of the Red Moundstone lithofacies
(BR-1) at Fox Cove. Thin lines (arrowed)
are <u>Retilamina</u> skeletons. Darker areas
are calcareous algae; Lighter area is
lime mud matrix.
Scale bar is in centimetres.

(less than 30 cm) and grades vertically but rapidly into
what can be termed the diversification stage (Fig.60),
which in the case of Red Moundstone consists of
Metaldetes _profundus_ (cone-form and stick-form),
Archaeocyathus _atlanticus_ (stick-form), and _Retilamina_
amourensis (retilaminiform) in equal proportions along
with the coelenterate, sponges, calcareous algae,
brachiopods, trilobites, and hyolithids, plus the
coelobitic assemblage. This diversification assemblage
forms the bulk of the mounds, as it does in the cases
cited by Walker and Alberstadt (1975). No domination
stage is seen in these rocks, instead the Red Moundstone
passes vertically into Nodular Moundstone (BN-1) which
consists of fewer archaeocyathids and a greatly reduced
subsidiary fauna (see Table IV). This is, treated as an
allogenic phase as there is an obvious change in the
style of sedimentation (into nodular limestones and
shales with calcarenites) and is not considered as part
of the vertical zonation.

As the calcarenite at the base of the succession
is probably allochthonous in origin it can hardly be used
as the stabilization assemblage in the sense of Walker
and Alberstadt (1975). The calcarenite is not part of a
biological succession, indeed its chief function was to
terminate the development of the underlying moundstone
as indicated by its erosive base in places. It is
impossible to ascertain whether or not the calcarenite
was still mobile when colonized by the _Retilamina_ assemblage.

If the calcarenite was still mobile then the _Retilamina_
assemblage must have served the dual purpose of
stabilization and colonization. If on the other hand
the calcarenite was stable at the time of colonization,
then the _Retilamina_ assemblage must have colonized a
stabilized, allochthonous substrate. If this is the
case with any of the other stabilization/colonization
successions previously described, then the terminology
of Walker and Alberstadt (1975) for this process needs
slight modification or qualification.

Variation in fauna/flora between lithofacies

The main differences in the diversity of organisms
between lithofacies appears to depend on the presence
or absence of _Retilamina_. It is totally absent from
both the Dolomitic Moundstone (BD-1) and rare in the
Nodular Moundstone (BN-1), hence, none of the coelobitic
organisms associated with _Retilamina_ are present in these
lithofacies. In addition, calcareous algae are completely
absent from outside cavities in the Dolomitic and Nodular
Moundstones.

Apart from the presence and absence of retilamini-
form archaeocyathids and calcareous algae, and the
variation in archaeocyathid morphology (see Autecology:
archaeocyathids), there is little difference in the
structure of the mounds in terms of organisms (see
Table 1V).

As regards diversity and abundance of organisms, it would appear that the Red Moundstone (BR-1) represented the optimum conditions for mound development with every organism present except _Salterella_.

CHAPTER VI: SUMMARY AND CONCLUSIONS

This study concentrated on a 15-20 m thick archaeocyathid-bearing biostrome complex in the Lower Cambrian Forteau Formation of southern Labrador. The Forteau Formation marks the first occurrence of carbonate in the development of the Lower Paleozoic stable continental margin, later destroyed by westward transported ophiolite complexes. The Forteau Formation overlies the sandstones of the Bradore Formation which rest unconformably on Precambrian basement. Two archaeocyathid horizons occur in the Forteau Formation: a lower 'patch reef series', and an upper 'biostrome complex.' The purpose of this study was to document the facies distribution, stratigraphy, sedimentology, diagenesis, and paleoecology of the biostrome complex.

Reconnaissance mapping and subsequent detailed analysis of eight selected areas revealed that the biostrome complex of the Forteau Formation can be divided into two laterally distinct facies; the Oolite Sand Facies, and the Biostrome Facies. Stratigraphical and sedimentological evidence suggests that the Biostrome Facies was deposited seaward of the Oolite Sand Facies with the paleoslope trending to the south or south-east. The contact between the two facies is highly irregular and indicates that there were salients and recesses in the Oolite Sand Facies with the Biostrome Facies occupying shallow swales in the recesses. Lateral shifting of facies is partly responsible for the complex lithofacies mosaic which makes any paleoenvironmental

reconstruction a simplification of the true paleogeography.

The Oolite Sand Facies consists of seven lithologies;
skeletal grainstone, oolitic grainstone, mixed oolitic
grainstone, mixed peloid packestone, mixed oncolitic grain-
stone, intraclast grainstone, and dolostone and dolomitic
siltstone. These lithologies can be attributed to an
origin within an oolite shoal complex comparable with
modern day environments (Persian Gulf, Bahamas). The
active oolite shoal consisted of cross-bedded oolitic grain-
stones which formed in a high-energy, inter-tidal or shallow
sub-tidal environment. Mixed oncolitic grainstones
accumulated in stable sand channels between shoals. Supra-
tidal dolomite developed on subaerially exposed areas on
top of shoals. Dolomitic siltstones and intraclast grain-
stone are interpreted as storm deposits in a usually
subaerial environment on top of the shoals. Skeletal
grainstones occurred in a well-aerated, shallow subtidal
environment seaward of the active shoal. Ooids from the
active shoal were transported into quieter areas behind
the shoal and accumulated as shoal spillover forming mixed
oolitic grainstones adjacent to the shoal with mixed peloid
packestones further away.

The Biostrome Facies was deposited seaward of the
Oolite Sand Facies and consists of five distinct units;
Dolomite Mound Unit (BD), Red Mound Unit (BR), Nodular
Mound Unit (BN), Oolite Bioherm Unit (BB), and Grey Mound
Unit (BG). For the most part, the five units consist of

two laterally equivalent lithofacies; moundstone and skeletal calcarenite. Moundstone is a new, non-genetic rock-type defined as an autochthonous assemblage of skeletons and matrix sediment ,commonly mudstone) of uncertain origin, which occurs as mounds or bioherms. In the rocks under study the skeletal components of the moundstone lithofacies are: common archaeocyathids, lesser amounts of brachiopods, trilobites, and hyolithids. Calcareous algae are sometimes very common. The moundstones form mounds, biostromes or bioherms of considerable lateral extent (tens of metres) but which had sea-floor relief of only 1 or 2 metres. The mounds are flanked by the second major lithofacies; skeletal calcarenite, which drapes off the mound at angles of up to 15 degrees. The calcarenite is essentially a skeletal packstone consisting mostly of echinoderm plates which show no signs of wear, unbroken, disarticulated brachiopod valves, with lesser amounts of trilobites and hyolithids. This fauna indicates a shallow, low-energy, sub-tidal environment. The skeletal calcarenite does not vary between the five units, but five different moundstone lithofacies are recognised which can be interpreted as forming in different environments.

Dolomitic Moundstone (BD-1) and Nodular Moundstone (BN-1) are both flanked by skeletal calcarenites and are devoid of calcareous algae. They formed low, but extensive (tens of metres) mounds or biostromes in relatively deep water. They were deposited seaward of the Red Moundstone

lithofacies (BR-1) which formed smaller mounds in shallow
water, flanked by Skeletal Calcarenites (BR-2) and in
lateral contact with the active oolite shoal. This well-
aerated, moderately high-energy environment supported a
fauna and flora of high diversity. Sediments of the Grey
Mound Unit (BG) and Oolite Bioherm Unit (BB) accumulated
on protected, low energy swales between oolite shoals.
For the most part, the Grey Moundstone lithofacies (BG-1)
formed low but extensive (tens of metres) mounds, flanked
by skeletal calcarenite (BG-2), deposited on a shallow
swale in a relatively quiet-water environment in lateral
contact with the oolite shoal spillover. Stromatolites,
interbedded within the unit suggest that at times, the
Grey Mound Unit was deposited in an inter-tidal environment.
Small (less than 10 m) Archaeocyathid Bioherms (BB-2)
are internally similar to the Red Moundstone lithofacies
(BR-1) but form discrete bioherms flanked by 'quiet-water'
Oolitic Calcarenites (BB-1). These lithofacies were also
deposited on shallow swales, but probably in a protected
environment adjacent to an active oolite shoal.

The diagenesis of the moundstones versus calcarenites
was documented and discussed in terms of process, fabric
and history. Several processes have modified the original
depositional texture. These include bioerosion, dissolution
and cementation, neomorphism, dolomitization, silicification,
pressure solution (stylolitization), and fracturing. These
processes are attributed to several diagenetic environments

including; submarine, a zone of mixing between meteoric phreatic and marine phreatic waters, vadose, phreatic, and a late, unspecified environment.

The two most important processes operating in the submarine environment were bioerosion and early cementation. Bioerosion was not extensive and consists of microborings (forming micritic envelopes and peloids, etc.) in calcarenites, and macroborings (ichnogenus, _Trypanites_) in some of the moundstones. Early submarine cementation, in the form of lithification of micrite in moundstone, and cloudy fibrous rim-cement which is facies specific (occurring only in the moundstones and not in the flanking calcarenites) is common. A radial fibrous/bladed rim-cement, which occurs in oolitic grainstones, may also be of submarine origin.

Selective, early dolomitization of muds (now dolomite) pods within the Dolomitic Moundstone lithofacies) and of bioturbation features in calcarenites occurred due to initial sediment heterogeneity in a zone of mixing between meteoric phreatic and marine phreatic waters.

Minor dissolution of aragonitic shells and considerable rim-cementation, including extensive syntaxial cements on echinoderm plates, occurred in the vadose diagenetic environment.

Diagenetic processes in the phreatic environment include fracturing, dissolution, cementation, neomorphism, and pressure solution (stylolitization). Calcium

carbonate released during extensive stylolitization was
the source of iron-rich cement which occluded pores
and filled fractures. A transitional neomorphic fabric,
micrite-microspar-pseudospar, is interpreted to be the
result of two events, or pulses of wet boundary migration
of a solution film.

Late diagenetic events include; extensive dolomitization
which often obscures earlier dolomite fabrics, rare
silicification, and rare stylolitization.

Certain aspects of the paleoecology of the Biostrome
Facies were investigated using field and laboratory
techniques. The autecology of archaeocyathids, calcareous
algae, stromatolites, a new, primitive 'coelenterate',
brachiopods, trilobites, hyolithids, echinoderms, and
agmata (Salterella) is reviewed and discussed as to the
role of the organism in the biostrome. The synecology
of three distinct faunal/floral assemblages are documented
using trophic grouping and the function of the organism
in the assemblage to describe the structure of the assemblage.

The mound flanking "skeletal calcarenite assemblage"
has a very simple structure dominated by suspension feeders
(echinoderms and brachiopods) with minor occurrences of
deposit feeders (trilobites, hyolithids, and Salterella).

The "mound dwelling assemblage" has a more complex
structure consisting of; primary producers (calcareous
algae and non-skeletal stromatolites), dominated by suspension
feeders (particularly archaeocyathids with lesser occurrences

of 'coelenterate', brachiopods, and rare sponges), with less significant occurrences of deposit feeders (trilobites and hyolithids).

The "coelobite (cavity dwelling) assemblage" occurs in cavities within the moundstone. The cavities are mostly formed by the dome-shaped archaeocyathid _Retilamina amourensis_ which may also contribute to the structure of the assemblage. A diverse biota either encrusts the cavity roof, or occurs on, or within internal sediment. Primary producers (calcareous algae; including _Bija_, if an algae) dominate the biota and occur as encrusters. Suspension feeders (Foraminifera, encrusting archaeocyathids, _Archaeotrypa_, and sponges) are common as are deposit feeders (trilobites and worms) which occur on or within internal sediment.

Vertical zonation occurs in the Red Moundstone lithofacies (BR-1) and is best defined as "a recolonization process leading to diversification".

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APPENDICES

INTRODUCTION

Appendices A to H document the vertical successions and lateral relationships of the areas studied in detail (see CH. II). The areas are documented in geographical order from west to east (Fig. 8), and the facies to which they belong are noted in the heading. Stratigraphic sections are included (where possible) for each area. The symbols used are the same for each section and a key is given in Figures 62 and 63. The sections are discussed in Chapter III of the text.

Appendix I is a detailed account of the history of archaeocyathid research and the present world distribution of archaeocyathids and associated reefs.

Fig. 62: Key to lithologies used in section figures.

SKELETAL COMPONENTS

▽ Archaeocyathids (cups)

⌒ _Retilamina_

A Calcareous algae

~ _Girvanella_

🝘 Stromatolites

↟ Coelenterate

▽ Brachiopods

🝘 Trilobites

△ Hyolithids

◇ Echinoderms

▷ _Salterella_

BIOGENIC STRUCTURES

⊤ Macroborings (_Trypanites_)

U^e Burrows (D=Dolomitized)

~ Tracks and trails

NON-SKELETAL COMPONENTS

o Ooids

⬬ Oncolites

. Peloids

⬭ Intraclasts

∴ Grapestones

⸱ Quartz silt

SEDIMENTARY STRUCTURES

⧹ Cross-bedding

⁄ Minor cross-bedding

⌒⌒ Symetrical ripples

⌒⌒ Asymmetrical ripples

⋀⋀ Interference ripples

f Graded bedding

✓⌐\ Stylolites (N=nodular)

Fig. 63: Key to symbols of components
          and structures used in section
          figures.

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Blanc Sablon (Biostrome Facies)

This outcrop is located 3.5 km north of Blanc Sablon (Fig. 8) where it forms a conspicuous topographic feature rising to a height of 461 ft. (150 m) above a flat tract of land consisting mostly of lowermost Forteau Formation. This butte is the western-most outcrop studied. Outcrop is restricted, however, to the south side of the hill and to the very top where exposures of moundstone form twin peaks, seperated by recessive weathering calcarenite. In all, approximately 7.0 m of continuous vertical exposure can be regarded as Biostrome Facies. Lateral exposure is relativiely poor, extending for not more than 20.0 m along any one horizon.

At the base of the Biostrome Facies siltstone is transitional and laterally equivalent to skeletal calcarenite (Fig. 64). About 0.50 m higher in the sequence, part of this calcarenite is replaced by archaeo-cyathid moundstone while the part of the calcarenite adjacent to the siltstone persists.

The siltstone lithofacies is 1.45 m thick, is slightly calcareous and contains an abundant ichnofauna with vertical burrows and numerous horizontal tracks and trails. The siltstone is laminated throughout and often ripple-marked. Asymmetrical ripple-marks are aligned along 025° and indicate a current direction toward the north-west (295°). Asymmetrical interference ripples occur with a wavelength for the major ripples of 9.5 cm and an amplitude of 1.2 cm. These major ripples trend 310° while the minor ripples trend 027°. This siltstone is identical to, and can be regarded as a continuation of, the open-shelf facies of the Lower Forteau Formation.

The siltstone passes laterally and is transitional into skeletal calcarenite (BG-3) which is often very coarse-grained, especially close to the moundstone contact where archaeocyathid fragements are common. The majority of the skeletal debris is echinoderm, but convex-up, disarticulated, inarticulate brachiopod shells, often leached, are also common. This calcarenite, best described as a truncated wedge, has a maximum thickness of 0.82 m and a lateral extent of 1.60 m. The contact with the moundstone is not well exposed but is interdigitatory. The calcarenite drapes off the moundstone at angles up to 15°. Minor cross-bedding, always dipping away from the moundstone, occurs in the draping calcarenites.
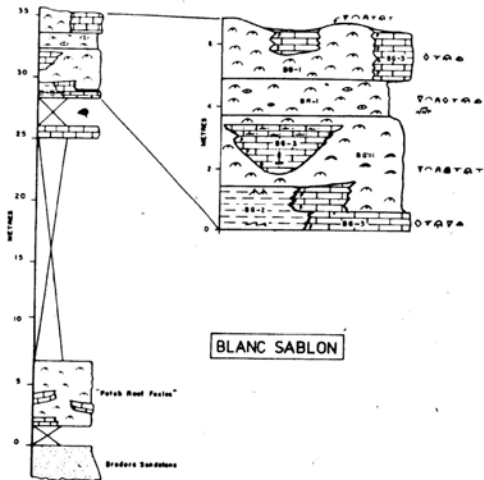
Fig. 64: Stratigraphic section in the Biostrome Facies at Blanc Sablon.

BLANC SABLON

"Patch Reef Facies"

Bradore Sandstone

Diffuse ripples occur at the very top of the calcarenite.

Laterally equivalent Grey Moundstone lithofacies (BG-1) lies directly on the calcarenite. Of the archeocythids, stick-forms dominate over narrow, thick-walled cones by a ratio of 2:1-3:1. Calcareous algae is abundant. The maximum thickness of the unit is 3.1 m, and within this unit, the density of archaeocyathids differs greatly. Archaeocyathids increase in density from the base towards the middle of the unit and become rare towards the top where only the occassional "colony" of stick-forms (Archaeocyathus) is present along with abundant, small, digitate, non-skeletal stromatolites (SH-V type of Logan et al., 1964). Inarticulate brachiopods are present where archaeocyathids occur. Stylolites are present but not as abundant as in other units.

The moundstone sequence is laterally persistent except for a "channel-like" body of calcarenite. This body is 7.60 m wide and 1.60 m thick with a horizontal top and a convex base and thins both ways from a maximum thickness in the centre. The calcarenite is graded, from a very coarse skeletal grainstone at the base upwards into packestone and wackestone, and into skeletal siltstone at the top where laminations and minor cross-bedding occur. The base and sides of the unit in contact with moundstone is covered.

Conformably overlying the Grey Mound Unit but with a distinct contact are rocks of the Red Moundstone litho-facies (BR-1). This bed is laterally persistant, averages 1.30 m thick, and has a stylonodular appearance. Small lenses of calcarenite occur within the moundstone. Upright archaeocyathids are abundant with stick forms (Archaeocyathus) and thinner-welled, low-angle cones (Metaldetas) being present in equal amounts. Retilamina, associated with calcareous algae is common and inarticulate brachiopods are present throughout. Echinoderm debris is also common throughout the lithofacies.

Overlying the Red Moundstone lithofacies is the Grey Mound Unit again with a thickness of 1.90 m. The unit begins with a thin (.08 m) mudstone layer which grades upward into a very stylolitized mudstone (0.10 m thick), almost stylolaminated, with well defined clay stylocumulates. The bulk of the unit consists of grey algal/archaeocyathid moundstone. Thin-walled, low-angle cones (Metaldetes) are the most common, out-numbering Archaeocyathus but Retilamina is also common. The cones become slightly

larger towards the top. Calcareous algae is abundant. The moundstone forms the two peaks at the top of the hill, separated by a tabular lens of skeletal calcarenite which extends for 40-50 m. Contacts between moundstone and calcarenite are straight but interdigitatory. A thicker unit of calcarenite (1.60 m) is partially exposed to the south-west of the main summit. No draping occurs in the calcarenites.

APPENDIX B

Diversion Reef (Oolite Sand Facies and Biostrome Facies transition)

This section in the Oolite facies is poorly exposed
along a track over a distance of some 0.8 kms, situated
approximately 4 kms to the north of L'Anse-au-Clair (Fig.8).
Because of the undulating nature of the topography in this
area, no continuous vertical section can be measured but
an approximate composite cross-section, consisting of 5
vertical sections can be compiled (Fig.65).

The transition from the Biostrome Facies to the Oolite
Sand Facies is not as sharply delineated as at Osprey
Reef (Appendix C) but occurs gradually. Skeletal calcarenites
(grainstones) of the Oolite Sand Facies consisting
predominantly of Salterella cones, echinoderm plates,
trilobite debris, and inarticulate brachiopods, both over-
lie and are in lateral contact with the Grey Mound Unit
(BG) of the Biostrome Facies. The Oolite Sand Facies
replaces the Biostrome Facies northwards (section a, b, c;
Fig.65).

Section c (Fig.65) begins with a small outcrop of
the archaeocyathidrich Grey Moundstone lithofacies (BG-1)
followed by a covered interval of 1.58 m. The next exposure
consists of Salterella-rich skeletal grainstone (2.22 m)
which passes upwards into 0.23 m of burrowed, oolitic,
skeletal grainstone. The burrows are dolomitized and the
skeletal fraction consists of abundant Salterella cones
and echinodermplates along with trilobites and inarticulate
brachiopods. A covered interval of 0.44 m is succeeded
by a light-to dark-grey, burrowed (dolomitized), skeletal
grainstone with abundant Salterella and echinoderm plates
along with minor amounts of trilobite debris, hyoliths,
silt-grade quartz, ooids, and coated (Girvanella) grains.
The thickness of this unit is 0.93 m. Another covered
interval (1.65 m) is followed by 1.3 m of burrowed,
oncolitic, skeletal grainstone. The oncolites, consisting
of Girvanella tubules, have a maximum size of 3 cm and
occur with minor amounts of silt-grade quartz, peloids,
and ooids. The skeletal fraction (40% of total rock-volume)
consists of Salterella cones, hyolithids, echinoderm plates,
and trilobites.

Section d (Fig.65) commences with shales and calcareous
silts rich in trace-fossils, characteristic of the lower
part of the Forteau Formation open-shelf facies (James
and Kobluk, 1978), and is apparently laterally equivalent
to the Biostrome Facies exposed to the south (section c,
Fig.65). This implies that the lower part of the Forteau
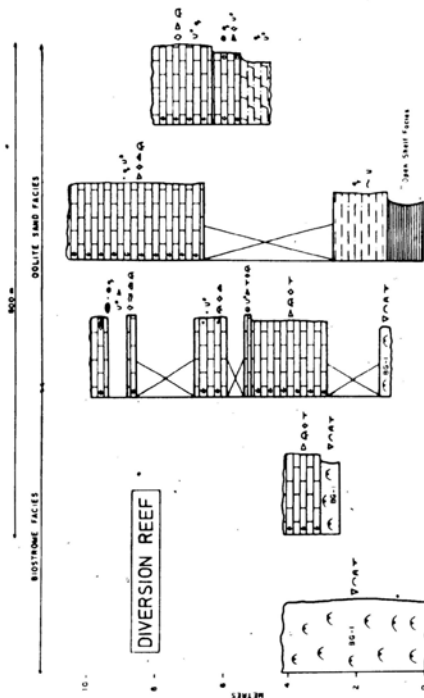Formation is much thicker to the north and consequently

Fig. 65: Stratigraphic sections in the Biostrome Facies – Oolite Sand Facies transition at Diversion Reef.

the Oolite Sand Facies must thin northwards. The base of the Oolite Sand Facies is taken here as a 1.6 m exposure of calcareous siltstone with numerous tracks, trails, and burrows, which conformably overlies the shales. This lithotype is taken as the base of the Oolite Sand Facies as it is often seen as the basal member of the Biostrome Facies elsewhere (Blanc Sablon, L'Anse Amour, and Fox Cove). A covered interval of 3.78 m is followed by 3.82 m of burrowed, skeletal grain-stones consisting of Salterella cones and echinoderm plates with subordinate elements of hyolithids and trilobites. These are the highest beds seen.

The northermost section outcrops in a small cliff (3.27 m) and is equivalent in part to the top of the covered unit and base of the skeletal grainstone in section d (see section e, Fig.65). The basal lithology (0.90 m) is burrowed dolomitic siltstone with a minor skeletal fraction (less than 10%) of echinoderm plates, trilobites, and rare Salterella cones. This is overlain by 0.77 m of oolitic grainstone containing less than 15% echinoderm plates and Salterella cones, plus a minor silt fraction. The ooids are dolomitized. The sequence terminates with 1.6 m of burrowed skeletal grainstones, again, dominated by echinoderm plates, Salterella cones, trilobites, and minor occurrences of silt and coated grains.

APPENDIX C

Osprey Reef (Oolite Sand Facies and Biostrome Facies transition)

This outcrop is situated approximately 4 km to the
north-east of L'Anse-au-Clair (pos. c, Fig.8) where the
rocks are exposed almost continually in a lateral section
extending for 800 m. The biostromal complex of the Forteau
Formation is here faulted against the lower patch-reef
series of the Forteau Formation. This is an important
section because it demonstrates the lateral relationship
between the two major facies; the Biostrome Facies
and the Oolite Sand Facies (Figs. 66 and 73).

The Biostrome Facies here is essentially a complex
of two distinct lithofacies; Red Moundstone (BR-1) and
Skeletal Calcarenite (BR-2) which are exposed in outcrop
at the ratio of 2:3, respectively. Lateral and vertical
changes in lithofacies are extremely rapid, occurring over
a few metres. The macro-relationships are shown diagram-
atically in Fig.73 (in pocket), compiled from a photo-mosaic
and field sketches. Field observations were restricted
due to the inaccessibility of much of the exposure. The
section is described from south-west to north-east.

To the south-west (section a on Figs. 66 and 73),
the section is predominantly a very coarse-grained skeletal
calcarenite with a thinly-bedded gainstone with a matrix
of archaeocyathids brachiopods, trilobites, and echinoderm,
debris. Vertically, the calcarenite becomes more massively
bedded but still retains its coarse-grained character.
At 6.15 m from the base of the section is a thin (9 cm)
band of calcareous siltstone with symmetrical ripple marks.
This siltstone is in turn overlain by coarse-grained
skeletal calcarenite. The total exposed sequence is
8.0 m thick.

Further to the north-east (section 2), skeletal
calcarenite both overlies and passes laterally into Red
Moundstone (BR-1). The skeletal calcarenite is interrupted
again by another, laterally impersistent calcareous silt
bed about 1.0 m wide and 8 cm thick at the maximum, tapering
both ways to the stylocumulate of a stylolite. The silt-
stone contains asymmetrical ripples with a wavelength of
50 mm and amplitude of 6 mm.

The sequence at section 3 is dominated by the typical
Red Moundstone lithofacies. Archaeocyathids are very
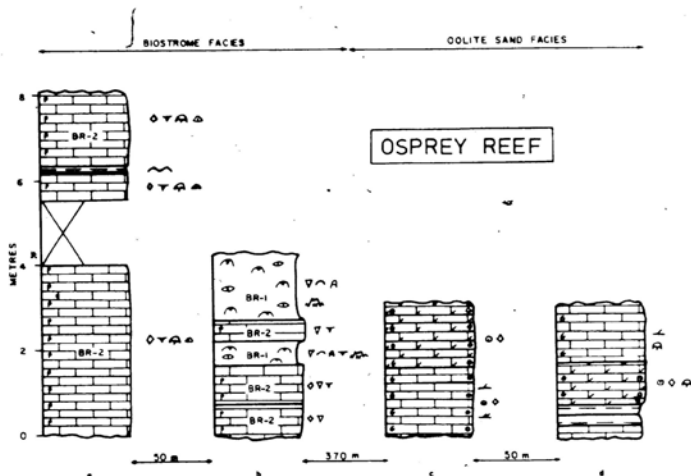abundant with low-angle cones (Metaldetes) outnumbering

Fig. 66: Stratigraphic sections in the Biostrome Facies - Oolite Sand Facies transition at Osprey Reef.

sticks (<u>Archaeocyathus</u>) by 2:1; <u>Retilamina</u> is common, as
are brachiopods. The moundstone has a stylonodular
appearance due to intense stylolitization. Contact with
the surrounding calcarenite is both straight and sharp,
draping (39° towards 140°), and interdigitatory. Small
lenses of calcarenite, averaging 20 cm x 7 cm (maximum
48 cm x 15 cm), occur within the moundstone but make up
less than 10% of the lithofacies.

Laterally equivalent to the moundstone is a thick
(5 m) sequence of homogenous skeletal calcarenite (section
5) which extends laterally for about 21 m before a contact
with moundstone (section 6). The contact between the
moundstone and calcarenite is straight but interdigitatory.
Within the moundstone are thin (up to 20 cm), persistent
(10.0 m) sheets of calcarenite. Wherever these sheets
occur, the overlying moundstone is "recolonised" by a thin
(25 cm) bed with numerous retilaminiform (<u>Retilamina</u>)
archaeocyathids in a grey to green to red mudstone matrix
with characteristic pendent calcareous algae growing on
the underside of each archaeocyathid. <u>Retilamina</u> skeletons
are all orientated convex-up, rarely touch each other,
but occur in profusion stacked close to each other. Coarsely
crystalline cement (pink) fills in the cavity between the
calcareous algae which grows on the underside of <u>Retilamina</u>
and internal sediment. Other fauna associated with
<u>Retilamina</u> is rare, although stick-form archaeocyathids
(<u>Archaeocyathus</u>) occassionally occur. A rapid transition
occurs vertically into the normal Red Moundstone where
cones (<u>Metaldetes</u>) and sticks (<u>Archaeocyathus</u>) are abundant
and <u>Retilamina</u> subordinate.

The same "recolonization" process is seen again (section
7) on top of an erosive channel of skeletal calcarenite.
This channel has a horizontal upper surface but a very
irregular bottom surface with relief varying by as much as
10 cm. Consequently the thickness of the body varies
between 25 cm and 35 cm. It is overlain by the retilamini-
form moundstone assemblage followed by typical Red Moundstone.

To the north-east of section 7, two normal faults
of small displacement occur and outcrop becomes sparse.
Rocks of the same unit, however, are picked up again
(section 8) where Red Moundstone and skeletal calcarenite
are seen laterally juxtaposed in small exposures.

One small exposure (section 9) represents the last
time that the Red Moundstone is seen along this section,
the remainder of the outcrop is formed of rocks of the Oolite

Sand Facies. The outcrop consists of both Red Moundstone and oolitic grainstone which are seen to grade on to the other. The Red Moundstone consists of three times as many stick-forms as cones and retilaminiforms. A considerable number of the cups are toppled. Ooids can be seen in abundance in the moundstone matrix which also contains a lot of skeletal debris. A lot of skeletal debris, including archaeocyathid cups, also occurs in the adjacent oolitic grainstone, which along with skeletal calcarenites, makes up the remainder of the section to the north-east.

Two small sections were measured in the Oolite Sand Facies (sections c and d on Figs. 66 and 73). Section c is located within 20 m of the contact with the biostrome and section d is located approximately 50 m to the north-east of section c.

Section c (total thickness 3.10 m) consists entirely of rocks of the Oolite Sand Facies. The basal 86 cm consists of light-grey, orange-speckled, cross-bedded, partially dolomitized, oolitic grainstones. All the ooids are dolomitized and there is also partial dolomitization of the matrix. It is overlain by a light-grey, cross-bedded, oolitic grainstone (74 cm) with a minor trilobite fraction and dolomitized ooids. The topmost unit is a light-grey oolitic grainstone (1.50 m) with a relatively high skeletal content consisting predominantly of echinoderm plates. The ooids are again dolomitized, but no cross-bedding occurs.

Section d (total thickness 2.94 m) consists of burrowed dolostones, skeletal, oolitic grainstones, and skeletal grainstones. The lowermost exposed beds consist of 66 cm of burrowed dolostones with a small silt fraction, apparently restricted to the burrows. This unit is interrupted by a thin (6 cm) bed of horizontally laminated dolomitic siltstone consisting of equal proportions of finely crystalline dolomite and sub-angular to sub-rounded silt-grade quartz. This bed occurs at 0.45 m from the base of the section.

The dolostones are overlain by 1.08 m of cross-bedded, light-grey oolitic grainstones with varying amounts of skeletal material and peloids. Towards the base of this bed dolomitized ooids and peloids occur in equal proportions with a relatively small (less than 15%) skeletal fraction consisting of echinoderm plates, inarticulate brachiopods, and trilobites. The peloid fraction disappears upwards

replaced by partially dolomitized ooids and a skeletal
fraction (20%) of echinoderm plates, brachiopods, and
trilobites.

The oolites are overlain by a partially dolomitized
(mottled, 20% of volume), cream to pink, skeletal grain-
stone consisting predominantly of echinoderm plates with
minor quantities of trilobites and brachiopods. This
grades into a skeletal grainstone with minor dolomitization
(less than 10%) and a 15% fraction of dolomitized ooids.
The combined thickness of the skeletal grainstones, the
highest beds exposed, is 1.20 m.

A rose diagram of 17 measurements of cross-bedding
current direction taken from the oolites (Fig.23)
indicates a widespread polymodal current direction. This
result may be due to insufficient data.

APPENDIX D

Forteau (Oolite Sand Facies)

The thickest measured section (18.5 m) in the Oolite Sand Facies occurs in poorly exposed outcrops along the main road about 1 km to the east of Forteau, and in small quarries adjacent to a track heading southwards off the main road (position d, Fig.8).

A complete section of the Forteau Formation from the contact with the Bradore Formation to the present day level of erosion can be measured. The base of the Oolite Sand Facies is taken at the conformable contact between platey limestone and shale beds, characteristic of the lower part of the Forteau Formation and a skeletal calcarenite characteristic of the upper part of the Forteau Formation in Labrador (Fig.67).

The basal calcarenite (1.6 m) is partially dolomitized (mottled, totaling 20% of total rock volume), burrowed, dark-grey, skeletal grainstone consisting of worn and broken fragments of echinoderm plates, Salterella cones, and trilobite debris, along with a 10% silt fraction.

This is overlain by a dark grey, intraclast grainstone (4.0 mm) consisting entirely of intraclasts cemented together by coarsely crystalline pink calcite which makes up 40% of the rock volume. The intraclasts are stretched-out or rounded 'rip-up' clasts consisting entirely of tubules of the blue-green algae Girvanella. At the base, the clasts are elongated with ragged margins but higher up the clasts are more rounded.

This passes vertically into a poorly-sorted, dolomite-mottled, oncolitic-oolitic grainstone (1.2 m) with a skeletal fraction consisting of Salterella cones, echinoderm plates, and minor occurrences of hyolithids and trilobites. The oncolites consist of a nucleus of composite grains, ooids, or skeletal fragments surrounded by tubules of Girvanella and are up to 3 cm long.

The oncolitic grainstone is succeeded by a dark grey skeletal grainstone (2.0 m) with brown-orange mottles (dolomite). The grainstone consists mainly of echinoderm plates and trilobite carapaces and the occassional hyolithid cone and brachiopod valve.

The grainstone is overlain by a light-grey to light-brown dolostone with a minor skeletal fraction of abraded
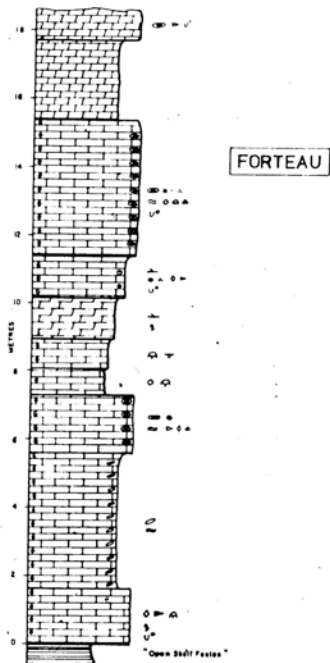
FORTEAU

Fig. 67: Stratigraphic section in the Oolite Sand
Facies at Forteau.

trilobites and brachiopods. This grades vertically into
a ripple-laminated domomitic siltstone with some burrows.
Altogether, this unit is 1 m thick.

Overlying the dolomite beds is a 1 m thick bed of
burrowed (dolomitized), dark-grey, oolitic grainstone
with a minor (less than 10%) skeletal fraction of echinoderm
plates and Salterella cones.

Following the oolite is a relatively thick (4 m)
sequence of black to dark-brown oncolitic and oolitic
grainstones. Oncolites, up to 2.5 cm across and
consisting of Girvanella tubules, occur in a matrix of
ooids, peloids, composite grains, echinoderm plates,
trilobite debris, and hyolithids.

The top of the exposed sequence consists of 3.5 m
of burrowed dolostone, often with dolomitized oncolites
and with a skeletal fraction of less than 5%.

APPENDIX E

L'Anse Amour (Biostrome Facies)

The largest continuous outcrop of the Biostrome Facies is found in a cliff-section to the south-west of the Pointe Amour Peninsula (position E, fig.8). This cliff is found about 50 m inland from the high-tide level and is in excess of 35 m high. The vertical exposure totals some 15 m and forms the brow of the cliff which extends laterally for 2.25 km. Several minor faults cross the cliff but the displacement is small. Although the land surface rises gently inland from the cliff-section, the strata is repeated by faulting so the most complete section is seen in the cliff itself. Four sections were measured along the length of the outcrop (Fig.68).

The contact with the open-shelf facies of the Forteau Formation is seen only at the southern end of the cliff. Dolomitic Moundstone (BD-1) is in direct contact with shales and siltstones of the open-shelf facies and the moundstone fauna here consists of large, high-angle cones and bowl-shape archaeocyathids (Metaldetes). Moundstone grades laterally into skeletal calcarenite which in turn grades laterally into a rippled calcareous siltstone and then back into skeletal calcarenite. The calcarenite is a skeletal grainstone with small archaeocyathid fragments brachiopods, and trilobites; is less than 20 cm thick and extends laterally for 75 cm from the moundstone to the siltstone. It passes both laterally and vertically into rippled-laminated calcareous siltstone (the ripples are asymmetrical, with a wavelength of 10 cm and an indicated current direction.towards 164°). The vertical extent of the siltstone varies between 10 cm adjacent to the moundstone and 25 cm away from it. Above the siltstone, adjacent to the mound is 40 cm of skeletal calcarenite which drapes off the moundstone at angles of less than 10°. The calcarenite is replaced vertically by moundstone.

The most complete section at L'Anse Amour occurs about 250 m from the southern end of the cliff. The basal division consists of 2.2 m of Dolomitic Moundstone (base not seen in measured section) which is at least in part equivalent to the shales and siltstones to the south. The moundstone is typically dark grey or green, archaeo-cyathid-rich with a mudstone matrix (lithofacies BD-1). No large dolomite pods are seen although small patches of dolomitization occur along with small lenses of skeletal calcarenite. Weathering obscures much of the detail although a certain vertical zonation of fauna is apparent.

L'ANSE AMOUR

Fig. 68: Stratigraphic sections in the Biostrome Facies
at L'Anse Amour.

Towards the base, narrow cone archaeocyathids (Metaldetes) dominate with only the occasional isolated stick-form (Archaeocyathus). In the top 0.35 m, clumps of branching stick-forms occur which are evenly spaced (c. 0.35 m apart) and are associated with scattered coelenterate fronds.

Overlying the Dolomitic Moundstone lithofacies (BD-1) is the thinnest and least persistent unit consisting of Red Moundstone (BR-1). The thickness is 1.20 m in the measured section but is often less and rarely more than that figure. This unit is characterized by the deep red colour of the mudstone matrix, the stylonodular appearance, and abundance of upright archaeocyathids. Narrow cones dominate the archaeocyathids fauna with stick-forms and retilaminiforms also playing an important role. Calcareous algae is common throughout the units, coelenterate fronds occur locally, and inarticulate brachiopods are common. Small lenses of skeletal calcarenite make up less than 10% of the rock by volume.

The main part of the outcrop consists of Nodular Moundstone (BN-1). This unit averages 6 m thick and consists of badly weathered, rubbly, black to dark grey, nodular moundstone with a mudstone to wackestone matrix. Small lenses of skeletal calcarenite and small isolated patches of shale occur within the moundstone. Archaeocyathid density is low but consists primarily of narrow and wide cones (Metaldetes). Brachiopods are rare. The unit is laterally persistent and occurs in sections measured 2 km away to the north. Within the L'Anse Amour area (and at Fox Cove) the Nodular Mound Unit (BN) is terminated by a planar erosion-surface contact with oolitic and skeletal grainstones (Unit BB).

Within all three units (BD, BR, BN) exposed below the erosion surface, large accumulations of skeletal calcarenite occur as wedges which flank the moundstone. In the area between the settlement of L'Anse Amour and the southern extent of the cliff (about 1.0 km) there are six such wedges which vary in size from 1.5 m to 4.5 m thick by 2.5 m to 28 m long at the base (maximum extent). In all six occurrences, calcarenite drape off the moundstone at angles between 11° and 18°, and in directions between 013° and 050°. Minor cross-bedding is often seen on the inclined beds, always dipping away from the mounds. Four of the wedges are adjacent to the nodular moundstone (BN-1), one is adjacent to the Red Moundstone (BR-1), and one, the largest, is adjacent to all three lithofacies (BD-1, BR-1, and BN-1). The largest wedge (size 4.5 m by 28 m) occurs at the southern end of the cliff. This

wedge consists of skeletal packstone to grainstone with
several beds, up to 20 cm thick, consisting solely of
unbroken brachiopod valves. These brachiopod-rich beds
dip gently off the mound (less than 10^0) but are horizontal
within 25 cm from the mound. The contact between the
moundstones and calcarenite interdigitates over 50 cm.
At the top of the wedge is a large symmetrical megaripple
with a wavelength of 1.85 m and an amplitude of 16 cm.
Current directions could not be measured. It is directly
underlain by a 4 cm thick bed with slightly asymmetrical
ripples (wavelength of 10 cm).

Overlying the Nodular Mound Unit (BN) and seperated
by a planar erosion surface described above is another
5.56 m of section, divisable into 2 units (BB and BG).
The Oolite Bioherm Unit (BB) lies on top of the erosion
surface and has a maximum thickness of 3.05 m. At the
south end of the cliff, coarse skeletal calcarenite (BB-3)
with a thickness of 27 cm occurs at the base and passes
vertically into skeletal oolitic calcarenite (BB-1) more
than 2 m thick, with no sedimentary structures. A small
archaeocyathid-rich moundstone occurs as a Bioherm (BB-2)
of unknown lateral dimensions (probably less than 1.50 m)
and 0.40 m thick.

About 250 m to the north a coarse, skeletal, oolitic
grainstone (occasionally floatstone) is at the base (thick-
ness 32 cm) and contains large archaeocyathid cups
echinoderm fragments, brachiopods, and trilobites as well
as asymmetric ooids. This grades upwards into an oolitic
packestone (48 cm thick), in which the ooids are selectively
dolomitized. Above the dolomitized oolite bed is a very
clean, light-grey oolitic packstone (6 cm thick) with
very little skeletal material which truncates the dolomitized
ooids underneath. The light-grey ooids are in turn,
truncated by 15 cm of very coarse skeletal oolitic
packestones (BB-1). Both erosive contacts are planar,
distinct lines but only occur locally.

The next horizon of oolitic packestones (95 cm)
contains another small bioherm of unknown, but restricted
dimensions. This bioherm has a flat lower surface and a
strongly convex upper surface with the top truncated by
the overlying unit. The bioherm, in the same level as the
one to the south and of another 1 km to the north, consists
of a red to grey archaeocyathid moundstone in a mudstone
to packestone matrix. Stick-form archaeocyathids out-number
cones by 2:1; retilaminiforms are common; trilobites,
brachiopods, and calcareous algae are present. The largest
bioherm is the one to the north which has a maximum height

of 1.60 m at the central point of the structure and is
5 m wide at the base. The contact between the bioherm
and the oolites is straight although interdigitatory.

Two kilometres to the north of L'Anse Amour,
equivalent beds consists of 1.15 m of skeletal packestone
to grainstone overlain by 1.60 m of coarse,
but fining upwards skeletal oolitic calcarenites.

The highest beds exposed overlie the Oolite Bioherm
Unit (BB) and consist of rocks of the Grey Mound Unit
(BG). The Grey Moundstone lithofacies (BG-1) consists of
abundant clacareous algae often associated with
retilaminiform archaeocyathids with cones outnumbering
stick-form archaeocyathids by 2:1. The cones (Metaldetes)
are large and thick-walled. Poorly exposed outcrops of
laterally equivalent calcarenites occur but their geometry
is unknown. About 1 km to the north of L'Anse Amour, a
course skeletal calcarenite (80 cm thick) which grades
upwards from the underlying oolitic packestone is
apparently the lateral equivalent of the moundstone.
One km further north, the same Grey Moundstone occurs
(0.50 m thick) although the basal 0.20 m of grey mudstone
appears unfossiliferous. At L'Anse Amour the grey
moundstone is 2.80 m thick, but the top 0.30 m consists
of skeletal (Girvanella) stromatolities (type LLH-C of
Logan et al., 1964) which are the highest beds seen but
are also laterally equivalent in part to the Grey Moundstone.

APPENDIX F

Fox Cove (Biostrome Facies)

The only coastal exposure of the Biostrome Facies is found at Fox Cove on the Pointe Amour peninsular (position F, Fig.8) where it is faulted against the patch-reef series of the Forteau Formation. Although less than 14 m of section is exposed vertically, about 300 m of strata is exposed laterally. The stratigraphical contact of the Biostrome Facies with the open-shelf facies of the Forteau Formation is seen only at the north-east end of Fox Cove (Figs. 69 and 70).

The sequence (see Figs. 69 and 70) commences with a thick (2.5 m) unit of massively bedded calcarenite which grades, 20 m to the south-west into calcareous siltstone with common trace fossils. Several sets of ripple-marks are associated with the siltstone including sinous symmetrical ripples, interference ripples, and asymmetrical ripples. Current direction varies between $030°$ and $172°$.

The skeletal calcarenite passes upward into 27 cm of well-laminated calcareous siltstone with interbedded shales containing small lenses of skeletal calcarenite. This unit is overlain by 1.20 m of massively bedded, homogenous, coarse-grained skeletal calcarenite (packestone to floatstone with packestone matrix). Archaeocyathid fragments are fairly common but most of the material consists of echinoderm plates, with brachiopods, and occasional trilobites and hyolithids. The unit terminates with a mega-rippled surface of symmetrical ripples having wave-lengths of between 18 and 35 cm. Crests of the ripples trend $055°$. This mega-rippled horizon is also seen 50 m to the south-west where the wavelength is 96 cm with symmetrical crests trending $049°$. Three hundred metres to the south-west, near to the beach, both symmetrical mega-ripples (wavelength of 34 to 45 cm, crests trending $066°- 085°$)and sinous, asymmetrical megaripples (wave-length of 15 cm, current direction $166°$) occur.

Overlying the mega-rippled calcarenite is a laterally diverse suite of shales and silts (lithofacies BD-2), Skeletal Calcarenite (BD-3) and Dolomitic Moundstone (BD-1); which together attain a maximum thickness of 4.0 m. Towards the north-east, the sequence commences with 1.60 m of shales and calcareous siltstones. Shales dominate at the base but sediments become silty towards the top with occasional small ripple laminations. Rare, small lenses of skeletal calcarenite (maximum size 33 cm x 5 cm) occur within the unit.
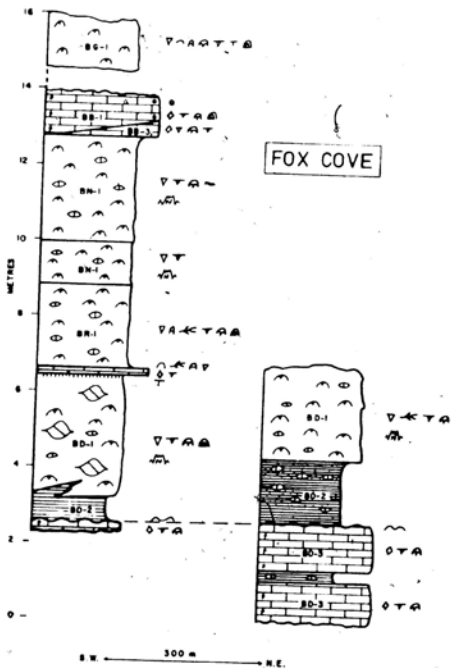
FOX COVE

Fig. 69: Stratigraphic sections in the Biostrome
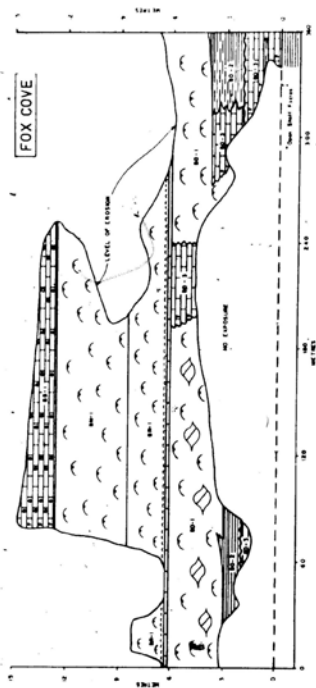Facies at Fox Cove.

Fig. 70: Cross-section of exposed strata in the Biostrome Facies at Fox Cove illustrating unit and lithofacies relationships.

Overlying the shales with an irregular contact is
the Dolomitic Moundstone (BD-1). In places, the base
of the moundstone consists of toppled stick-form
archaeocyathids (Archaeocyathus) in a mud/silt matrix.
This grades laterally into either a purer calcareous
siltstone or a brachiopod packestone with convex-up in-
articulate brachiopod valves forming beds less than
15 cm thick. Most of the time, the moundstone lies
directly onto the shales and silts. In this situation,
very large, wide cones and bowl-shaped archaeocyathids
(Metaldetes) with diameters averaging 10.5 cm dominate
the fauna along with inarticulate brachiopods. Associated
fauna includes large stick-form archaeocyathids and an
occasional frond of coelenterate. About 1.0 m higher,
however, sticks outnumber narrow cones and the coelenterate
has an erratic distribution from absent to very abundant,
sometimes occurring as the sole skeletal element.
Branching, stick-form archaeocyathid (Archaeocyathus)
"colonies" are common at this horizon and very evenly
spaced 35 cm apart. Skeletal calcarenite lenses or pods
and small pods of fine-grained dolomite are present but
are not extensive. The top of this unit is not exposed
at the north-east end of Fox Cove.

Traced to the south-west, the underlying shales
(BD-2) become more silty in nature and eventually
calcareous siltstone is replaced by Skeletal Calcarenite
(BD-3), all within 50 m from the north-east end.
Dolomitic Moundstone overlies the calcarenite. Thirty
metres further to the south-west the calcarenite thins
against laterally equivalent Dolomitic Moundstone (BD-1).
The calcarenite drapes off the moundstone at angles of
less than 10°, and has an interdigitatory contact.

The shales are seen again to overlie the mega-rippled
calcarenite at the south-west end of Fox Cove, 300 m from
the previously described occurrence, and on the same
stratigraphical horizon. The shales here are black,
featureless, almost 1 m thick and extend at least 50 m
further to the south-west. They underlie the Dolomitic
Moundstone in the lower part and occur as lateral equivalents
in the upper part where a tongue of shale drapes off the
moundstone at angles up to 30°.

The Dolomitic Moundstone to the south-west differs
from that to the north-east in at least two important
ways. The proportion of dolomite present and the size
of the pods in which it is found is much greater to
the south-west. The dolomite makes up approximately 25%
of the lithofacies and is found in large pods and lenses

(maximum more than 2 m long) which are surrounded by stylonodular moundstone which because of the differential intensity of stylolitization, appears to have wrapped itself around the dolomite pod. Some pods on weathered surfaces show laminations and bioturbation features (vertical and inclined burrows). Upright archaeocyathid cups and 'relict' (?) patches of skeletal calcarenite occur occasionally. The second difference between the two areas is the absence of coelenterate in the south-west, the fauna there consisting predominantly of narrow cones (Metaldetes) dominant over stick-forms (Archaeocyathus). Between the two main exposures is a lens of skeletal calcarenite (coarse-grained packestone) at least 1,40 m thick and extending laterally for 35 m. Only one contact with the moundstone is seen (south-west end) where the calcarenite thins towards and drapes off the mounds at gentle angles. Adjacent to the contact, archaeocyathid cups are seen in the calcarenite, otherwise the skeletal composition consists of echinoderms, brachiopods, or trilobites.

The Dolomite Unit (BD) at Fox Cove is brought to an abrupt end by a very thin but laterally extensive (more than 300 m) sheet of skeletal calcarenite. Two occurrences of ripples are seen in the sheet. They are both symmetrical with wavelengths ranging from 5.0 to 7.5 cm and crests of the ripples trending 150° and 277° in one case, and 124° in the other. The contact with the underlying moundstone is planar and apparently erosional as archaeocyathids are truncated. The upper eroded surface of the moundstone is covered with numerous, small black dots which represent the apertures of marcoborings, similar to those described from the lower patch-reef series (James et al., 1977) and attributed to the morphogenus Trypanites. These borings, now filled with sediment are seen to penetrate archaeocyathid skeletons and surrounding matrix (Fig. 31). They are absent in some places and very dense in others; up to 260 borings occurring in 10 square centimetre areas in places although the average is between 150 per 10 square centimetres (n=5).

Overlying the calcarenite sheet are isolated exposures of Red Moundstone lithofacies (BR-1). Whenever the base is exposed, the colonization assemblage documented from Osprey Reef occurs averaging 30 cm thick. This grey/green mudstone consists mainly of abundant reilaminiform archaeocyathids associated with the pendent growth-form of calcareous algae on the underside. Another significant skeletal component is the coelenterate whose fronds appear to spread out both horizontally and downwards. Occasional

stick-form archaeocyathids are also found. This unit passes transitionally upwards into more typical Red Moundstone (BR-1) where abundant, upright narrow cones are the dominant fauna, along with stick-forms; bowls are rare. Calcareous algae is common, inarticulate brachiopods are present to common while trilobites are rare. The coelenterate is locally common. The unit, of maximum thickness 2.25 m has a stylonodular appearance. Small lenses of skeletal calcarenite make up less than 10% of the volume. The corresponding skeletal calcarenite lithofacies (BR-2) does not occur at Fox Cove probably due to inadequate exposure.

Red Moundstone passes transitionally over a few centimetres into the overlying Nodular Moundstone lithofacies (BN-1) which is 3.9 m thick. Although very badly weathered, it can be discerned that there is a distinct partition between adjacent areas where archaeocyathids are common and where they are rare. They are common in areas of up to 1 - 2 m across and about 1 m high. Thick-walled archaeocyathids and funnels dominate with minor stick-forms in a mudstone matrix. Brachiopods are common. Skeletal calcarenite makes up to 50% of this unit and occurs as small lenses and alongated tubular lens (maximum size 1.0 m by 0:15 m). The composition of the calcarenite is often dominated by unbroken, inarticulate brachiopod valves.

The adjacent strata, with a sparse archaeocyathid fauna is a nodular mudstone with small, skeletal (brachiopods) calcarenite lenses (less than 10% volume) and green, limy shales (5%). Although fossils are rare, isolated archaeocyathids do occur, particularly towards the top. Branching stick-forms dominate this sparse fauna along with wide cones, funnels and bowls. Narrow cones were not observed.

The Nodular Mound Unit (BN) is truncated by a planar erosion surface and overlain by skeletal, oolitic packestones (BB-1). At the base, both skeletal grainstone containing several large trilobites (Wanneria) along with minor ooids; and oolitic grainstones occur. The skeletal grainstone has a maximum thickness of 60 cm and thins laterally and eventually passes into oolitic packestone. Throughout the oolite sequence exposed (1.05 m thick) there is a skeletal element present. The basal 0.65 m consists of a fining upwards sequence of ooids with a corresponding decrease in skeletal content. The base is extremely coarse-grained with several large archaeocyathid cups. The oolite sequence is interrupted by a thin, 4 cm bed of skeletal packestone which is followed by another

coarse oolitic skeletal packestone bed (8 cm) and then by
a purer oolitic packestone (28 cm).

Although confused by faulting and poor exposure, the
succession continues inland with further isolated exposures
of oolitic packestone. In some of the oolitic packestones
however, small (several centimetres) ovoid in plan,
skeletal (Girvanella) stromatolites (LLH-S/LLH-C of Logan
et al., 1964) occur. Apparently overlying the oolites
are grey moundstones and calcarenites indicative of the
Grey Moundstone lithofacies (BG-1).

APPENDIX G

Schooner Cove (Mixed Biostrome and Oolite Sand Facies)

The cliffs at Schooner Cove, found at the north-east
end of Pointe Amour (position G, Fig.8), show an exposed
sequence from the Bradore Formation through to the Forteau
Formation biostrome complex. Exposure of the biostrome
complex is limited laterally except at the very top of
the hill, but a useful, though incomplete sequence occurs
(Fig.71).

The contact with the open shelf facies of the Forteau
Formation is not seen but can be placed to within 1 m.
The base of the biostrome consists of 3.76 m of Dolomitic
Moundstone (BD-1), comparable to that at the north-east
end of Fox Cove although no coelenterate occurs. This is
overlain by 1.18 m of coarsely skeletal, partly oolitic
packstone which becomes a purer oolitic grainstone towards
the top. No sedimentary structures occur in this rock.

A thin (65 cm), poorly-exposed unit of grey,
weathering orange-brown, moundstone with a mudstone matrix
follows with a fauna dominated by stick-form archaeocyathids
and retilaminiforms occuring with calcareous algae.
This rock is comparable with the Grey Moundstone lithofacies
(BG-1). It is overlain by skeletal, partly oolitic,
partly oncolitic grainstone of thickness 1.30 m. The
top 10 cm exposed (top is covered) consists of large (3 cm),
brown weathering oncolites set in a skeletal, oolitic
matrix. This bed may be thicker but the next 0.80 m is
not exposed.

The sequence recommences with a large exposure of Grey
Moundstone (BG-1) with laterally equivalent coarse skeletal
calcarenite. Thick-walled wide cones and retilaminiforms
with associated calcareous algae dominate the skeletal
element. Trilobites (Bonnia) are present. The maximum
exposed thickness is 1.96 m but neither the base nor top
is exposed. A gap of 0.80 m is followed by a thin (20 cm)
bed of poorly exposed skeletal packstone which grades
upwards into a sequence of oolitic, skeletal grainstones
associated with small bioherms, typical of the Oolite
Bioherm Unit (BB). Less than 2.0 m of this unit is
exposed vertically but widespread lateral exposures occur
as the beds lie on the top of a hill. A total of 9 small
bioherms, mostly of unknown maximum dimensions are partially
exposed. The largest bioherm is 11 m by 5.5 m and 2 m high
although the top is never seen. These bioherms consist of
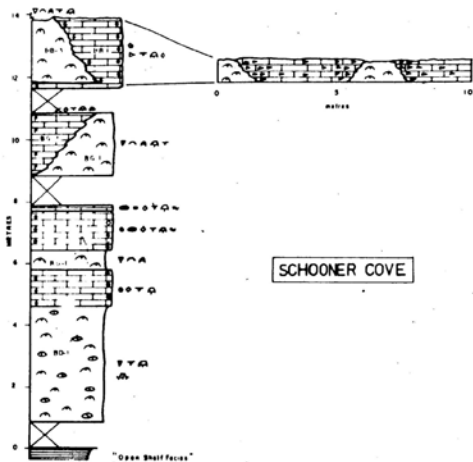grey/green algal-archaeocyathid moundstones with a mudstone

Fig. 71: Stratigraphic section in the mixed Biostrome Facies and Oolite Sand Facies at Schooner Cove.

matrix. The bioherms have a flat base with a strongly
convex upper surface. Calcareous algae appears to be the
dominant organism, with stick-form archaeocyathids,
low-angle cones, and retilaminiforms common. The bioherms
are surrounded by an apprently structureless but well-
bedded assemblage of oolitic, skeletal grainstones. The
contact with the bioherms is interdigitatory but no
draping of the calcarenites occurs. Close to the bioherm,
the oolitic grainstones show an abundance of Salterella
cones which diminish in density away from the bioherm until,
at about 3 m distance, they become scarce. This is seen
on all sides of the bioherms and is not restricted to
just one side.

L'Anse au Loup (Oolite Sand Facies)

Along the main road, to the north-east of L'Anse au Loup (position H, Fig. 8), the Oolite Sand Facies is poorly and infrequently exposed so that no measured section could be obtained. Houwever, rocks characteristic of the Oolite Sand Facies do occur there. These include mottled, dolomitic siltstones; oolitic, skeletal grainstones, and burrowed skeletal grainstones.

APPENDIX I

Archaeocyathids: Research and Distribution

Archaeocyathids are possibly the only major animal phylum to have become extinct (Hill, 1972). Their lack of descendants is reflected by the uncertainty of their affinity. They were regarded primarily as corals by the discoverer, Capt. Bayfield, in 1845, and later by Billings (1861), Bornemann (1886), and Hinde (1889). During the same period of time, however, they were also regarded as Protozoan (Billings, 1865) as foraminifera (Dawson, 1865; Meek, 1868) as sponges (Walcott, 1886; Taylor, 1910) as a receptaculitid (Roemer, 1878), and as calcareous algae (Van Toll, 1889). Taylor's work was apprently regarded as definitive as it was over 25 years later before the question of their affinity was again discussed when they were placed into a subphylum of the Porifera (Bedford and Bedford, 1939; Vologdin, 1937). They were first placed into a phylum of their own, the Archaeocyatha, by Okulitch and De Laubenfels (1953) and have maintained that status ever since (Hill, 1964; 1972) although several workers regard them as being so similar to the sponges as to not warrant a separate phylum (Ziegler and Rietschel, 1970; Balsam, 1973).

Although morphological variation is great, the most common form, an inverted cone, superficially resembles a rugose coral, but the similarity ends there. The archaeocyathid skeleton consists of 1 or, more commonly, 2 perforate walls which are connected by perforate radial plates and rods, imperforate dissepiments and tabulae or tubules (Hill, 1964). A cavity occupies the central part of the skeleton. The morphology varies from stick-like forms (sometimes branching), to bowl-and plate-like forms. Nothing is known of the soft tissues of archaeocyathids.

Stratigraphically, archaeocyathids range throughout the Lower Cambrian after which they became extinct. Most taxonomic and stratigraphic work has been done in Russia, particularly on the Siberia platform (Lena River section) and Altai-Sajan fold-belt where archaeocyathids are present throughout the Lower Cambrian strata from the earliest Tommotian through the Atdabanian, Lenian, and Elankian. Nowhere else in the world is there such a complete sequence (Rozanov and Debrenne, 1974).

Early history of archaeocyathid research

Archaeocyathids were discovered on the south coast of Labrador in 1845 by Captain H.W. Bayfield, but were misidentified as a rugose coral Cyathophyllum (Bayfield, 1845). The first Russian discovery of an archaeocyathid was by a mining engineer, Meglisky, in 1850 along the Lena River section in Siberia, but it was identified as the Upper Carboniferous plant Calamites cannaeformis. The first scientist to collect archaeocyathids was Richardson of the Geological Survey of Canada. Unfortunately, his collection, all from southern Labrador, was lost as the ship, returning to Montreal with the specimens, sank. Only one specimen survived and was subsequently illustrated by Logan (1863).

The term archaeocyathid was derived by Billings (1861) who erected the genus Archaeocyathus, and named two species: A. atlanticus and A. minganensis, both from the Forteau Formation in Labrador. A. minganensis was also found in the Ordovician age Beekmentown Group on Mingan Island in the Gulf of St. Lawrence. Billings (1861) first believed these forms to be corals but later changed his mind and designated them as protozoa (Billings, 1865). Much later, A. minganensis was found to be a sponge (Archaeoscyphia) but A. atlanticus was an archaeocyathid.

Present day distribution of archaeocyathids

World-wide distribution

Since 1861 archaeocyathids have been reported from every continent and substantiated in all but South America where they were described by Fergulio (1949) but refuted by Hill (1972).

By far the most extensive occurrences of archaeocyathids are in the USSR, and this has resulted in a vast amount of literature, mainly monographic, which is summarized by Hill (1964). The forms occur in two main areas; the Siberian platform, including the Lena River section, and the Altai-Sajan fold-belt. As archaeocyathids are present throughout the continuous Lower and lower Middle Cambrian sections in these regions, it has been suggested that four stratigraphic stages can be recognised using the development of archaeocyathids as the time control, and that these stages could serve as the basis for a division of the Lower Cambrian and world-wide correlation (Rozanov and Debrenne, 1974). The four stages recognised in ascending order are the Tommotian, Atdabanian, Lenian, and Elankian. The Elankian may, in

part, be Middle Cambrian (Rozanov and Debrenne, 1974).
The only other Asian occurrence of archaeocyathids is
from China (Blackwelder, 1904; Ogawa, 1905).

European occurrences of archaeocyathids are relatively
few. Probably the best exposed outcrops are in Spain
where 2 major localities are known, both in the north-west
part of the country. Archaeocyathids are found in the
Lancasa Formation of the Esla Valley where they are
associated with oncolites and bioclastic debris (Debrenne
and Zamarreño, 1970), and in the equivalent Vegadeo
Formation in the region of Ponferrada, both of Lenian
age (Debrenne and Zamarreño, 1975). The second occurrence
is from Las Ermitas and yields an older, early Atdabanian
age fauna (Rozanov and Debrenne, 1974).

In the Iglesiente-Sulcis region of S.W. Sardinia,
archaeocyathids occur in algal bioherms and within clastic
strata of the Matoppa member of the Nebida Fm. (Debrenne,
1964; Brasier, 1976). A Lenian or possibly Upper Atdabanian
age is indicated by the assemblages (Rozanov and Debrenne,
1974).

Two poor exposures are found in France. Lenian
archaeocyathids are found in the 'Calcaire a Archaeocyathus'
of the Montagne Noir area (Debrenne, 1974), while a poor
fauna, possibly of Atdabanian age (Rozanov and Debrenne,
1974), is found in Carteret, Normandy (Debrenne, 1964).

In N. Norway, on the Isle of Sørøy, archaeocyathids
have been reported within a highly deformed, matamorphosed
sequence occuring in rafts of calc -silicate rocks within
the Storelv Gabbro (Holland and Sturt, 1970). As they are
so badly preserved, they can only be placed down to the
order Ajacicyathida.

The most recent European discovery of archaeocyathids
was at Inchnadamph in N.W. Scotland where they occur as
rare fragments in silicified dolomite clasts, 10 m above
the base of the Eilean Dubh Formation of the Durness Group,
and assigned, in this preliminary study, to the family
Ajacicyathacea (Brasier, 1977).

Archaeocyathids have been reported from the Middle
Cambrian of the Holy Cross Mountains in Poland (Orlowski,
1959; 1960) but have since been re-interpreted as the
blastozoan echinoderm class Ctenocystoidea (Sprinkle,
1973, p. 111).

Archaeocyathids have been reported from erratics in

the Dwyka Tillite in S. Africa (Rozanov and Debrenne, 1974),
but the major African occurrence is in Morocco where Lower
Lenian forms are found from the slopes of the Anti-Atlas
Mountains (Rozanov and Debrenne, 1974) and also in older,
Middle Atdabanian (possibly Tommotian) rocks in the
"Schisto-Calcaire" succession of the north slope of the
Anti-Atlas (Debrenne, 1964) where they occur in bioherms
(Debrenne, 1975).

Extensive archaeocyathid bearing beds are found in
the Flinders Range of Australia, described by Taylor (1910)
and subsequently revised by Debrenne (1970; and the Ajax
Mine fauna, 1974). Aspects of the paleoecology are
discussed by Brasier (1976). Two levels of archaeocyathids
are found in the Flinders Range. The lowest is the
Wilkowillina Limestone of Atdabanian age and the uppermost
is the Wirreolpa Limestone of Lenian age (Rozanov and
Debrenne, 1974).

In Antarctica, there was a 50 year gap between the
discovery of archaeocyathids in glacial erratics (Priestly
and David, 1910) and of their _in situ_ discovery (Laird
and Waterhouse, 1962) and subsequent documentation (Hill,
1965). A possible Atdabanian or Lenian age has been
proposed for this fauna (Rozanov and Debrenne, 1974).

The genus _Archaeocyathus_ is illustrated, amongst other
fossils, from the Ella Ø Formation of the East-Central
Greenland fold-belt where they occur in large numbers
(Poulsen, 1932).

North American occurrences

The distribution of archaeocyathids in North America
can be divided into two distinct geographical areas: the
Western Cordillera and the Appalachians.

The Western Cordillera: The Western Cordillera of
Canada has numerous reports of archaeocyathids which are
listed and well-referenced by Stelck and Hedinger (1975).
They occur in a linear belt approximately 1200 kms long
and 250 kms wide, trending N.N.W. - S.S.E. (Stelck and
Hedinger, 1975; p. 2015) which presumably extends into
the U.S.A. where they have been described from Washington
State (Okulitch and Greggs, 1958). A well-documented
occurrence from the McKenzie and Cassiar Mountains of the
North-West Territories, the Yukon, and British Columbia
(Handfield, 1971) gives a Sanoshtykgol age when correlated
with the Altai-Sajan fold-belt of Russia, but Rozanov and
Debrenne (1974) suggest a younger, Lower Lenian age when

correlated with the Siberian Platform. The occurrence of archaeocyathids in bioherms is often mentioned from the Canadian Cordillera (e.g. Brabb, 1967; Fritz, 1974) but they have not been described in detail.

In the Great Basin Silver Peak Range of W. Nevada and the White and Inyo Mountains of California, archaeocyathids occur within a 6,000 ft. (1828 m) thick Lower Cambrian sequence which is part of a continuous section from the late Precambrian to the late Cambrian (McKee and Gangloff, 1969). The archaeocyathids, which occur in the middle one-third of the sequence, have been correlated with the Lenian stage of the Siberian Platform (Rozanov and Debrenne, 1974). They form bioherms less than 100 ft. (30 m) long, 5 ft. (1.5 m) high in the Montenegro Member of the Campito Formation and the lower part of the Harkless Formation, and occur as isolated individuals in the intervening Poleta Formation (McKee and Gangloff, 1969; Morgan, 1976).

The Appalachians: Isolated occurrences of archaeocyathids are documented throughout the Canadian and U.S.A. Appalachian Mountain system.

The northernmost occurrence is from the Forteau Formation of southern Labrador, eastern Quebec, and N.W. Newfoundland (Schuchert and Dunbar, 1934; James and Kobluk, 1978; Cumming, in press). These are probably the best exposures of such rocks in the Appalachian system, partly because they are exposed to the west of the western limit of Appalachian deformation.

The only reported occurrence of Middle Cambrian archaeocyathids in North America is from the St. John Group at St. Martins in New Brunswick and are allied to the Atlantic Province faunas (Okulitch, 1943).

Fragments of archaeocyathids have been reported from limestone blocks in the Bic Conglomerate at Bic Harbour, Quebec (Okulitch, 1943).

In the northern U.S.A., archaeocyathids are known from the Schodack Formation to the north-east of Troy, New York State (Ford, 1873; Okulitch, 1943), and from York Co., Pennsylvania (Stose and Jonas, 1939). They have recently been described as occurring as scattered individuals and in small bioherms from the base of the Leithsville Formation in New Jersey, and subsequently correlated with the Forteau Formation (Palmer and Rozanov, 1976).

Archaeocyathids have long been known from the Shady

Dolomite and Weisner Formation in the southern
Appalachians. Archaeocyathid "reefs" were described
from Austinville, Virginia (Resser, 1938). These
structures have been re-investigated and re-interpreted
as burrow complexes (Balsam, 1970; 1974) although
isolated archaeocyathid individuals are present in the
area (Balsam, 1974; Willoughby, 1976). Archaeocyathids
were also reported from the Shady Dolomite in Georgia
(Kesler, 1950) and Alabama (Butts, 1926).

The most recently documented occurrence is from
the Valley and Ridge "Sleeping Giants" Province which is
part of the Coosa deformed belt near Talladega, Alabama,
where small mounds and individuals are reported (Bearce
and McKinney, 1977).

Archaeocyathids as "reef"-builders

Compared with the vast amount of literature on the
taxonomy of archaeocyathids, notably by workers in the
USSR, very little research has been aimed towards an
understanding of the paleoecology of the organisms,
particularly as to their role as Cambrian reef-builders.

Archaeocyathids are recognised as occuring in biohermal
structures in many places (see previous section on
distribution), but these structures have not been
described in any detail. Debrenne (1959) recognised three
modes of occurrence of archaeocyathids; as isolated
individuals associated with other organisms such as
trilobites, brachiopods, and hyolithids; in laterally
continuous banks (biostromes); and in bioherms having
topographical relief and sometimes associated with calcareous
algae.

Zhuravleva (1960; 1966) recognised a variety of
archaeocyathid biohermal structures from the Siberian
Platform and suggested that the distribution of
archaeocyathids was depth controlled (in Hill, 1972, p. E.
28). She claimed that small bioherms flourished at
depths of 20-30 m and down to 50 m. This idea was based
on the association of the archaeocyathids with the calcareous
alga Renalcis. When archaeocyathids are found associated
with the calcareous alga Epiphyton, then depths of 50-
100 m are suggested (Zhuravleva, 1960; in Hill, 1972).

Archaeocyathid (organogenic) build-ups from the
Altai-Sajan fold-belt of Russia have been classified into
four structures (Zadorozhnaya, 1975); biostromes, bioherms,
biohermal massifs, and reefs. The distribution of these
structures in both time and tectonic setting is also noted.

- 240 -

In North America, Okulitch (1969) doubted the potenial of archaeocyathids to form reefs unless accompanied by algae. However, he recorded 'colonies' of the organisms in structures with lateral dimensions of up to several miles but with vertical expressions of only a few feet.

Biohermal structures have long been known from the White and Inyo Mountains of Eastern California (McKee and Gangloff, 1969) where they form lense-shaped limestone beds 100 ft. (30 m) long and 5 ft. (1.5 m) high with primary topographical relief. The maximum thickness observed by McKee and Gangloff is 18 ft. (5.5 m), but from the same area and formation (Montenegro Member of the Campito Formation), lenticular mounds of 194 m long with thicknesses of 10 m are recorded (Morgan, 1975). These structures are mud-supported with the mud supposedly derived from the breakdown of algal thalli, a situation analagous to the carbonate banks of Florida (Morgan, 1975).

The only detailed work on archaeocyathids from both a sedimentological and paleontological view deals with the "patch-reefs" of the Forteau Formation in southern Labrador (James and Kobluk, 1978). It has emerged from their study that features which characterized modern reefs such as biological accretion, internal sedimentation, early lithification, and biological destruction can be recognised in these Cambrian structures. These patch-reefs consist of loaf-shaped mounds of archaeocyathid-rich mudstone along with Renalcis and are stacked on top of each other and flanked by skeletal calcarenites and shales (James and Kobluk, 1978).

Fig.72. Geology of the study area between Lourdes de Blanc Sablon (Québec) and West St. Modeste (S. Labrador)

Key

CAMBRIAN

Forteau Formation

| 5 | OOLITE SAND FACIES oolites, calcarenites

BIOSTROME FACIES moundstones,

PATCH-REEF FACIES AND OPEN-SHELF FACIES patch-reefs, calcarenites, siltstones, shales, dolom

Bradore Formation

BRADORE SANDSTONE conglomerates, sandstones

PRECAMBRIAN

GRENVILLE BASEMENT gneiss, granites, schists

geological contact

fault

facies contact

geographical boundary

road

lake, stream

settlement

airfield

Sablon (Québec)

N
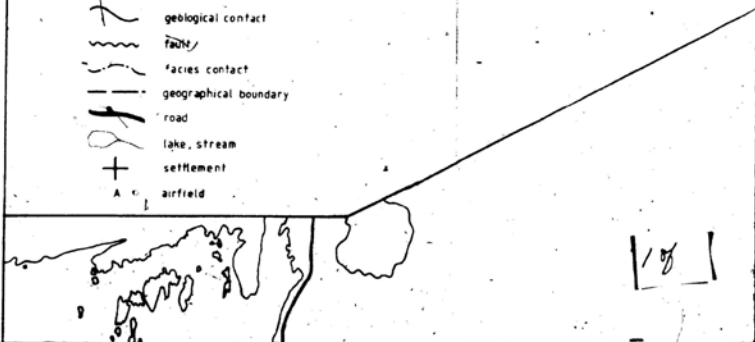
...CIES moundstones, calcarenites

...tones shales dolomites

SCALE 1 : 50,000

1 KM

NEWFOUNDLAND
QUÉBEC
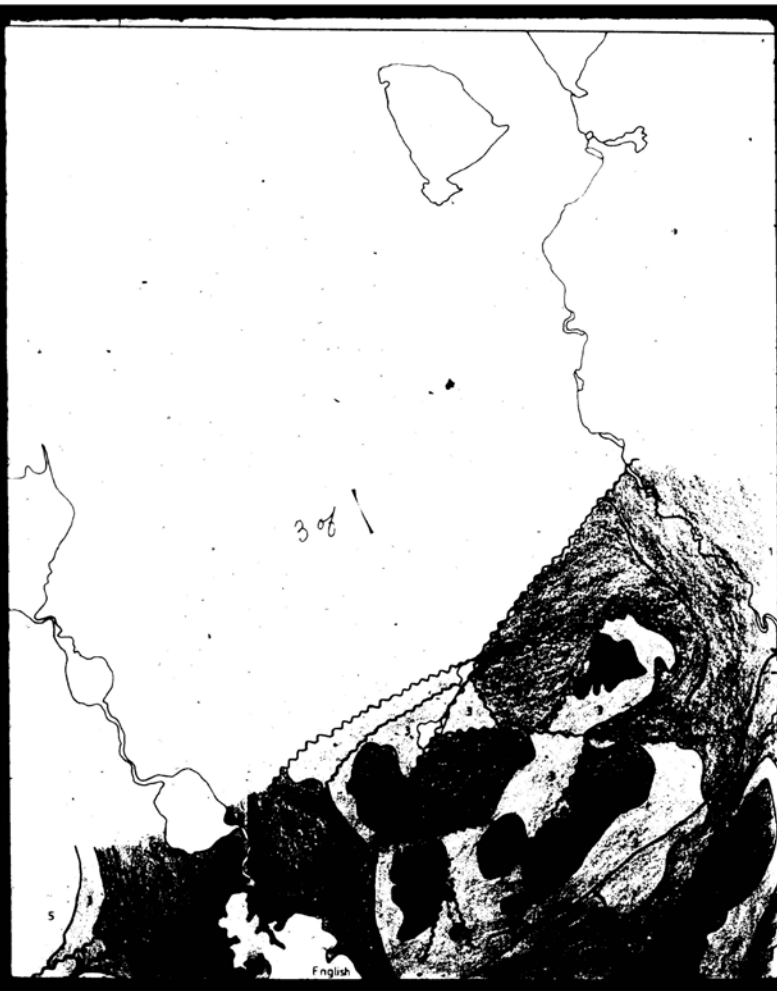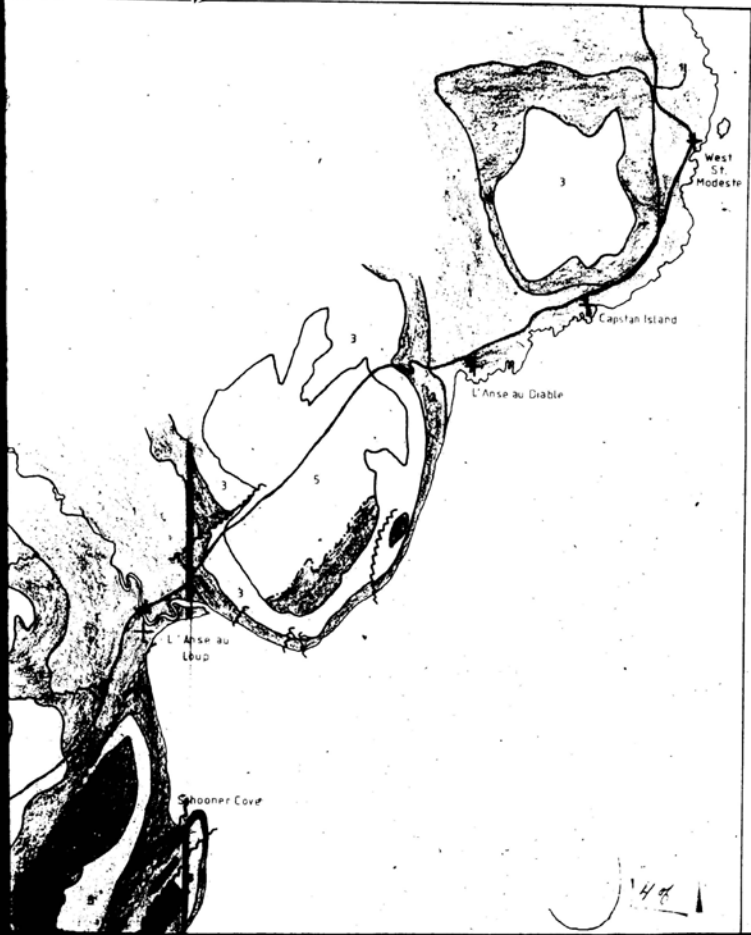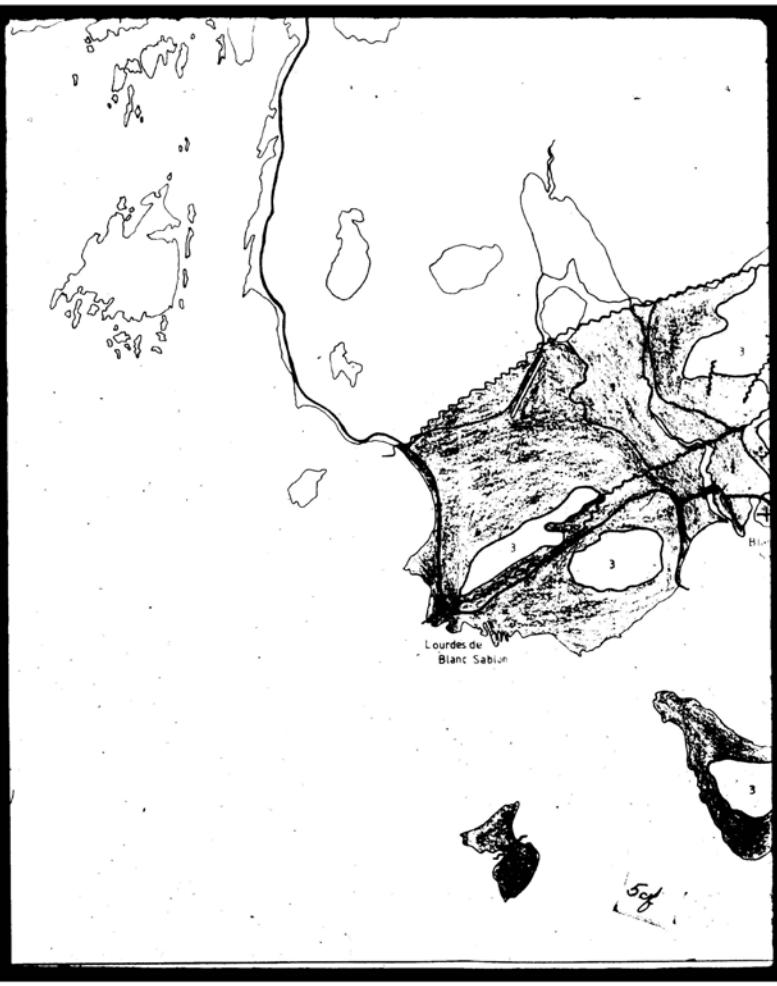
3 of

English

West
St.
Modeste

Capstan Island

L'Anse au Diable

L'Anse au
Loup

Schooner Cove

Lourdes de
Blanc Sablon

3

3

3

3

5 cf

STRAIT OF BELLE

Blanc
Sablon

L'Anse
au
Clair

English Point

Forteau

L'Anse Amour

Pointe Amour

BELLE ISLE

Pointe Amour

LABRADOR

QUEBEC

study area

N

NEWFOUNDLAND

0   KM   100

18 of 18

Fig. 73. Facies relationships of exposed strata at Osprey Reef
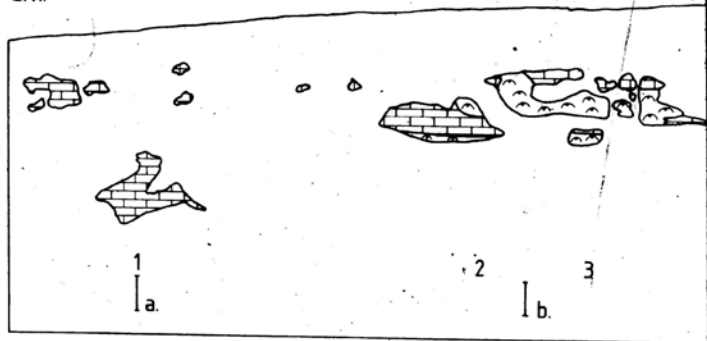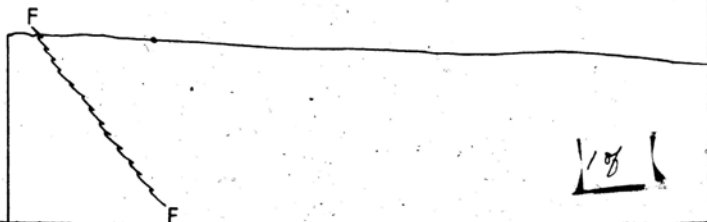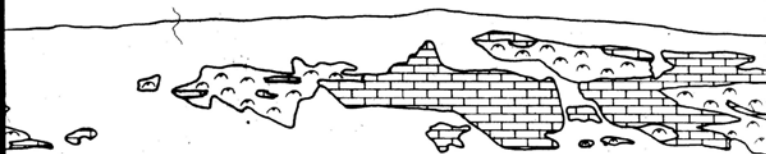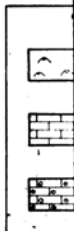
4   5   6

BIO STROME FACIES   OOLIT

KEY

MOUNDSTONE (BR-1)

SKELETAL CALCARENITE (BR-2)

OOLITE SAND FACIES

1-12 SECTION NUMBER (see text)

a.-d. MEASURED SECTIONS (see fig. 66)

F FAULT
F

6

7

F
F

B

N.E.

STROME FACIES OOLITE SAND FACIES

3 of

S.W.

1   2 3

a.   b.

A

F

F

B

0 metres 10

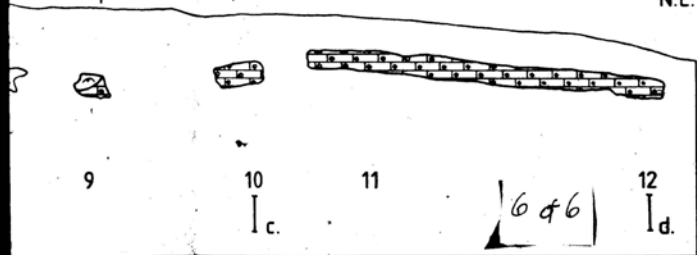3   4   5

BIO STRO

8

50f

OOLITE SAND FACIES

F

F

FAULT

F

F

F

F

6

7

B

STROME FACIES OOLITE SAND FACIES

N.E.

9

10

11

12

c.

d.

6 & 6

C