BORING AND CAVITY - DWELLING ALGAE

BORING AND CAVITY - DWELLING ALGAE: EFFECTS ON CEMENTATION AND DIAGENESIS IN MARINE CARBONATES

By

DAVID RONALD KOBLUK, B.Sc., M.Sc.

A Thesis
Submitted to the School of Graduate Studies
in Partial Fulfilment of the Requirements
For the Degree
Doctor of Philosophy

McMaster University

December 1976

DOCTOR OF PHILOSOPHY (1976)
(Geology)

McMaster University
Hamilton, Ontario

TITLE: BORING AND CAVITY - DWELLING ALGAE: EFFECTS ON CEMENTATION AND DIAGENESIS IN MARINE CARBONATES

AUTHOR: DAVID RONALD KOBLUK, B.Sc. (McGill University)
M.Sc. (McGill University)

SUPERVISOR: Professor Michael J. Risk

NUMBER OF PAGES: i-xiv; 1-224

ABSTRACT

Endolithic (boring) and chasmolithic (cavity-dwelling) marine filamentous algae are important erosive and diagenetic agents in modern carbonate environments. The rates at which endolithic algae bore into crystals of Iceland spar calcite and other substrates are geologically very rapid. Within 213 days the surface of Iceland spar monitored in the sea in Discovery Bay Jamaica is found completely infested by the algae. The curve of infestation versus time is similar to a normal population growth curve.

Variations in environmental conditions, notably light and agitation of the substrate, are important controls on rate of infestation, though agitation may not be quite as important as previously thought. The amount and composition of light available to the algae affects their activity, to the point where the algae apparently will not bore in the absence of light (this includes at depth within the sediment). This indicates that most endolithic algal infestation occurs at, or very close to, the sediment surface; as a result endolithic algae may be of value in the determination of paleophotic zones in ancient carbonate sequences.

Substrate crystallography exercises strong control over filament orientation during initial infestation; this control breaks down as infestation of the substrate proceeds.

Several processes of micritization are observed on the Iceland spar crystals, including partial boring infilling, residue micritization, and exteriour micrite envelope formation. The micrite envelopes form on the surface of the crystal by the coalescence of cemented

(calcified) exposed endolithic or chasmolithic filaments. The low Mg calcite precipitated on the filaments is deposited only on dead algae and is found as early as 65 to 95 days after the crystals are placed in the sea. The broken filaments are a significant source of micrite and peloidal sediment in the reef and nearby environments. "Constructive" micrite envelopes and calcified algal filaments are found throughout the Phanerozoic as far as the Ordovician.

Constructive micrite envelopes will not likely develop in highly agitated environments where grains are constantly moved about, unless periods of quiescence in the order of weeks or months occur. During quiet water periods endolithic algae growing out of grains or micrite envelopes, or chasmolithic algae, may become calcified in intergranular pores by precipitated calcite. These intergranular calcified filaments, found as far back as the Ordovician, stabilize the sediment and may prevent remobilization. This may allow further filament calcification, micrite envelope formation, and complete to partial infilling of intergranular pores by calcified filaments and associated micrite and microspar cement.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TEXT FIGURES

Page

Page

LIST OF APPENDIX FIGURES

CHAPTER 1

INTRODUCTION

1.1 SCOPE AND PURPOSE

In the last decade, the development and use of highly sophisticated electronic microscopy (TEM + SEM), and electronic micro-analytical equipment (Microprobe, EDAX, etc.), vast improvements in light microscopy, and their application to geological problems, have revolutionized geology. The study of Holocene marine carbonates has experienced the full brunt of this revolution. Understanding of ancient carbonate depositional environments has benefited dramatically from these developments, and yet, as is always the case, problems and processes have surfaced which were undreamt of a few years ago.

The relationship between organisms and the substrate they inhabit has attracted a great deal of attention recently, in the light of the realization that organisms in modern carbonate environments may be extremely important early diagenetic agents. Cementation phenomena, porosity and permeability modification, substrate breakdown and construction, geochemical alteration, sediment mixing (bioturbation), etc., are now being viewed as biologically influenced. Similar biologically influenced systems undoubtedly operated throughout most, or all, of the Phanerozoic.

Carbonate reef structures provide an ideal natural laboratory to study biological-diagenetic systems, because of their accessibility, density of organisms and organism-substrate interactions, presence through the Phanerozoic, high productivity, and diversity of internal geologic environments. Of all major groups present within the reef ecosystem, the algae are one of the most ubiquitous, most important, and yet poorly understood of diagenetic agents.

This study is an investigation of the endolithic (and chasmolithic) habitat and the algae that make use of it. Filamentous algal borers (endoliths) are known to have a significant role to play in carbonate diagenesis, yet little is as yet known of the rates or specific mechanisms.

This investigation treats boring algae as both erosive and constructive agents; the latter role was previously almost entirely unknown. The approach to the problem used here is both descriptive and experimental.

Almost nothing is known of rates of endolithic algal penetration and substrate breakdown; this was investigated under semi-controlled conditions by monitoring Iceland spar crystals in the sea at Discovery Bay Jamaica. The scanning electron microscope and related analytical techniques were applied to attempt to understand substrate alteration by algal borers, and algal contribution to substrate construction and sediment stabilization.

"The present is the key to the past" is a major premise in this study. The results will be of value in unravelling the complex role of boring algae in carbonate diagenesis today and in the geologic past, particularly their role in substrate cementation, micritization, micrite envelope formation, substrate breakdown, and sediment stabilization. This study shows as well that much more work is needed in microbiologically-influenced diagenesis if eventually we are to understand fully the processes that have determined the diagenetic fabric and texture of carbonate rocks throughout the stratigraphic record.

FIGURE 1-1 Ostreobium queketii (?) boring into Iceland spar calcite monitored in the sea at Discovery Bay Jamaica. Sample J-183.

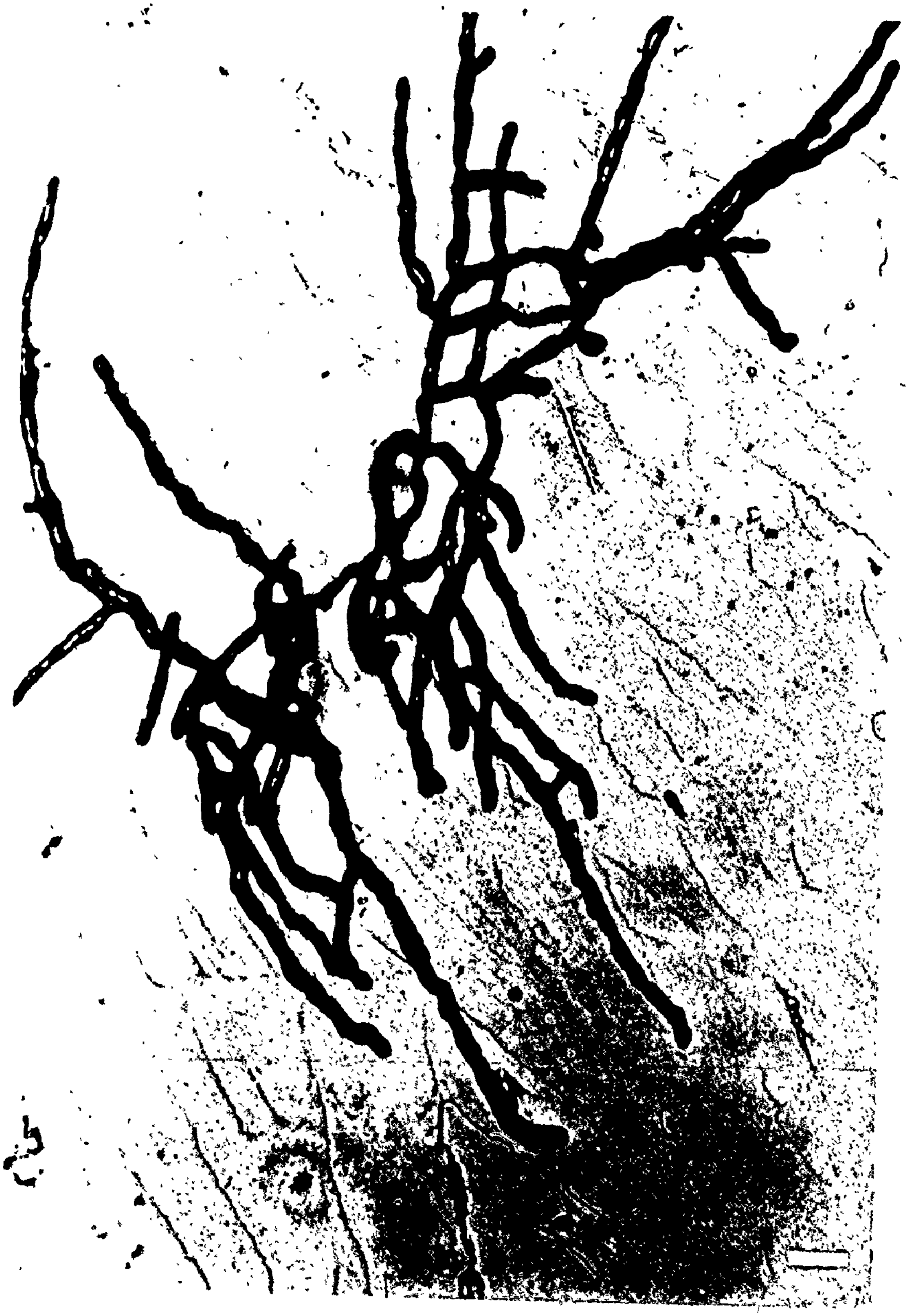
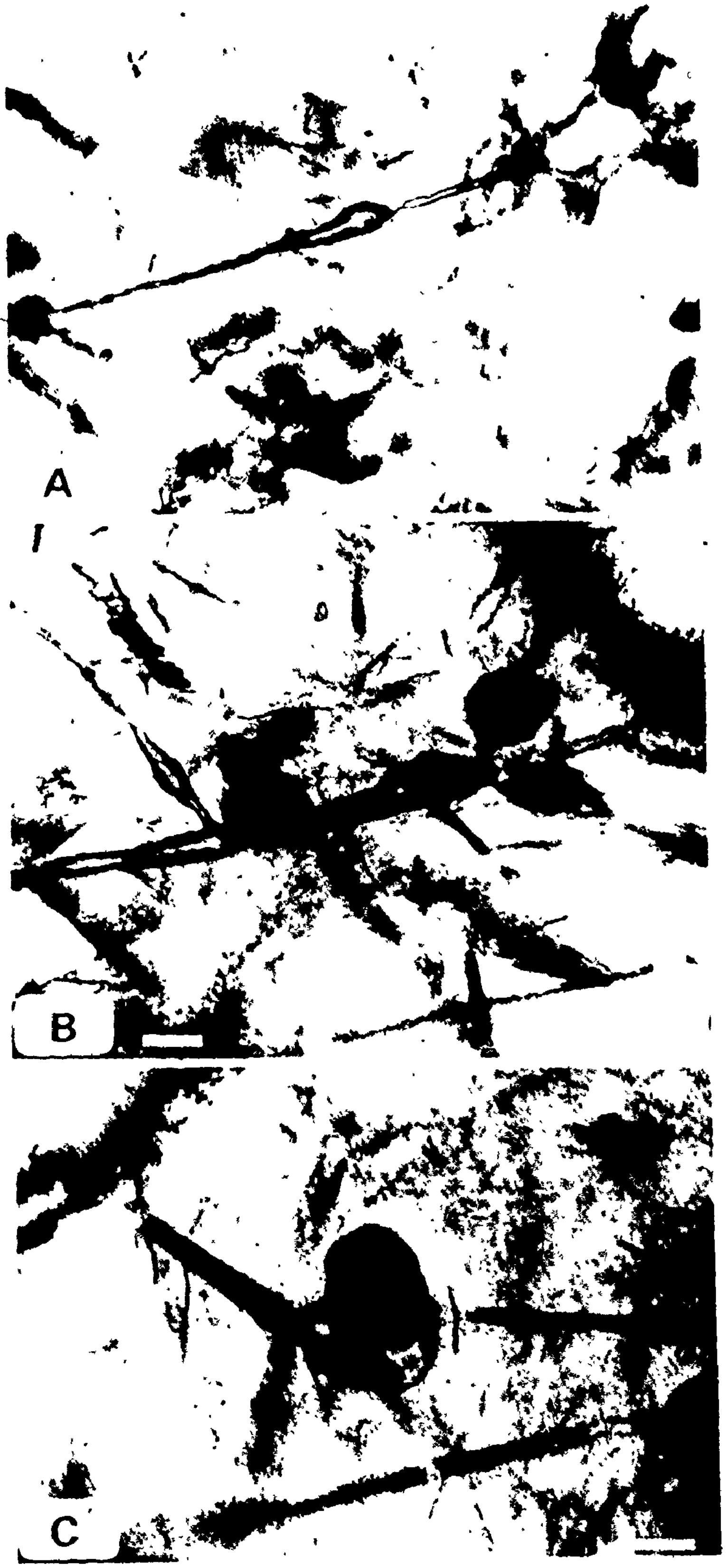


FIGURE 1-2 Fungal borings in Pleistocene M. annularis from the Key Largo Limestone at Key Largo, Florida. All the borings are vacant, but some contain remnants of organic material, possibly from the original fungi. The round structures are reproductive bodies (sporangia). The presence of spherical endolithic structures such as these points to solution, rather than physical penetration of the substrate. a) Scale bar 25 um. b) Scale bar 20 um. c) Scale bar 15 um. Light microscope, transmitted light.

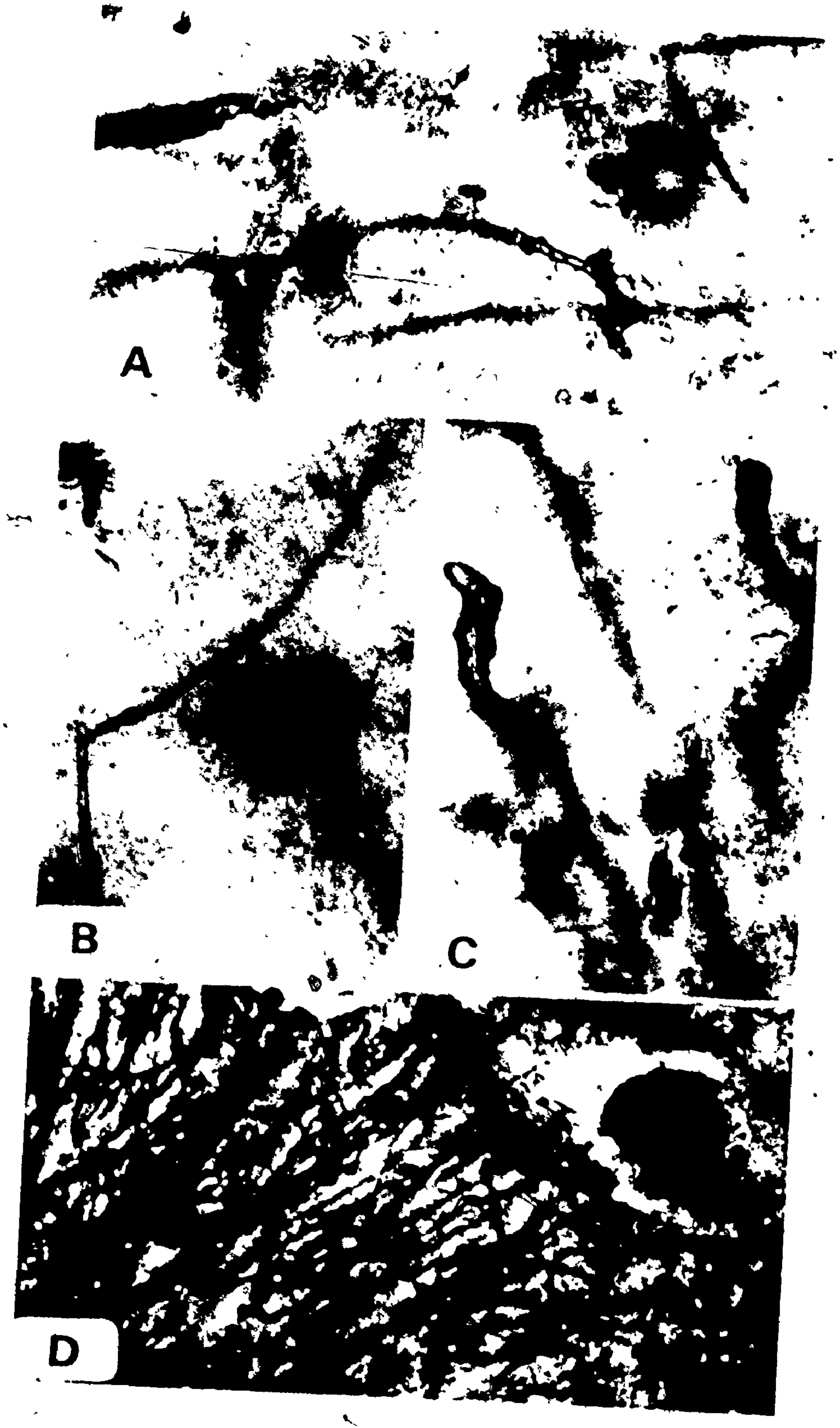

A
B
C

1.2 GENERAL

Filamentous marine endolithic (boring) algae (Fig. 1-1) have long been known to play a significant role in the breakdown and alteration of carbonate substrates (Duerden, 1902; Ginsburg, 1956; Gunatilaka, 1976). As early as 1842, Bowerbank recognized filamentous endoliths in coral skeletons, but mistakenly interpreted them as part of the coelenterate. Carpenter (1845) considered them integral parts of mollusc shells, when present, and to be of some taxonomic value. The early workers (Rose, 1855; Kolliker, 1859, 1860; Moseley, 1875; Duncan, 1876, 1881) who recognized filamentous endoliths as independant microphytic penetrants interpreted them as fungal parasites (Fig. 1-2), even when the filaments retained green coloration (Moseley, 1875; Duncan, 1876, 1881). Wedl (1859) and Topsent (1887) were the earliest to recognize endolithic algae (Fig. 1-3). The confusion extant in the early literature on the fungal and algal affinities of filamentous endoliths is wholly understandable when even today, the recognition of members of the two groups is not always straightforward. When dealing with vacated or infilled boreholes, the determination of fungal versus algal origins is often very difficult (Bromley, 1965; Bathurst, 1971, 1975), if not presently impossible. The criteria erected by Bromley (1965) and discussed by Bathurst (1971), though not consistantly reliable in separating endolithic fungi and algae, do provide a start.

Very little is known at present of the ecology and paleoecology of endolithic algae, and even less of the fungi. Separation of algal from fungal filaments and boreholes in ancient carbonates is a major problem and requires solution, if the full potential of endoliths is paleoecological and diagenetic interpretation is to be realized. The

FIGURE 1-3 Pleistocene algal borings. a) Vacated algal borings in the corallum of *Montastrea annularis* from the Key Largo Lmst. at Key Largo. Specimen F-64. Scale bar 30 um. b) Vacated fungal (?) boring in *Siderastrea radians* (?) from the first reef terrace at Piscadera Baai, Curacao. Specimen C-35. Scale bar 30 um. c) Vacated, irregular algal borings in *Acropora palmata*, from the first reef terrace at Oracabessca, Jamaica. Specimen J-270. Scale bar 25 um. d) Heavily bored carbonate grain from calcarenite, 83,000 year terrace at North Point, Barbados. Specimen B-13. Scale bar 100 um.

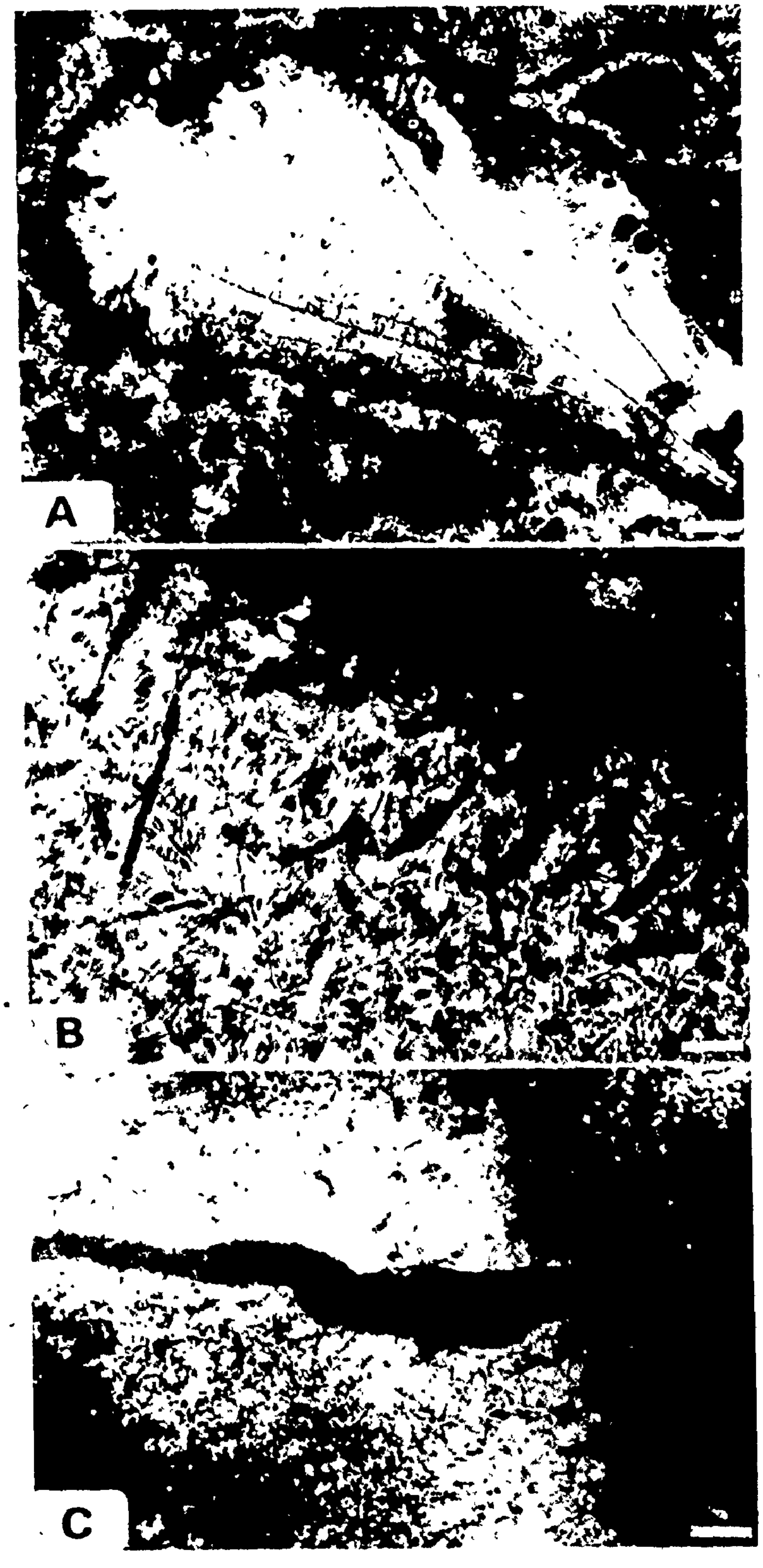

A
B
C
D

potential usefullness of endolithic algae in the recognition of paleophotic zones, and in the determination of paleobathymetry, has been stressed repeatedly (Swinchatt, 1969; Halsey, 1970; Perkins and Halsey, 1971; Golubic et al, 1975; Riding, 1975), and has been applied in some investigations (Swinchatt, 1965; Scoffin, 1971), perhaps a little prematurely.

It has been suggested (Golubic et al, 1975), though not demonstrated, that endolithic microphytes may provide a significant source of nutrients for certain grazing organisms in reef environments (eg: urchins and parrot fish) which ingest parts of the carbonate substrate during feeding. Endolithic microphytes are also known to have variably detrimental effects upon shelled populations (oysters and barnacles) which may cumulate in mass mortalities (Korringa, 1951; Kohlmeyer, 1969; Schäfer, 1972). The effects of boring algae and fungi in fouling wood and concrete structures in the sea is known to be important, but has been little studied (Schäfer, 1972).

A potentially very significant, but as well poorly understood effect of boring microphytes, is their influence on carbonate geochemistry. Many of the diverse metabolic secretives of marine algae and fungi, including compounds such as citrate, glycogen, malate, succinate, pyruvate, oxalate; lactate, etc., (Foster, 1949; Fogg, 1962) have profound effects on carbonate chemistry and mineralogy. Kitano (1968), Kitano et al. (1969), and Kitano and Hood (1965), suggest on an empirical basis, that organic compounds such as the above (many of which are produced by boring microphytes), may play a key role in carbonate geochemical equilibrium. Their work, although never applied to the problem of carbonate diagenesis by boring organisms, sheds light on the possible mechanisms involved.

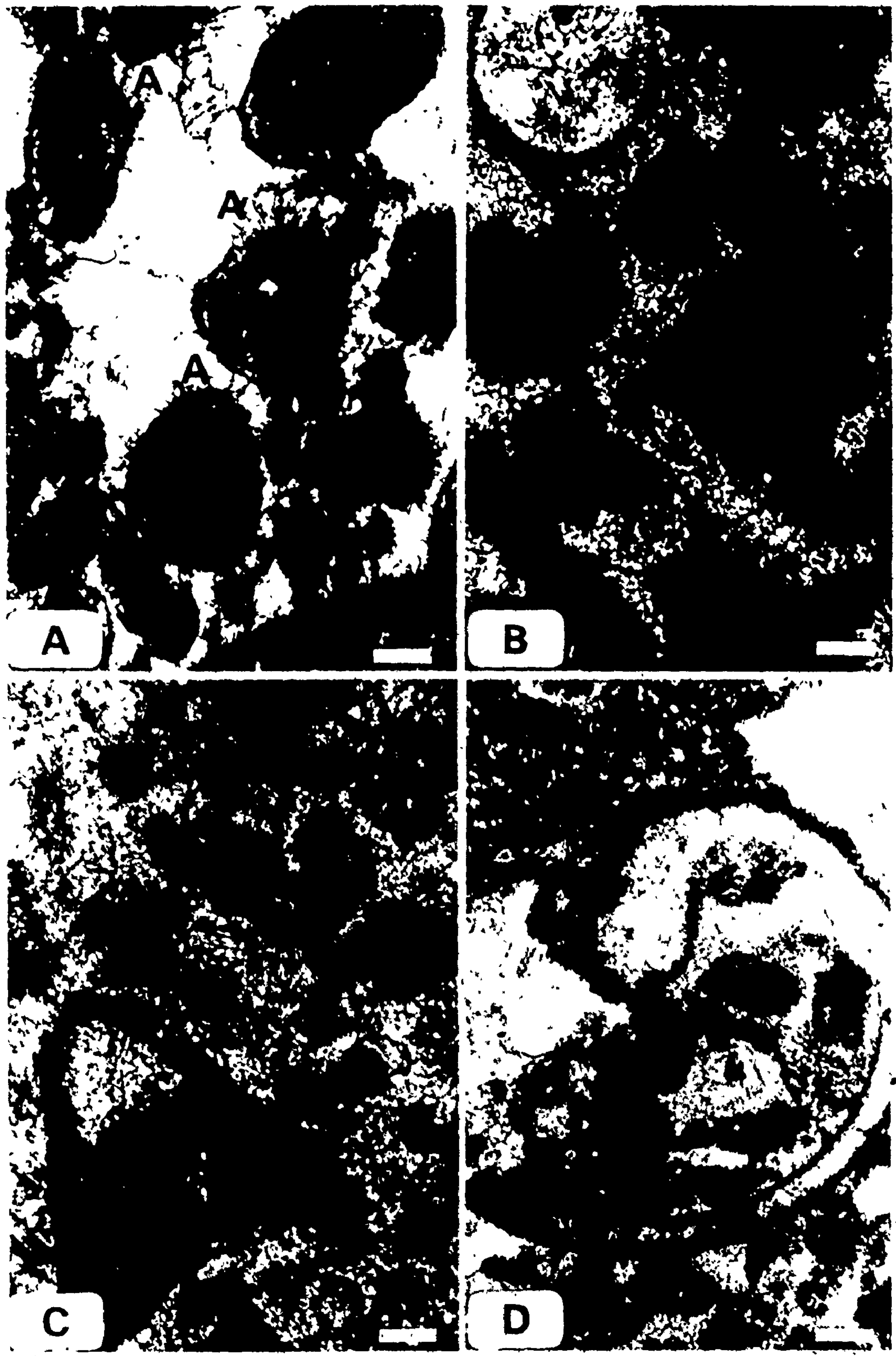
FIGURE 1-4 Micrite-infilled algal borings and micrite envelopes. a) Micrite envelope on a pelecypod fragment from the Pleistocene terrace at Animal Flower Caves, Barbados. Sample B-1. Scale bar 300 um. b) Detail of micrite tubules and a destructive micrite envelope on a coral fragment from the 1st reef terrace at North Point Barbados. Sample B-3. Scale bar 50 um. c) Algal boring in coral fragment from the Oligocene of Oamara, South Island, New Zealand. The boring is infilled with micrite. Scale bar 60 um. Specimen loaned by E.W. Mountjoy. Light microscope, transmitted plane polarized light.


A
B
C

Endolithic microphytes have long been known to be agents of erosion of carbonate substrates, particularly in reef environments (Duerden, 1902; Bertram, 1937; Swinchatt, 1965; Winland, 1968; Lukas, 1973), but also in cold water environments (Alexandersson, 1972; Gunatilaka, 1976). It was not until Bathurst published his classic work on micritization of carbonate particles by endolithic algae (Bathurst, 1966), that the full potential geologic importance of marine microphytic endoliths was realized. Bathurst observed a process of micritization of carbonate substrates by repeated boring by algae and infilling of the bores by micrite (Fig. 1-4b, c). Purdy (1963) also recognized the replacement phenomenon but did not understand the process and termed it recrystalization. Monty (1967) also described the role of boring algae in micritization.

Incomplete micritization of carbonate grains, according to Bathurst (1966), results in a micrite envelope (or rind), of variable thickness, encircling the grain (Fig. 1-4a, b). The envelope is essentially a replacement of the original grain periphery by micrite filling vacated algal bores. Complete boring of grain and infilling of the bores may result in a fully micritized grain (Fig. 1-5) (Bathurst, 1966, 1971, 1975). Grains which have been completely micritized by algal boring, and which contain no traces of the original carbonate skeleton, may become rounded to subrounded, indistinguishable from pellets, and would be termed peloids (Swinchatt, 1965; Bathurst, 1971). Indeed, many peloidal carbonates probably originated as bored skeletal calcarenites. Taylor and Illing (1969) described such a process from the Qatar Peninsula of the Persian Gulf; Pusey (1975) described cryptocrystalline grains from the northern Belize shelf which originated in a similar way.

FIGURE 1-5 Micritization, upper Cairn Fm., Miette reef complex Alberta, southeast 1 section. a) Rounded peloids, all consisting of micrite, in spar cement. Micrite coats, and calcified algal filaments projecting from the grains are seen adjacent the A's. Scale bar 200 um. Specimen M-13. b) Specimen similar to (a), but the rock has undergone some recrystallization. The peloids have diffuse peripheries, and only under the SEM are remnants of algal filaments visible. Scale bar 160 um. Specimen M-18. c) Peloids and micritized skeletal grains in a partly recrystallized (micritized) spar cement. This micrite fabric is similar to that in (b) above, but probably did not originate due to endolithic microphytic activity. Scale bar 200 um. Specimen M-20. d) Micrite envelope about a gastropod grain. Under higher magnification micrite tubules are visible in the grain periphery, indicating probable destructive-type algal micritization. Scale bar 800 um. Specimen M-21.


A
A
A
A
B
C
D

Bathurst's (1966) method of micritization involves infilling, presumably by precipitated micrite, but it appears that a similar result may be obtained through alteration to micrite of the walls of algal borings (Kendall and Skipwith, 1969). Presumably this occurs through recrystallization, influenced by secreted algal metabolites (Kendall and Skipwith, 1968; Winland, 1968), but how this occurs is not explained; bacterial activity may be involved in the bore wall alteration. Bacterial activity, like "organic decomposition" (Purdy, 1968), is all too readily invoked to explain a micritization or alteration phenomenon for which no mechanism is apparent. Bacteria may certainly be involved in certain carbonate precipitation processes (Drew, 1914; Lipman, 1924, 1929; Oppenheimer, 1961; Greenfield, 1963; Bathurst, 1971, 1975), but their role in carbonate breakdown and alteration, though strongly suspected, is not demonstrated.

The mechanism by which filamentous endolithic algae bore is not known with certainty, but is generally assumed to be chemical solution (Kolliker, 1859; Duncan 1876; Nadson, 1902; Fremy, 1936; Golubic, 1969; Lukas, 1973; Golubic et al, 1975). Physical processes of boring have not been ruled out completely, but it is difficult to envisage how a filamentous alga would physically penetrate a substrate. It is not unreasonable, however, to entertain the possibility that both chemical solution and physical activity are jointly involved. Turgor pressure exerted by growing cells weakening the structure of the substrate and causing minute dislocations or fractures along which solution is enhanced, could conceivably be involved; on a different scale, root systems employ a similar method in breaking rock along weaknesses (this is elaborated in further detail in Chapter 2 where Nomarski interference optics are discussed in relation to the mechanism of boring). This is all, however, speculative in the absence of firm data. What is known is that the ultrastructure of the internal surfaces of borings, and the morphology of borings in well ordered substrates such as Iceland spar, strongly suggests chemical solution (Golubic, 1969; Golubic et al, 1975).

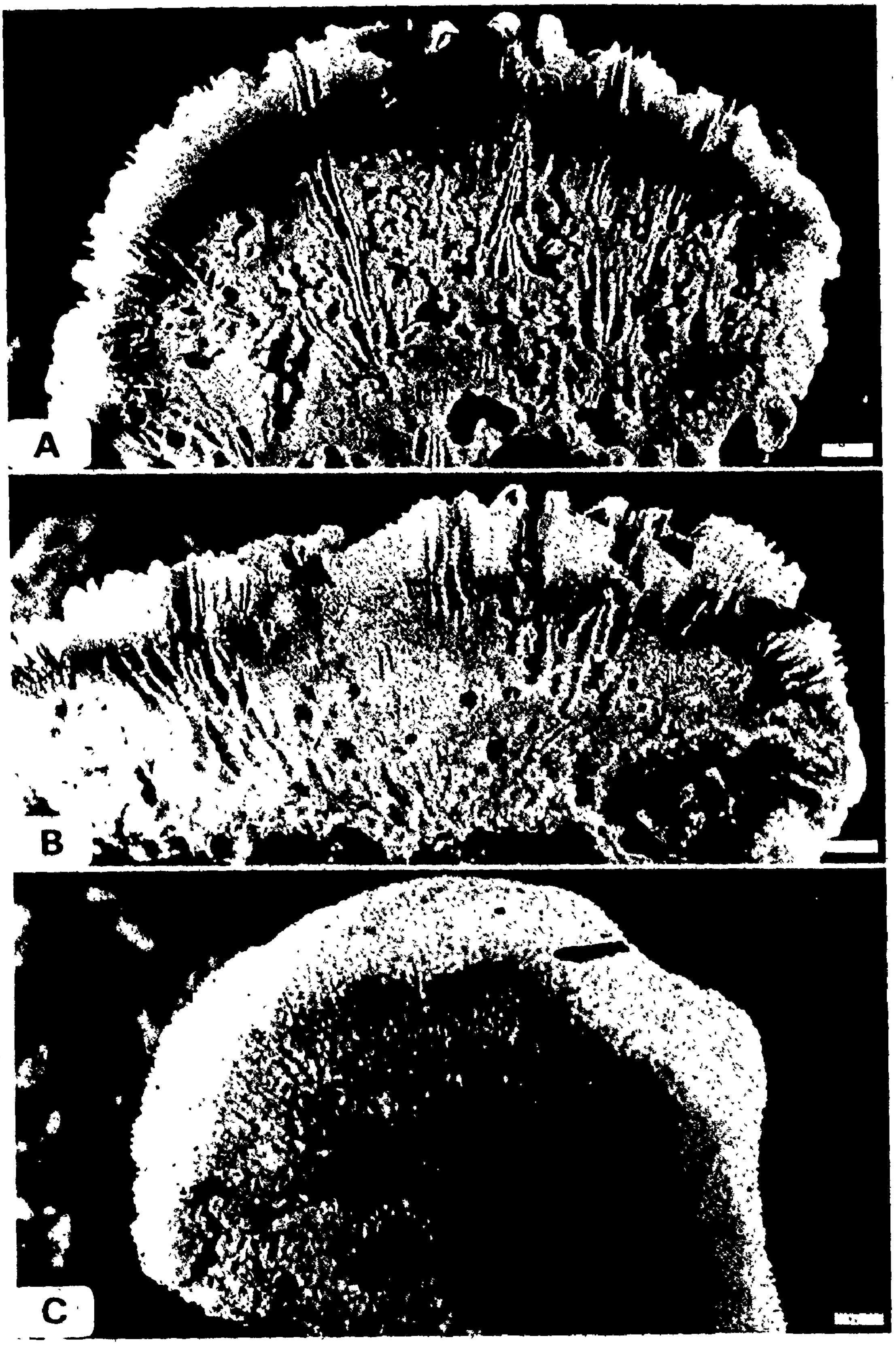
Why some filamentous algae and fungi bore is unknown. Some possible explanations are:

1) An adaptive strategy developed in response to predation by organisms such as grazing urchins, etc.
2) To take advantage of nutrients present in the substrate.
3) A strategy in which the organism reduces incident light intensity and/or spectral composition through filtering effects of the substrate; alternately, forms capable of effectively utilizing low light intensities, or portions of light spectra, are taking advantage of a habitat in which these conditions are present.

Not all filamentous marine algae and fungi bore. Whatever the reason for exploiting the endolithic mode, it is something that is apparently of advantage to only a small fraction of all filamentous microphytes.

Although grazing pressure is undoubtedly an extremely important factor in determining marine algal adaptive strategy, its influence on boring algae is largely unknown. It is certainly a reasonable speculation that boring was developed by algae in response to grazing pressure, but there is no way of knowing at present if that was the case. The oldest endolithic algal borings known are lower Cambrian (Hessland, 1949; Balsam, 1973); grazing organisms, or organisms capable of having been grazers are

FIGURE 1-6 Endolithic algal bands in coral skeletons: the "Ostreobium" layer. a,b) The dark band about 1 cm below the surface of these coral coenostea (Dichocoenia stokesii) from Jamaica, is the endolithic algal band. Scale bars 9 mm, and 6 mm respectively. c) Coenosteum of Porites sp. from Pickles reef, Florida, showing "brown band" development. The once green endolithic algal bands have been degraded by bacteria and fungi (many of which have become endolithic) to produce a brown area of dead endolithic algae. Scale bar 7 mm.

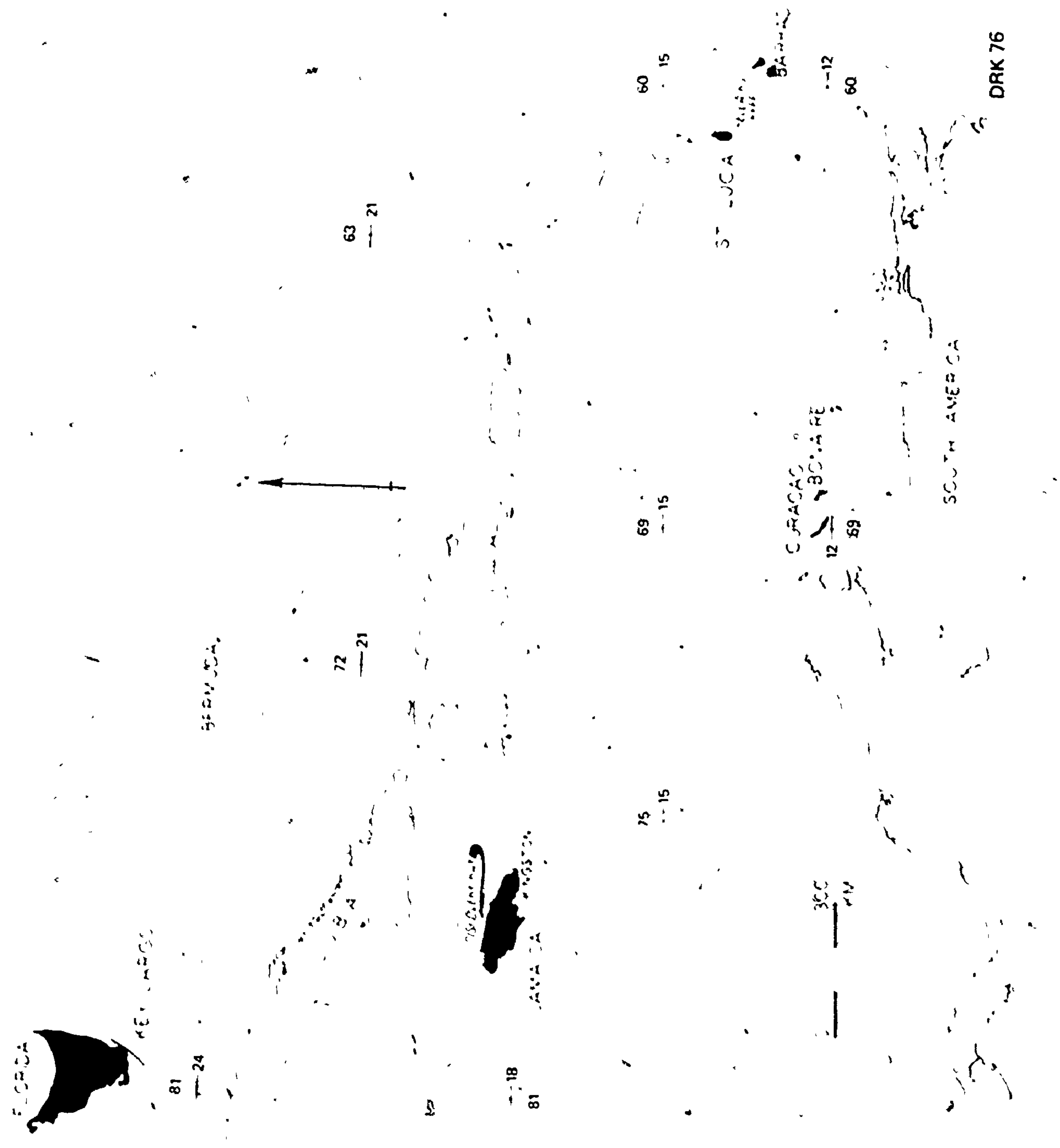

A
B
C

also known from the lower Cambrian (trilobites, echinoderms, worm phyla, etc.). If endolithic algae are found in the part of the Precambrian before grazers evolved, or the boring algae can be demonstrated to have been absent, the hypothesis can be tested.

Calcium, magnesium, carbon, etc., present within marine carbonates may be used in the metabolism of marine algae and fungi. Marine boring algae and fungi could be taking advantage of a nutrient source. The fungi apparently do this, as they are most commonly found boring in carbonates containing organic materials. Whether the boring algae do this as well, is not known. Metabolic excretions present in algal borings, such as acids and enzymes, which probably accomplish the excavation (by solution) of the bores, could be used in conversion of parts of the substrate into a form metabolically useful to the algae.

In a study of light penetration into the massive coral Favia pallida (as well as Astreopora ocellata, Goneastrea mantonae, Platygyra rustica, and Porites lutea without significant deviation from the observations in Favia), Halldal (1968) found that only 0.10% of incident reaches the "Ostreobium" green layer (Fig. 1-5) within the coral skeleton (the "Ostreobium" layer within coral skeletons is a layer, a centimeter or a fraction of a centimeter below the coral surface, is a dense zone of living endolithic algae, generally assumed to belong to Ostreobium; Lukas 1973, describes the layer in some detail). Only 100-150 lux reaches the top of the green layer, and a fraction of a lux penetrates to the bottom of the green layer, given an average 100,000 lux under a midday tropical sun. Ostreobium (Halldal may have confused several genera and species) is apparently capable of making use of extremely low light levels, or lives heterotrophically. The spectral composition of the light

FIGURE 1-7 Study areas in the Caribbean.


FLORIDA
KEY LARGO
81
24
CUBA
JAMAICA
KINGSTON
81
18
75
15
BERMUDA
72
21
69
15
63
21
60
15
ST LUCIA
BARBADOS
12
60
CURACAO
BONAIRE
12
69
SOUTH AMERICA
300
KM
DRK 76

reaching the endoliths is also altered, consisting almost entirely of wavelengths in the far red. As a result, photosynthesis predominates at the top of the green layer, and photooxidation toward the base, in response to decreasing light intensities (Halldal, 1968; Shibata and Haxo, 1969).

If these observations can be extended generally to other endolithic algae in other substrates, it appears that the endolithic habitat requires very special adaptations to low light levels and unusual spectral composition. This is evidenced by the photosynthetic and photo-oxidative action spectra for Ostreobium (Halldal, 1968; Shibata and Haxo, 1969). It seems unlikely, therefore, that endolithic algae are using the substrate as a "shield" or "filter". The advantage to some algae in boring into substrates may therefore lie in the ability to make use of a habitat which excludes most other algae, and provides fairly stable, relatively non-competitive living conditions. Although other algae may be physiologically capable of boring, they may be excluded from boring by their inability to photosynthesize and photooxidize in the low light intensities and altered spectral composition within the substrate.

1.3 STUDY AREAS AND SAMPLE MATERIALS

A wide variety of study areas was selected in order to provide as large a sample of modern and ancient endolithic microphytes and associated diagenetic processes from as many different reef environments and types as possible. Work in the modern carbonate reef environment concentrated upon the following areas in order of emphasis (see Fig. 1-7):

FIGURE 1-8 Palinspastic reconstruction of the approximate location of the margin of the Miette carbonate complex, and the location of studied stratigraphic sections within the complex. The main sections that were studied, were the N.W., and the S.E. 1 section.

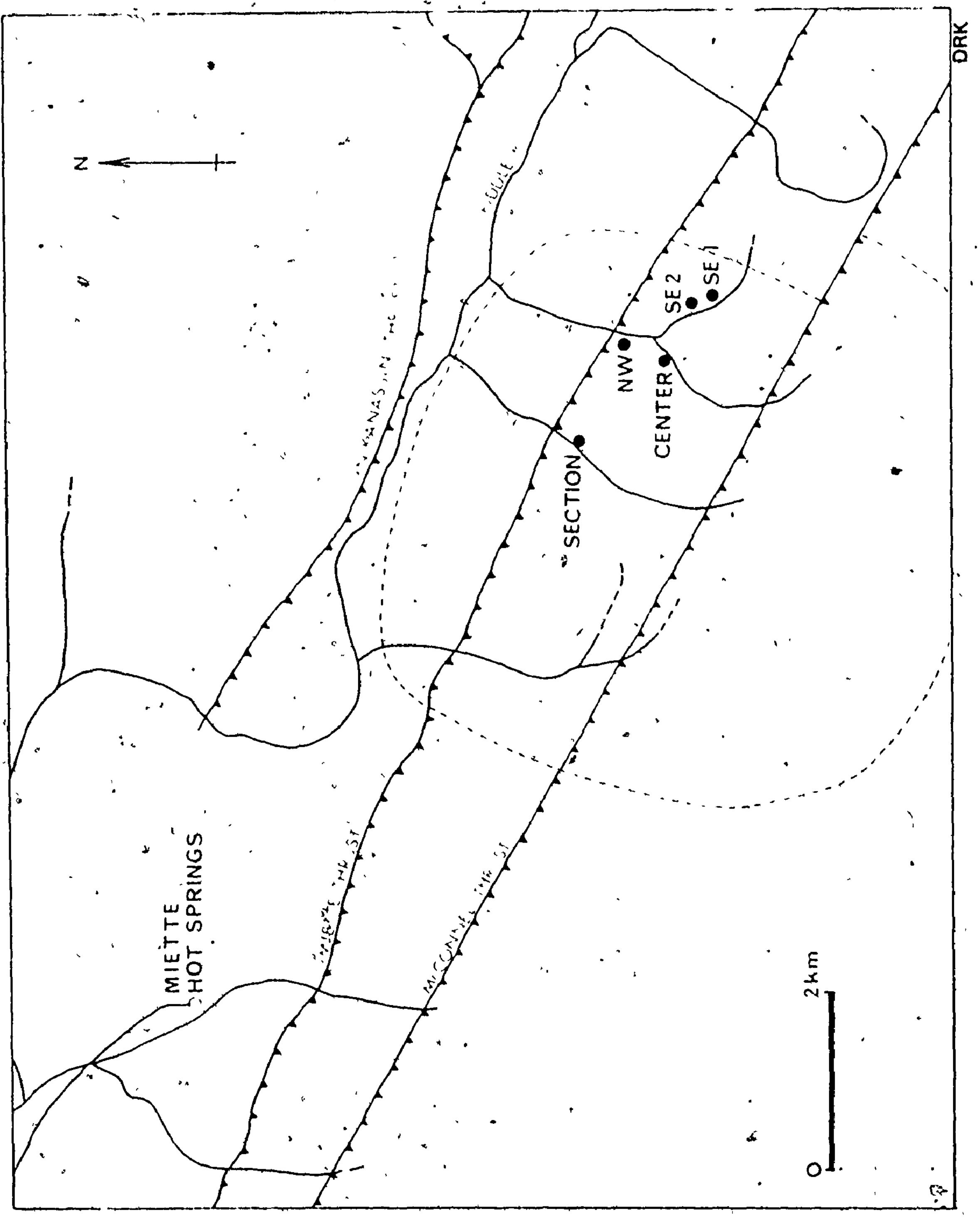

DRK
N
SE 1
SE 2
NW
CENTER
SECTION
MIETTE
HOT SPRINGS
McCONNELL
2km
0

FIGURE 1-9 Sample areas in Ontario, Quebec and Vermont.

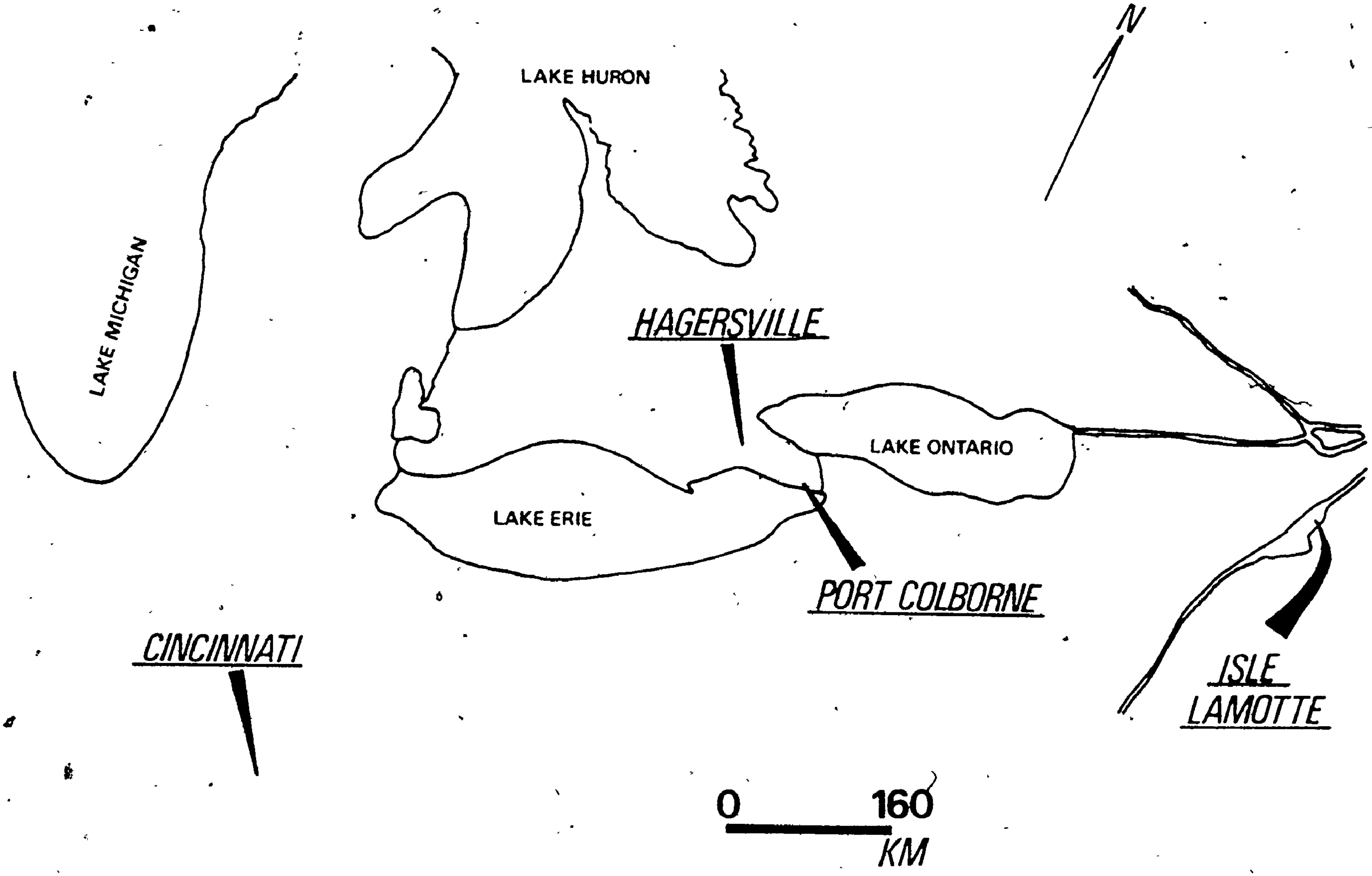
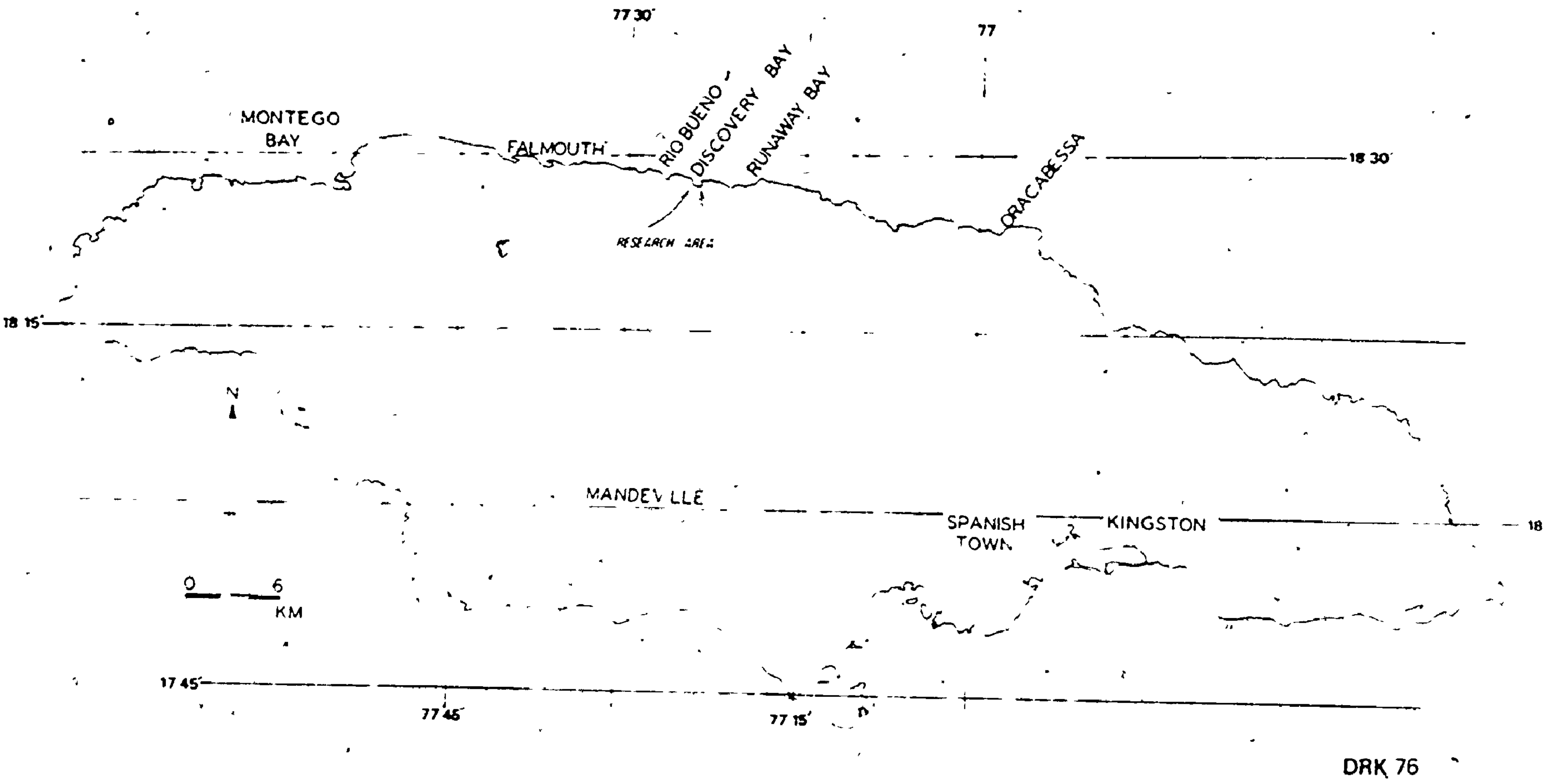

N
LAKE HURON
LAKE MICHIGAN
HAGERSVILLE
LAKE ONTARIO
LAKE ERIE
PORT COLBORNE
CINCINNATI
ISLE
LAMOTTE
0
160
KM

FIGURE 1-10 Study areas in Jamaica, West Indies. The work on modern reefs was carried out at Negril (approx. 60 km west of Montego Bay), Rio Bueno, and Discovery Bay. The Pleistocene reef carbonates were studied about Oracabessca, Runaway Bay, Discovery Bay, Rio Bueno, and the Falmouth area.


77 30'
77
MONTEGO BAY
FALMOUTH
RIO BUENO
DISCOVERY BAY
RUNAWAY BAY
ORACABESSA
18 30'
RESEARCH AREA
18 15'
N
MANDEVILLE
SPANISH TOWN
KINGSTON
18
0
6
KM
17 45'
77 45'
77 15'
DRK 76

1. Jamaica
2. Barbados
3. Florida Keys
4. Curacao
5. Bonaire
6. Bermuda
7. St. Lucia

Exposures of Pleistocene reef carbonates were studied in (Fig. 1-7):

1. Jamaica
2. Barbados
3. Florida Keys
4. Curacao
5. Bonaire

Studies of Paleozoic endolithic microphytes were carried out using samples collected in (Figs. 1-8; 1-9):

1. Ohio
2. Alberta Rockies
3. Southern Ontario
4. Southern Quebec and Vermont

1.3.1 Jamaica W.I.

The main study area was at Discovery Bay Jamaica, (Fig. 1-10), where the reef, forereef, and lagoon environments were surveyed in detail, and where experimental installations were maintained.

Shallow water sediments were sampled over the entire western forereef, the backreef, and all around the bay (lagoon) to a depth of about 25 m. This involved 153 sample stations approximately 3 m apart in depth. Reef rubble, live coral, and calcareous algal carbonates were also sampled at most of these stations, to provide as diverse sampling as possible of the various substrates being infested with endoliths (Fig. 1-11).

Discovery Bay was also the site for field experiments to establish rates of endolithic algal infestation using substrate plates, substrate

FIGURE 1-11 Major recent sediment, rubble, and live coral sample stations in Discovery Bay Jamaica, and on the western forereef. The Iceland spar crystal installations were located opposite station 3 near the Marine Labs, and on the artificial reefs, eastern lagoon. The substrate rods were buried in the Blue Hole (station 13-20).

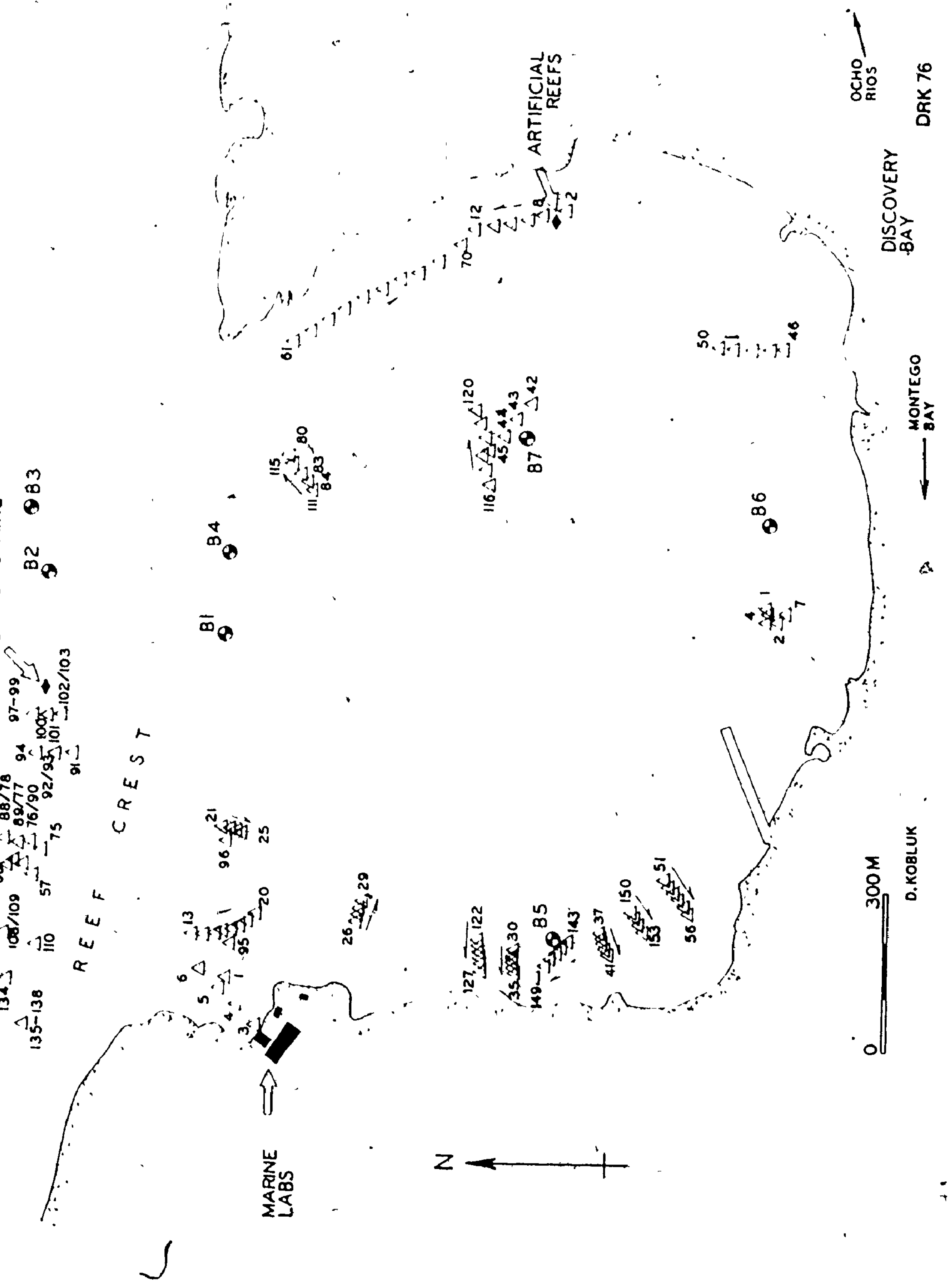
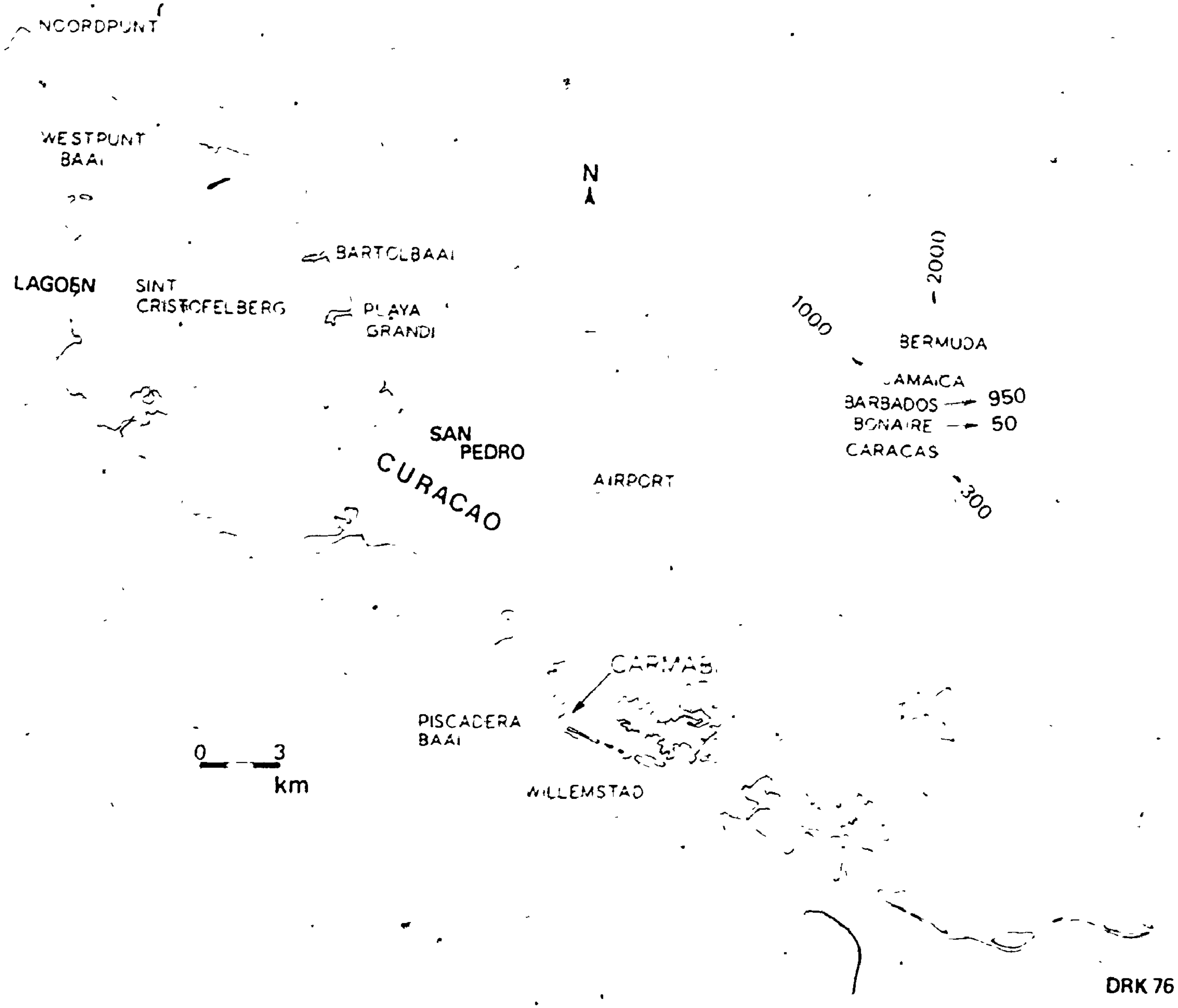

LYNTON'S MINE
ARTIFICIAL REEFS
REEF CREST
B1
B2
B3
B4
B5
B6
B7
MARINE LABS
N
DISCOVERY BAY
OCHO RIOS
MONTEGO BAY
DRK 76
0
300M
D. KOBLUK

FIGURE 1-12 Curacao, Dutch West Indies.


NOORDPUNT
WESTPUNT BAAI
LAGOEN
SINT CRISTOFELBERG
BARTOLBAAI
PLAYA GRANDI
N
SAN PEDRO
CURACAO
AIRPORT
1000
2000
BERMUDA
JAMAICA
BARBADOS 950
BONAIRE 50
CARACAS
300
CARMABI
PISCADERA BAAI
WILLEMSTAD
0 3 km
DRK 76

rods, and Iceland spar crystals.

The (less than) 120,000 year old Pleistocene reef terrace at Discovery Bay and Rio Bueno (5 miles west of Discovery Bay) was studied and sampled to provide comparative material (Fig. 1-10). Samples were also taken from the lowest reef terrace at Oracabessca (east of Ocho Rios).

The geology of Jamaican Pleistocene rocks is presented in Land (1973a, b, c), Land and Epstein (1970). Goreau (1959), and Land and Goreau (1970), Goreau and Goreau (1973), Moore (1973), Goreau and Land (1974), and Lang, Hartman, and Land (1975), summarize the ecology and structure of modern Jamaican reefs.

1.3.2 Curacao N.A.

Curacao, situated in the Dutch West Indies, about 1000 km southeast of Jamaica (Fig. 1-12), was visited in order to provide a study area as close to the equator as possible (12°6' north latitude). The living coral reef was studied at Westpunt Baai and Piscadera Baai, on the west coast of the Island (Fig. 1-12). Sands, live coral and reef rubble were collected at 3 m depth intervals to 30 m depth along several transects running from shore down onto the forereef.

Pleistocene reef carbonates were collected from the 30,000 to 40,000 year old reef terrace at the head of Piscadera Baai, at Noordpunt, Playa Grandi, and in the coastal area between Noordpunt and Bartolbaai.

De Buisonje (1974), Alexander (1961), and Schaub (1948) summarize the geology of Curacao.

FIGURE 1-13 Bonaire, Dutch West Indies.

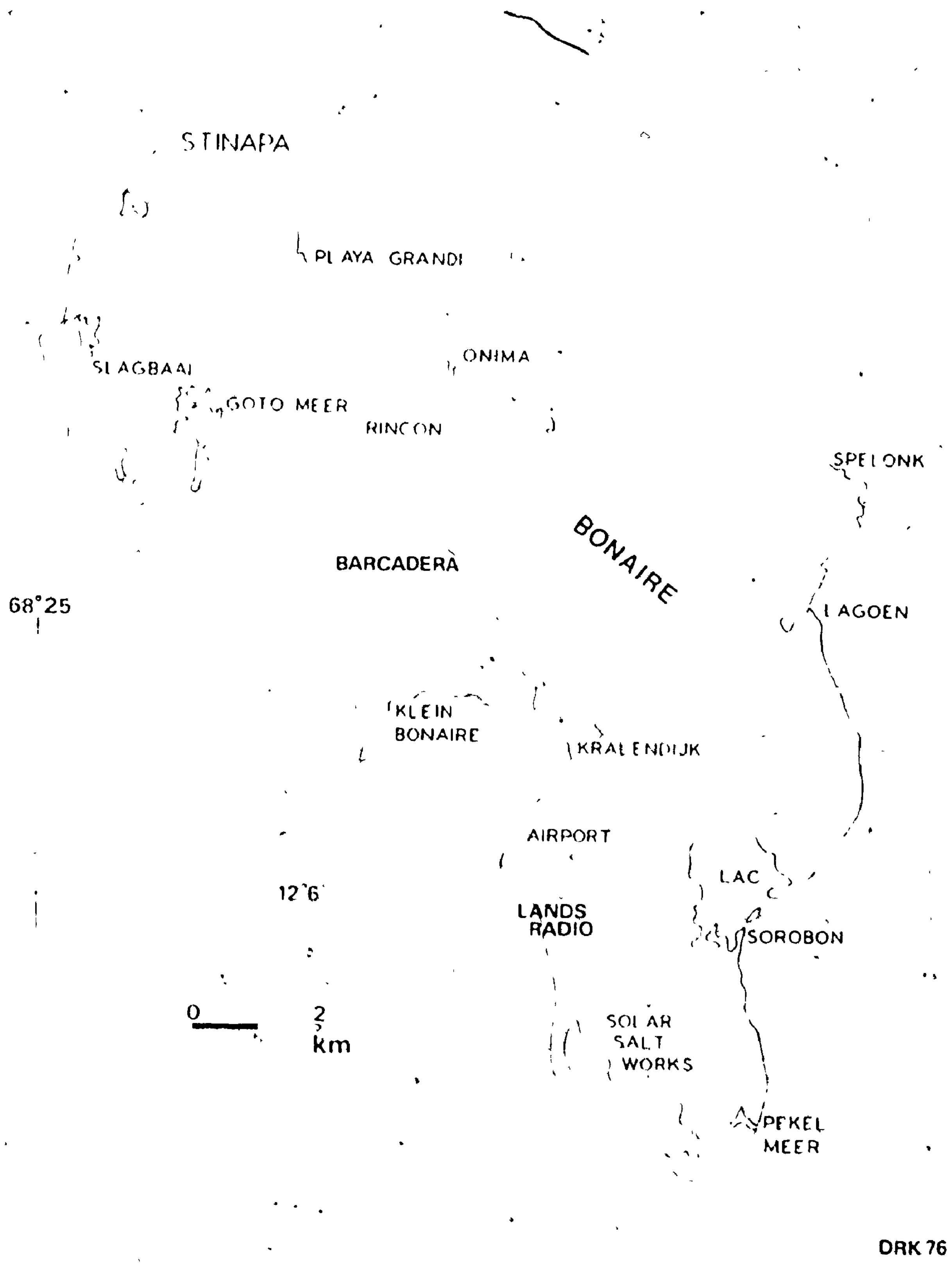
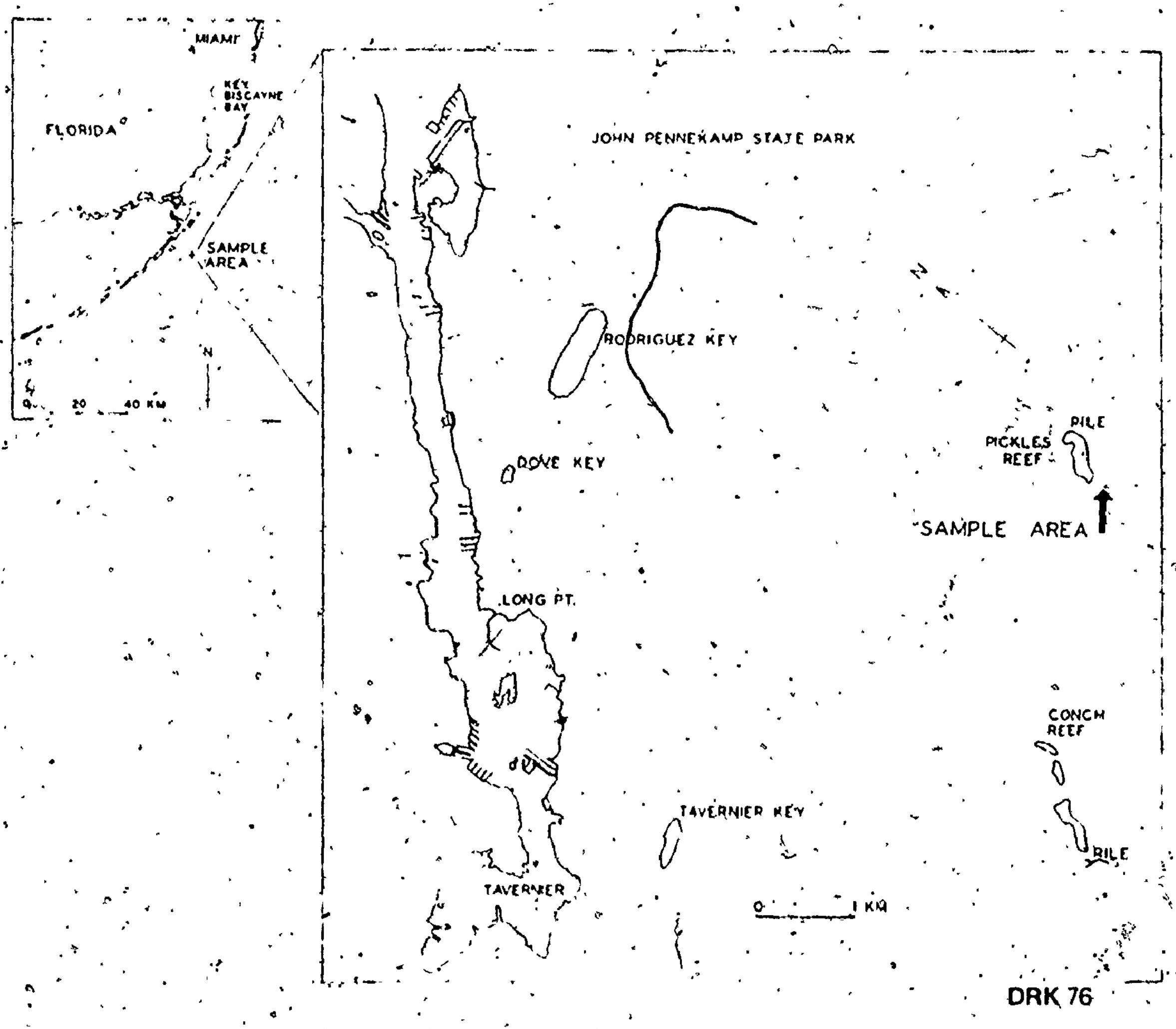

STINAPA
PLAYA GRANDI
ONIMA
SLAGBAAI
GOTO MEER
RINCON
SPELONK
BONAIRE
BARCADERA
68°25
LAGOEN
KLEIN BONAIRE
KRALENDIJK
AIRPORT
LAC
12°6
LANDS RADIO
SOROBON
0
2 km
SOLAR SALT WORKS
PEKEL MEER
DRK 76

FIGURE 1-14 Location of Pickles reef, the major sample area off Key Largo, Florida Keys.


MIAMI
KEY BISCAYNE BAY
FLORIDA
SAMPLE AREA
N
0 20 40 KM
JOHN PENNEKAMP STATE PARK
N
RODRIGUEZ KEY
DOVE KEY
PILE
PICKLES REEF
SAMPLE AREA
LONG PT.
CONCH REEF
TAVERNIER KEY
PILE
TAVERNIER
0 1 KM
DRK 76

1.3.3 Bonaire N.A.

Bonaire, Dutch West Indies, a small, sparsely-populated desert island located 50 km east of Curacao (Fig. 1-13), provides an opportunity to study endolithic microphytes in an untouched and virtually pollution-free reef environment.

The modern reef was studied at Barcadera, south of Rincon, just east of the Goto Meer inlet, and offshore of a cobble beach 1 km south of the Solar Salt Works plant on the southeast coast. Carbonate sand and reef rubble were collected to a depth of 20 m, at stations 3 m apart in depth along transects perpendicular to the shore. Sand samples were also collected from the shallow floor of the Lac just west of Sorobon point.

Pleistocene samples were collected from the first reef terrace (40,000 years old) at Barcadera, Stinapa, Playa Grandi, and Lagoen.

The geology of the island is summarized in De Buisonje (1974).

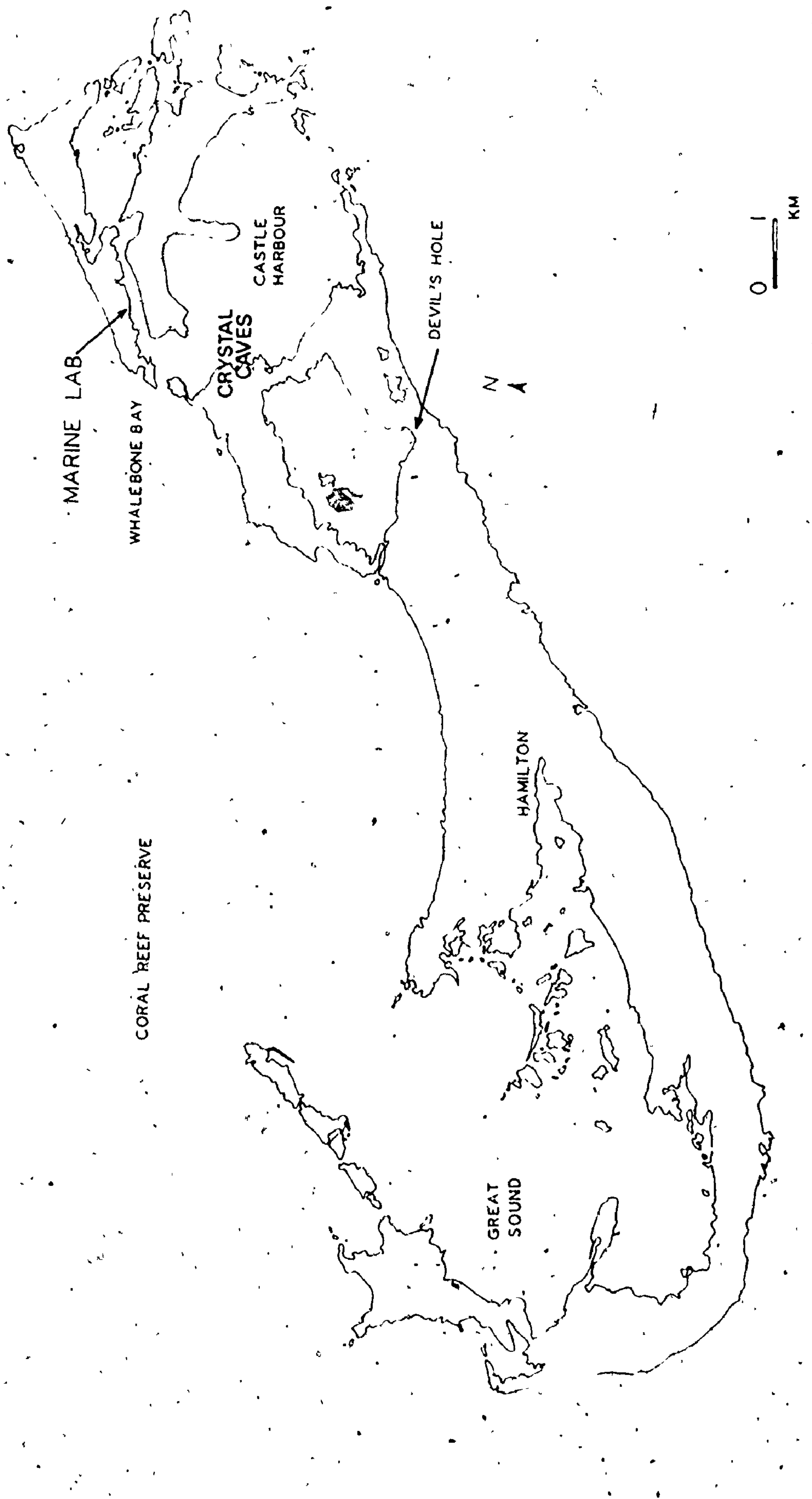
1.3.4 Florida Keys

Sands and reef rubble were collected from channels in and around Pickles Reef, 6 km offshore of Key Largo in the Florida Keys (Fig. 1-14). Collections of sands and muds were also taken on the flats adjacent to the east shore of Lower Matecumbe Key, as well as in Florida Bay, offshore of Turkey Key.

The Key Largo Formation (Pleistocene) was studied and sampled at Key Largo, Pigeon Key, and Sugar Loaf Key. The Miami Oolite was sampled on the south coast of Pigeon Key. Multer and Hoffmeister, (1968) and Multer (1975), summarize aspects of the geology and reef ecology of the Florida Keys pertinent to this study.

FIGURE 1-15 Bermuda.

DRK 76


MARINE LAB
WHALEBONE BAY
CRYSTAL CAVES
CASTLE HARBOUR
DEVIL'S HOLE
N
0
1
KM
HAMILTON
CORAL REEF PRESERVE
GREAT SOUND

1.3.5 Bermuda

Bermuda Island (Fig. 1-15) provides an example of northern, relatively coolwater, coral reef environment.

Sand and reef rubble were collected from the northern edge of the Bermuda Platform at North Rock, from the shallow waters (3-5 m) at Ferry Reach (adjacent to the Biological Station) and in Whalebone Bay. In addition, broken cave stalactites were collected from the floor of the Crystal Cave (Fig. 1-15), at a depth of 5 m below salt water level in the cave. See Land et al. (1967), Garrett et al. (1971), and Jordan (1973), for discussions of the reefs and Pleistocene geology of Bermuda.

1.3.6 Barbados W.I.

The magnificent Pleistocene lower (80,000 year old) reef terrace exposures on Barbados, W.I. (Fig. 1-16) were sampled at a number of locations: 2 stations at North Point, at River Bay north of Morgan Lewis, and at Crane Beach. Sands and reef rubble were collected from the living reef at Bellairs St. James, to a depth of 10 m and from the backreef at Silver Sands, 2 km southeast of Bridgetown, and included a wide variety of substrate types. Lewis (1960) provides an introduction to the reefs of Barbados, and James (1972) summarizes the geology.

1.3.7 St. Lucia

A very limited amount of work was carried out on the volcanic Caribbean island of St. Lucia (Fig. 1-7) located immediately west of Barbados, and south of Martinique. Sand samples and specimens of dead coral material were collected in Vigie Bay along the northwest coast to a depth of 3 m. There are no reported Pleistocene reef terraces on the

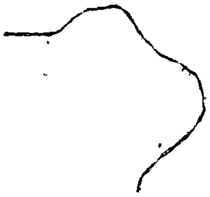
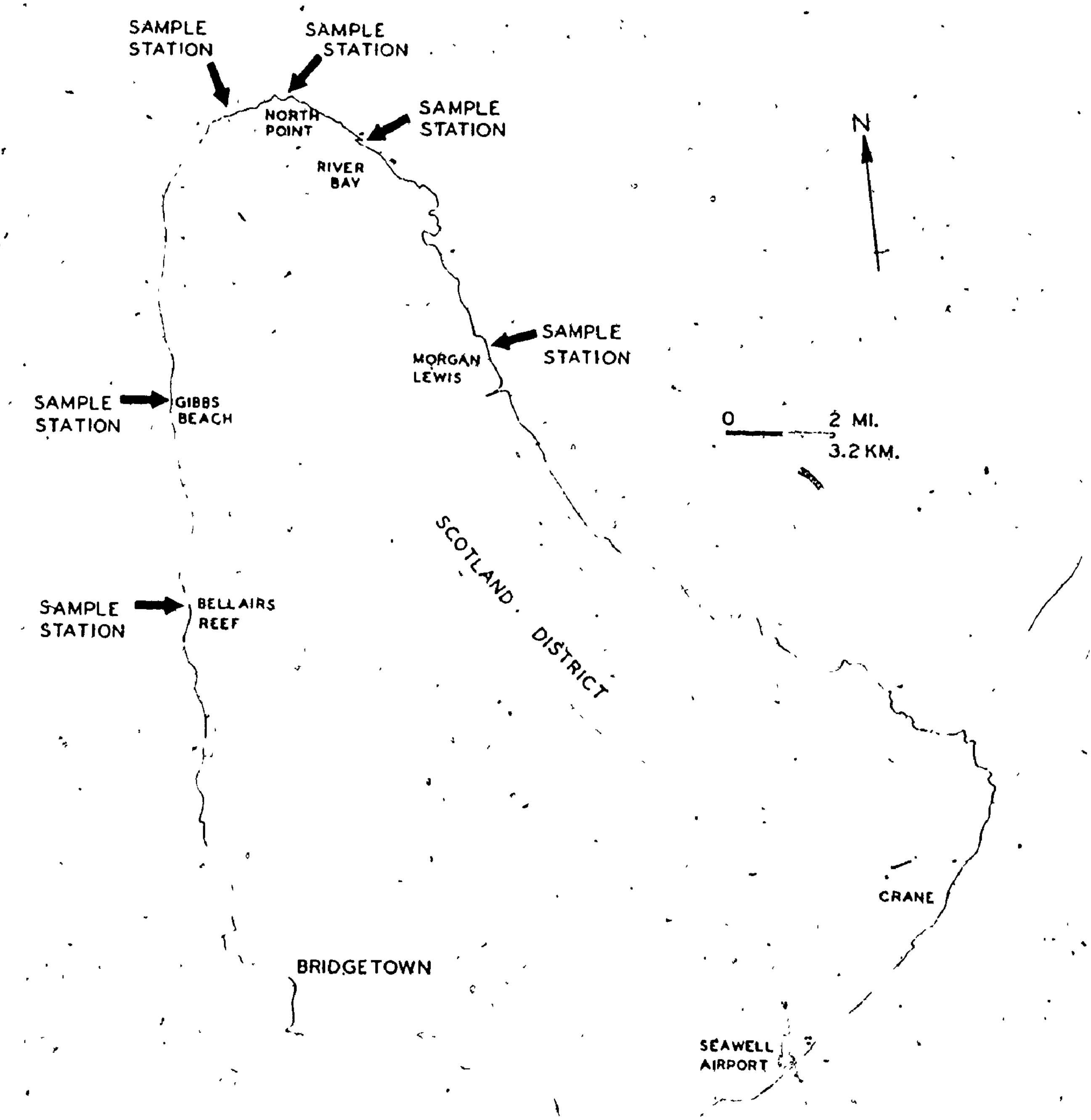


FIGURE 1-16 Sample stations on Barbados, West Indies.


SAMPLE STATION
SAMPLE STATION
SAMPLE STATION
NORTH POINT
RIVER BAY
N
SAMPLE STATION
MORGAN LEWIS
SAMPLE STATION
GIBBS BEACH
0
2 MI.
3.2 KM.
SCOTLAND DISTRICT
SAMPLE STATION
BELLAIRS REEF
CRANE
BRIDGETOWN
SEAWELL AIRPORT

DRK 76

FIGURE 1-17 Stratigraphy of the Miette reef complex, Jasper Park Alberta. The complex is contained within the Cairn and Southesk Formations. The Perdrix and Mount Hawk Formations are basin facies.

<table>
<tr><td colspan="3">PALLISER FORMATION</td></tr>
<tr><td colspan="3">SASSENACH FORMATION</td></tr>
<tr><td rowspan="4">SOUTHESK FORMATION</td><td>RONDE MBR.</td><td rowspan="4">MOUNT HAWK FORMATION</td></tr>
<tr><td>ARCS MBR.</td></tr>
<tr><td>GROTTO MBR.</td></tr>
<tr><td>PEECHEE MBR.</td></tr>
<tr><td rowspan="3">CAIRN FORMATION</td><td>UPPER CAIRN MBR.</td><td rowspan="2">PERDRIX FORMATION</td></tr>
<tr><td>MIDDLE CAIRN MBR.</td></tr>
<tr><td>FLUME MBR.</td><td>FORMATION</td></tr>
</table>

DRK

island, and limestones appear to be almost totally absent. However, a small exposure of reef limestone (apparently undescribed and unmapped) of possible Pleistocene age was found on the lee of Pigeon Island (extreme northern tip of the island); it may be the only surviving remnant of Pleistocene reef terraces that may have once fringed the island.

1.3.8 Alberta Rocky Mountains

The well-exposed Upper Devonian (Frasnian) Miette reef complex in Jasper National Park Alberta (Fig. 1-8), provides an excellent opportunity to investigate the role of endolithic algae and fungi in Devonian reef environments. Samples were collected from the Cairn Formation and the Southesk Formation from the southeast margin of the complex (Fig. 1-17). The stratigraphy and paleoecology of the complex are outlined in Mountjoy (1965), Noble (1966), and Kobluk (1975).

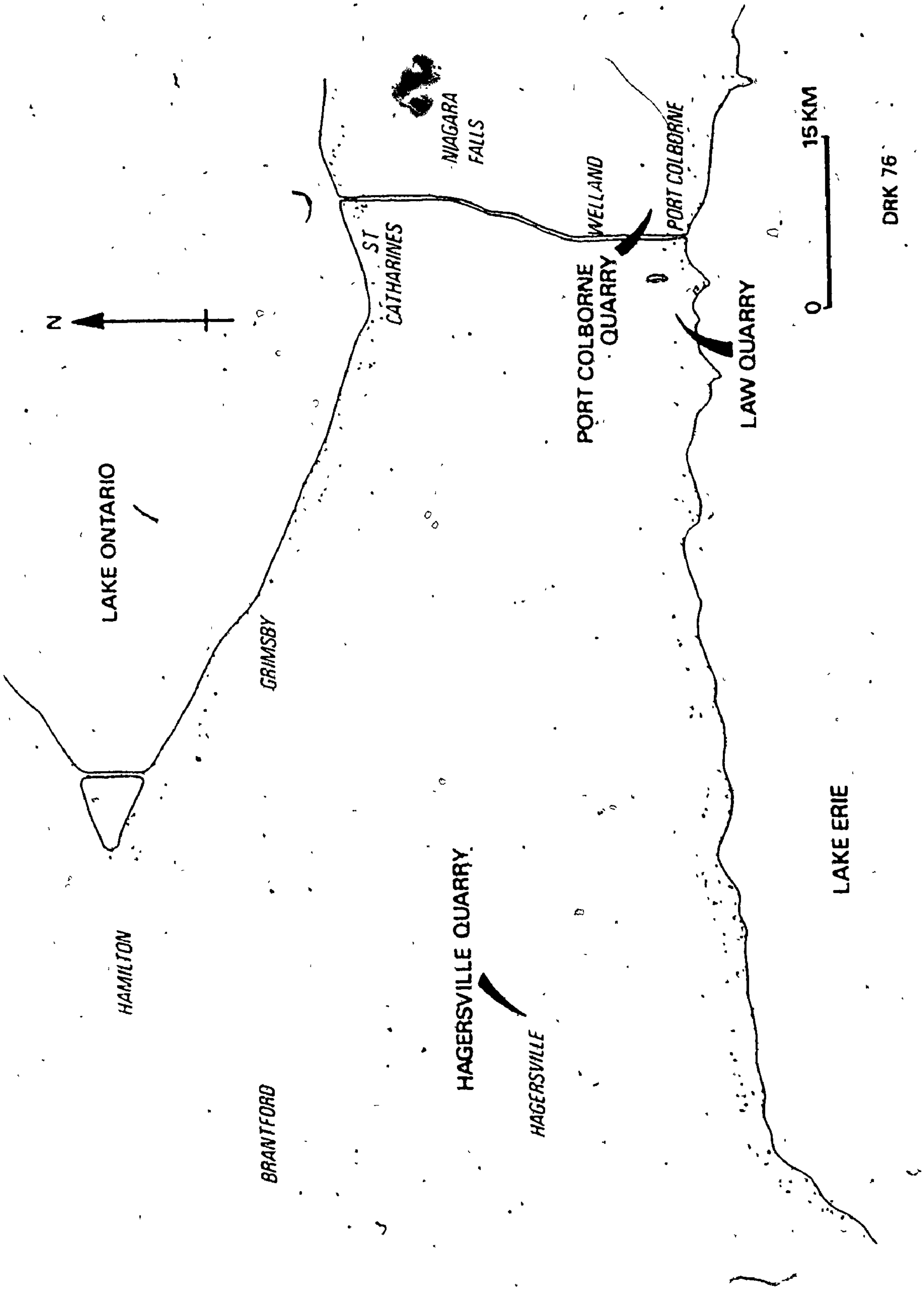
1.3.9 Ohio

Samples collected from the Richmond Formation (Ordovician) at Cincinnati (by P.R. Richards, Oberlin College), which included specimens of the brachiopods Hebertella and Plaesiomys, were included in this study (Fig. 1-9). The brachiopods contain exceptionally well-preserved algal borings associated with framboidal pyrite.

1.3.10 Southern Ontario

The Silurian/Devonian disconformity in southern Ontario was studied. The disconformity provides examples of endolithic infestation of Paleozoic limestone coasts and submerged limestone outcrop. Samples

FIGURE 1-18 Study areas in southern Ontario where the Silurian-Devonian disconformity was investigated (Hagersville and Port Colborne). See appendix IV.


N
LAKE ONTARIO
HAMILTON
GRIMSBY
ST CATHARINES
NIAGARA FALLS
WELLAND
PORT COLBORNE
PORT COLBORNE QUARRY
LAW QUARRY
HAGERSVILLE QUARRY
HAGERSVILLE
BRANTFORD
LAKE ERIE
0
15 KM
DRK 76

were collected from 3 of the best exposures of the disconformity, at the Law quarry in Humberstone, the quarry of Port Colborne Quarries Ltd. in Port Colborne, and the Haldimand Quarry at Hagersville (Figs. 1-9, 1-18).

1.3.11 Southern Quebec and Vermont

Extensive sampling was carried out in the St. Lawrence Lowlands on the Island of Montreal (Fig. 1-9), in the Middle Ordovician Black River Group, and the Chazy Group (Lower Middle Ordovician) to provide comparative material from the lower Paleozoic, and to aid in the investigation into the nature of Girvanella and similar calcified filamentous algae.

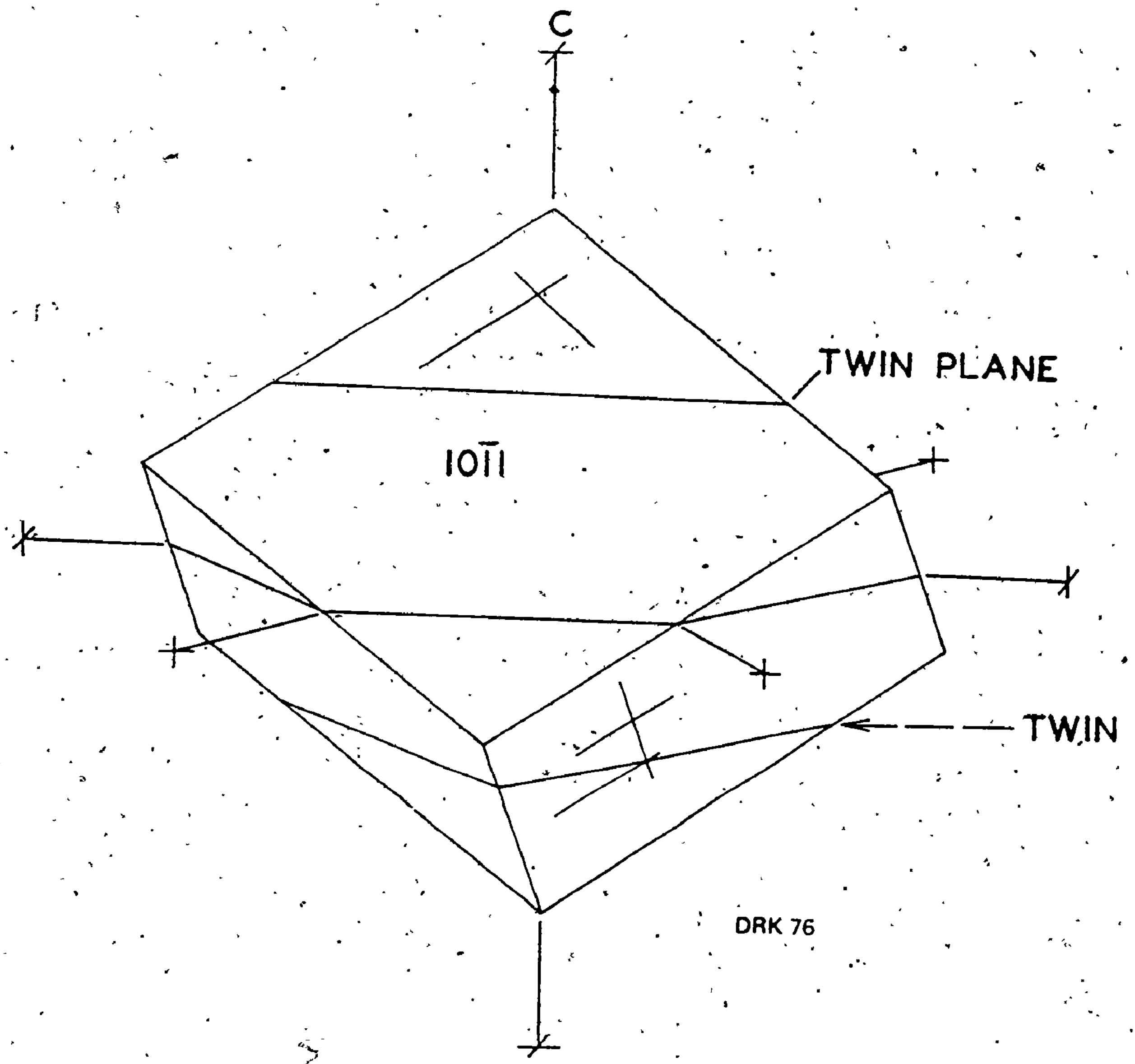
Some of the earliest Peleozoic stromatoporoid reef structures, exposed at Isle LaMotte, Vermont, were sampled to investigate endolith activity in some of the most ancient of Paleozoic reefs.

Clark (1972) provides a general introduction to St. Lawrence Lowlands geology; Pitcher (1964) and Kapp (1975) discuss the stromatoporoid mounds at Isle LaMotte.

1.4 GENERAL PROCEDURES

The quantification of algal infestation of carbonates is at present a difficult procedure, and no wholly accurate technique is yet available. Complications arising from contemporaneous infestation by other endoliths such as sponges, bryozoa, molluscs, and polychaetes, and by numerous encrusting organisms, make most present methods inaccurate (particularly quantification by acid digestion and residue studies). Attempts were made early in this study at the quantification of endolithic algal and fungal infestation of corals and other substrates, by acid dissolution (acetic and HCL). Production of calcium acetate, other

FIGURE 1-19 Rhombohedral Iceland spar crystal like the crystals used in the Iceland spar experiments in Jamaica.



DRK 76

compounds, and the inclusion of other organisms present in the sands within the residue, indicated the high degree of inaccuracy and the inapplicability of this approach.

Iceland spar crystals (low Mg calcite) were selected for this work, in order to eliminate as many complicating variables as possible. No organic matrix is present in the crystals, the crystallography and chemical composition is uniform and well known, and the crystals are inorganic in origin and have never been in sea water. The crystals are also transparent, which facilitates direct observation of the endoliths (Fig. 1-19).

Five installations using unanchored Iceland spar calcite crystals were placed in the sea at Discovery Bay Jamaica. Installations 3, 4, and 5 (see below) were used to test the variability with time in the initial infestation of the substrate. Installation 2 was used to test the effect of shallow sediment cover on infestation by algae; installation 1 was used for the detailed, long-term study of infestation:

Installation 1: Shallow (60 m mean depth) subtidal near coast. Water was constantly mildly agitated, but the crystals were not open to wave impact and apparently were never overturned. Crystals rested on a sand bottom.

Installation 2: Conditions were identical to those of No. 1 above, except that the crystals were covered in a 1 cm deep layer of carbonate sand.

Installation 3: An isolated, supratidal pool on the limestone coast. Water depth 50 cm; very little exchange with the sea except by wave splash or during storms, or during very high tides. The water rarely became slightly clouded and slightly hypersaline due to evaporation.

Installation 4: An isolated, subtidal pool, open to mild circulation, but never subjected to wave agitation. Sand bottom; water depth 55 cm.

Installation 5: Sand channel along the coast. Bordered by limestone cliffs, open to direct wave impact. Sands rippled, mobile; crystals rested on sand. Depth 70 cm.

The crystals were all placed in the sea with the $(10\bar{1}1)$ face upwards for consistency; all measurements were made on the $(10\bar{1}1)$ face, though other crystal faces were also examined (Fig. 1-19).

At installation 1, 75 crystals were used. One crystal was harvested every 24 to 48 hours for the first 65 days and at different time intervals thereafter up to 381 days.

Crystals were removed from installation 2 at widely spaced intervals to be compared with crystals from installation 1. Crystals were harvested from installations 3, 4, and 5 over a period of 7 days solely to establish the length of time required for initial infestation of the substrate under different environmental conditions. The crystals from all the installations were washed in distilled water, air dried, and subsequently cleaned of organic matter in $CaCO_3$-buffered hydrogen peroxide.

The intensity of endolithic algal infestation of the spar was measured as the percentage of the crystal face bored by the algae. Randomly spaced, parallel transects were made across the crystal faces (at 200 diameters), on a petrographic microscope equipped with a point-counting stage; approximately 1000 counts were made on each crystal and each count was recorded as a boring or as unbored calcite (Tables 1-3). The counts were converted to percentage of the crystal face by surface area.

FIGURE 1-20 The twelve epoxy and polylite resin plates anchored to the artificial "reef" constructed in 5 m of water offshore Puerto Seco Beach, Discovery Bay, Jamaica. a) Each plate contains a section of a pelecypod valve; an Iceland spar crystal; a block of porous quartz sandstone; an orthoclase crystal. b) These plates contain each of the materials used in (a) above, but some also contain obsidian, albite, quartz, and chalcedony.

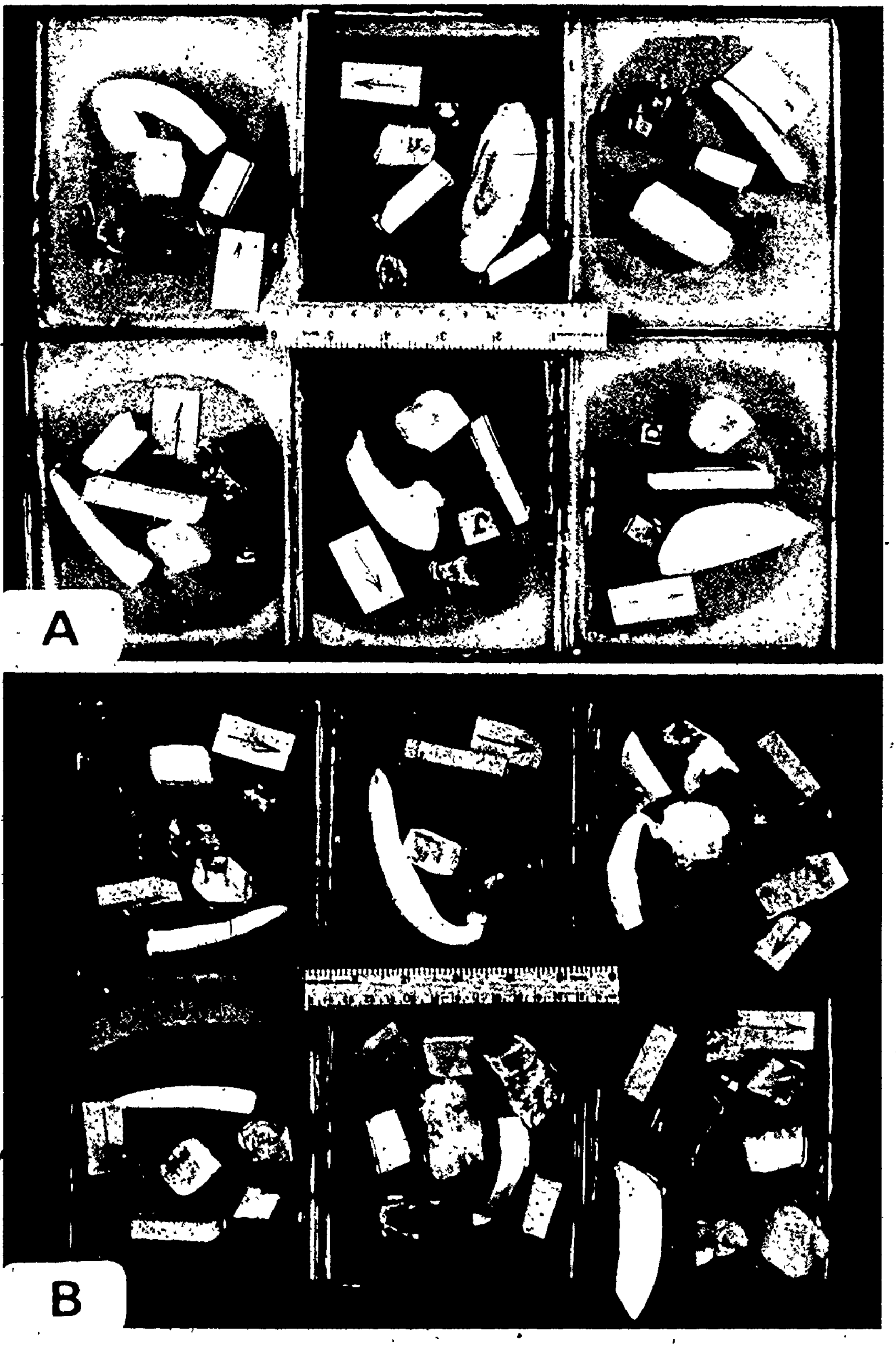
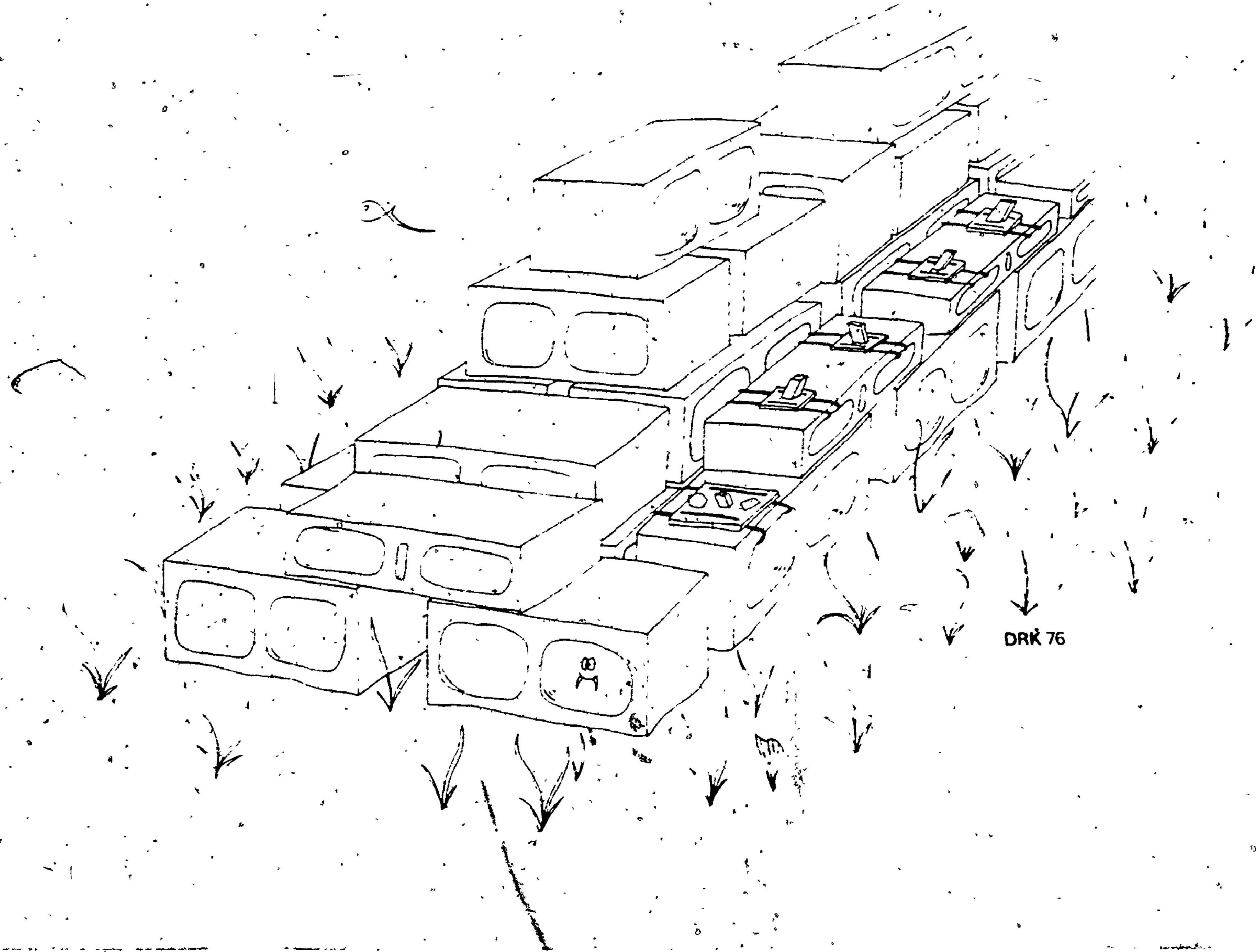

A
B

FIGURE 1-21 Artificial "reef" made of cement blocks, built on sands in Thalassia grass beds, east side of Discovery Bay Jamaica. Depth is 5 m. Note the substrate plates attached to the blocks. Refer to Fig. 1-11 for detailed location in Discovery Bay and Fig. 1-20 for a photo of the epoxy plates.

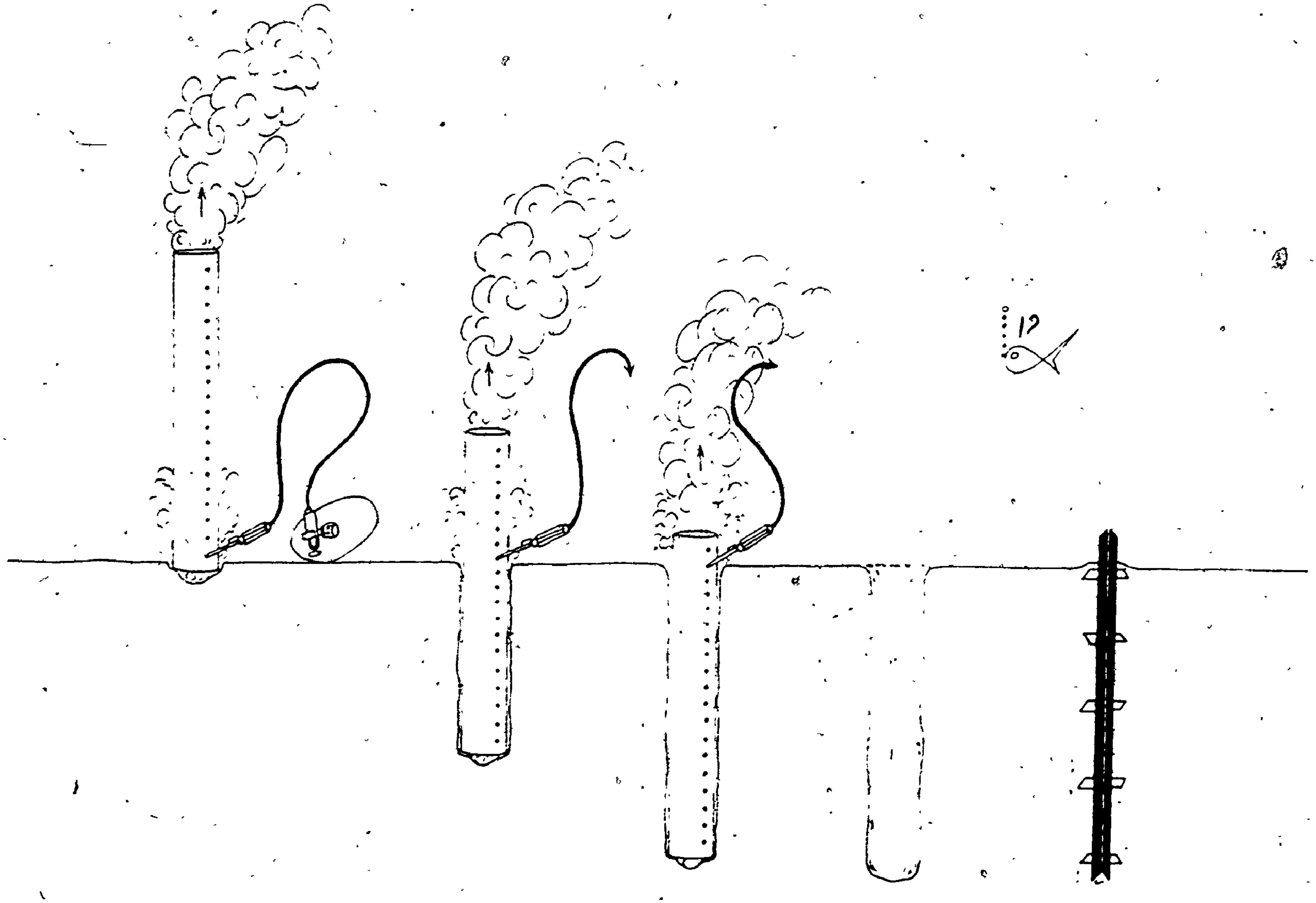

DRK 76

For control and comparative purposes, 9 Iceland spar crystals were placed in approximately 38 cm of sea water (the mean tidal fluctuation at Discovery Bay) in a sea water system at McMaster University. This is a well aerated, water-circulating system (250 l) maintained at 21.5°C under artificial light (four 160 watt Sylvania Gro Lux fluorescent lamps) on an automatic 12 hour cycle. The tank system closely duplicates the general environmental conditions present in the study area at Discovery Bay except for the intensity of illumination. These crystals were harvested over a period of 563 days, at the following intervals after placement: 35, 60, 74, 84, 105, 126, 255, 441, and 563 days. The penetration of the crystals, and the technique used to quantify algal infestation, were the same as applied to crystals harvested at Discovery Bay.

Algal borings and calcified filaments in Iceland spar were studied in transmitted light, under oil immersion, and on an AMR model 1000 scanning electron microscope. Compositional analysis was carried out on an energy dispersive x-ray analyser (KEVEX unit) on a Hitachi scanning electron microscope and using an EDAX unit on a Cambridge scanning electron microscope. The specimens are extremely delicate and are not amenable to polishing or impregnation and sectioning; standard thin section and microprobe techniques could not be applied.

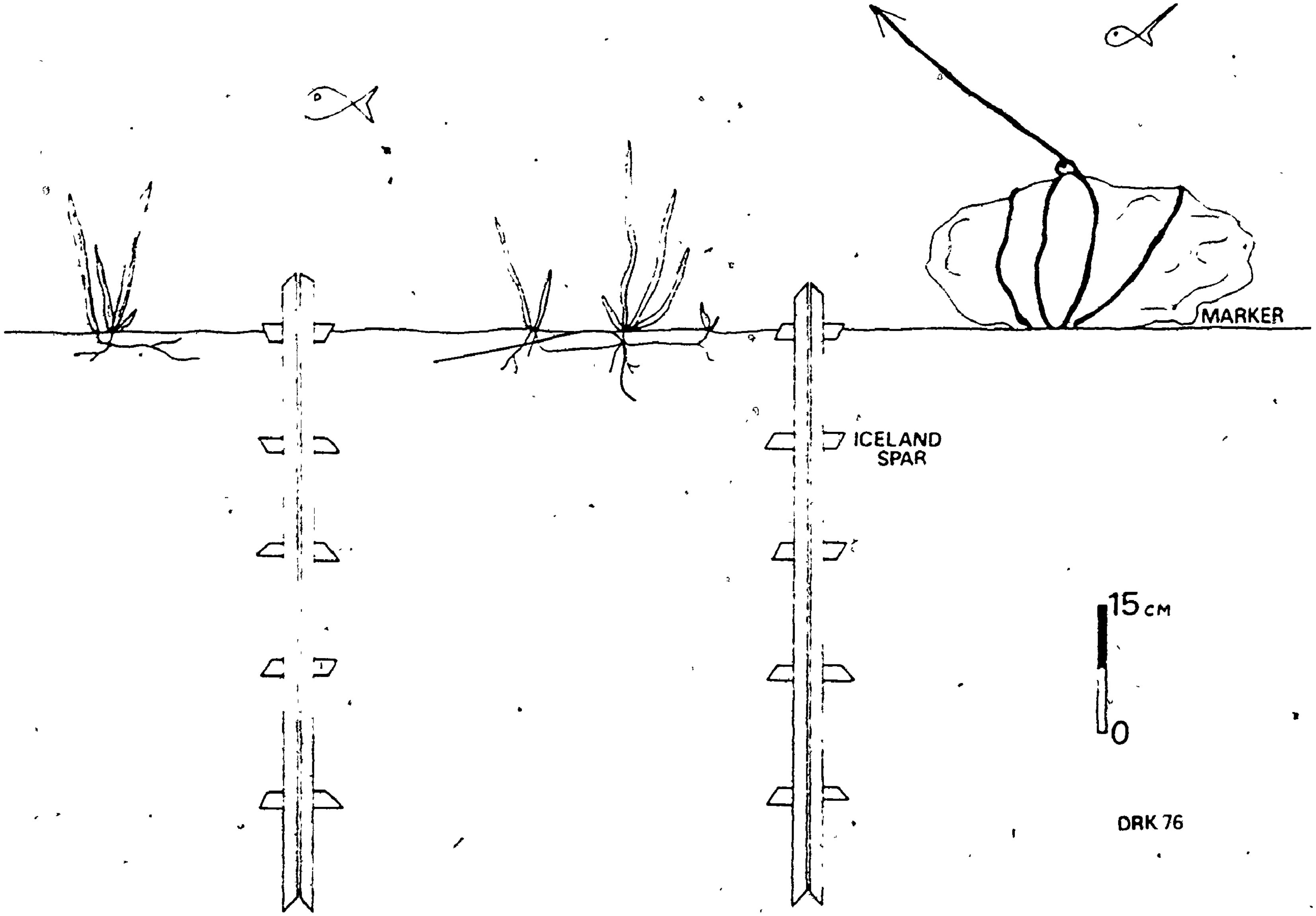
Ten epoxy substrate plates (Fig. 1-20) were also anchored to an artificial reef constructed in December 1973 in 5 m of water offshore of the north end of Puerto Seco beach, on the east of Discovery Bay (Fig. 1-21). Each plate contained several substrate materials embedded in polylite resin and epoxy (araldite), including Iceland spar calcite, obsidian, albite, orthoclase, quartz, and a section of a pelecypod valve. The plates were

FIGURE 1-22 Method of emplacement of the Iceland spar-epoxy substrate rods using an air lift system operated from a SCUBA tank; Discovery Bay Jamaica.



DRK 76

FIGURE 1-23 Iceland spar-epoxy substrate rods in place in the sediment at Discovery Bay Jamaica. The rock was used as a marker to locate the rods. Rods were removed at 6 months and 12 months after placement in December, 1974.


MARKER
ICELAND SPAR
15 CM
0
DRK 76

removed individually at various time intervals over a period of 18 months.

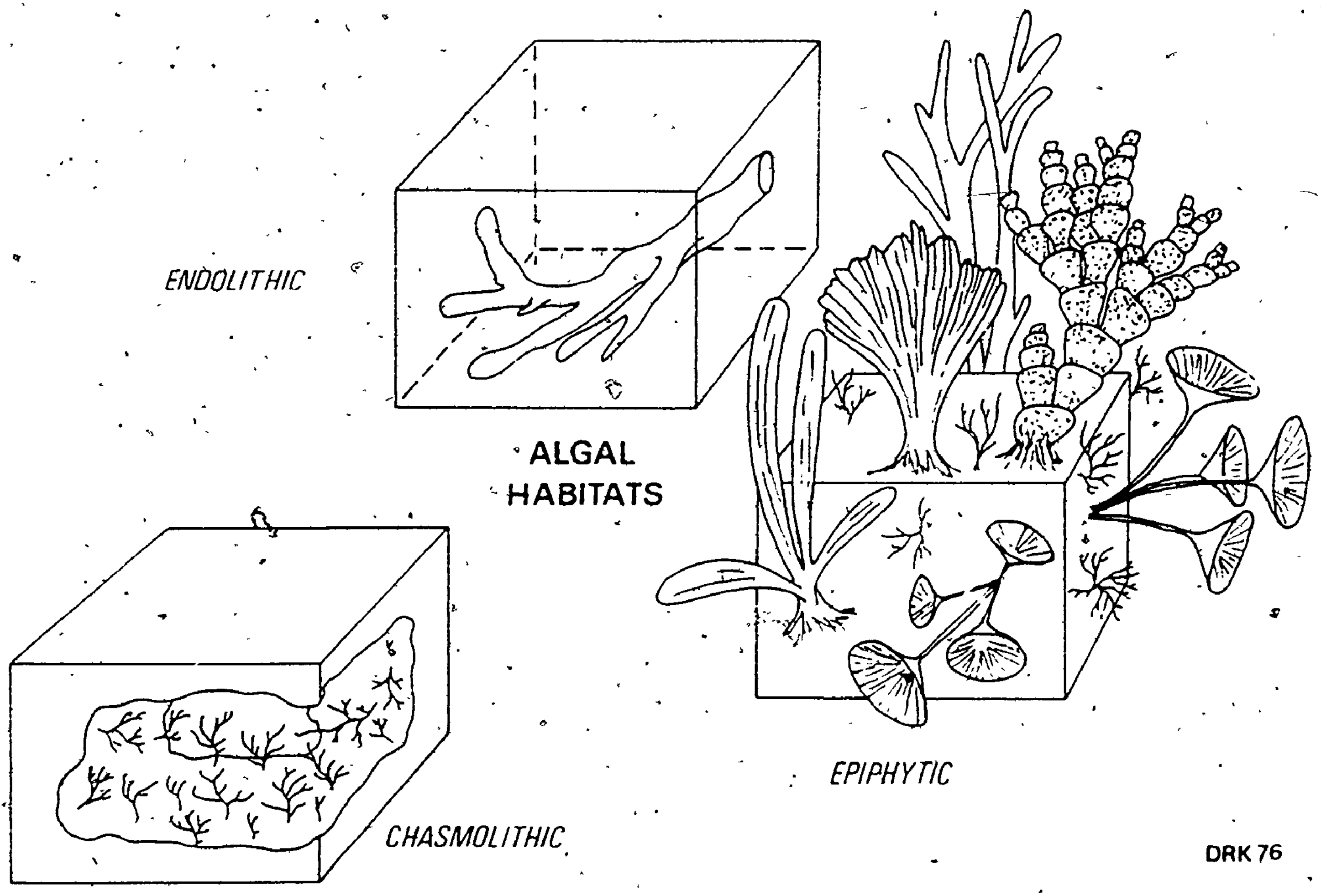
Four substrate rods, each 60 cm long and containing 5 Iceland spar crystals spaced 10 cm apart, were buried vertically in the sediment at a depth of 6 m on the north slope of the "blue-hole" opposite the Marine Laboratory in Jamaica (Figs. 1-22, 1-23). The top crystal on each rod was placed flush with the sediment surface. Two rods were harvested 6 months after burial, and the remaining 2, 12 months after burial. The rods, on removal, were washed in distilled water and air dried.

The modern carbonate and Pleistocene carbonate samples were impregnated with epoxy and thin-sectioned; malachite green stain was used in some cases to help delineate algal filaments, mucous coats, and mucous-lined borings (Kendall and Skipwith, 1969; Eutsler, 1970; Kahle et al, 1973). Devonian and Ordovician specimens were thin-sectioned. Many of the modern, Pleistocene, Devonian, and Ordovician specimens were sectioned, polished, etched in 5% acetic acid for 15 seconds, and coated in aluminum or gold for study on the scanning electron microscope.

1.5 TERMINOLOGY

The term endolith is used here to refer to algae which live in holes which they create themselves (actively bore into calcareous substrates), following the usage of Lukas (1973) and Golubic et al. (1975). Synonyms commonly encountered, and which are employed in this study, include endophyte, endolithophyte, endolithic microphyte, tranophyte (Setchell, 1924), and perforating algae (from "algues perforantes" of Chodat, 1898). Chasmolith refers to algae living in holes or cavities not of their own making, and epilith (also epiphyte) is used to refer to algae living upon the substrate and not within cavities (Fig. 1-24).

FIGURE 1-24 The 3 major marine algal habitats.


ENDOLITHIC
ALGAL HABITATS
CHASMOLITHIC
EPIPHYTIC
DRK 76

The use of the terms boring and burrow does not follow the recommended usage of Carriker and Smith (1969) in which differentiation is made on the basis of the size of the perforation: a boring is smaller than the organism whereas a burrow is the same size. Although intended to help reduce or eliminate the extant confusion in the use of these terms, the Carriker and Smith (1969) system has not found wide acceptance. Therefore, the terms are used in the conventional sense: boring refers to a hole produced by organisms in a soft, unconsolidated, or semi-consolidated substrate.

Micrite, as originally proposed by Folk (1959) refered to a precipitated lime mud of 1-4 um particle size, formed within the basin of deposition. However, the term since has been so widely mis-applied that it has come to be used, and accepted, as referring to almost any carbonate sediment of 1-4 um particle size, regardless of origin. It is used here in the latter sense, and is considered strictly a size term. Microspar refers to carbonate crystals (generally neomorphic) of 4 um to 10 um (or even 50 um diameter; Bathurst, 1971, 1975) diameter (Folk, 1965), and can be applied to minerals other than calcite. Spar includes microspar, and refers to cement or neomorphic crystals of larger size than micrite.

Both calcification and cementation are used here, and may be confused. Cementation is used to refer to the precipitation of calcium carbonate which serves to bind particles or reduce porosity (and may include some calcification). Calcification as used here includes skeletogenesis or biological calcification, but also includes the precipitation of cement on organic substrates, be it organically induced or inorganic precipitation. Therefore, as an example, the process of skeletongenesis in a modern coral is biological calcification, but an algal filament upon which micrite or microspar cement precipitates is also calcified, though not skeletogenetically. The encrustation of an algal filament with calcium carbonate by process other than the metabolism of the alga itself is here termed calcification; it may in fact also be termed a cementation process, but is distinguished from precipitation of carbonate on an inorganic substrate. Therefore, the term calcification is used here in a descriptive, not genetic sense.

1.6 TAXONOMY

The taxonomy of the filamentous endolithic algae, as a group, is confused. The endolithic algae are not a biologically unified group, but rather are made up of 4 distinct major algal groups, all of which utilize the endolithic habitat. The Cyanophyta (blue-green), chlorophyta (green), rhodophyta (red), and phaeophyta (brown), in order of importance, all contain endolithic species (Golubic, 1969); many of these species are, however, geographically and ecologically restricted, and are of no significance to this study, which concentrates upon Caribbean areas.

In her study of endolithic algae in Caribbean corals, Lukas (1973) found only a few species making up the entire endolithic flora. Substrate specificity is suspected, and it is possible that a study of substrate types other than corals would reveal a largely different endolithic microflora.

The chlorophyte Ostreobium quekettii Bornet and Flahault, O. constrictum Lukas, Plectonema terebrans Bonet and Flauhault, were the endolithic algae reported by Lukas (1973) from Caribbean corals. Ostreobium duerdenii Weber-van Bosse, reported by Duerden (1902) from

Jamaican corals, was included synonymously with O. quekettii and O. constrictum by Lukas (1973).

Ostreobium quekettii (?) is the endolithic alga most frequently encountered in this study. It infested the Iceland spar crystals and was commonly found in many sands and other carbonate fragments. Species of Hyella and Hormatonema (cyanophyta) were also encountered, but not in Iceland spar.

The species and generic determinations were made following Lukas (1973).

The taxonomy of the endolithic algae is not a major concern of this study. The algae are treated largely as a group, and viewed primarily as diagenetic agents. Although there are undoubtedly interspecific differences in the diagenetic affects of these forms, the close correlation of species and diagenetic process has proved well beyond the scope of this study.

1.7 ACKNOWLEDGEMENTS

Dr. Michael J. Risk supervised the project, reviewed the thesis, and was helpful in many ways, including funding, discussion, and techniques. Charles Kahle (Bowling Green State) was an endless source of help and encouragement and very generously gave of his time in the field in Ohio. Noel P. James (Memorial University), and J.H. Schroeder (Technische Universitat, Berlin), provided helpful comment and constructive criticism. Colin W. Stearn kindly allowed access to the Ordovician and Devonian collections at McGill University, and arranged for the use of facilities. K.J. Lukas (Harbour Branch Foundation Laboratory), Robert Riding (Cardiff), and R.D. Perkins (Duke University), were invaluable sources of comment and

information. Michael Rhodes (Amoca Canada, Calgary), Dale Winland, and Eric Michaelis (both of Amoco Production Co., Tulsa), were extremely helpful, and provided both encouragement and material support. Paul Sammarco, Bill Iams, Les Kauffman, and Kirk MacGeachy, were all sources of constructive comment. Marika Karolyi (Bourque) was an endless and stimulating source of aid and encouragement, and deserves my sincere thanks. Jeff Dravis (Miami University, Rosenstiel School) gave of his experience in the Bahamas, and provided access to his unpublished data of calcified algal filaments. R.P. Richards (Oberlin College) kindly loaned brachiopod specimens containing algal borings. Bob Cavan, Brian Pratt, Joseph Lambiase, and Michael Beattie all assisted in the field at one time or another in the Rockies or the Caribbean. Jack Whorwood was invaluable in the varied aspects of technical photography. Paulette Burns assisted in the study of borings and associated framboids. Diane Kobluk typed the final copy of the thesis. The Bermuda Biological Station, St. George, The Bellairs Research Institute of McGill University in Barbados, The Discovery Bay Marine Laboratory in Jamaica, and the Caribbean Marine Biological Institute (CARMABI) in Curacao and Bonaire, made available facilities, equipment, accomodation and arranged for specimen shipment. Eileen Graham, Jeremy Woodley (both Discovery Bay), Finn Sander (Bellairs), and Ingvar Kristensen (CARMABI), are all especially deserving of thanks.

Financial support was provided by the National Research Council of Canada, by the McMaster Science and Engineering Research Board, by the Department of Geology, the Office of Graduate Studies of McMaster University, and McMaster University Assistantships. Support was also made available through an Ontario Graduate Fellowship, and Geological

Society of America Penrose Bequest grants nos. 1865-74 and 2031-75. Amoco Canada Petroleum Company, and Amoco Production Company (Tulsa) financed field work in the Rocky Mountains, and provided thin sections and material support.

My wife Elizabeth was the greatest help, providing constant encouragement, and demonstrating an unearthly tolerance of neverending trips east, west, and to the Caribbean. She spent days at the typewriter and was a very capable assistant in the field in Florida, Barbados, St. Lucia, Ontario, Quebec, and Vermont.

CHAPTER 2

RATE AND NATURE OF INFESTATION

2.1 INTRODUCTION

Marine algae generally grow rapidly and there is some evidence that endolithic algae, in particular, penetrate carbonate substrates very quickly (Golubic, 1969; Perkins and Tsentas, 1973; Golubic et al, 1975). Little is known, however, of the rate at which many of the geologic processes associated with endolithic algal activity take place, including algal-induced substrate erosion and micritization. A knowledge of these rates would aid dramatically in better understanding the overall geologic influence of the boring algae.

Most of the detailed work on endolithic algal growth, and rates of penetration of carbonate substrates, has been carried out in laboratory culture. Kornmann (1959) noted the settlement (and release) of spores of Codiolum polyrhizum on shell fragments within 1.25 hours; germination occured within 12 days. Golubic et al. (1975) report, from calculations using the data of Kurogi (1953) and Drew (1954), that the Conchocelis-phase of Porphyra sp. began penetration 3 days after germination. Filaments studied by Kurogi (1953) bored rapidly, and penetrated 500 um into the substrates after 30 days; the filaments studied by Drew (1954) bored at twice this rate, penetrating 500 um in 14 days. The filamentous cyanophyte Hyella sp. is reported to bore immediately after germination and to penetrate 30 um to 50 um into the substrate in 21 to 28 days (Golubic et al, 1975). Perkins and Tsentas (1973) reported what they termed "heavy" infestation in Iceland spar calcite 6 months after the crystals were placed in the sea off Puerto Rico. The skeletons of living organisms are also attacked by boring microphytes. Parke and Moore (1935) recorded a rate of penetration of 100 um per year to a maximum depth of 300 um within 2 years in the plates of barnacles, beginning 4 to 6 months after initial settlement of the barnacle larvae. Gruvel (1905, cited in Parke and Moore, 1935; Lukas, 1973) found depths of penetration of 1000 um to 2000 um in barnacle shells.

The rate at which endolithic algae will bore and the depth to which they will penetrate is light dependant. Photosynthesis, and hence the boring rate, varies with the density of epilithic algae, density and thickness of encrusting calcareous organisms on the substrate, the depth in the substrate at which the algae occur, as well as the depth of water (all of these factors influence the composition and intensity of light reaching the algae).

The published literature (cited above) describes the rate of growth or rate of penetration of carbonates by filamentous microphytes. To the author's knowledge, no studies have been published which quantify the overall rate of infestation or breakdown of carbonate substrate with time. Reports of rapid penetration into a substrate by a filamentous alga may be easily misinterpreted (with reference to the rate of erosion and breakdown of the substrate), if the overall density of the filaments, and the increase with time in the number of borings, both inhabited and vacated, are not reported. In attempting to appreciate the significance of endolithic algae as bioerosive agents, it is important to know not only the rate of penetration of the filaments, but also the cumulative increase with time of the density of borings in the substrate.

FIGURE 2-1 Initial infestation in Iceland spar after 8 days in the sea at Discovery Bay Jamaica. The small ellipses are diatoms. Scale bars 300 um.

FIGURE 2-2 Algae in Iceland spar calcite: 56 days, Discovery Bay Jamaica, installation no. 1. Specimen J-211. b) Infestation at a corner of a crystal; scale bar 250 um. c) Scale bar 220 um. d) Scale bar 110 um. Note the strong control of filament orientation in (c, d). Light microscope, transmitted light.

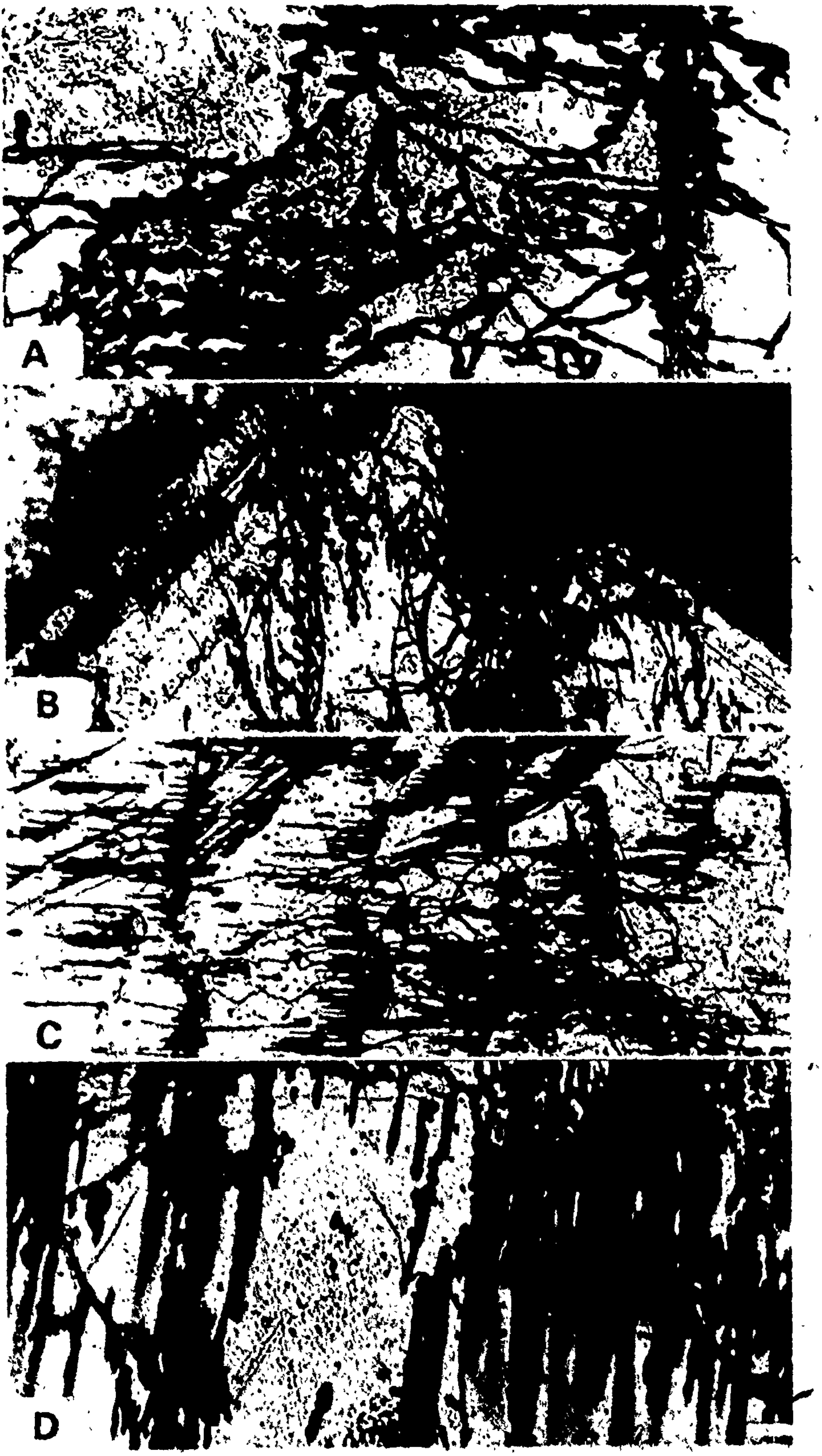

A
B
C
D

FIGURE 2-3 Infestation in Iceland spar calcite after 213 days in the sea at Discovery Bay Jamaica. Installation no. 1 Same figure as 2-9c. Scale bar 1.5 um.

16

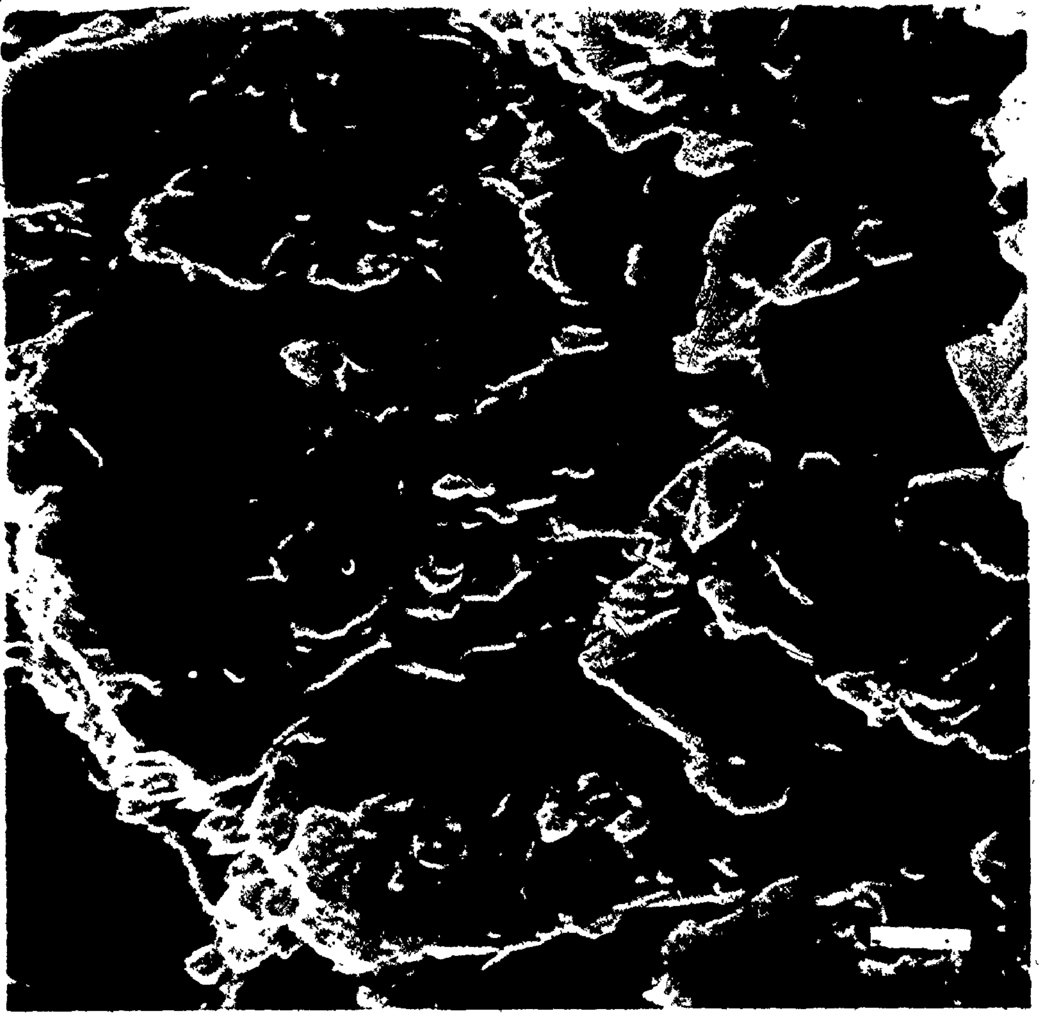
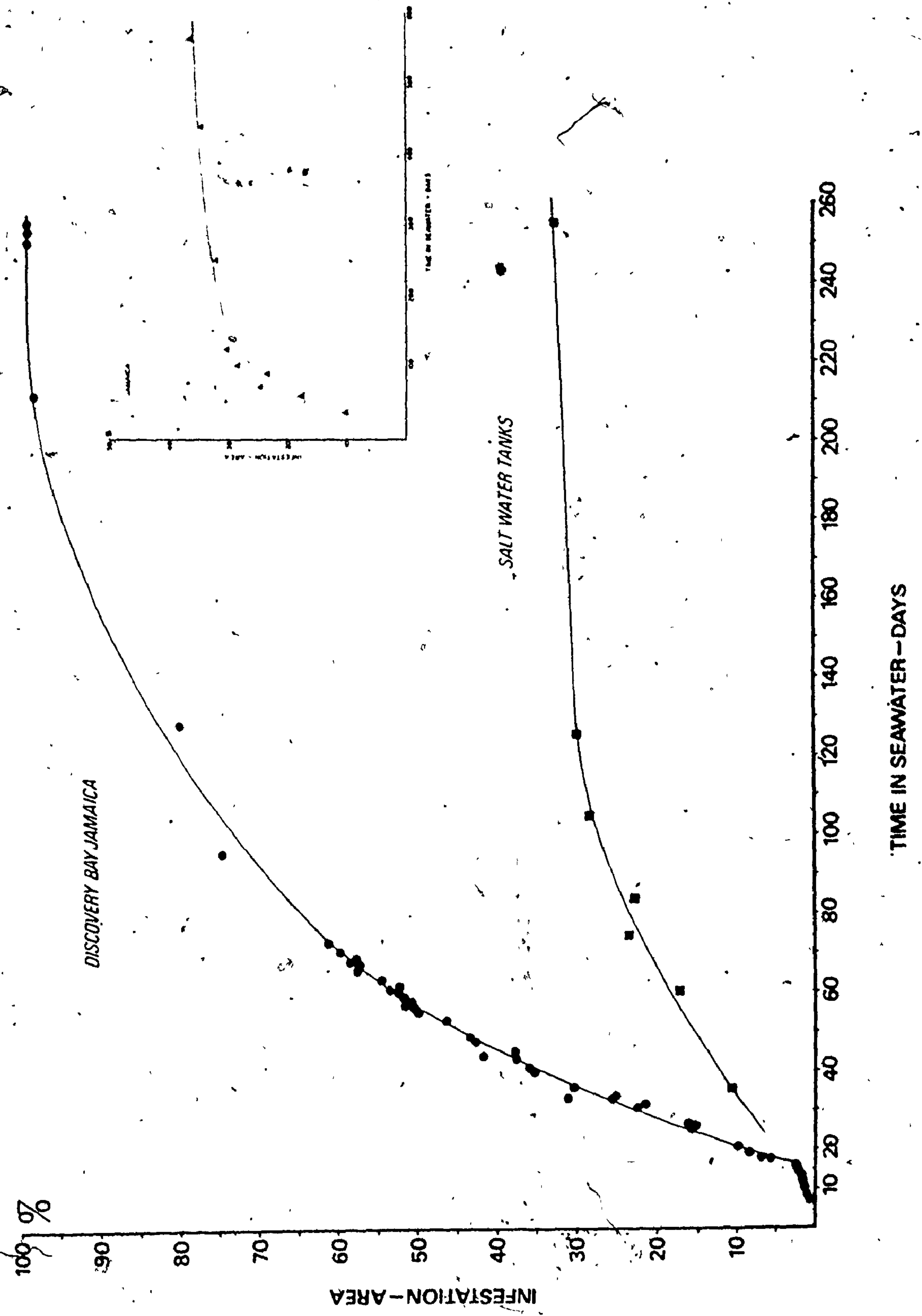


FIGURE 2-4 Infestation of Iceland spar calcite by the endolithic alga <u>Ostreobium</u> sp. with time. The lower curve represents infestation in spar in the salt water tanks at McMaster University. The upper curve represents infestation in spar placed in the sea at Discovery Bay Jamaica. The inset at upper right shows the complete documented curve of infestation of the crystals in the salt water tanks over a 600 day period.


INFESTATION—AREA
%
100
90
80
70
60
50
40
30
20
10
TIME IN SEAWATER—DAYS
10
20
40
60
80
100
120
140
160
180
200
220
240
260
DISCOVERY BAY JAMAICA
SALT WATER TANKS

2.2 RATE OF INFESTATION

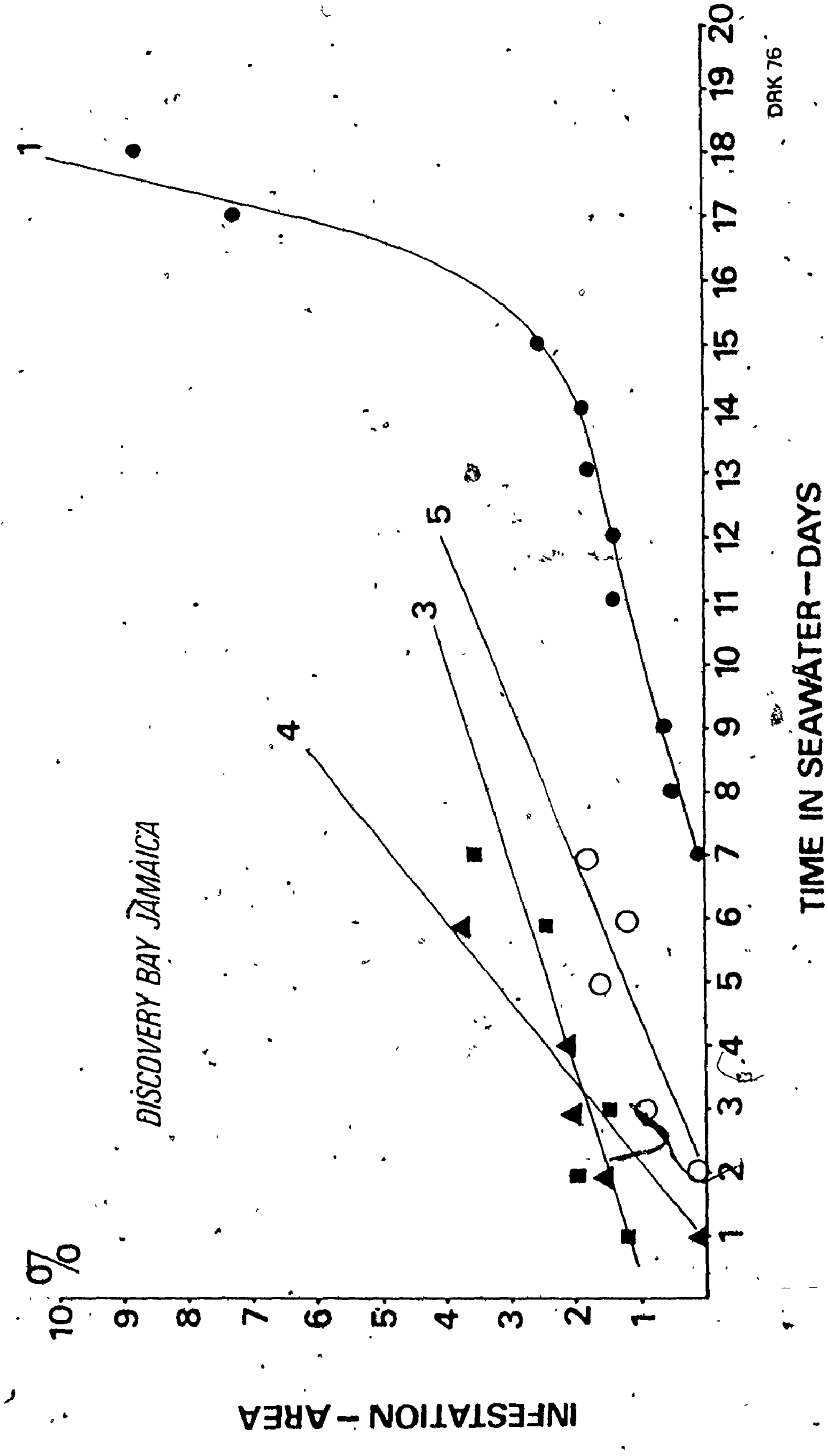
The endolithic alga found to be boring into the Iceland spar in all the Iceland spar installations, throughout the duration of the study, was Ostreobium sp., a filamentous chlorophyte commonly found in Caribbean coral skeletons and other carbonates (Lukas, 1973, 1974).

In installation 1, the first signs of infestation were visible on crystal no. 6, which was removed from the sea after 8 days (Fig. 2-1); infestation of the spar was only 0.5% by surface area (Table 1). From day 8 to 15, the average increase in percent endolithic algal infestation was 0.25% per day. Between day 15 and 17 the infestation increased dramatically, at an average of 0.9% per day until day 95, when it reached 76.7% by surface area (Fig. 2-2 and Table 1). Total (100%) infestation of the surface of the spar and obliteration of the smooth, original surface of the spar to a depth of 30 um was achieved after 213 days (Figs. 2-3, 2-4).

The initial stages of infestation of the spar in installation 2 (crystals covered by 1 cm of sand) showed very little variation from the pattern in no. 1 (Tables 1, 2). The main difference between the early stages in installations nos. 1 and 2 lies in the percentage infestation at a given time, and the time at which boring was initiated. Boring did not begin until 2 days later in crystals from no. 2; infestation by surface area of crystals from no. 2 generally was only 1/2 to 2/3 that of installation 1. This is most likely attributable to the thin sand cover, which would reduce illumination reaching the crystals and probably reduce algal recruitment rates.

Crystals from installation 3 (supratidal pool) showed the earliest initial infestation, (somewhat less than 1 day) but had the same general

FIGURE 2-5 Initial infestation of Iceland spar calcite monitored in installations 1, 3, 4, 5 in Discovery Bay Jamaica.


DISCOVERY BAY JAMAICA
INFESTATION - AREA
%
10
9
8
7
6
5
4
3
2
1
TIME IN SEAWATER—DAYS
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
1
5
3
4
DRK 76

rate of increase as in installations 1, 2, and 5. The rapid erosion of deep pockets in tropical limestone coasts therefore may be very significantly influenced by endolithic algal activity. Shallow depressions collect water which fosters endolithic activity, which further deepens and widens the pocket.

Installation 4 (isolated, subtidal pool) also showed early infestation of the crystals, but also a higher rate of increase of infestation than in the other localities (about 0.7% per day as compared to about 0.2% per day in no. 1 for the first 5 days after initial infestation) (Fig. 2-5).

Installation 5, the most rigorous of the 5 areas in which crystals were monitored, showed suprisingly early initial infestation (2 days). The crystals were often disturbed, and were constantly being covered and uncovered by mobile carbonate sand. Alexandersson (1972) noted that endolithic algae will either infest particles in mobile substrates at low rates and densities, or not at all. These results indicate that endolithic algae can infest particles in mobile, abrasive environments, and that they can do so rapidly. Once initial penetration has taken place, the endolithic algal population apparently grows in a normal manner (slope of initial infestation curve in no. 5 is essentially the same as that for crystals from installations nos. 1, 2, 3). Certainly, however, the degree of agitation of the substrate is important: a highly agitated substrate probably will be infested only during periods of quiescence; the endolithic algae and their borings would be quickly abraded away when agitation resumed.

2.3 SUBSTRATE CONTROL

For the first 15 days in installation 1, the algae generally

FIGURE 2-6 Early infestation in Iceland spar calcite: 7 days in the sea at Discovery Bay Jamaica, installation no. 1. a, b, c) Note the etch pits developed as rhombohedra. Each is occupied by 1 or more algal cells. Some show early filament penetration from the acute angles of the etch pits. Scale bars 150 um, 160 um, and 200 um respectively. d) Very early infestation after only 7 days; note the high filament density achieved in such a short period of time, and the crystallographic control of the filament orientation. Scale bar 300 um. Light microscope, transmitted light.

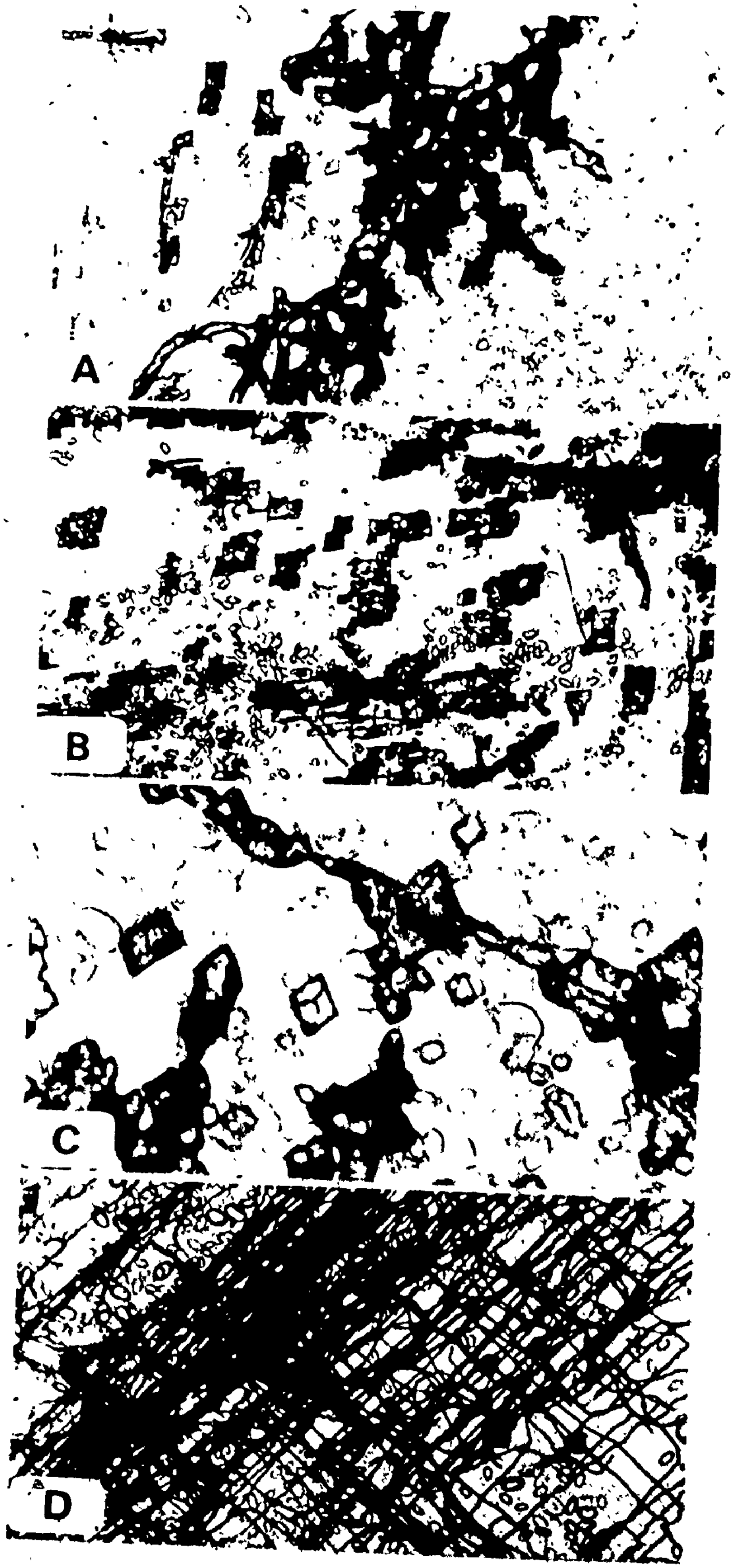
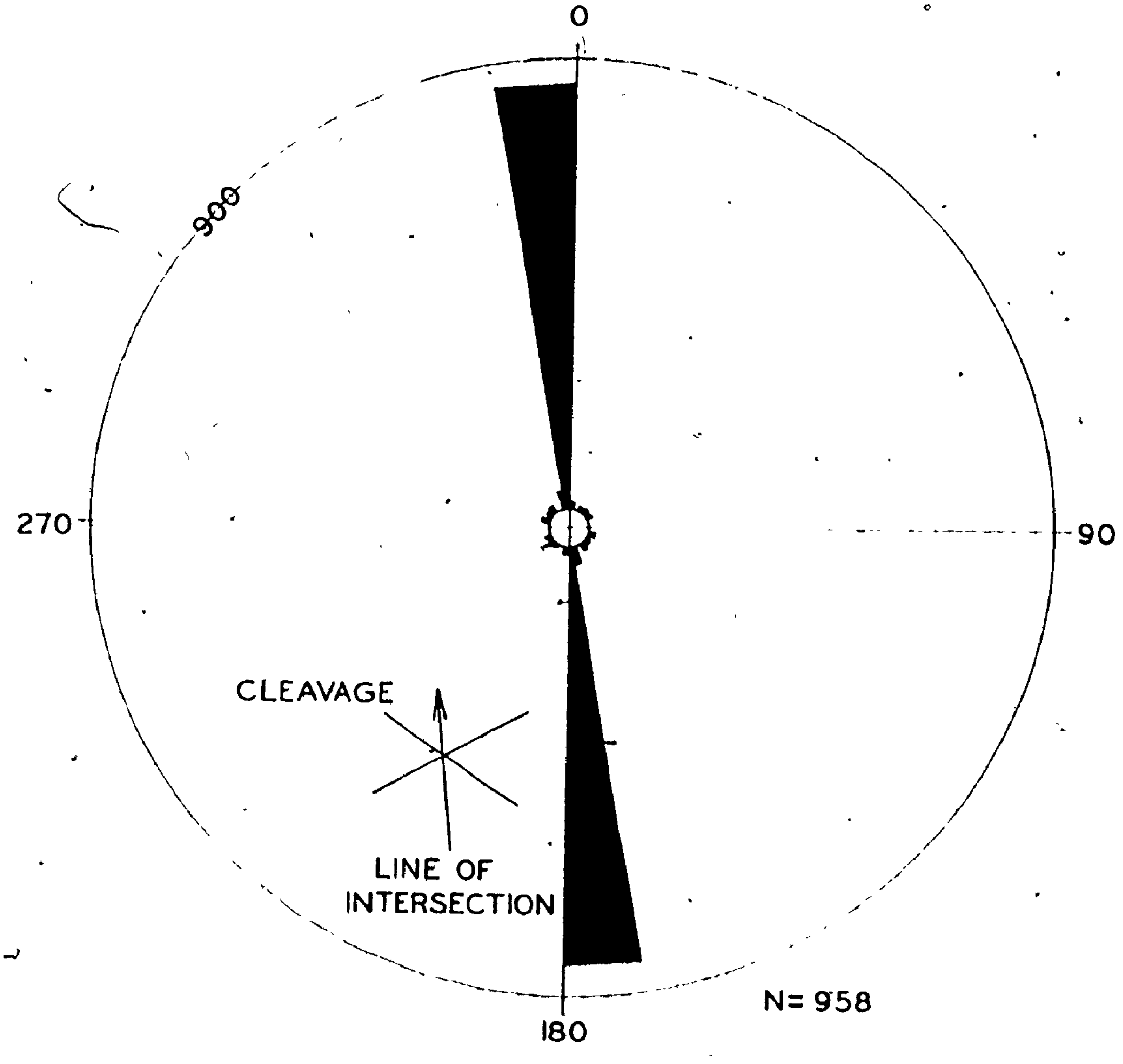

A
B
C
D

FIGURE 2-7 Rose diagram of the orientation of endolithic algal filaments in Iceland spar calcite. Measurement of 958 filaments shows a preferred orientation in the early stages of infestation which generally parallels the twin plane-cleavage line of intersection.



DRK 76

FIGURE 2-8 Algae in Iceland spar calcite: 67 days, salt water tanks at McMaster University. Specimen J-219. a) Note the strong crystallographic control of even the most newly recruited algae. Scale bar 160 um. b) Scale bar 150 um. c) Scale bar 150 um. Light microscope, transmitted light.

A
B
C

FIGURE 2-9 Algal borings in Iceland spar. All are from installation no. 1, Discovery Bay Jamaica. Specimen J-222. a, b) Surface of Iceland spar, 95 days, showing high density of borings. Vacated borings. Scale bars both 20 um. c) Detail, bored surface, 213 days. Scale bar 2 um. d, e) Detail of heavily bored surface, showing vacated algal borings. 95 days. Scale bars 2 um, 5 um, respectively. Scanning electron micrographs.

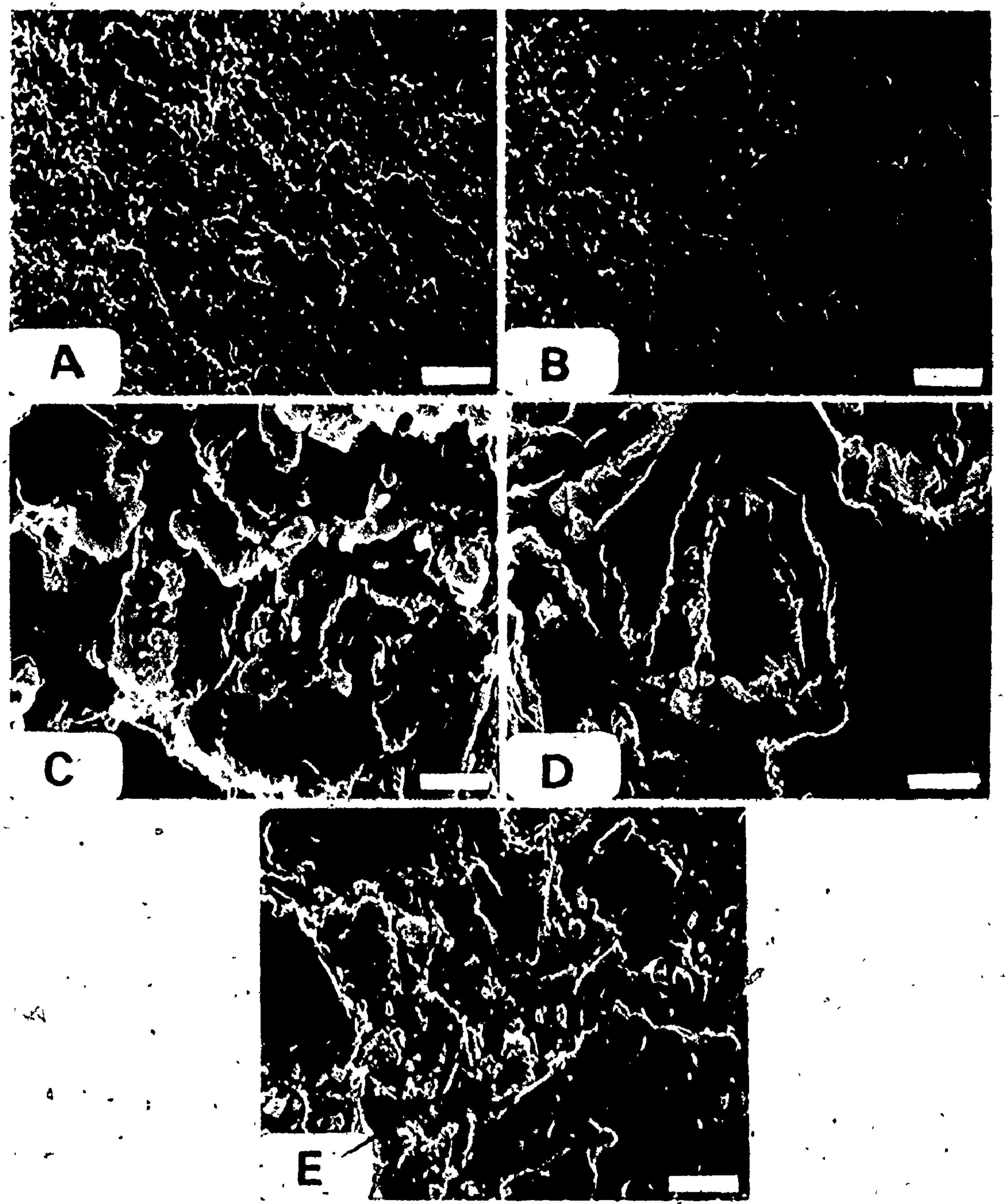
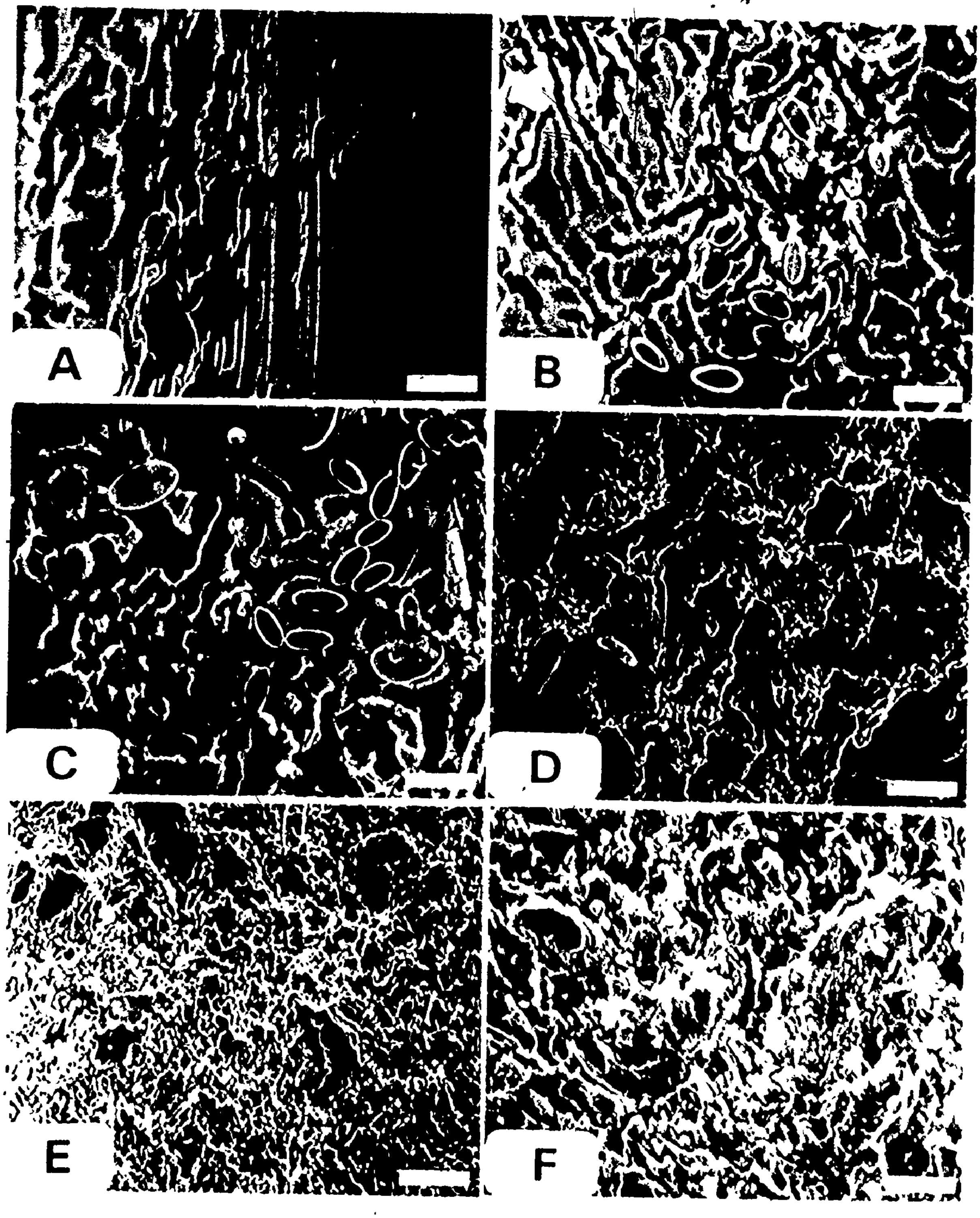

A
B
C
D
E

FIGURE 2-10 Algal borings in Iceland spar calcite monitored in the sea (installation no. 1) at Discovery Bay Jamaica. a) Margin between unbored calcite and heavily bored spar. 95 days. Scale bar 10 um. b, c) Vacated borings near the spar surface. 65 days. Ellipses are diatoms. Scale bars 10 um, and 10 um, respectively d) 95 days. Scale bar 15 um. e, f) Surface of Iceland spar calcite after 219 days in the sea. Very little remains of the original spar surface. Scale bars 20 um, and 5 um, respectively. Scanning electron micrographs.


A
B
C
D
E
F

bored parallel to the surface of ths spar or only a few microns down into the crystal, along cleavage twin-plane intersections (Fig. 2-6) control of the direction of boring was very strong (Fig. 2-7). After 15 days, crystallographic control of the direction of filament penetration became progressively weaker (Fig. 2-8); by 95 days, borings above 300 um depth were no longer significantly crystallographically controlled (Figs. 2-9; 2-10). Penetration below 300 um depth generally followed the cleavage twin-plane intersections, however, even after 95 days. The substrate therefore appears to exercise strong crystallographic control over the orientation of endolithic filaments during the earliest stages of infestation. The same pattern followed in the spar harvested from the sea water tanks, though the pronounced breakdown of crystallographic control did not occur until after 100 days.

The algae bore along the cleavage twin-plane intersection due to the higher solubility of calcite in that direction. When the density of filaments becomes sufficiently high (5% to 20%), some algal filaments no longer necessarily follow the direction of highest solubility, but rather bore to avoid one another (a chemotactic tendency, phobotropism, noted by other workers, eg: Alexandersson, 1972; Bromley and Tendal, 1973; Lukas, 1973; Golubic _et al_, 1975).

Specimens of the sclerosponge _Ceratoporella nicholsoni_, collected at depths between 40 um and 60 um off Discovery Bay, show that crystallographic control of endolithic filament orientation occurs in natural substrates as well (Figs. 2-11; 2-12). The sclerosponge coenostea are aragonite, not calcite, and consist of splays of long, prismatic, orthohombic aragonite crystals. Cleavages are developed along the 110 and 010 planes, and twinning along the 110 plane. In thin sections oriented

FIGURE 2-11 Endolithic algae in the sclerosponge Ceratoporella nicholsoni, collected from under a ledge at a depth of 40 m on the forereef at Discovery Bay Jamaica. Sample J-174. a) Filaments within the aragonite skeleton. Filaments are preferentially oriented horizontally, siliceous spicules vertically. Scale bar 100 um. b) Detail of filaments. Scale bar 70 um. c) Siliceous spicule and nearby algal filaments. Scale bar 25 um. Light microscope, transmitted light.

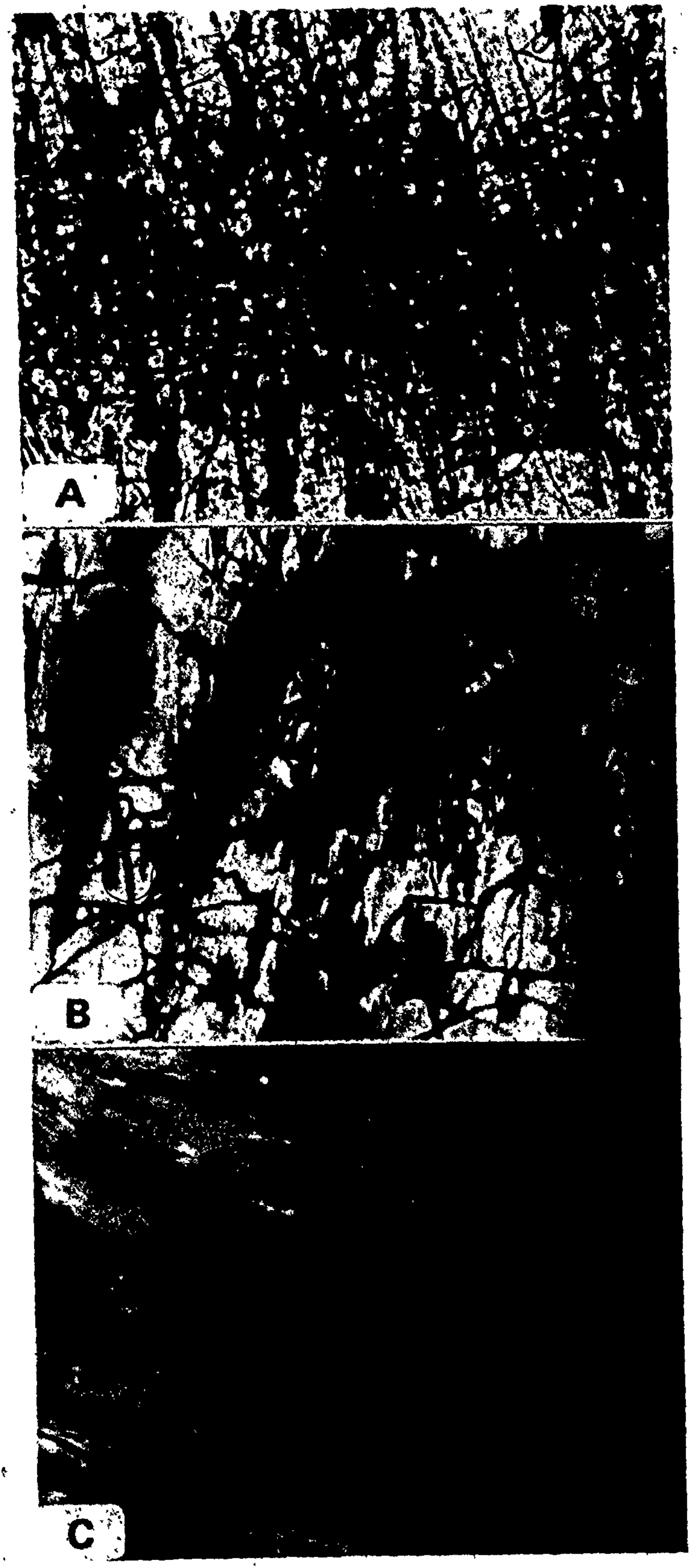
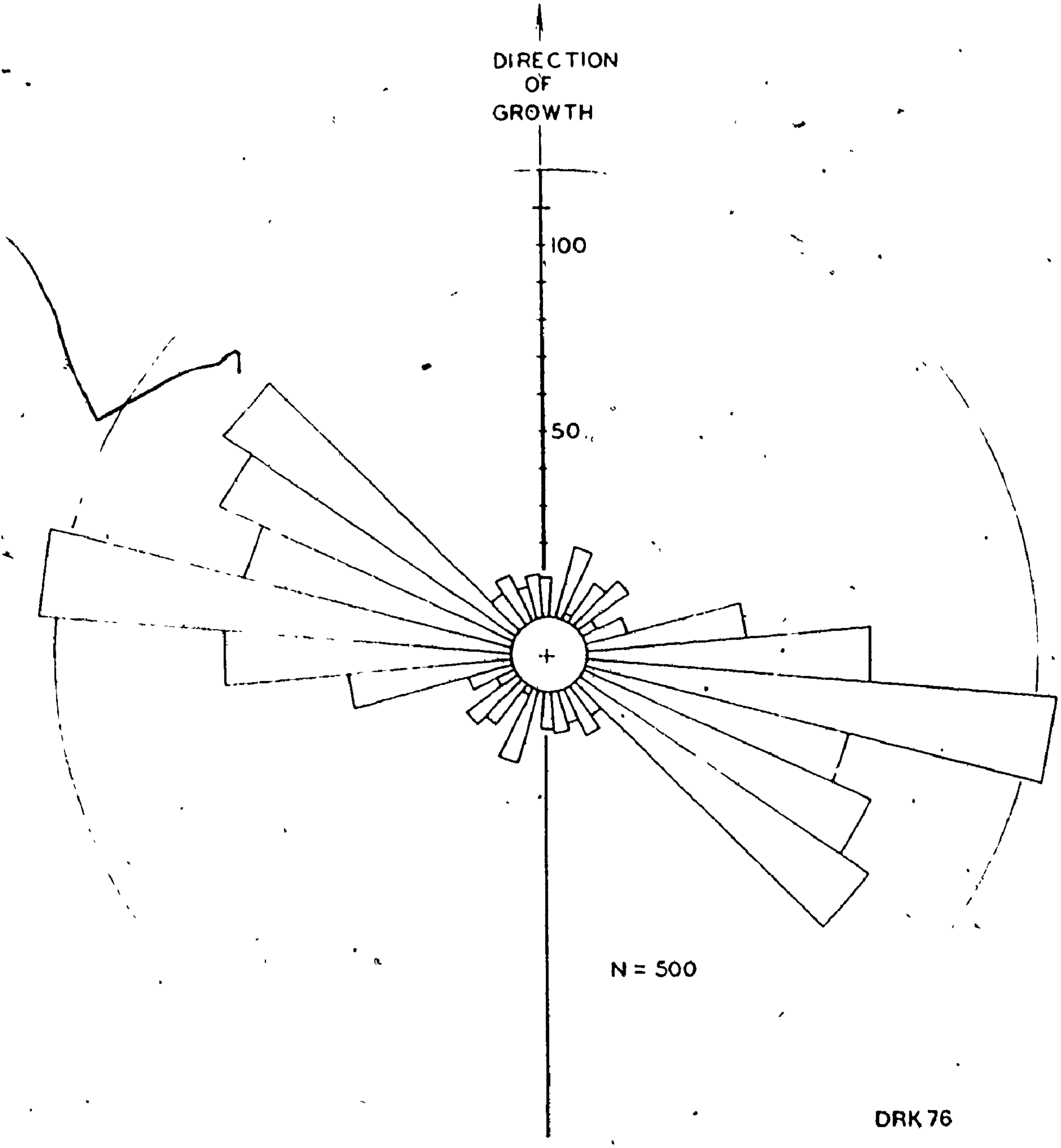
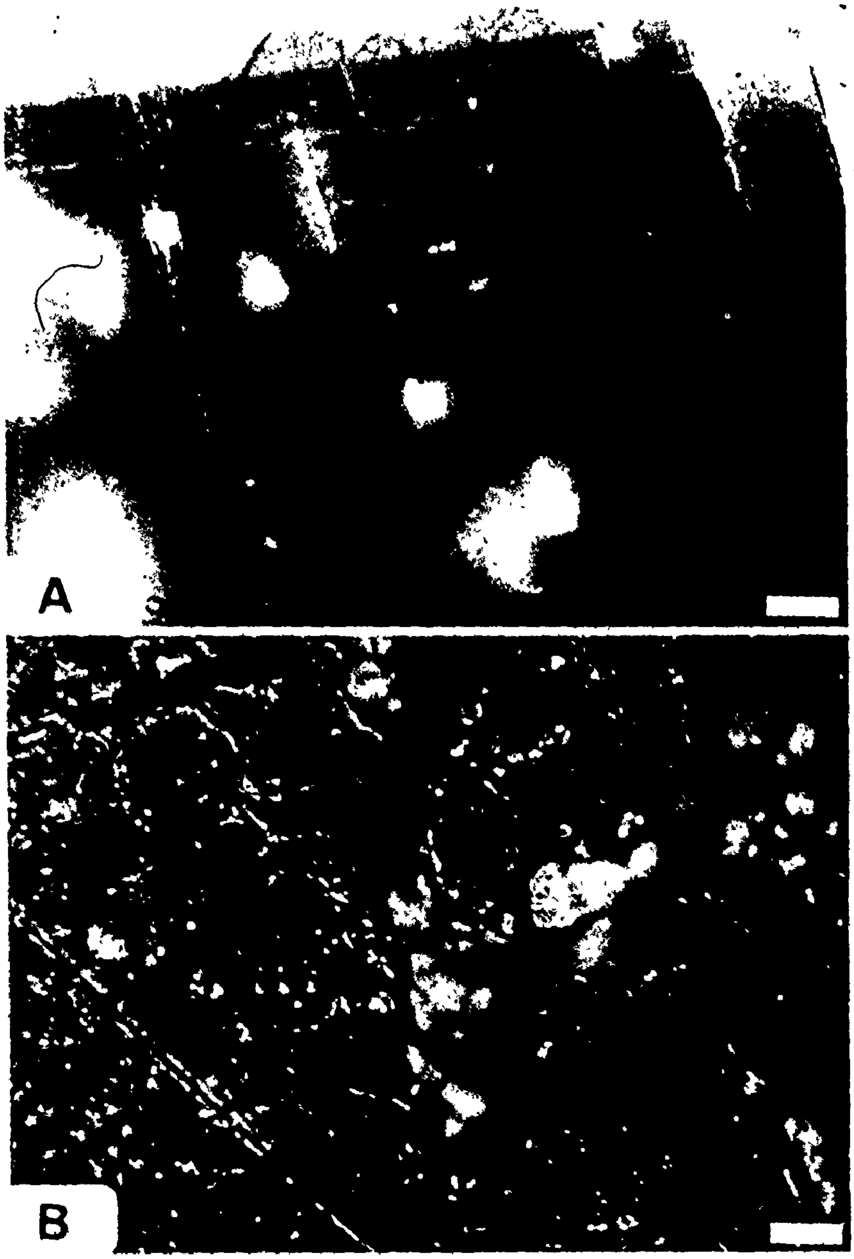

A
B
C

FIGURE 2-12 Orientation of endolithic filaments within the aragonite coenosteum of Ceratoporella nicholsoni from 40 m off the forereef, Discovery Bay Jamaica.


DIRECTION
OF
GROWTH
100
50
N = 500
DRK 76

FIGUER 2-13 Nomarski optics on Iceland spar calcite from Jamaica.

a) Minor dislocations, twins, etc., developed in Iceland spar as a result of a minor scratch on the spar surface (upper left). Scale bar 300 um. b) Vacated algal bores in Iceland spar. Note the total absence of any indications of or dislocation of the crystal lattice by the boring activity of the algae. Scale bar 80 um.


A
B

perpendicular to the crystallographic axis and the sclerosponge growth surface, the endolithic filaments are normally found oriented parallel to the growth surface, and along cleavage and twin-planes.

2.4 MECHANISM OF BORING

The mechanism by which algae bore into carbonates has generally been assumed to be chemical dissolution (Golubic et al, 1975), possibly mediated by organic acids such as carbonic acid or oxalic acid produced as metabolic by-products. The assumption of chemically-induced boring is supported by observations of etched surfaces on boring walls and the common tendency for the shape of the filament to reflect the crystal structure of the mineral they penetrate (Fig. 2-1). A physical boring mechanism, possibly involving lattice deformation and crystal fracturing by increased turgor pressure, has not as yet been ruled out.

The crystals were studied using a Nomarski differential contrast interference optical system on a Ziess Ultraphot II microscope, at 1200 diameters. Deformations of the calcite are observed as distortions of the regular interference colour band pattern, or as calcite twins, crazes, etc. Not one of the several hundred algal borings studied showed any signs of distortion of the adjacent calcite (Fig. 2-13). Scratches and fractures on the surface of the spar and gouges at the edges of some of the crystals caused by grazing parrot fish, showed dislocations, calcite twins, and distortion of the adjacent calcite.

All minerals are somewhat elastic and will rebound to some extent once applied stress is released. Calcite, however, is one of the most easily deformed of minerals. Elastic rebound even after a small but prolonged strain will not be complete, and some evidence of deformation (twins, crazes, bends, etc.) will remain. The absence of any of these effects in the adjacent calcite strongly suggests that the algal filaments do not exert any significant stress on the calcite and that no physical boring mechanism is involved.

Boring appears to take place in 2 ways: in Iceland spar, the advancing tips of the algal filaments dissolve out spaces conforming to the 3 intersection cleavages of the calcite (fig. 2-1). This has been described by other workers, particularly Golubic (1969) and Golubic et al (1975); boring by new side branches off the main thallus, which expands outward to the tip, and dissolve the calcite as they do so, until a "mature" diameter of 10 um to 30 um has been achieved. Morphologically similar, though probably functionally different, structures were described by Alexandersson (1975) in limestones bored by the cyanophyte Hormatonema sp.

2.5 LIMITING FACTORS

The slow increase in the percentage infestation up to 15 days in installation no. 1 is likely a function of the initially small filament population; a rapid expansion of the algal population occurs after 15 days (Figs. 2-4; 2-5), during which most of the available Iceland spar near the crystal surface is infested, and crowding becomes an important controlling factor. Infestation appears therefore to be somewhat self-limiting. The same pattern is present in the spar crystals harvested from the sea water tanks (Fig. 2-4; Table 3); however, the rapid rate of increase of infestation slowed down at about 30% surface area.

The most significant difference between the environment in the tanks and that in the sea at Discovery Bay appears to be the intensity of illumination, which in the tanks is a fraction of that in Jamaica. This suggests that the overall rate at which infestation of the spar takes place is strongly influenced by available light, and that the density to which a filamentous endolithic algal population will expand in the early stages of infestation is in some way controlled by available light. Though 100% infestation may take place under both high and low intensity illumination, the time required will be much greater the lower the available light level as reflected by the differences in infestation between crystals in installations 1 and 2 in Jamaica (as indicated by the separation of the two curves in Fig. 2-4). A period of rapid early increase in infestation takes place in both cases. This provides empirical support for the common observation that endolithic algal infestation decreases with water depth (decreasing illumination) (Halsey, 1970; Perkins and Halsey, 1971; Rooney and Perkins, 1972a, b; Wilkinson and Burrows, 1972; Lukas, 1973, 1974; Golubic et al, 1975).

The infestation curves of Figs. 2-4, 2-5, do not represent an increase with time in the number of living filaments penetrating the spar. Percent infestation (Figs. 2-4; 2-5 and Tables 1, 2, 3) refers to all the borings present, whether they are occupied by living or dead filaments, or just vacated borings. The curves are therefore cumulative, and show the increase in the total number of borings present in the spar; they are an index of the endolithic algal erosion of the spar substrate with time.

The proportion of living filaments versus dead filaments in vacated borings was very high in the early stages (first 15 days) of infestation (90%-100%), but decreased with time, as more filaments died and the number of vacated borings accumulated. By the later stages of infestation (95-257 days), the proportion of living filaments dropped to 5%-10% of the total filaments and vacated borings to a depth of 50 um to 100 um (Discovery Bay, Jamaica). At late stages, higher proportions of living filaments were found at greater depths in the substrate; at 95 to 129 days, 90%-100% of the boring at depths greater than 300 um contained living filaments (Jamaica). Other workers have reported that only a small proportion of the borings (approx. 5%) contained living filaments at any one time (eg: Alexandersson, 1975). Even in a single crystal, the proportion of living filaments is highly variable, ranging from high proportions (90%-100%) during early infestation, or at depths where the boring front is advancing, to very low (5%-10%) in the older, more heavily bored areas near the substrate surface. As the limits of endolithic infestation are reached, the proportion of living filaments decreases as the number of dead filaments and vacated borings accumulate and the available unbored substrate is used up.

The Iceland spar crystals in Jamaica were in the shallow subtidal near the rocky shore. Though open to sunlight, water circulation, and minor wave action, the crystals were never observed to have been greatly disturbed or overturned, even during storms. Thus, the above observations of the rate of infestation are not necessarily directly applicable to algal infestation of mobile and loose carbonate sands, or carbonate fragments which are constantly being moved about, as the algae have a difficult time establishing themselves under such conditions (Swinchatt, 1965; Alexandersson, 1972; Golubic <u>et al</u>, 1975). Limestone coasts, larger stable carbonate blocks, reef substrates, and cemented carbonate substrates, however, are easily and rapidly infested. Infestation of such substrates will probably take place in much the same way as observed in the spar.

The transparency of the substrate, depth of water, and the particular algal species involved, are probably factors determining the actual rate of infestation, filament density, and subsequent erosion of the carbonate. Nevertheless, the basic pattern of slow early infestation, followed by a rapid burst of activity, and a levelling off of infestation at relatively high filament densities is expected to occur in most carbonate substrates regardless of whether the substrates are fixed or mobile.

The effects of grazing by herbivores upon endolithic algal infestations are largely unknown. Herbivorous grazing fish, urchins, and other organisms which crop epiphytes from hard carbonate substrates, and which are known to ingest portions of the substrate in the process, should have an important affect on endolithic algal populations and upon the rate of algal erosion of substrates. Grazers removing several hundred microns of heavily infested and bored carbonate open up new surfaces to infestation and permit deeper algal penetration, possibly permitting the reinitiation of rapid infestation (as described above) in interior areas of the substrate otherwise inaccessible to the algae. The endoliths may also provide a source of nutrients to the grazers.

Although grazing of the epiphytes on the spar crystals may have begun early, it was not until 253 days that any sign of damage to the crystals by grazing activity was noted (installation 1, Jamaica). The grazing marks consist of long parallel grooves 1.0-1.5 mm wide, and several hundred microns deep, which were probably produced by small parrot fish. By 253 days after placement in the sea, the Iceland spar was very heavily bored by algae to a depth of several hundred microns, and should have been easily damaged by grazing activity. Gygi (1975) shows that grazing parrot fish in Bermuda do remove algae-bored carbonate.

Gygi (1975) does not comment on the relative rates of fish and endolithic algal erosion of the reef, but he does state that subtidal borers in general (this includes several groups) are probably more quantitatively significant bio-erosive agents than grazing fish.

CHAPTER 3

CALCIFICATION, MICRITIZATION AND GRAIN BINDING: ASSOCIATED CEMENTATION AND DIAGENESIS

3.1 INTRODUCTION

3.1.1 Filament Calcification

Many studies in modern carbonate environments have shown that a significant amount of carbonate precipitation takes place at or near the sediment-water interface, in environments ranging from peritidal to the deep sea. Work by Smith (1940), Cloud (1962), Friedman (1964), Fuchtbauer (1969), Bricker et al. (1969), Ginsburg and Schroeder (1969), Ginsburg et al. (1968, 1971), Schroeder and Ginsburg (1971), and Schroeder (1972a, b), Alexandersson (1972), James et al. (1976), and others has shown that precipitation occurs extensively and can take place rapidly. Little is known, however, of exactly how fast submarine precipitation of calcium carbonate takes place. Studies in which the rate of precipitation has been estimated have used ^{14}C dating methods (Cloud, 1972; Ginsburg et al., 1968; Shinn et al., 1969; Milliman et al., 1969; Land and Goreau, 1970; James et al., 1976). Estimates of the age of sublittoral submarine cements range from about 100 years or less to several thousand years; the limitations of the methods, however, preclude exact measurements. The consensus at the present time is that the non-skeletonogenic precipitation of carbonate is a process requiring time of the order of years or decades (Alexandersson, 1972; Bathurst, 1975). To the best of the author's knowledge, there are no studies in which the submarine precipitation of calcium carbonate has been closely monitored so as to allow accurate rate estimates.

Schroeder and Ginsburg (1971) and Schroeder (1972a, b, 1974) showed that submarine cementation and calcification of exposed filaments of endolithic algae is possible within reef cavities; Lukas (1974) noted calcified filaments of endolithic algae (Ostreobium quekettii) within intraskeletal pores in modern corals (calcification is used here to refer to the precipitation of calcium carbonate on, and within, algal filaments, resulting in the complete or partial encrustation of the filaments by crystals of calcium carbonate).

Calcified algal filaments have been known from the subaerial (Schlonleber, 1936), fresh water (Moret, 1934; Barron, 1975), and marine environments (Nadson, 1932; Schroeder, 1972) for some time. There are no reports of calcified marine endolithic algal filaments occurring outside both the endolithic habitat and cavities within reefs, nor are there data accurately describing the rate at which the calcification of exposed algal filaments takes place within the marine environment.

In the course of this study of the rates of algal infestation of marine carbonates, it was found that filaments of single endolithic algal genus present, Ostreobium sp., commonly projected out from the substrate a short distance into the sea. The exposure of endolithic filaments, living as epiliths or chasmoliths, has been described previously (Golubic, 1969; Schroeder, 1972a, b; Lukas, 1974); it is a common feature of the endolithic algae. After a period of time many of the exposed filaments became calcified. In the light of Schroeder's work (Schroeder, 1972a, b) it is apparent that this provides an opportunity to study the rate and sequence of calcification of exposed filaments under at least partially controlled conditions.

FIGURE 3-1 Micrite infilled algal borings. a) Micrite partially infilling an algal boring in Iceland spar calcite, monitored in the sea at Discovery Bay Jamaica. Installation no. 1. Scale bar 2 um. b) Infilled algal boring in a grain within Pleistocene calcarenite (83,000 yr. terrace) from North Point, Barbados. Sample B-4. Scale bar 8 um. c) Detail of centripetally-precipitated micrite in an algal boring in a grain. Pleistocene calcarenite, (83,000 yr. terrace), North Point, Barbados. Sample B-2. Scale bar 3 um. d) Micrite-infilled boring of a septate algae, Pleistocene, North Point, Barbados. Compare with detail in Figure 3-2. Sample B-2. Scale bar 6 um. e, f) Infilled algal boring in grain from Pleistocene calcarenite at North Point, Barbados. Sample B-5. Scale bars 14 um, and 7 um respectively. Scanning electron micrographs.

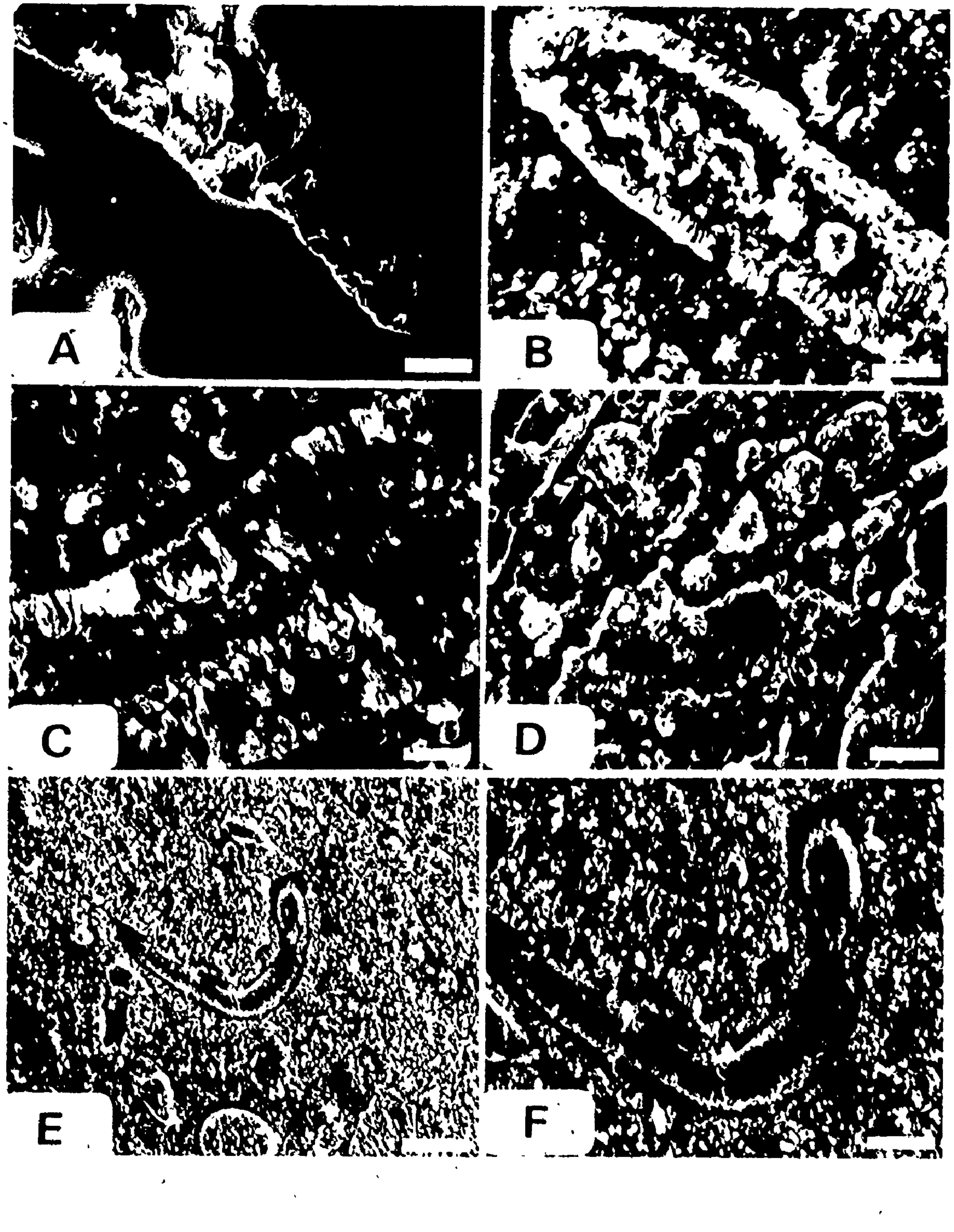
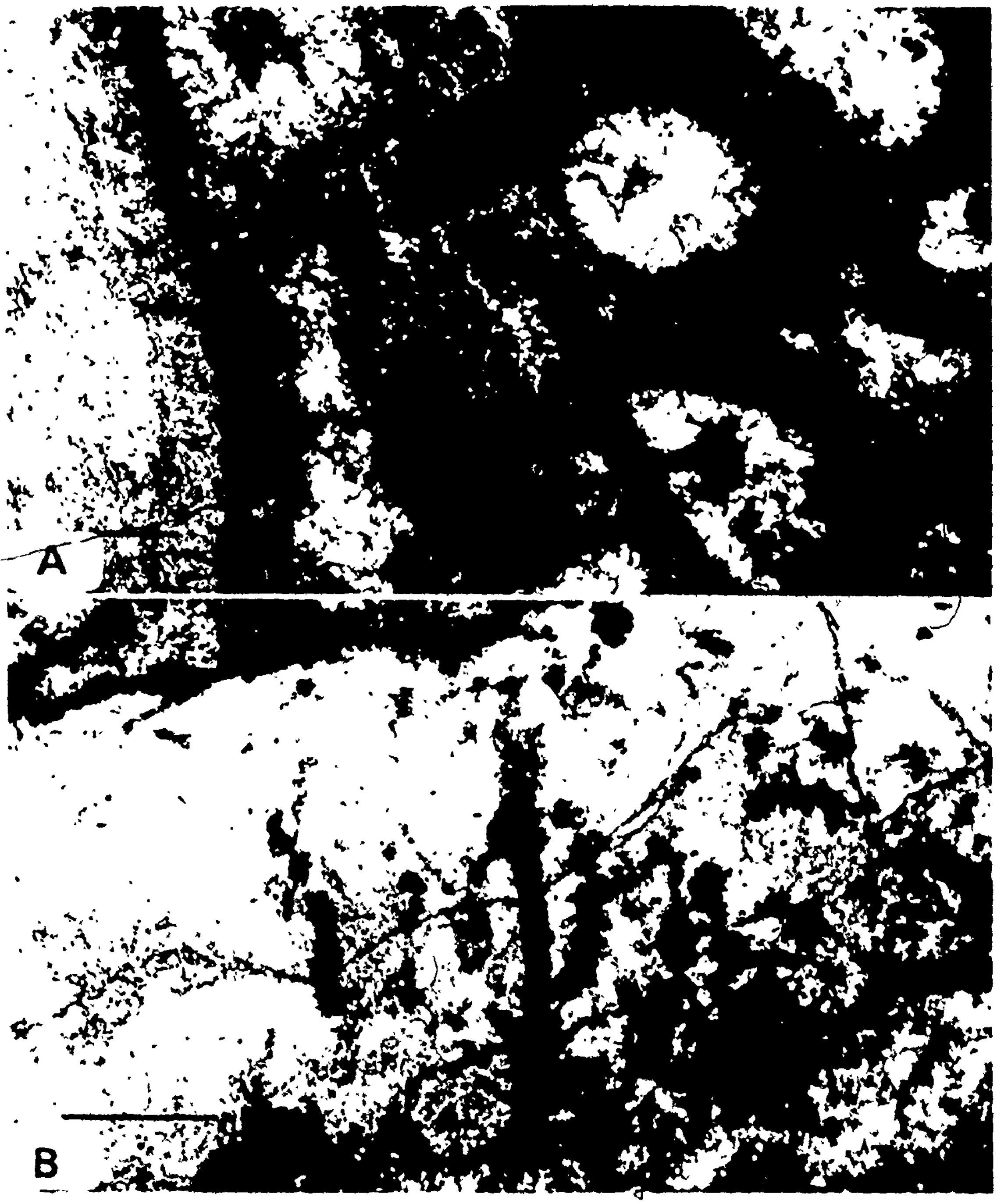

A
B
C
D
E
F

FIGURE 3-2 Detail of a septate algal boring in a pelecypod valve (see Fig. 3-1d), from the 83, 000 year old terrace at River Bay, Barbados. The boring is infilled with micrite, visible in the photo. In this section this type of infilled boring is almost indistinguishable from borings produced by non-septate algae. Precipitation of micrite must have taken place before removal of the thallus and septae, in order for the internal morphology of the filament to be preserved. Scale bar 0.35 um.

FIGURE 3-3 Algal boring in a Devonian tetracoral, *Tabulophyllum* from the Cairn Fm. of the Miette reef complex, Jasper Park, Alberta. a) Stromatoporoid encrusting the outer surface of the corallite. Note the absence of boring below the stromatoporoid, indicating that algal boring post-dated encrustation. Scale bar 65 um. b) Micrite tubules penetrating the outer wall of *Tabulophyllum*. Scale bar 80 um.


A
B

3.1.2 Micritization Associated With Endolithic Algae

Bathurst (1966, 1971) described a process of micritization (Figs. 1-4; 3-1; 3-2) involving repeated infilling of vacated algal borings in carbonate grains by micrite-size carbonate (micrite here refers to carbonate particles of less than 4 um in size). In this process, complete micritization of the grain takes place, or a rind of micrite developes within the original grain periphery. This type of micritization has been recognized as one of the most significant and widespread geologic effects of the boring algae, and is found to some extent in virtually every modern or ancient shallow water marine carbonate environment (Fig. 3-3) (Klement and Toomey, 1967; Winland, 1968; Swinchatt, 1969; Loreau, 1970; Alexandersson, 1972, 1975; Golubic *et al*., 1975; Kahle, 1974, 1976), although micritization is not a necessary by-product of boring algal activity (Alexandersson, 1972; Gunatilaka, 1976).

A number of micritization mechanisms have been proposed (Bathurst, 1966, 1971; Purdy, 1968; Winland, 1968; Kendall and Skipwith, 1972; Friedman, Gebelein and Sanders, 1971; Alexandersson, 1972; Kahle, 1974, 1976), but the specific effects that endolithic algae, or other micro-organisms, have on these processes is as yet uncertain.

Endolithic algae are dominantly photosynthetic (Golubic *et al*., 1975), and show a species zonation from the supratidal to the light compensation level (LeCampion-Alsumard, 1969, 1970; Golubic *et al*., 1975) which may have wide paleoecological application (Boekschoten, 1966; Swinchatt, 1969). Halsey (1970) and Perkins and Halsey (1971) found endolithic fungi became relatively more abundant than endolithic algae as light penetration decreased with depth.

FIGURE 3-4 Calcified algal filaments projecting out of Iceland spar calcite after 95 days in the sea at Discovery Bay, Jamaica. a) Two branching calcified filaments can be seen projecting from the spar. The long thin filament is an uncalcified epilithic alga not removed during cleaning of the spar.. Scale bar 20 um. b, c) Details of the external calcification on the larger calcified filament in (a) above. Scale bars 5 um, and 2 um respectively. d, e, f) Calcified branching filament, showing termination clusters of calcite on the short branches. Scale bars 20 um, 10 um, and 2 um respectively.

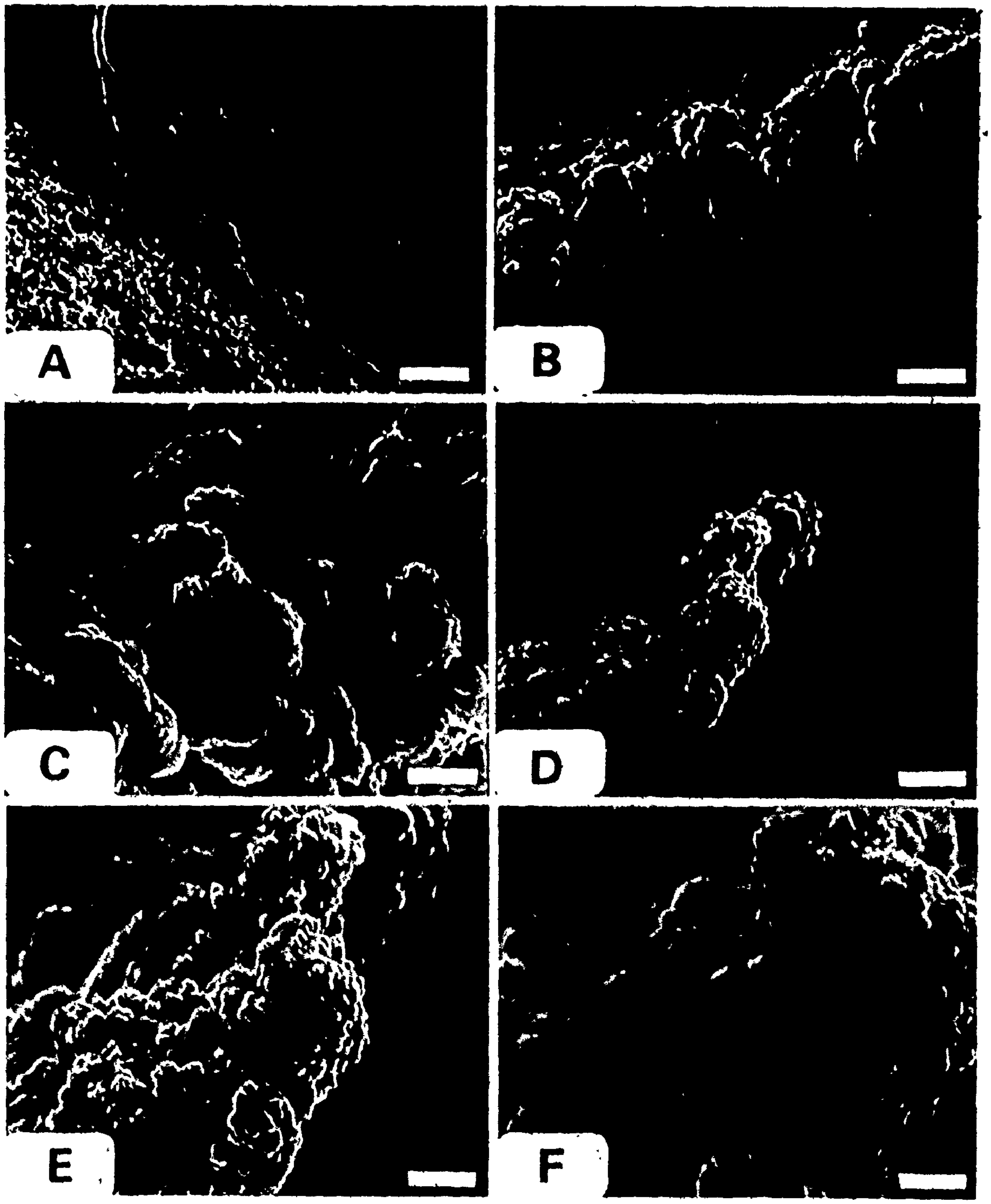
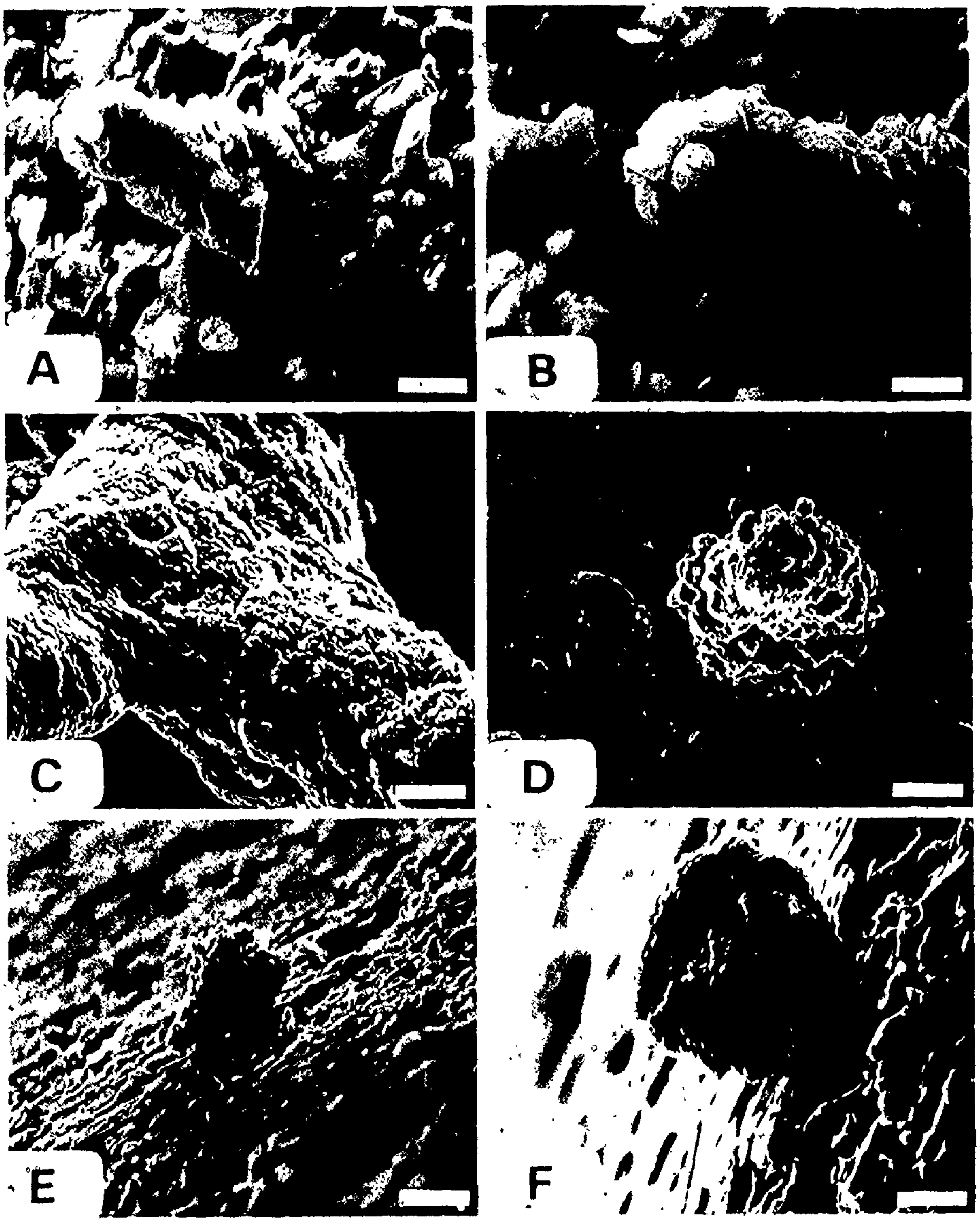

A
B
C
D
E
F

FIGURE 3-5 Calcified algal filaments projecting out of Iceland spar after 95 days in the sea at Discovery Bay Jamaica. a, b) Broken calcified filament showing interior fill, algal thallus, and exterior encrustation. Scale bars 7.5 um and 3 um. c) Branching calcified filament, near base where filament emerges from spar crystal. Crystals are very fine. Scale bar 5 um. d) Terminations of calcified filament projecting from spar. Scale bar 10 um. e) Irregular calcification on a short filament. Scale bar 15 um. f) "Bulb-like" calcification. Note tapering toward base where the filament emerges from the spar. Scale bar 7.5 um.


A
B
C
D
E
F

3.2 DESCRIPTION AND DISCUSSION

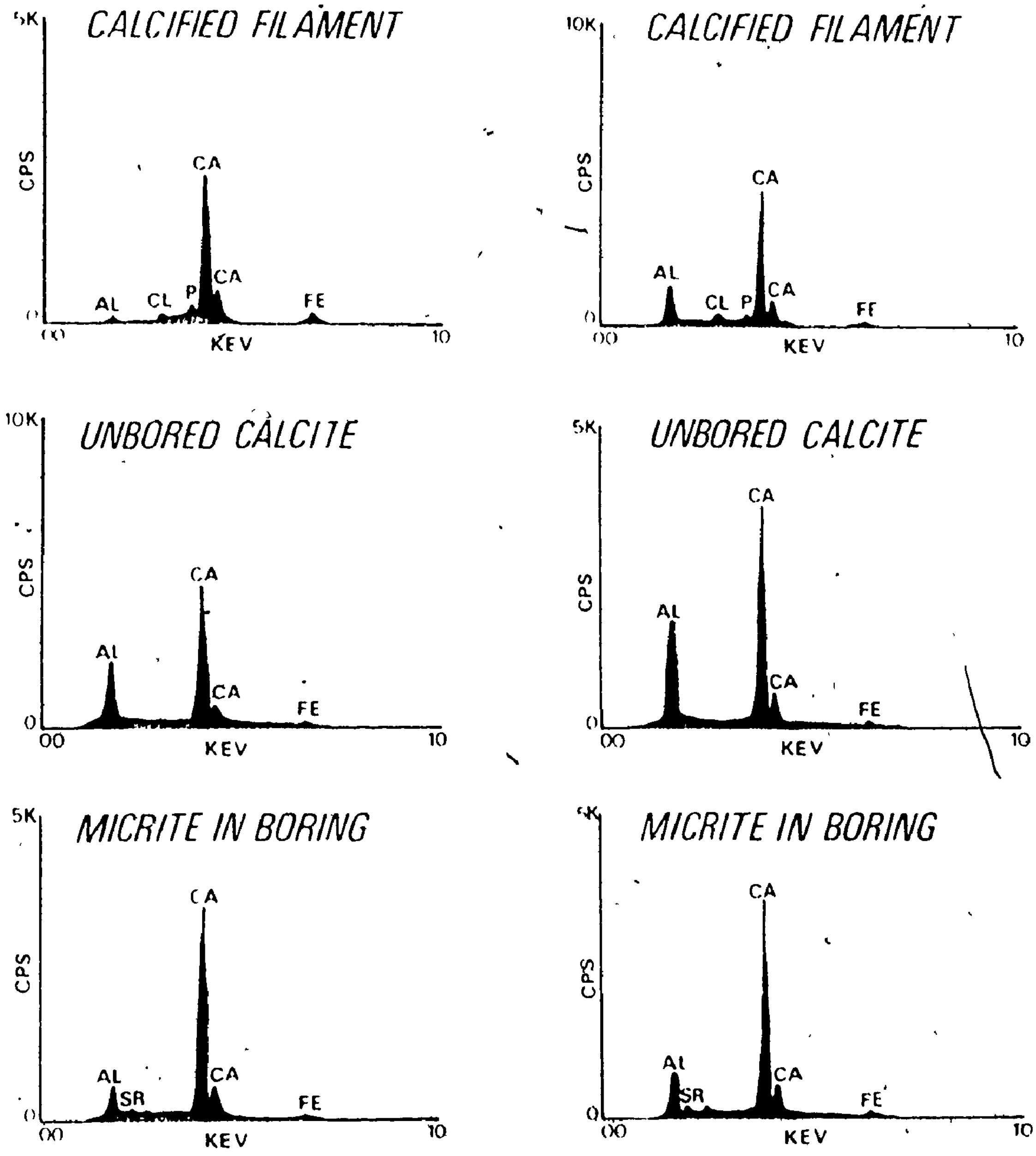
3.2.1 General

It is not known what causes the change in habitat from endolithic to chasmolithic (within cavities not of their own making; after Ercegovic, 1925; Lukas, 1973) or even epilithic, but it is apparent that Ostreobium sp., and other endoliths, do not function solely as endoliths, but can grow outside the substrate (Golubic, 1973). In this study, Ostreobium sp. begins growth in the Iceland spar crystals as an endolith and afterwards becomes chasmolithic or epilithic. Initially the alga lives very close to the surface, and is in contact with the sea, though living in a hole of its own making.

The exposed filaments are heavily calcified with scale-like crystal clusters (Schroeder, 1972) or mica-like books (Figs. 3-4; 3-5), all of which are rhombohedral. Palisade crusts, as described by Schroeder (1972), are also very common. Crystal growth is perpendicular to the wall of the algal thallus, fills the interior, and forms a thick external crust. Crystal terminations are euhedral to subhedral and, where observed to have been broken, commonly display a rhombic cleavage on a very fine scale. Rare acicular crystals (aragonite?) are developed on the scale or book-like crystals, and are a later precipitate. Very rare and very small (under 0.1 um) rhombs with straight, uncurved faces are found.

Calcification, although present on the exposed portions of the thalli, is never found on thalli in the borings, even though micrite (detrital or precipitated) is found within some empty borings (Fig. 3-1). The diameter of the calcified filaments is between 8 um and 30 um, and they very in length from 10 um to 250 um. Cylindrical stubs are often seen projecting from the Iceland spar crystals (Figs. 3-5a, b) representing

FIGURE 3-6 KEVEX analyses of calcite encrustations in exposed calcified filaments, the unbored Iceland spar calcite, and precipitated micrite in the algal borings.



CALCIFIED FILAMENT

CALCIFIED FILAMENT

UNBORED CALCITE

UNBORED CALCITE

MICRITE IN BORING

MICRITE IN BORING

KEVEX ANALYSIS

DRK 76

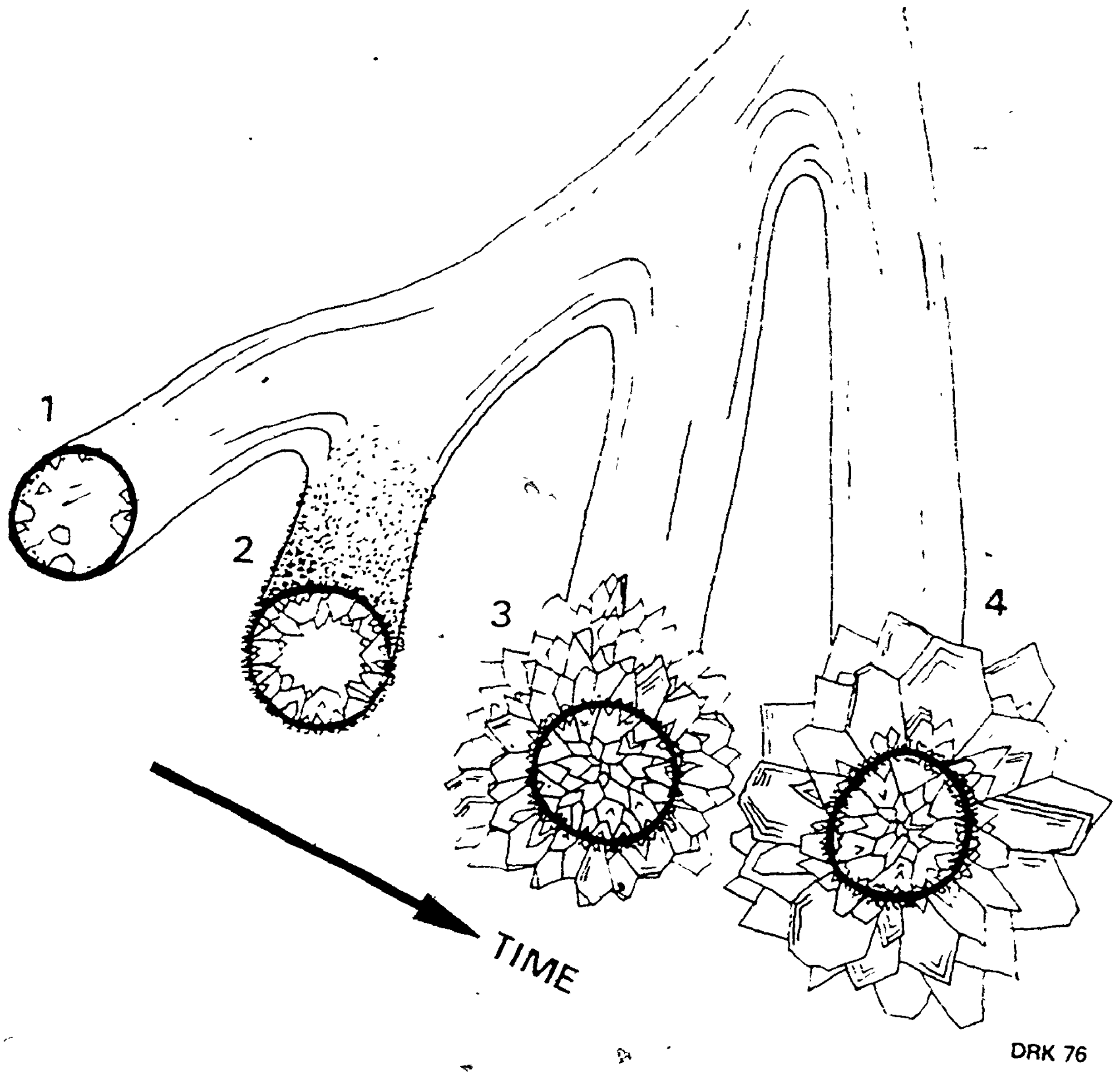
remnants of broken calcified filaments.

Six of the 60 calcified filaments studied in great detail with the SEM (many more were studied in less detail) were fractured and presented an opportunity to study the internal structure and composition, and to measure the actual diameters of the exposed thalli (Figs. 3-5a, b). The non-calcified thalli vary in diameter from 2 um to 15 um, a range commonly found in living Ostreobium sp. (Lukas, 1973). Crystals developed on the exterior of the thalli range in size from 0.5 um to 2.5 um. The smallest crystals (0.05 um to 0.1 um) are generally found on the part of the filaments closest to the surface of the spar (Fig. 3-5c). Crystal size increases toward the tip of the filaments, to a maximum of 2.5 um in areas well along the exposed part of the thallus. Crystals filling the interior of the thalli vary in size from 1.0 um to 0.05 um. Filaments which project only a short distance outside the spar crystals have a "bulb-like" calcification developed (Fig. 3-5d, e, f). The bases of these structures are calcified by crystals of extremely small size (under 0.05 um). A few microns above the spar surface, these filaments are heavily calcified and the apparent diameter increases abruptly to about 8 um to 30 um (Fig. 3-5f).

Analyses were carried out on the Iceland spar, the calcified filaments and the micrite in the vacated algal borings (Fig. 3-6) using a KEVEX energy dispersive analyser on a Hitachi scanning electron microscope (Woldseth, 1973, provides a guide to the use and interpretation of KEVEX and other x-ray spectrographic techniques). The Iceland spar, micrite in the borings, and the calcified filaments are low Mg calcite; the micrite in the borings differs lightly in composition from the Iceland spar by containing small amounts of strontium, and the carbonate on the filaments differs by containing small amounts of chlorine and phosphorus. The specimens were coated in aluminum, which tends to mask the presence of magnesium, in x-ray dispersive analysis. To test the sensitivity of the unit, duplicate specimens, of material known to contain small amounts of magnesium, were coated with both aluminum and carbon. Although aluminum coating considerably reduced the sensitivity to magnesium, the magnesium was still detectable, even when only trace quantities were present.

Though many of the crystal forms on the calcified filaments are similar to those described by Schroeder (1972a, b) from cavities in Bermuda reefs, the composition differs. Schroeder's filaments are calcified by 15-17 mole percent Mg calcite, whereas those described here contain no detectable magnesium. The reason for the differences is unknown. Possible explanations include the effects of organic materials on the crystallizing carbonate or the existence of a relationship between the carbonate calcifying the filaments and the composition of the immediate substrate. It appears unlikely that the composition of the calcite on the filaments would be so similar to that of the non-marine Iceland spar if there were no relationship, as calcite is precipitated only rarely as a marine cement. Similar relationships between the composition of precipitated micrite and the substrate, particularly with respect to Mg, are noted by Glover and Pray (1971), Alexandersson (1972, 1974), and Gunatilaka (1976). This strengthens the arguement that the substrate influences the composition of micrite cement, be it within pores, borings, or on filaments. The source of the calcite on the filaments could be the calcite removed by the boring activities of the algae in the spar. The calcite is dissolved in the borings, and possibly precipitated on dead

FIGURE 3-7 The sequence of calcification of an exposed filament. 1) The filament dies and crystal growth begins on the interior; external crystal growth may or may not begin at this time. Stage 1 may begin as early as 65 days. 2) The interior is almost filled with crystals and the exterior is fully calcified by minute crystals. 3) The exterior is covered by small crystals; the interior is fully calcified and filled. 4) Exterior crystal development has increased and produced a mass as wide as 30 um. This represents the structure of most filaments after 95 to 213 days.


1
2
3
4
TIME
DRK 76

algal filaments projecting from the surface of the spar. Direct precipitation from seawater, perhaps mediated by the spar substrate or organic materials (see earlier discussion of the work of Kitano) in the algal filaments is also possible.

3.2.2 Pattern and Sequence of Calcification

The calcified filaments were studied to determine if there was a determinable pattern or sequence of calcification.

When an alga which has grown outside the Iceland spar crystal dies, extremely small crystals (about 0.001 um to 0.05 um) form on the exterior of the thallus (Fig. 3-7); these small enough that, except under very high magnification (over 20,000 diameters), the surface of the thallus appears smooth and uncalcified (Fig. 35). In time, these crystals grow to produce the thick encrustations described above (Figs. 3-7; 3-4; 3-5). Calcification of the empty interior of the thallus takes place until it is filled with small crystals from under 0.05 um to 1.0 um in size. The relative times at which external and internal calcification take place are not known, though examples were seen in which the thallus interior was so thick of the very smallest crystals. This suggests that internal calcification may take place before, or more rapidly than, external calcification.

3.2.3 Rate of Calcification

Crystals were removed from installation 1 at Discovery Bay every 24 to 48 hours for the first 65 days of the study. Thereafter specimens were removed at 95 days, 129 days and 213 days. Although exposed filaments are common on crystals up to 65 days, no calcification was observed. Live, uncalcified filaments were found protruding from the spar crystals from day 25 to day 65. The first fully calcified filaments (the first ones found were already fully calcified) were found on the crystals removed from the sea after 95 days and also on the 129 day and 213 day crystals. Calcification, therefore, took place between 65 days and 95 days after the crystals were placed in the sea. Living filaments were observed projecting from the crystals as early as 25 days, but no calcification was seen on living filaments for the next 40 days. This observation, together with the fact that the longest calcified filament observed is only 250 um, while longer uncalcified filaments were seen, suggests that only dead filaments were being calcified.

These results are significant, particularly in the light of the paucity of accurate rate data elsewhere on the submarine precipitation of calcium carbonate. The rate of organic carbonate skeletogenesis has, of course, been well studied, but the process described here is not in vivo calcification and hence not skeletogenesis. The process is one of submarine precipitation (cementation) not directly related to the life activities of the algae, as precipitation appears to take place on only dead filaments. The precipitation is not likely purely inorganic however, but may be biochemically influenced or controlled by organic materials in the algal thalli, or by associated bacteria acting to break down the algae. Calcification of the filaments is geologically extremely rapid and shows that the rates of precipitation of some sublittoral marine carbonate is measured in weeks or less, rather than years or decades.

3.2.4 Exposure of the Filaments and the Microenvironment

Results of this and other studies (Golubic, 1969) show that some endolithic algae, including Ostreobium sp., can live not only in reef cavities where Schroeder (1972a, b) found them, but can also live as epiliths, either on the substrate surface, or perpendicular to it and essentially free of it. A microenvironment (in the sense of a closed or at least highly restricted cavity in which special conditions develop and are maintained) is not essential to survival, growth, or calcification of the exposed filaments. If a microenvironment existed about the exposed filaments on the Iceland spar, it may have consisted of little more than an area of reduced circulation, or modified chemical environment created by the presence of algae (fungi and bacteria as well), both alive and dead, and their metabolic products. The maintenance of such conditions on the surface of the Iceland spar could only have been temporary, though perhaps enhanced by the protective effects of populations of truly epilithic algae growing on the crystal surface.

Precipitation of carbonate is much more common on the exposed algal filaments than on the surface of the Iceland spar; a few rare examples of carbonate precipitation on the spar surface were noted, however. This suggests that organic compounds played an important role in precipitation. Mucilanginous coating on dead filaments, and organic materials bound in the algal thalli, together with the associated activities of bacteria during the process of decay, may create a local microenvironment suitable for the concentration of metal ions, of the correct pH, etc., to induce precipitation (Kendall and Skipwith, 1969). Organic materials are known to be important in some carbonate precipitation and in the determination of crystal composition and morphology (Wilbur and Watabe, 1963; Kitano and Hood, 1965; Kitano et al, 1969), so that it is not unlikely that the most important factor in the rapid calcification of the exposed filaments is the presence and type of organic compounds.

The relation between magnesium and the type and quantity of organic compounds present may be of great importance in the precipitation of some carbonates (Kitano and Hood, 1965; Kitano et al., 1969). The precipitation of carbonate on the filaments appear to have been influenced by the organic substrate. Low concentrations of available magnesium (from the substrate Iceland spar) and the presence of organic compounds in the algae, released by algal breakdown, or metabolism (neighbouring living filaments), such as succinate, lactate, citrate, malate, glycogen, pyruvate, etc., (many of which are algal metabolic by-products) favour a stable low Mg calcite (Kitano and Hood, 1965). The precipitation of low Mg calcite on the filaments could be a result, therefore, of the decreased influence of the low concentration of available Mg, and the increased influence of organic compounds. An influence by Mg ions greater than that of available organic materials, would favour aragonite or high Mg calcite. It is possible, therefore, that under normal conditions, a high Mg calcite substrate would favour aragonite or Mg calcite precipitation, assuming of course, that the presence or absence of Mg in the substrate does influence the local carbonate geochemistry.

3.3 RELATION TO SEDIMENT PRODUCTION

This study shows that a significant number of calcified filaments are produced on the exterior of the Iceland spar crystals at a geologically rapid rate. Speculatively extending these observations to natural carbonate substrates other than Iceland spar, then over a period of time breakage of the exposed calcified filaments could produce a significant amount of sediment. This has occured on the Iceland spar, as broken calcified filaments are quite common, and is also found among calcified filaments on sand grains in Curacao, Bonaire, and Jamaica. Exactly how much material is generated and how rapidly ~~breakage~~ breakage occurs is a matter for further detailed investigation. Reduction of the broken filaments by abrasion or other erosive processes, such as additional algal or fungal boring, could contribute to the accumulation of micrite-size material. A rough and somewhat speculative calculation may be made, using the following: 1. the filaments are treated as cylinders, so that branching is not considered; 2. an average observed filament spacing of 100 um; 3. an average observed filament length of 60 um; 4. an average observed filament diameter of 15 um; 5. an average Iceland spar surface area of 20 cm^2 (the crystal surface in contact with the substrate was not included). This results in a minimun contribution of about 2.4×10^{-2} mm^3 of micrite to the sediment budget in 4 months (the period in which the first generation of calcified filaments is produced) from a crystal area of 20 cm^2 (equivalent to the surface area of a single calcite crystal used in this study) from the breakdown of all the exposed filaments on the spar. This is equivelent to the production of 0.72 $cm^3/\ m^2/$ yr of micrite with no porosity. Given a porosity of 60% for the loose sediment, the volume of sediment generated is 1 $cm^3/\ m^2/$ yr. These figures are based upon the assumption that similar rates of production will occur on substrates other than the Iceland spar, and that the conditions under which the growth took place are near the norm for the area. There is, of course, a wide variation in conditions and rates of growth to be expected, so that these figures must be regarded as an estimate subject to wide variation. The calculated value of 1 $cm^3/\ m^2/$ yr is based upon an ideal surface with no topography (i.e. boring takes place in a mirror smooth plane). This is of course not the case in nature, so that the vagaries of the surface such as unevenness, grain surfaces, etc., will serve to make more surface available, and as a result increase the number of exposed filaments and the resultant sediment production.

Limestone cliffs will also be sources of sediment input as the calcification of exposed filaments on these surfaces bordering areas of carbonate deposition will probably take place on nearly as great a scale as within the carbonate depositional substrate.

Calculations of this type have been made for various other algae which contribute to sediment production. *Acetabularia antillana* produces as much as 620 cm^3/ m^2/ yr (Marszalek, 1975), which is much more than either *Penicillus* or *Halimeda*; both these genera are found to produce significant quantities of sediment, however, amounting to between 2 to 23 cm^3/ m^2/ yr for *Penicillus* (Stockman, *et al*, 1967). The estimated possible contribution of 1 cm^3/ m^2/ yr for the breakdown of calcified algal filaments (this paper), though not large, is significant in the light of the 2 cm^3/ m^2/ yr contribution of *Penicillus* in some parts of the Florida Bay and back reef areas (Stockman, *et al*, 1967).

Though present in the lagoon and back reef areas of reef complexes, endolithic algae are also very common within the reef itself. The breakage and reduction of exposed filaments could be a source of some of the micrite found within the reef.

3.4 MICRITIZATION OF CARBONATE SUBSTRATES

3.4.1 Infilling of Algal Borings

The Iceland spar crystals monitored at Discovery Bay, Jamaica, provide an opportunity to study with time the progressive development of carbonate substrate erosion, micritization, and cementation associated with endolithic algal activity.

Vacated algal borings within the Iceland spar crystals commonly show precipitation of low Mg calcite on the boring walls by 95 days after placement in the sea, and rarely earlier (Fig. 3-1a). None of the borings are filled completely by precipitated micrite even up to 257 days, though an estimated 25% by volume of the borings is filled by 257 days.

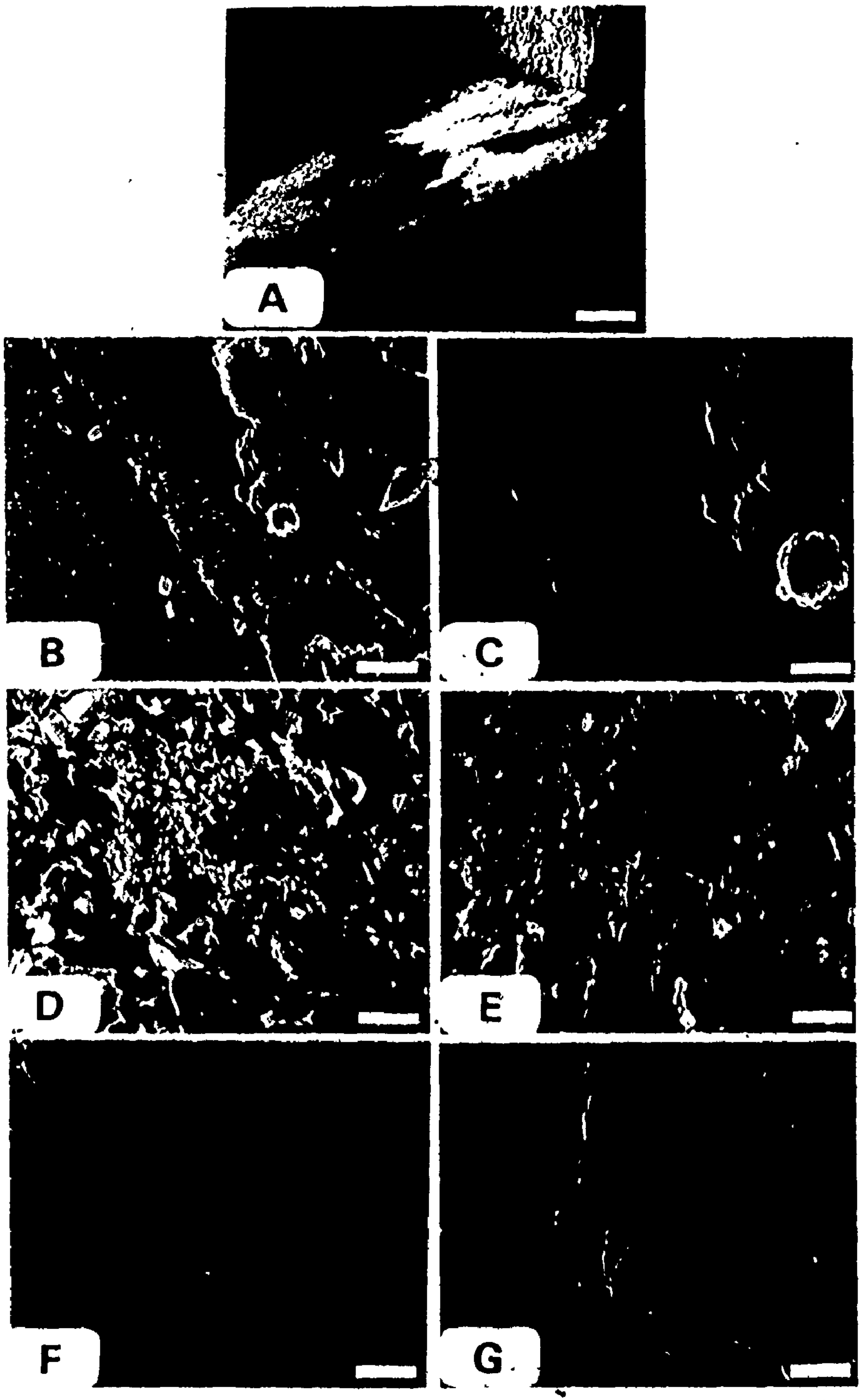
The composition of the precipitated micrite infill is the same as that of the Iceland spar as determined by EDAX and KEVEX analyses. This suggests a relationship between composition of the substrate and the precipitated infill, which is supported by other workers (Glover and Pray, 1971; Alexandersson, 1972, 1974; Schroeder, 1972a; Gunatilaka, 1976) who found similar direct relationships. Winland (1968), however, noted no relation between the composition of the substrate and the micrite infill. The controls on the precipitation of carbonate in borings are unknown, and serve to emphasize the general and basic lack of understanding of the processes involved.

In this study, micrite composed of low Mg calcite was found to precipitate in algal borings in the Iceland spar calcite (Fig. 3-1a) (low Mg calcite substrate). The end result of the process of infilling by precipitated calcite is micrite tubules and finally a micrite envelope about the spar, similar to that described by Bathurst (1966, 1971, 1975) (Fig. 3-1b). How long complete infilling of a boring would take is unknown. Projection from the results of this study, in which up to 25% infilling occurs after 257 days, gives a minimum time to complete infilling of about 3 years; it is not known if the rate of infilling is a linear function. This estimate agrees with Alexandersson's (1972) conclusion that years, rather than hundreds of years, are required for infilling of algal borings by micrite carbonate (see also, Friedman, 1964; Fuchtbauer, 1969; Ginsburg and Schroeder, 1969; Ginsburg et al, 1968, 1971; Schroeder and Ginsburg, 1971). In shallow tropical marine environments micrite infilling of algal borings is geologically rapid, but how fast this process and any associated micrite envelope formation can be expected to take place with increasing depth is unknown.

The influence that the endolithic algae or associated micro-organisms have upon the nucleation and mineralogy of the carbonate filling borings is a matter for further investigation. Alexandersson (1972), Bathurst (1966), and Gunatilaka (1976) conclude that the algae do little else than produce the holes in which crystal growth takes place, and that the precipitation is a function of the degree of carbonate saturation of the surrounding seawater. The picture may be somewhat more complex than this, however. Margolis and Rex (1971) suggest that algal metabolism and boring, or bacteria associated with the aglae, play a key role in the growth of aragonite crystals within algal borings in Bahamian oolites (see also, Wilbur and Watabe, 1963; Kitano and Hood, 1965; Kendall and Skipwith, 1969; Gebelein and Hoffman, 1971). The question is far from resolved; indeed, more than one process may be involved, and the particular biogenic, biochemical, or physico-chemical precipitative mechanism may be a function of variability in the immediate environment.

In the Iceland spar crystals studied in the Jamaican experiments, only vacated algal borings contain precipitated acicular or rhombohedral crystals of low Mg calcite; no aragonite or high Mg calcite was found in the borings. It is unlikely that endolithic algal metabolism is directly involved, although circulating metabolites secreted by live algae in

FIGURE 3-8 Residue micrite. a) Etched surface of Iceland spar developed below mucous coat, which has subsequently been removed. Installation no. 1, Discovery Bay. Scale bar 75 um. b, c) Detail of the etched surface of Iceland spar seen in (a) above. Note the regularity, typical of early stages in residue micrite formation. Scale bars 5 um, and 2 um, respectively. d, e) Patches of "mature" residue micrite, showing its porous nature, on the surface of Iceland spar. Scale bars 10 um, and 5 um, respectively. f, g) Residue micrite, showing scale-like development typical of some areas developed on Iceland spar. Scale bars both 5 um. Scanning electron micrographs.


A
B
C
D
E
F
G

neighbouring bores may be important. Precipitation associated with bacterial activity or decomposing algal filaments cannot be ruled out, nor can inorganic precipitation from supersaturated seawater.

3.4.2 Residue Micrite

After 95 days in the sea, scattered, irregular (100 um to 800 um) patches of microporous calcite surrounded by algal borings are found on the surface of Iceland spar crystals (Fig. 3-8). The patches are white in incident light and very light brown in transmitted light, and consist of rhombic and irregular remnants of spar from under 0.1 um to 5.0 um in diameter. The patches are the result of dissolution of the spar surface, and correspond with the "residue micrite" described by Alexandersson (1972). Residue micrite is a porous microcrystalline fabric, produced by selective leaching of the substrate which leaves behind a residue of original substrate material, composed of micrite-size particles.

Residue micrite has been described as a feature of carbonate undersaturated waters (Alexandersson, 1972) or of subaerial meteoric diagenesis (Land, 1967). Neither carbonate undersaturation nor subaerial diagenesis obtains for the Iceland spar experiments in Jamaica. Patches of etched calcite were found invariably beneath algal mucous coats on the surface of the spar. In some cases, the etch pattern was very ordered (Fig. 3-8a, b, c), representing early stages in the development of residue micrite. Alexandersson (1972) mentions similar early strong substrate control of the surface etch pattern on carbonate grains, which disappears as etching proceeds. Alexandersson (1972, 1975) also noted however, the complete absence of etched surfaces on grains from the carbonate saturated and supersaturated waters of the Mediterranean and West Indies. Although this may be the case in carbonates exposed directly to carbonate saturated and supersaturated sea water, the presence of mediating algal mucous coat and possible associated mildly acidic conditions may produce etched surfaces even in tropical carbonate supersaturated waters. The comment by Alexandersson (1972) that selectively-leached residue micrite and etched carbonate surfaces may be restricted to carbonate undersaturated waters is valid in theory, but not always in practice. An etched carbonate grain from carbonate saturated and supersaturated waters which has lost its mucous coat will be indistinguishable from an etched grain from undersaturated waters.

The development of patches of residue micrite under algal mucous coats on the Iceland spar represents the early stages in the production of micrite envelopes similar to that described by Kendall and Skipwith (1969) from the Persian Gulf (though the reprecipitation described by Kendall and Skipwith need not necessarily take place). The first small patches of residue micrite are found at 95 days on the spar; by 257 days they are several hundred microns across and up to 100 um deep. The patches do not represent any accretionary growth but simply selective leaching of the spar calcite. Continued leaching of the low Mg Iceland spar under algal mucous coats would result in a micrite envelope of porous, low Mg calcite, up to several hundred microns thick.

3.4.3 Constructively-Generated Micrite Envelopes

Between 65 days and 95 days, dead exposed filaments are first observed to become completely calcified (a cementation phenomenon not related to algal life processes) by low Mg calcium carbonate, both internally and externally. The process of calcification of dead, exposed

FIGURE 3-9 Schematic representation of the development of dense, coalescing masses of calcified exposed endolithic algal filaments on Iceland spar calcite. The small inset at the upper left shows the development of calcified filaments, calcified filament masses, and constructive micrite envelopes, in a cross-sectional view.

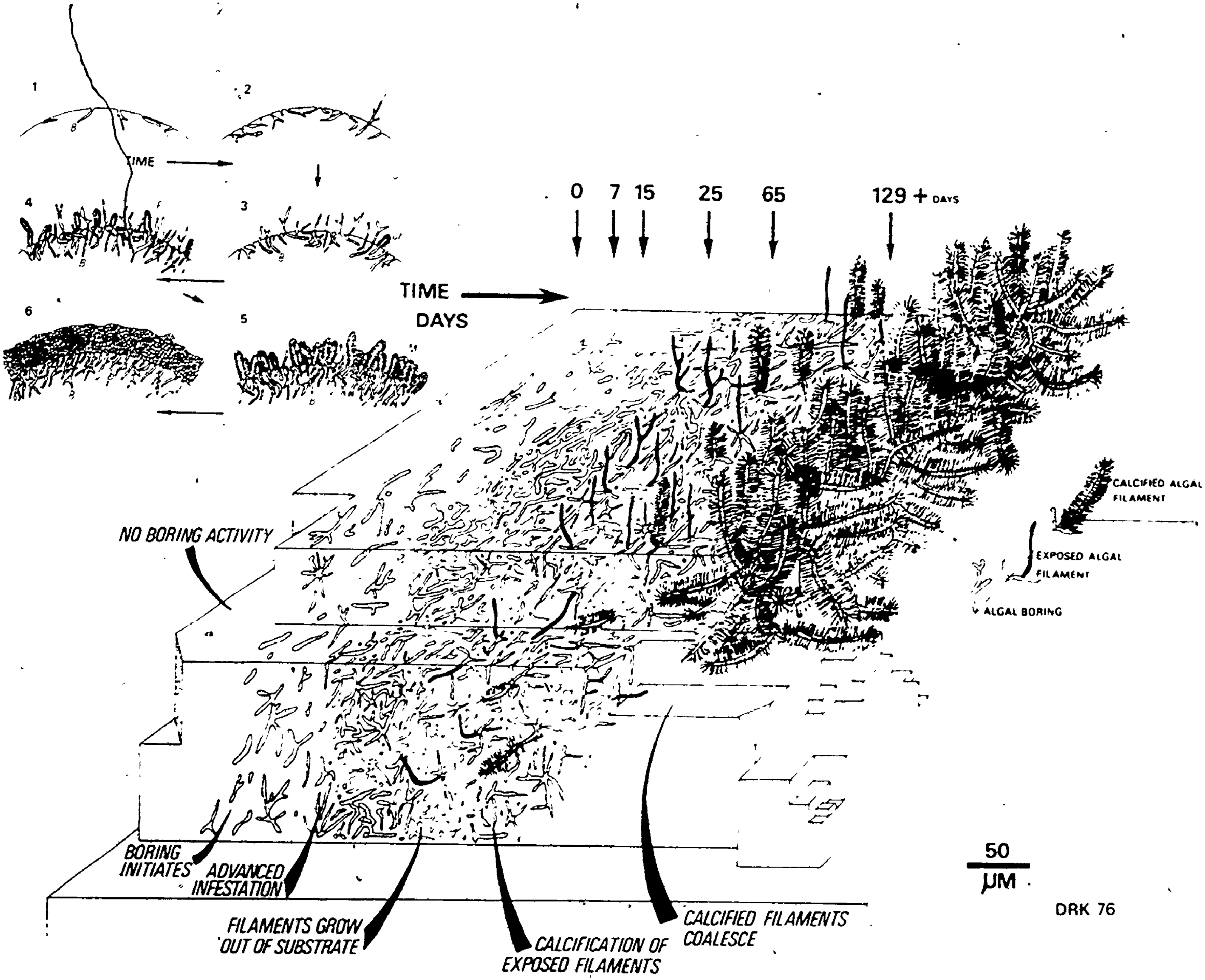

1
2
TIME
3
4
5
6
TIME
DAYS
0
7
15
25
65
129 + DAYS
NO BORING ACTIVITY
BORING INITIATES
ADVANCED INFESTATION
FILAMENTS GROW OUT OF SUBSTRATE
CALCIFICATION OF EXPOSED FILAMENTS
CALCIFIED FILAMENTS COALESCE
CALCIFIED ALGAL FILAMENT
EXPOSED ALGAL FILAMENT
ALGAL BORING
50 μM
DRK 76

FIGURE 3-10 Detail, constructive micrite envelopes. a) Intertwined calcified filaments in a micrite envelope from the Pleistocene terrace at North Point, Barbados. Sample B-14. Scale bar 60 um. b) Constructive envelope. Mottling due to dense calcified filaments. Surface of grain seen at top. Note branching calcified filament at bottom center. Scale bar 40 um. c) Detail of branching filament from (b) above. Sample B-16. Scale bar 20 um. d) Detail of calcified filaments at high magnification under the light microscope to show the characteristic poor resolution of these structures using light micrography. Radial fabric is external palisade cement. Scale bar 8.5 um. Sample B-16. Transmitted plane polarized light.

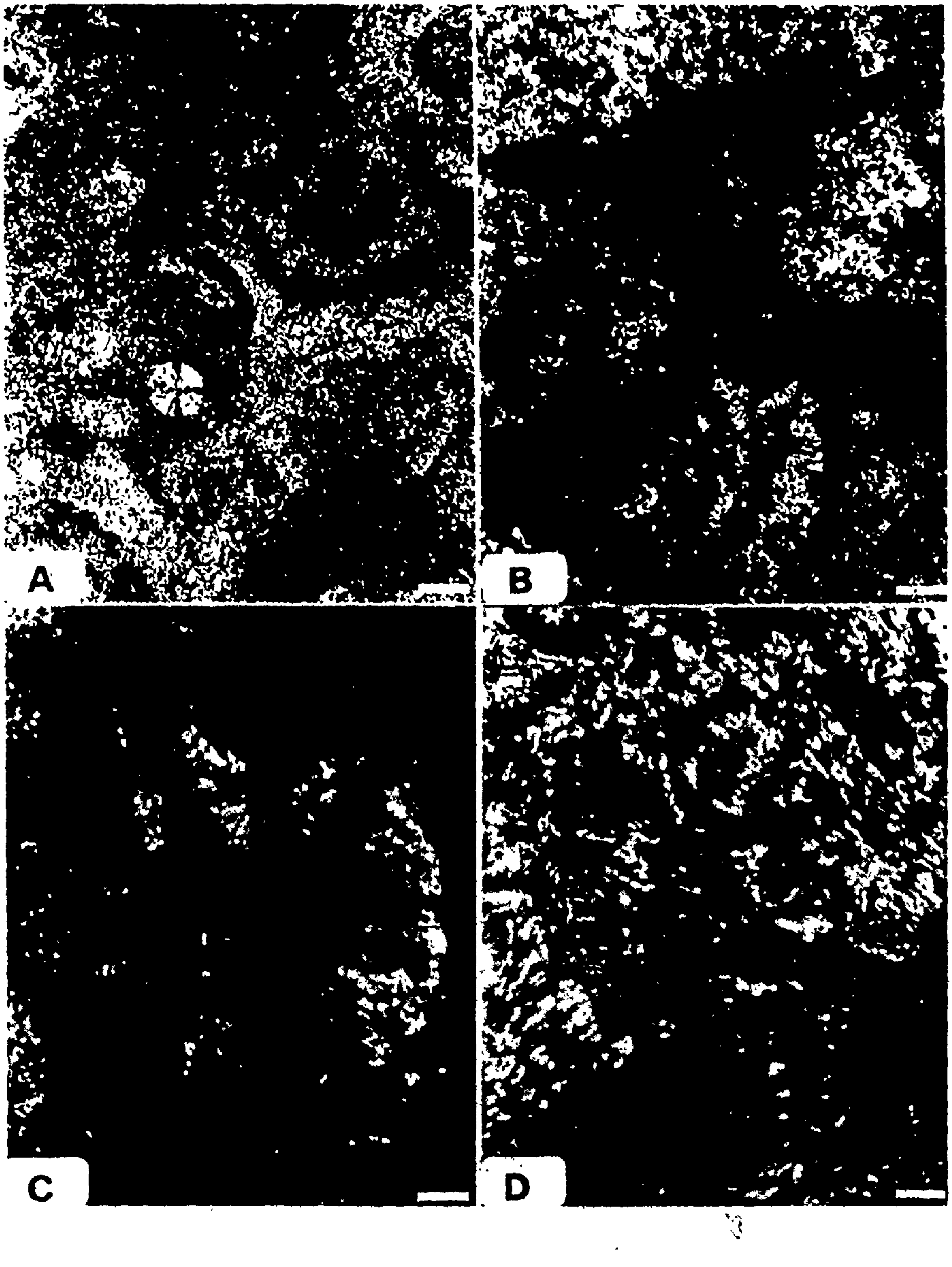

A
B
C
D

FIGURE 3-11 Boundary between a grain and a constructive micrite envelope, from Discovery Bay Jamaica, first reef terrace. Sample J-314. a) Micrite-infilled algal boring in grain, in contact with constructive envelope at right. Scale bar 8 um. b) Detail, showing boundary between grain and envelope. Scale bar 4 um. Scanning electron micrographs.

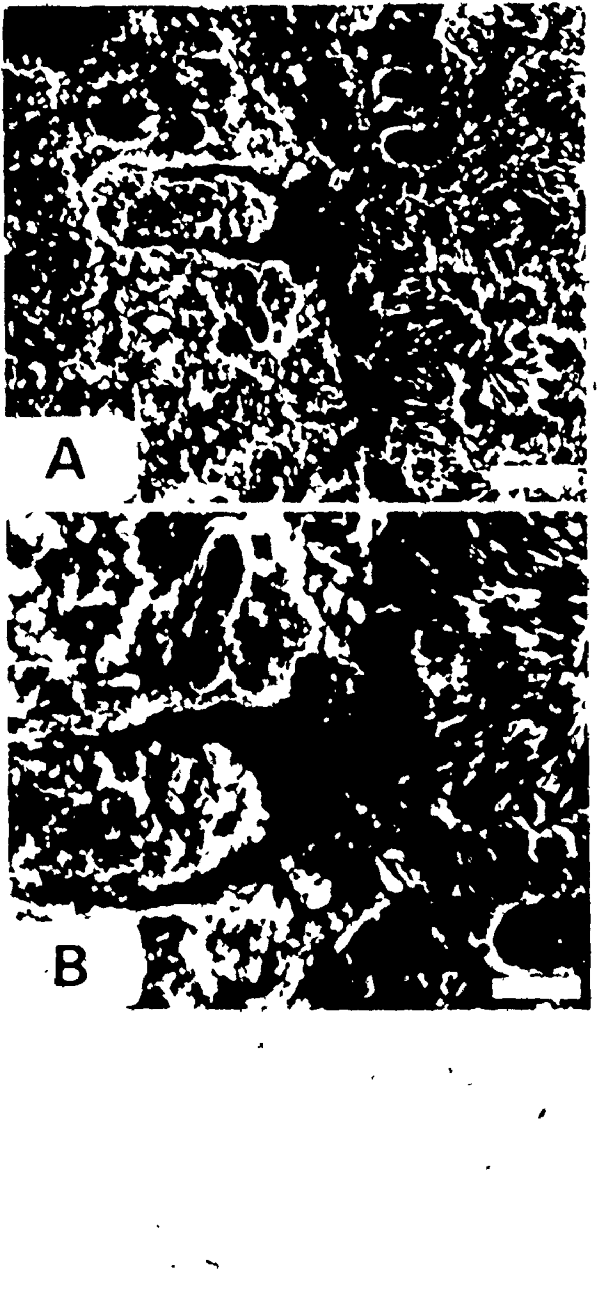
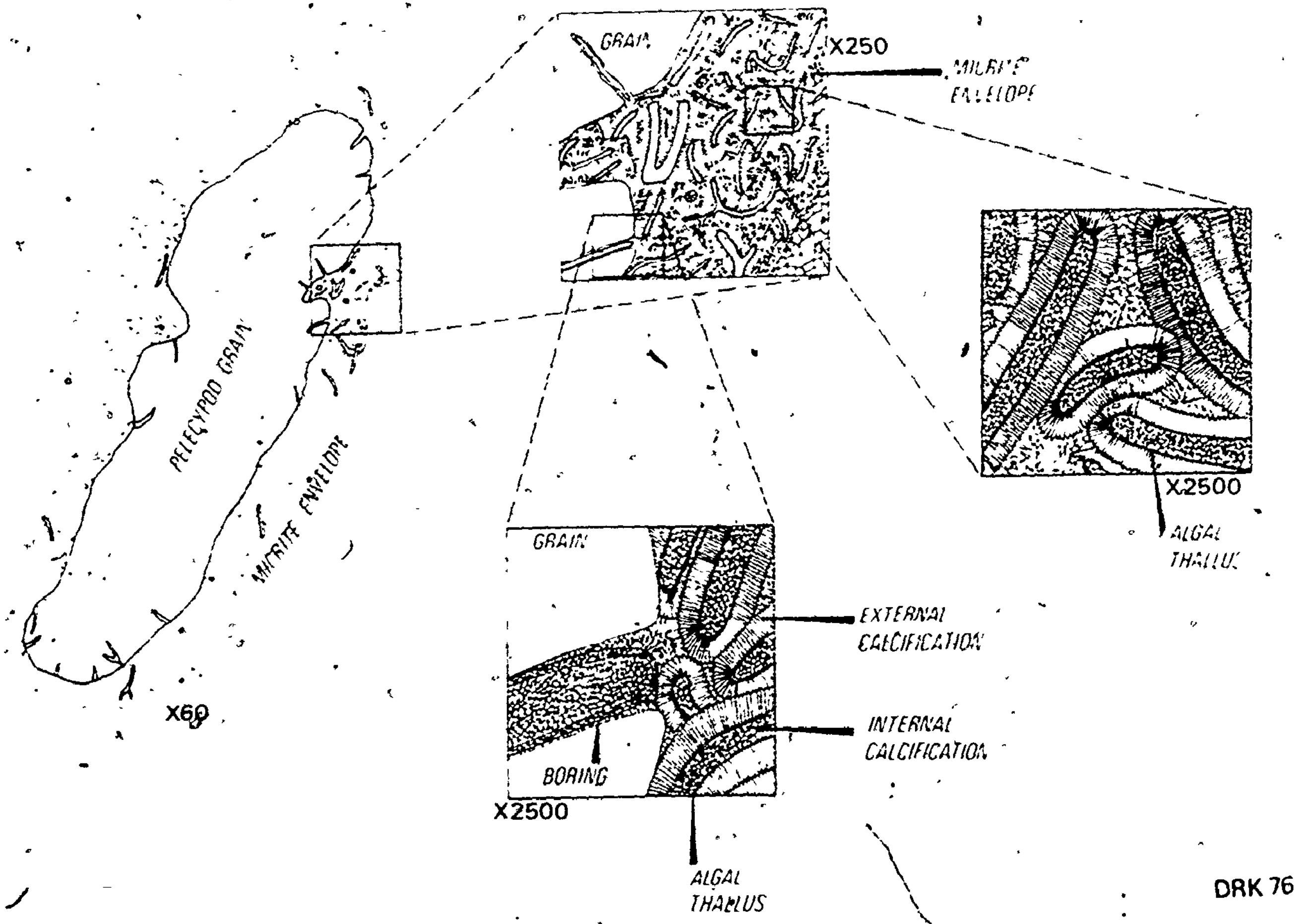
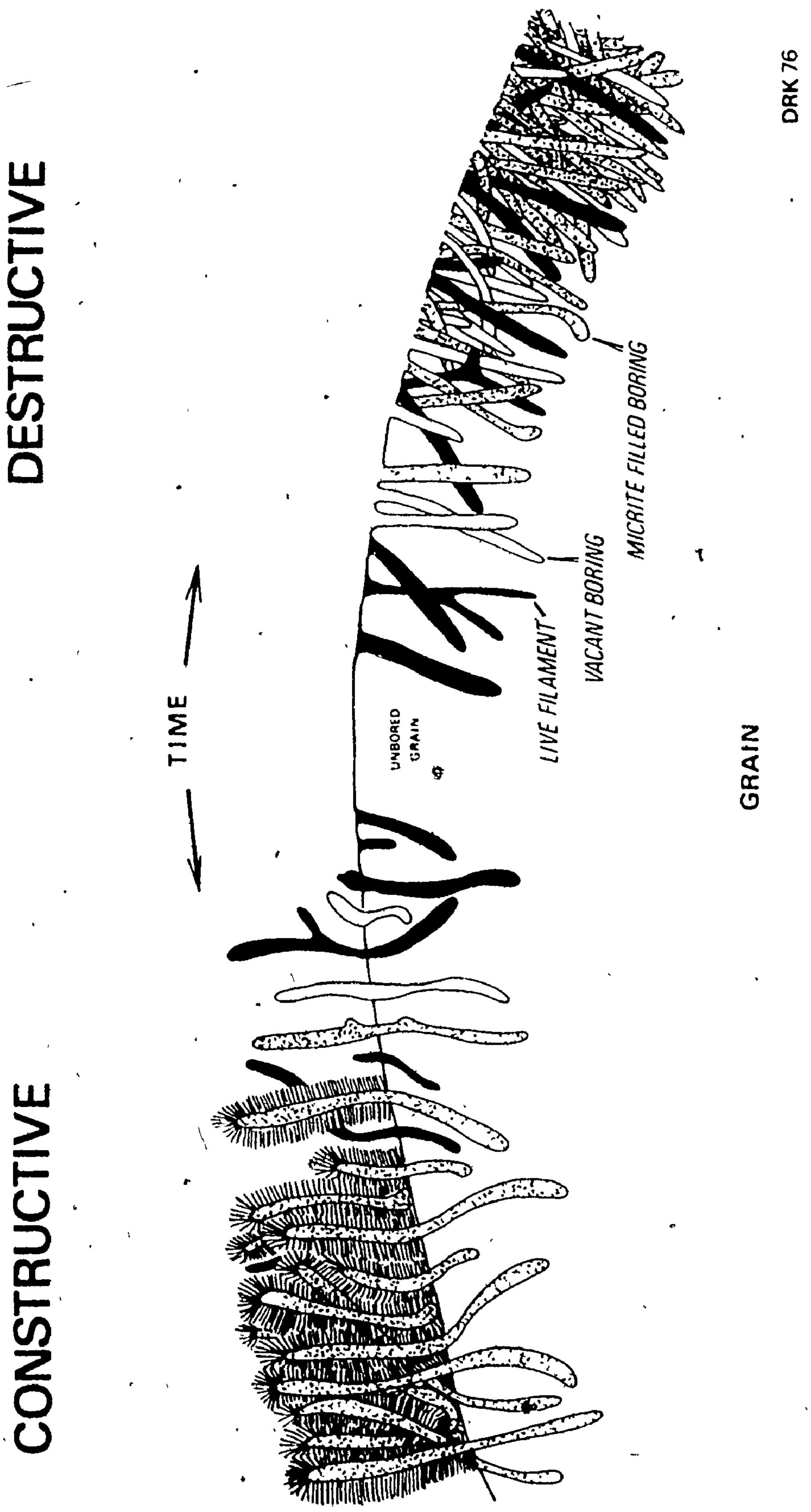

A
B

FIGURE 3-12 Schematic representation of pelecypod grain containing micrite-infilled algal borings, and coated with a constructive micrite envelope. The micrite envelope at 250 diameters shows little detail, but appears as a spaghetti-like entanglement of filaments and micrite. At higher magnifications (2500 diameters) the detailed structure of the calcified algal filaments is visible.


PELECYPOD GRAIN
MICRITE ENVELOPE
X60
GRAIN
X250
MICRITE ENVELOPE
X2500
ALGAL THALLUS
GRAIN
EXTERNAL CALCIFICATION
INTERNAL CALCIFICATION
BORING
X2500
ALGAL THALLUS

DRK 76

FIGURE 3-13 Comparison of constructive and destructive type micrite envelopes.


CONSTRUCTIVE
DESTRUCTIVE
TIME
UNBORED GRAIN
LIVE FILAMENT
VACANT BORING
MICRITE FILLED BORING
GRAIN
DRK 76

(endolithic) algal filaments proceeds until, by 213 days, masses of calcified algal filaments are formed. There is no known limit to the process, aside from complete or nearly complete coverage of the crystal by a coalescent mass of calcified filaments (Fig. 3-9). The "constructively-generated" envelope formed in this way consists of dead algal thalli filled with rhombohedral and acicular low Mg micrite calcite and covered in low Mg palisade cement (Schroeder, 1972a). The boundaries between adjoining calcified filaments are distinct only under high magnification (greater than about 1000 diameters); under the light microscope, the micritic masses do not readily show their algal thalli or palisade cement (Fig. 3-10). The structure of the calcified filaments is clearly visible only under the scanning electron microscope (Figs. 3-11; 3-12).

The constructive micrite envelopes differ from the destructive envelopes described by Bathurst (1966), by forming on the external surface of the grain, although some boring of the spar and infilling of the borings takes place as well (Figs. 3-11; 3-13). Actual destruction of the spar (or grain periphery) need not take place during constructive envelope formation, though there is no apparent reason why the two processes could not occur simultaneously.

Schroeder (1972a, b) described calcified endolithic algal filaments virtually identical to those described above, lining cavities within Bermuda reefs. The filaments Schroeder (1972a, b) described also produce calcified masses, but these lined only the cavity walls. Calcified filaments and masses of coalescing calcified filaments are apparently quite common in tropical marine carbonate environments. The calcification of endolithic and chasmolithic algal filaments is a cementation phenomenon

FIGURE 3-14 Calcified algal filaments projecting out of carbonate grains from Discovery Bay Jamaica. Sample J-28. a) Calcified filaments of grain exterior. Many have coalesced into masses. Compare with James _et al_. (1976) Figs. 13a, b. Scale bar 60 um. b) Detail of (a) above. Scale bar 22 um. c) Mass of calcified algal filaments. Scale bar 10 um. d) Three calcified filaments which have coalesced. Scale bar 10 um. e, f) Detail, calcified algal filaments on grain exterior. Scale bars 2.5 um and 6 um, respectively.

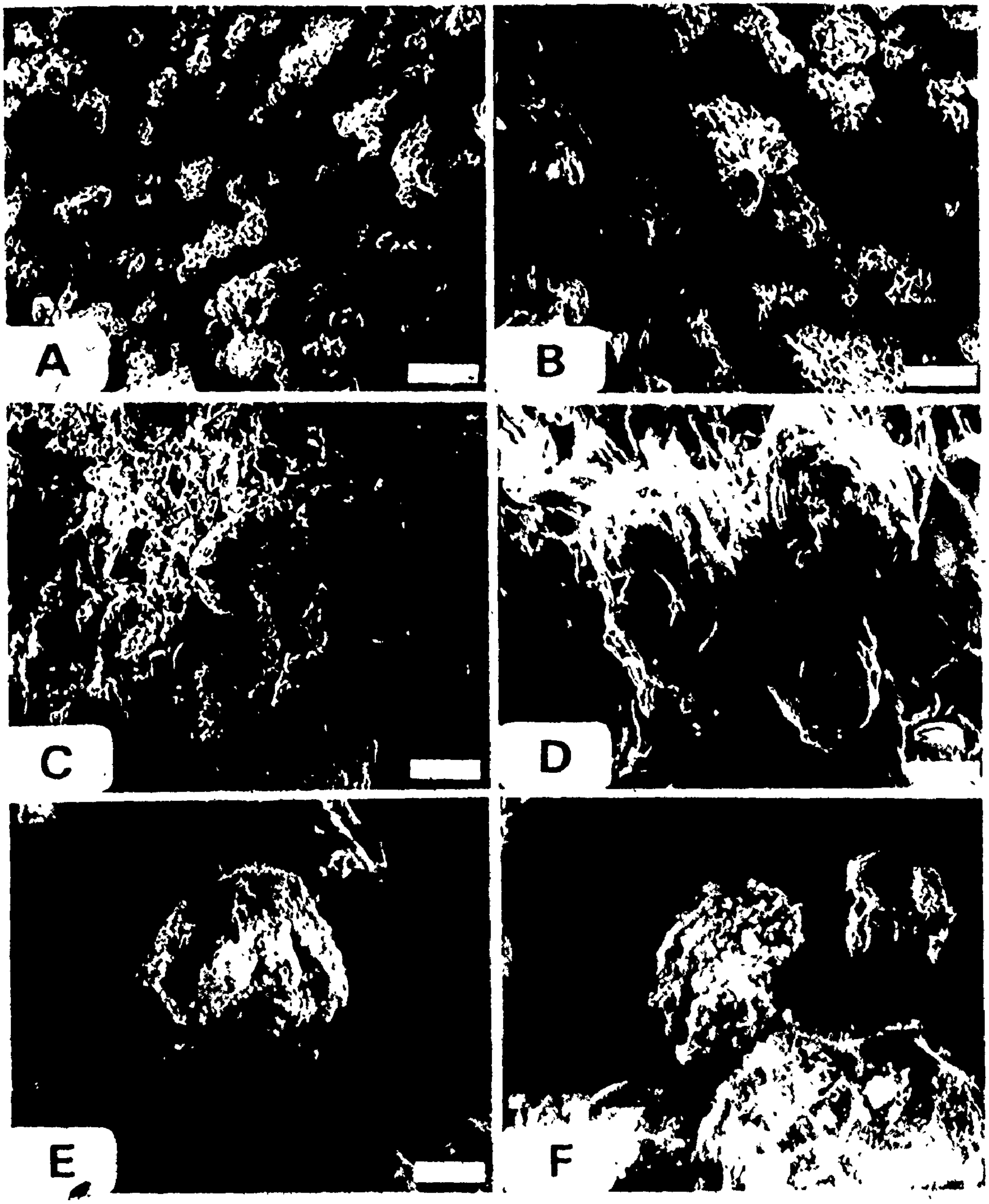
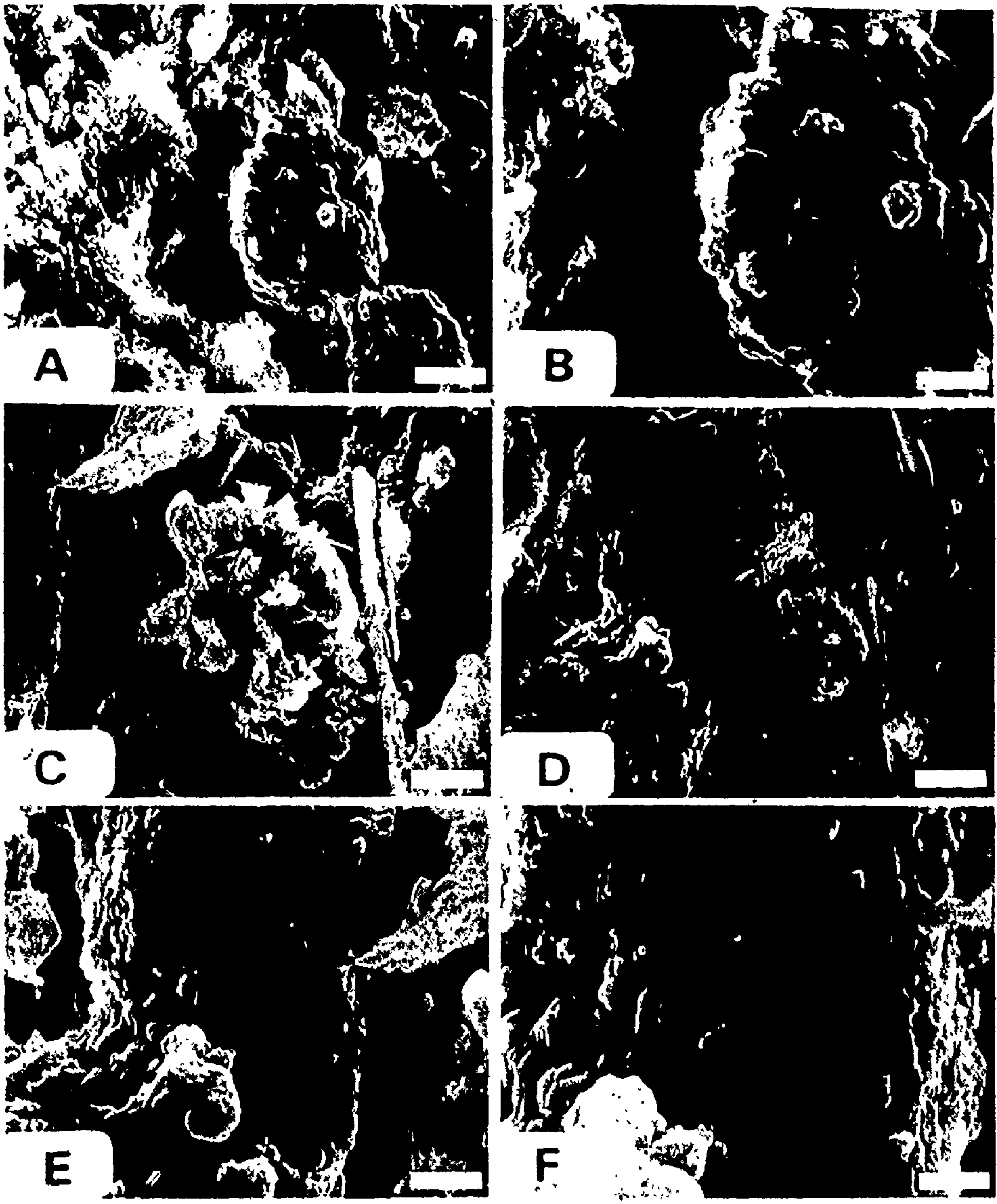

A
B
C
D
E
F

FIGURE 3-15 Calcified algal filaments projecting out of carbonate sand grains from Jamaica, West Indies. Specimen J-26, Discovery Bay. a, b) Calcified filament with "bulb-like" calcification developed. Scale bars 2.2 um and 1 um, respectively. c) Calcified algal filament termination. Scale bar 1 um. d, e, f) Exterior of a calcified algal filament showing calcite developed along the thallus. Scale bars 2 um, 1 um, and 0.5 um, respectively.


A
B
C
D
E
F

rather than a product of algal metabolism. Although Schroeder (1972a) suggests that calcification occurs during the lifetime of the algae in reef carbonates from Bermuda, only dead filaments become calcified on the Iceland spar. The precipitation mechanism involved is unknown, but the close similarity between the composition of the spar and the calcite encrusting the filaments is more than coincidental (see discussion on similar phenomena by Gunatilaka, 1976). Calcite dissolved and removed by the boring activity of living endolithic filaments in the spar may be precipitated outside the spar on the dead filaments. An organic catalytic reaction or bacteria-associated reaction on the dead filaments is suggested by the almost complete absence of any calcite precipitated on the exposed surface of the spar outside tha algal borings.

Incomplete constructive envelopes and isolated calcified exposed endolithic algal filaments have been found in modern sediments and reef rubble (Figs. 3-14; 3-15). In Jamaica (Discovery Bay), Curacao (Westpunt Baai), Bonaire (Barcadera), and Barbados (Bellairs) they have been found to a depth of 20 m, though they probably occur deeper.

A control on the development of constructive micrite envelopes and isolated calcified algal filaments is the degree of agitation of the sediment. Alexandersson (1972) noted the same control on micrite envelope formation (destructive type). Calcified filaments will constantly be broken from grains, and constructive envelopes will not be likely to develop under agitated conditions, unless periods of quiescence occur and the filaments are given sufficent time to calcify (and possibly bind the grains as described below).

The Pleistocene (83,000 year) reef terrace at River Bay and North Point Barbados (for a description of the geology see James, 1972) has

FIGURE 3-16 Possible constructive micrite envelope from the Devonian middle Cairn Formation at the Miette reef complex, Jasper Park (Sample M-13). The stromatoporoid at the lower right is encrusted by the envelope, and is, in places, penetrated by micrite tubules (representing endolithic algae). The micrite envelope is seen to consist of small patches of microspar cement, micrite, and dendritic micrite-infilled structures of probable algal origin. The similarity between this, and similar structures of demonstrable "constructive" origin, is striking. Scale bar 50 um.

FIGURE 3-17 Micrite envelope probably of the constructive type, on a brachiopod fragment from the Valcour Fm., Chazy at Isle LaMotte, Vermont. The envelope consists of microspar, micrite, and intertwined calcified algal filaments. Scale bar 100 um.

provided excellent examples of constructive envelopes in lithified calcirudites and calcarenities. Pelecypod, echinoderm, and coral fragments and grains are commonly found with a 20 um to 600 um thick micrite envelope, consisting of a tangled mass of calcified algal filaments 10 um to 40 um in diameter, and each up to several hundred microns long (Fig. 3-10). Under the petrographic microscope these envelopes are commonly very difficult to distinguish from destructively-generated envelopes (Bathurst, 1966) made up of micrite-infilled algal tubules. Apparent under the scanning electron microscope, however, are the algal thalli, micrite infilling of the filaments, coalescing palisade cement coats on the filaments, and interfilament micrite cement (Figs. 3-12; 3-11). Micrite tubules produced by filling of algal bores are also common (Fig. 3-1), however, as are empty and vacated algal and fungal borings in the grains. The difference in fabric between the original grain, any destructive envelopes that have developed, and constructive envelopes, is unmistakeable when viewed on the scanning electron microscope. The boundaries between the grains and lower surfaces of constructive envelopes are generally very sharp and distinct (Fig. 3-11).

Envelopes exhibiting external micrite development by the calcification of exposed endolithic algal filaments are found throughout the Phanerozoic. Many examples have been found during the course of this study from the Devonian Miette reef complex (Frasnian) of Alberta (Fig. 3-16) (for a description of the complex see: Mountjoy, 1965; Kobluk, 1975), and the Ordovician Isle LaMotte, Vermont (Fig. 3-17) (for a description of the geology, see: Kapp, 1975); these included the same features as observed in the modern and Pleistocene calcarenites of Florida, Barbados, Jamaica, Curacao, Bonaire, and Bermuda, and other Caribbean islands.

FIGURE 3-18 Calcified intergranular algal filaments. All under plane polarized light. a, b) Calcified filaments showing interior fill, exterior cement, and surficial micrite and microspar cement in the inter-filament pores. Sample B-13. Pleistocene at North Point Barbados. Scale both 160 um. c) Tightly-packed calcified filaments between 2 grains from the first reef terrace (Pleistocene) at Discovery Bay Jamaica. Sample J-285. Scale bar 65 um.

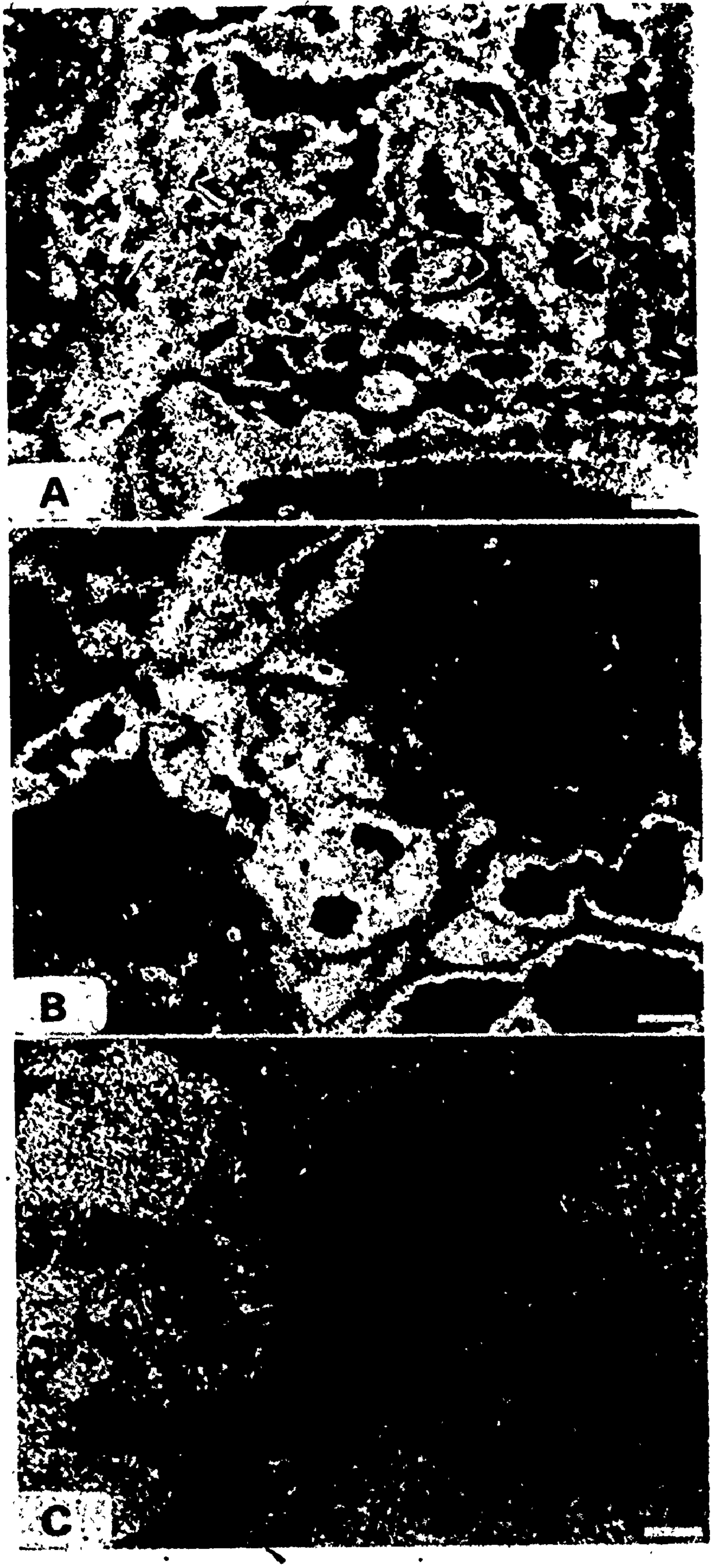

A
B
C

FIGURE 3-19 Calcified intergranular algal filaments. All samples from Pleistocene calcarenite at Animal Flower Caves (83,000 yr. terrace), Barbados. a, b, c, d, e) Intertwined calcified filaments, developed in original pore space between grains. Note infilled algal filaments and the palisade cement precipitated on the exterior. Sample B-13. Scale bars 16 um, 16.5 um, 16 um, 16 um, 8 um, respectively. f) Micrite and microspar lined pore between calcified intergranular filaments. Sample B-16. Scale bar 3.5 um. Scanning electron micrographs.

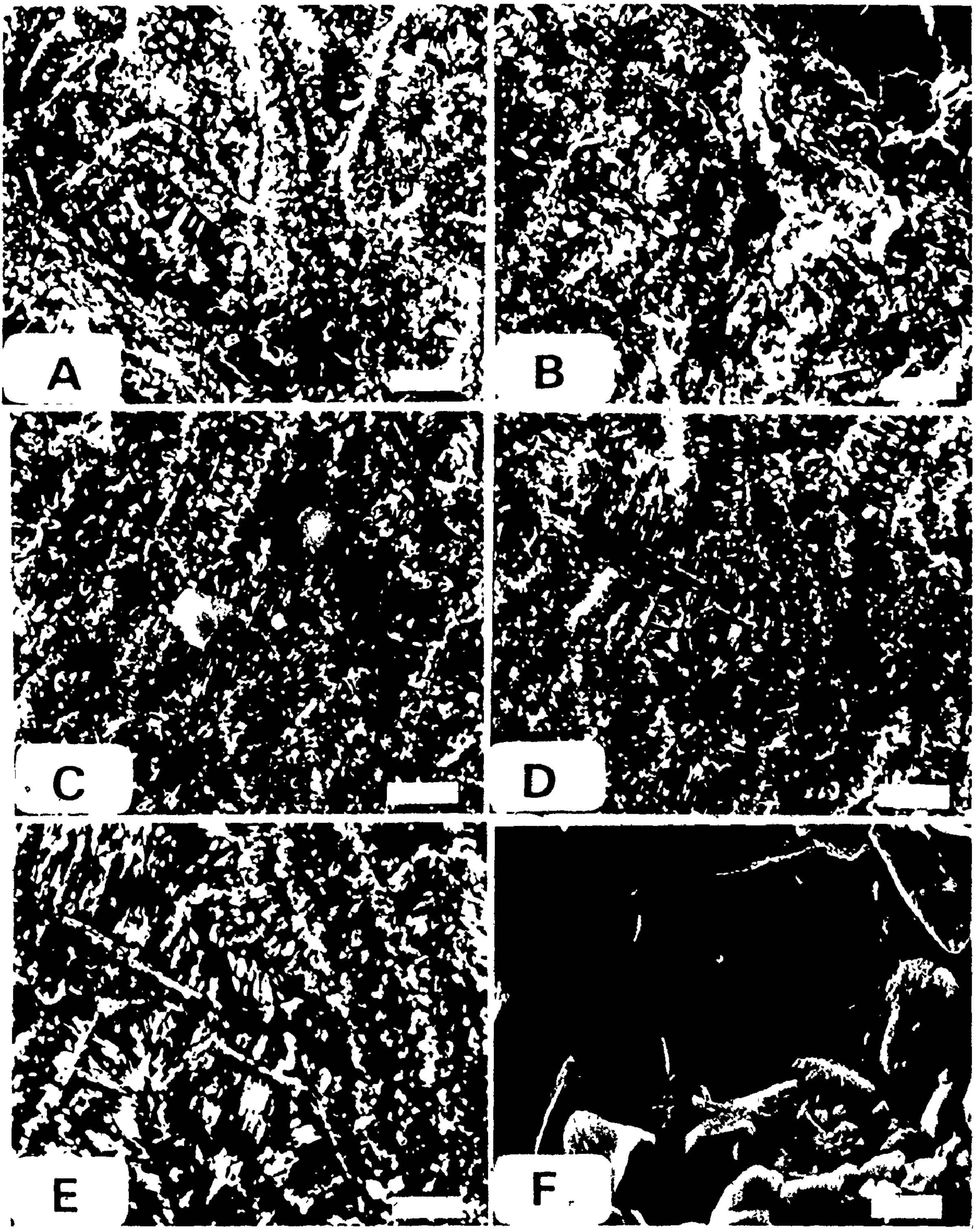
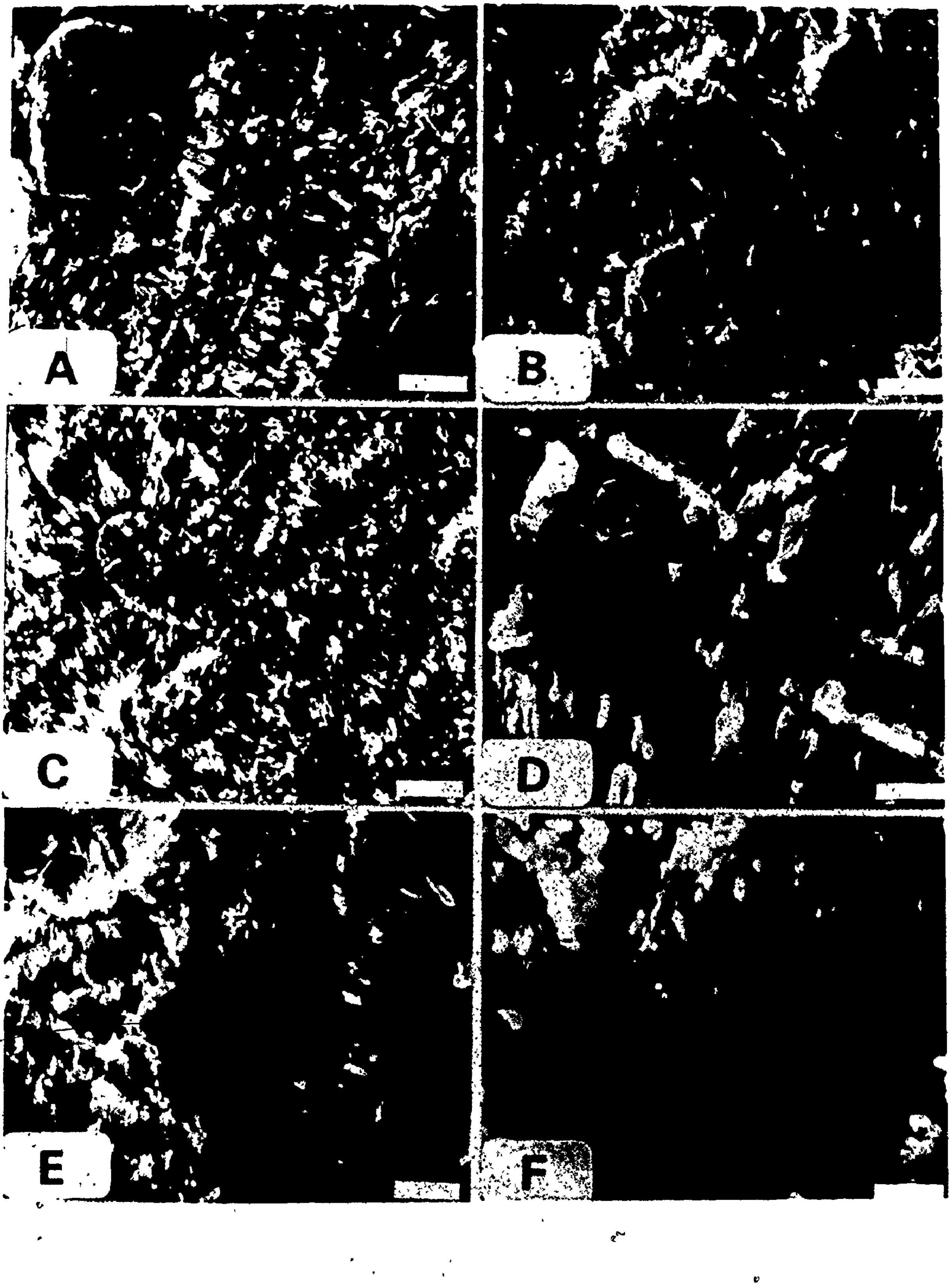

A
B
C
D
E
F

FIGURE 3-20 Details of calcified intergranular algal filaments. All specimens from Pleistocene (83,000 yr. terrace) calcarenite at Animal Flower Caves, Barbados. a, b, c) Calcified filaments in cross section showing thallus, interior fill, and exterior palisade cement. Sample B-9. Scale bars all 8 um. d) Detail of algal thallus, with interior fill and external cement. Sample B-11. Scale bar 1.5 um. e, f) Surface of the interior micrite fill in an algal thallus. Note centripetal development of crystals. Sample B-9. Scale bars 3.5 um and 1.5 um, respectively. Scanning electron micrographs.


A
B
C
D
E
F

3.5 GRAIN BINDING AND INTERGRANULAR PORE FILLING

Algae living as endoliths grow through micrite envelopes (both constructive and destructive) into intergranular pore spaces to become chasmoliths, as well as living and growing entirely as chasmoliths within the intergranular pores. In this study, the extensions of endolithic algal filaments forming constructive micrite envelopes, while chasmolithic, are distinguished from the intergranular chasmolithic algal filaments inhabiting the pores outside both the grains and the micrite envelopes.

Dead (intergranular) chasmolithic algal filaments are calcified in the same manner as those forming constructive micrite envelopes on grain surfaces (Fig. 3-18; 3-19; 3-20). Intergranular calcified filaments are filled with micrite and encrusted in palisade cement (see also Schroeder, 1972a, b); they intertwine to produce a complex of interwoven calcified filaments. Micropores left between calcified filaments are partially to completely filled by rhombohedral micrite and microspar cement which precipitates on the palisade cement coating the algal filaments (Fig. 3-19b; 3-21). Intergranular porosity (and possibly permeability) is reduced in this way, and the grains are bound by the entanglement of calcified algal filament and micrite cement (Fig. 3-18; 3-19; 3-20; 3-21; 3-22).

Whether or not the chasmolithic intergranular filaments most commonly grow and become calcified at or near the sediment water interface, or deep in the sediment, is unknown. Jeff Dravis (1976, pers. comm.) however, has found calcified algal filaments binding oolites in oolite shoals on the Bahamas in the same way as described above; the binding of the oolites appears to be taking place at, or near, the sediment-water interface and occurs very rapidly, perhaps in the order of a year or less.

FIGURE 3-21 Intergranular pore between calcified intergranular algal filaments from a Pleistocene calcarenite from the 83,000 year terrace at North Point, Barbados. The elongate crystals are now low Mg calcite; original composition unknown. The crystals precipitated in micropores between calcified algal filaments, but never filled the pore completely. Sample B-5. Scale bar 0.5 um.

FIGURE 3-22 Schematic representation of pore filling and micrite envelope formation by calcified exposed endolithic and chasmolithic algal filaments.

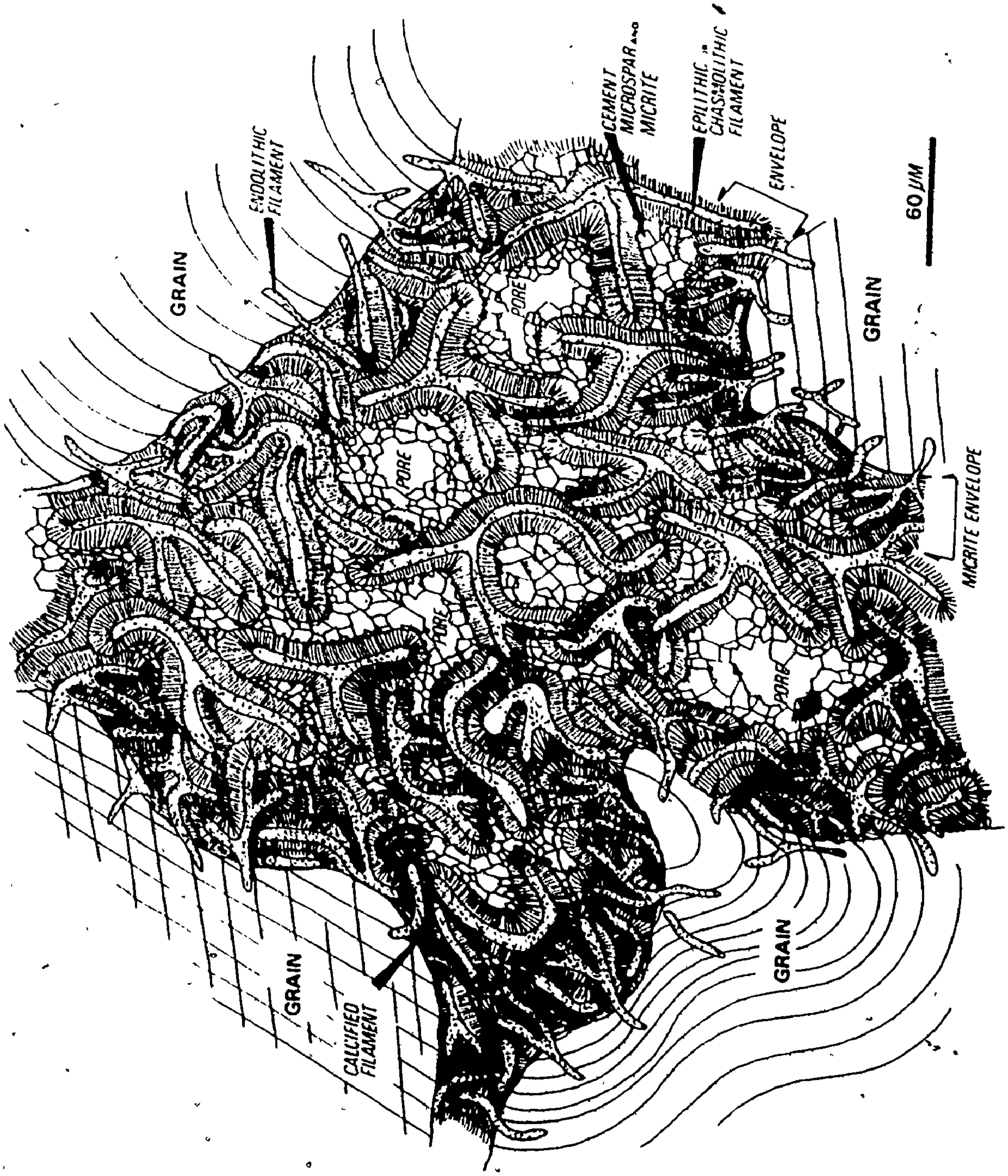

ENDOLITHIC FILAMENT
GRAIN
CEMENT MICROSPAR AND MICRITE
EPILITHIC OR CHASMOLITHIC FILAMENT
ENVELOPE
60 µM
PORE
PORE
PORE
PORE
GRAIN
MICRITE ENVELOPE
GRAIN
GRAIN
CALCIFIED FILAMENT

FIGURE 3-23 Calcified exposed endolithic and intergranular chasmolithic algal filaments projecting from oolites in the Miami Oolite. Specimen F-19. a) Scale bar 55 um. b) Scale bar 22 um. c) Scale bar 5.5 um. d) Scale bar 11 um. f) Scale bar 20 um. Scanning electron micrographs.

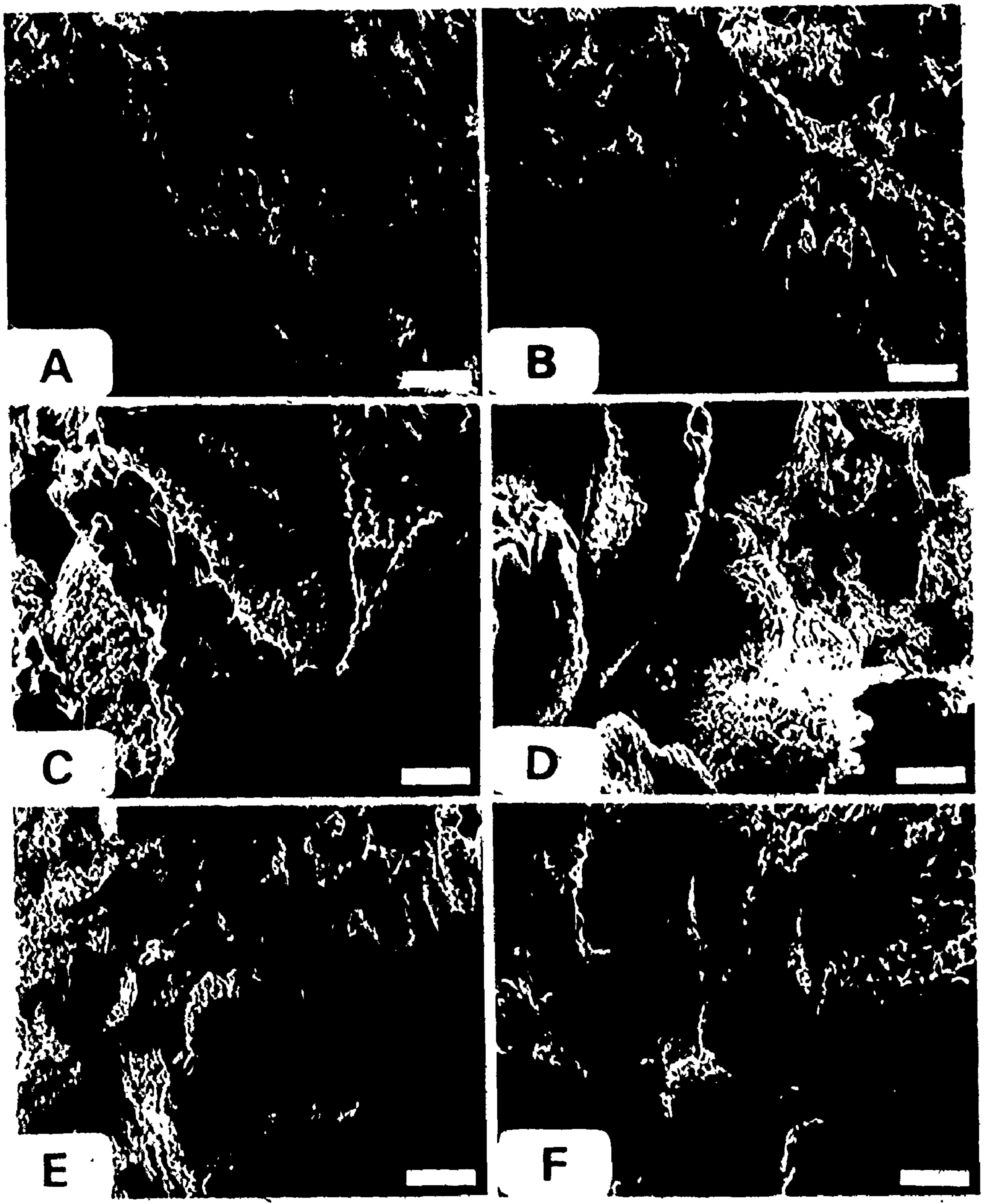
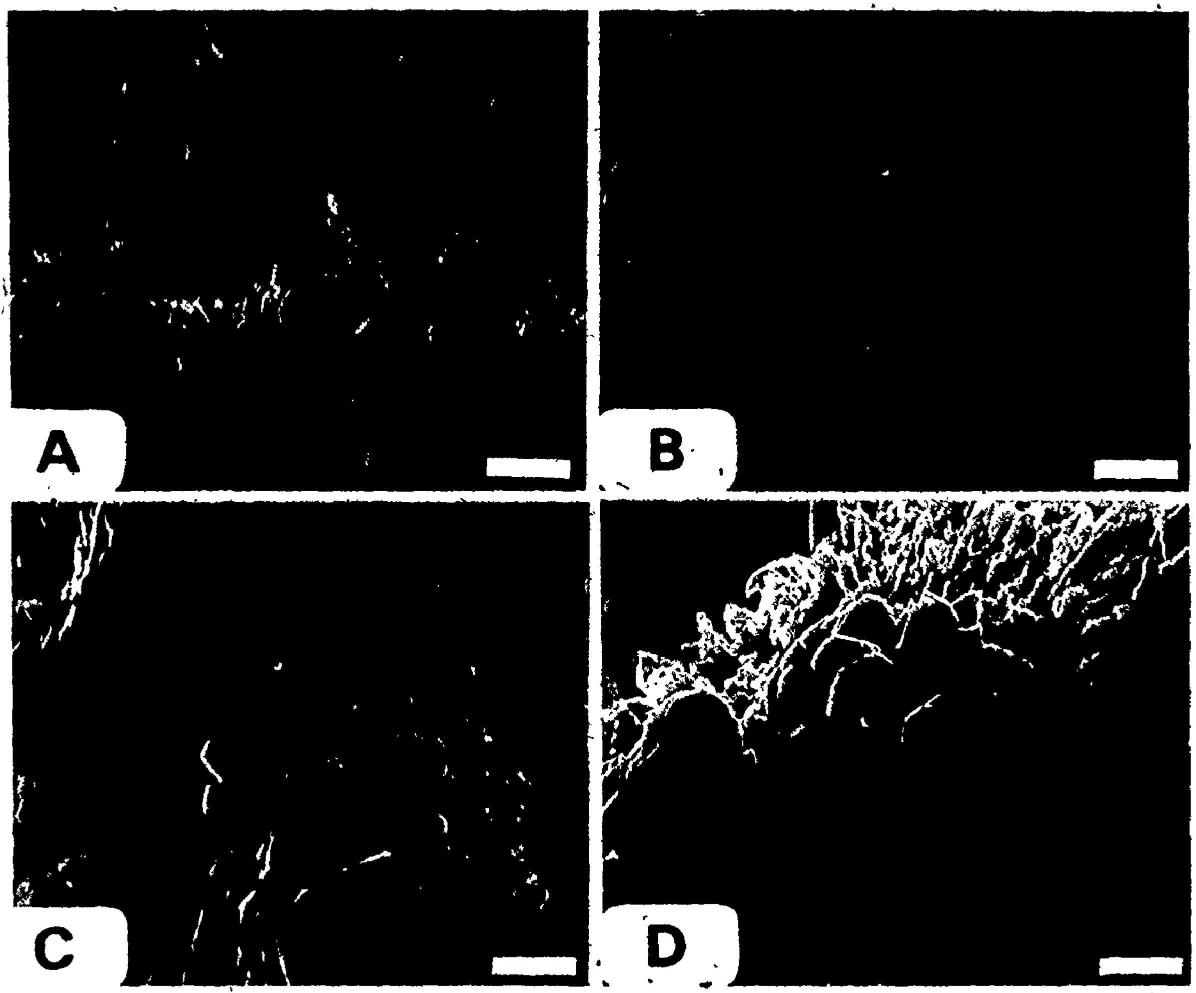

A
B
C
D
E
F

FIGURE 3-24 Calcified exposed endolithic (chasmolithic) algal filaments projecting from the surface of oolite grain in the Miami Oolite. Specimen F-84. a, b, c) View down the longitudinal axis of calcified filaments. Scale bars 5.5 um, 5.5 um, and 11 um, respectively. d) End of a broken calcified filament showing external calcification and interior infill. Compare with James *et al.* (1976), Fig. 16c. Scale bar 2.2 um. Scanning electron micrographs.


A
B
C
D

Similar features were found abundantly in the Miami Oolite (Figs. 3-23; 3-24), where calcified algal filaments occur between, and bind grains. Many of the filaments are calcified extensions of endolithic algae, and some are true chasmoliths. The specimens of the oolite showed cross-bedding, and represent an agitated environment; the calcified filaments are covered in rhombohedral cement, and therefore were calcified before the majority of the microspar cement was precipitated. This suggests early filament calcification below the sediment surface, or near it, as Dravis (1976, pers. comm.) found in the Bahamas.

Winland and Matthews (1974) describe grain binding by chasmolithic or endolithic filamentous cyanophytes (Entophysalia deusta) in grapestone from the Bahamas. Calcified algal sheaths are figured between grapestone grains that are interpreted as recrystallized ooids. Calcite encrusting the filaments is Mg calcite, and is developed as rhombic and acicular crystals. The intergranular calcified filaments described above are the same as those described by Winland and Matthews (1974) and by Dravis and are very similar to those from the Miami Oolite. James et al. (1976) figure structures from Belize (Figs. 13a, b; 16c in Jemes et al, 1976) which resemble some calcified chasmolithic algae.

The comment that intergranular calcified filaments serve a grain binding function is supported by Dravis and Winland and Matthews (1974). Binding of grains by the filaments requires only periods of quiescence even in highly agitated oolite shoals, and occurs rapidly.

Fine examples of intergranular calcified filaments are found in calcarenites in the Pleistocene (83,000 year terrace; James, 1972) at River Bay and North Point, Barbados, from the Pleistocene at Discovery Bay, Jamaica, and the Miami Oolite, but they are also found in the Devonian

FIGURE 3-25 Ancient calcified intergranular algal filaments. a) Part of an entanglement of calcified intergranular filaments. Specimen M-17. Devonian of the Miette reef complex. Scale bar 50 um. b) Detail of one of the filaments from (a) above. Scale bar 25 um. c) Algal filament entanglement, in the spar from the Chazy at Isle LaMotte. Specimen Q-10. Scale bar 28 um. Light microscope, transmitted light.

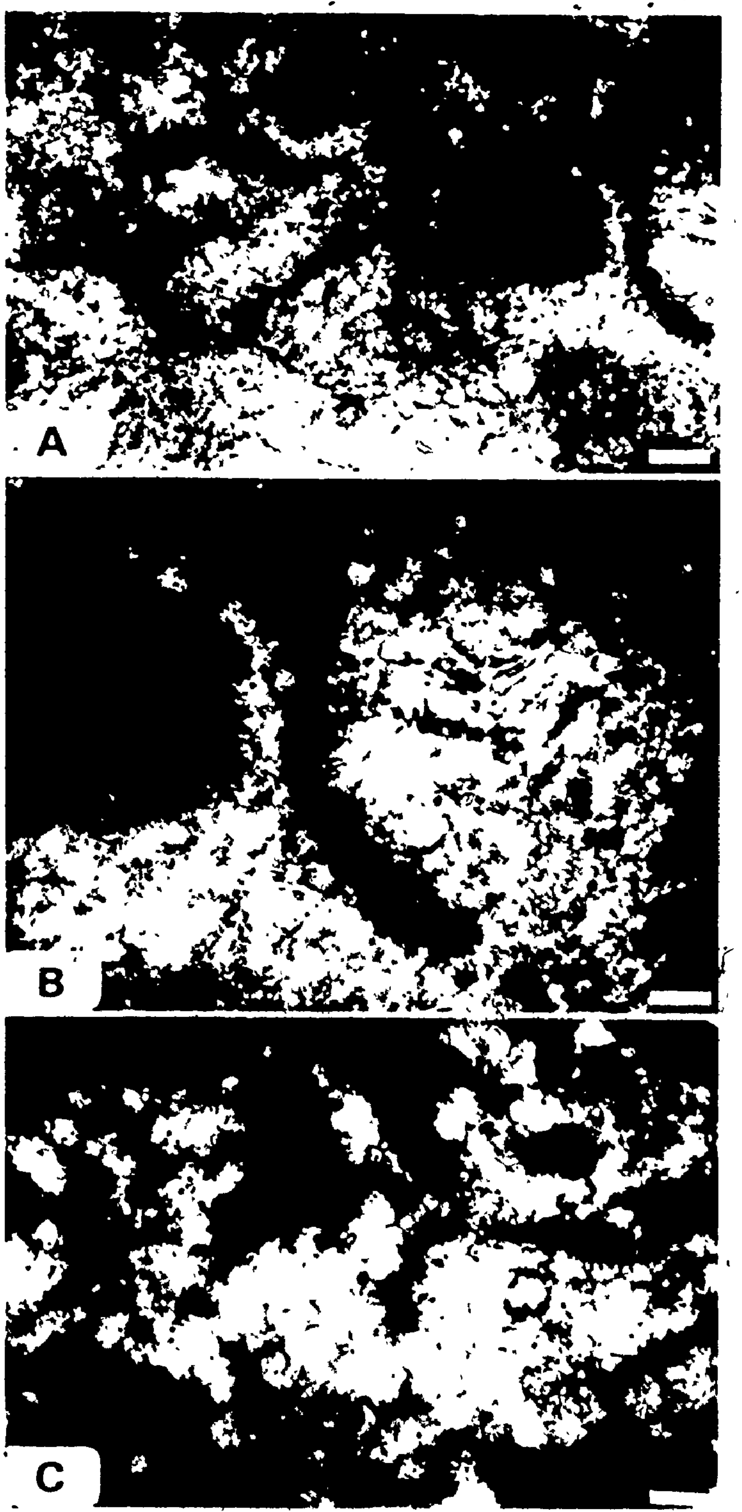
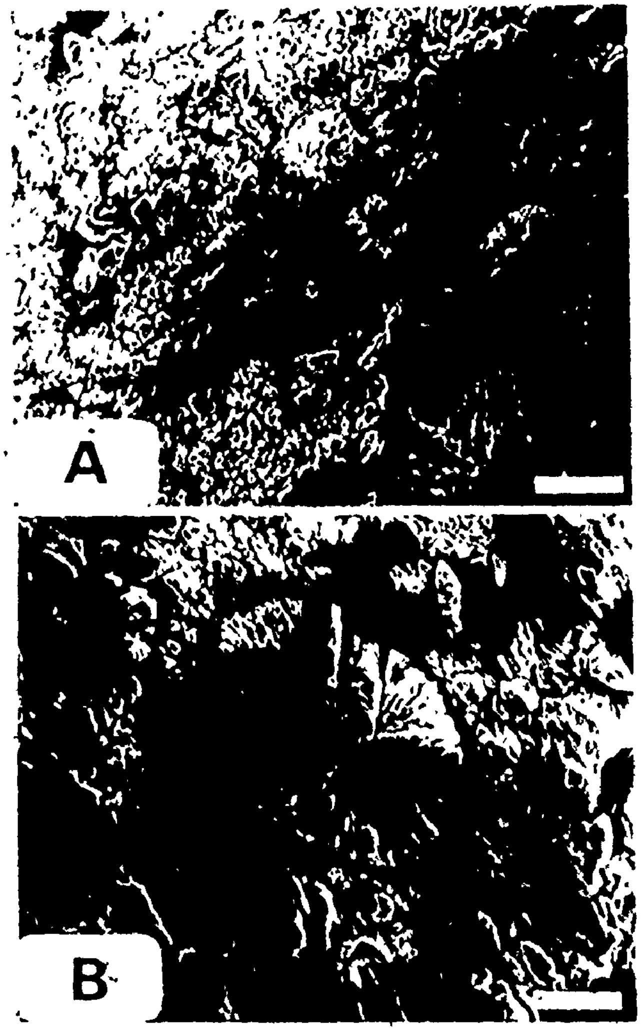

A
B
C

FIGURE 3-26 Etched surface of specimen M-16; from the Miette complex, Alberta. Both a, and b show calcified algal filaments. a) Scale bar 14 um. b) Scale bar 14.5 um. Scanning electron micrographs.


A
B

at Miette (Figs. 3-25; 3-26) and possibly as far back as the Ordovician (Chazyan) at Isle LaMotte, Vermont (Fig. 3-25c).

3.6 GIRVANELLA

Girvanella Nicholson and Etheridge (1880), (and other similar forms such as Ortonella, Nostocites, etc.) is locally a common and significant microfossil (Fig. 3-27) ranging from the Cambrian to the Cretaceous (Johnson, 1961a, b, 1965), and possibly to the Recent (Monty, 1965, 1967; Shinn et al, 1969; Riding, 1972, 1975). The affinities of Girvanella are are as yet uncertain, but the concensus is that it represents one, or several, distinct species or even genera within the Cyanophyta (Bornemann, 1886; Pollock, 1918; Pia, 1937; Seward, 1931; Klement and Toomey, 1967; Riding, 1972, 1975). Riding (1975) argued that it may represent members of the Oscillatoriaceae, Sytonemataceae, and Stigonematacea. Other suggested affinities have included sponges (Hinde, 1887), foraminifera (Nicholson and Etheridge, 1878; Rhumbler, 1895), and Chlorophyta (Rothpletz, 1891; Romanes, 1916; Fremy and Dangeard, 1935; Scoffin, 1971).

The calcified sheaths of Girvanella (normally ranging from 10 um to 30 um in diameter) are generally considered to have been produced by the alga itself, by analogy to extant calcified cyanophytes (Monty, 1965; Riding, 1975, and in press).

Girvanella is commonly found as isolated filaments or pairs of filaments; as masses of closely intertwined filaments, or as masses of intertwined filaments with interspersed patches of spar cement (Fig. 3-27); as a grain encrustation, forming envelopes (Fig. 3-27); as intertwined masses between grains, apparently serving a grain binding function; and as an endolith (Fig. 3-27; Klement and Toomey, 1967). Filaments of each

FIGURE 3-27 Girvanella envelopes on grains. All are from the Ordovician (Chazy) at Isle LaMotte. a, b) Envelopes of Girvanella filaments on stromatoporoid grains. Filaments are seen which are endolithic. Samples Q-15 and Q-10. Scale bars 65 um, and 100 um, respectively. c) Detail of Girvanella in micrite envelope on a stromatoporoid fragment. Sample Q-15. Scale bar 35 μm. Light microscope, transmitted light.

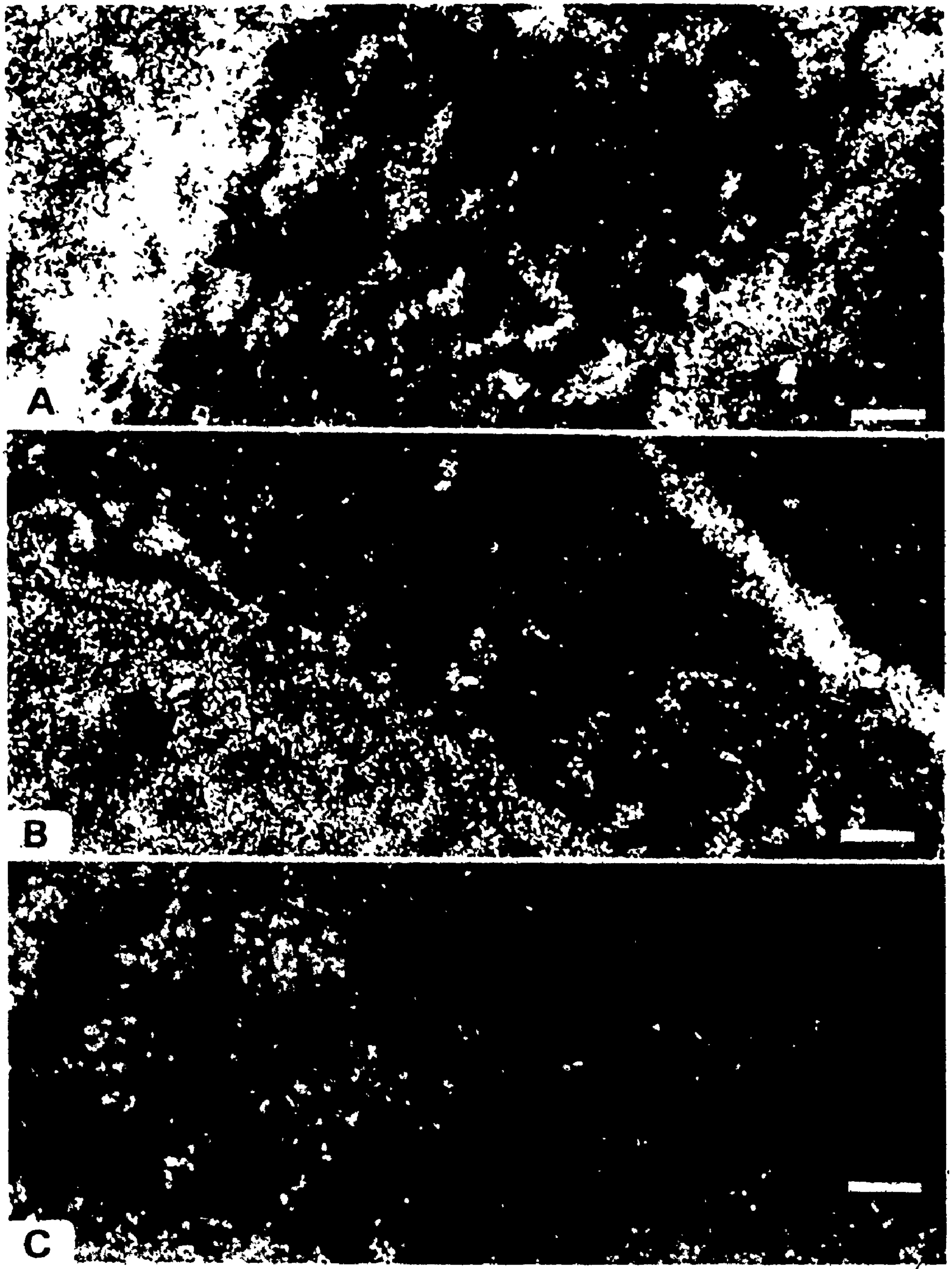
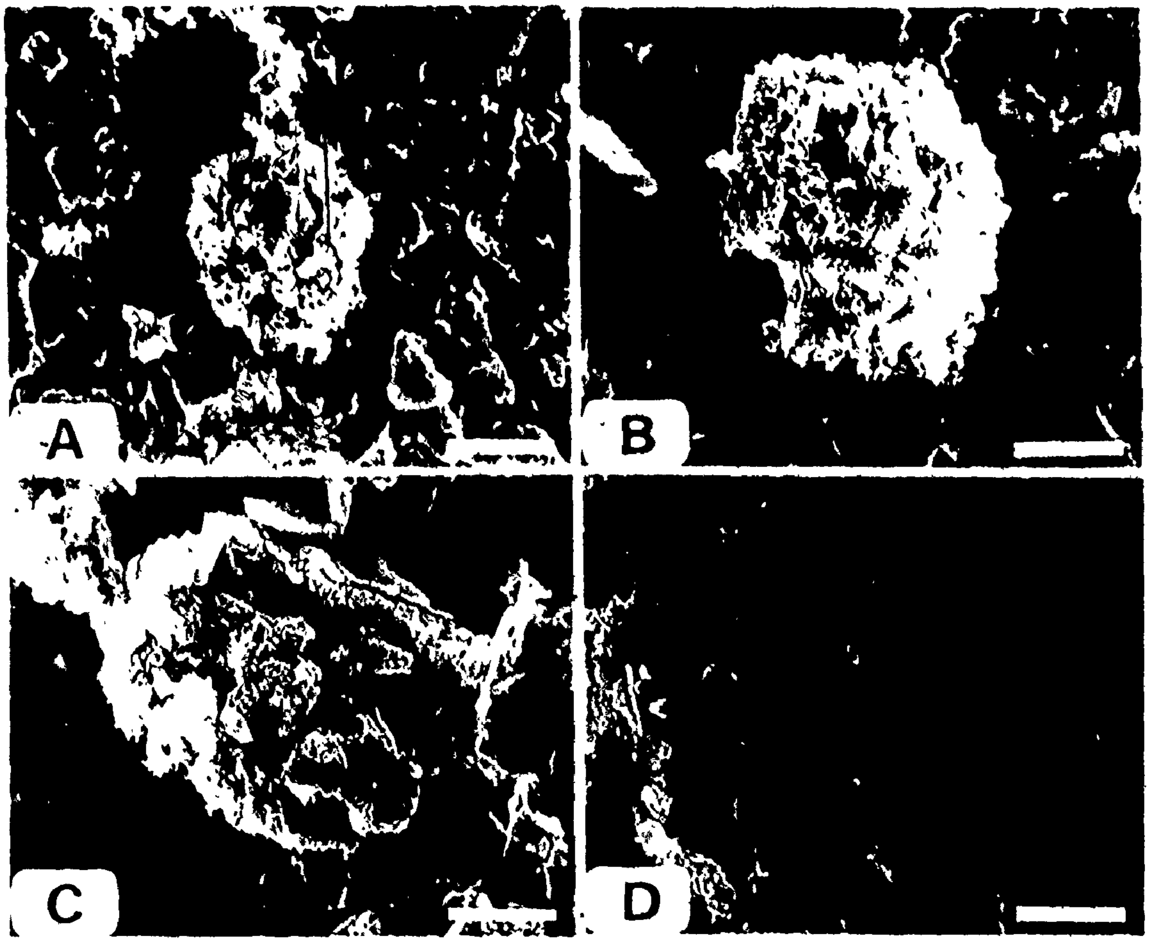

A
B
C

FIGURE 3-28 Isolated filaments of Girvanella, showing calcification. All are from the Ordovician (Chazy) at Isle LaMotte. Specimens were prepared by etching polished limestone slabs. a, b, c) Though damaged by the etching, these specimens crudely demonstrate the presence of interior fill and exterior encrustation on Girvanella. Sample Q-15. Scale bars 11 um, 5 um, and 5 um, respectively. d) Detail of the center of the broken end of a Girvanella filament. The position of the sheath is delineated by the dark, curved line at center. Sample Q-15. Scale bar 2 um. Scanning electron micrographs.


A
B
C
D

of these types are in fact often found calcified both internally and externally by micritic calcite (original composition unknown) in contrast to impregnated sheaths. Commonly the calcite has been recrystallized, but where well-preserved material occurs, the interior fill is centripetal, consisting of rhombohedra or blade-like crystals. The exterior calcite coat is also radially developed and grew outward from the external surface of the sheath (Fig. 3-28).

Calcified algal filaments are by no means rare. Scytonema, Schizothrix, and Lyngbya are commonly found calcified in nature (Geiter, 1930; Friedman et al, 1964; Monty, 1965, 1967; Winland and Matthews, 1974) and have been studied in culture (Ulrich, 1927; Schlonleber, 1936). Calcification in Scytonema appears to be related to algal metabolism whereas in other forms, such as Schizothrix, the mechanism is not known with certainty and could involve bacterial activity within mucilaginous coats (Monty, 1965). Analogy has been drawn between these calcified algae and preserved Girvanella and Ortonella (Monty, 1965, 1967; Riding, 1975). However, the habitat of calcified Scytonema and Schizothrix described by Monty (1965, 1967), and the forms figured by Shinn et al.(1969) and others, differ greatly from the inferred paleoenvironment of Girvanella and similar forms. Calcified filaments of Ostreobium quekettii described lining cavities in Bermuda reefs (Schroeder 1972a), within intraskeletal cavities in corals (Lukas, 1974), observed forming on Iceland spar calcite in Jamaica (Figs. 3-4; 3-5) and from modern sediments (Figs. 3-14; 3-15; 3-23; 3-24) and the Pleistocene Jamaica, Barbados, Curacao, and Florida have very similar structures to Girvanella. Filamentous endolithic algae commonly grow out to the grains they inhabit and become calcified by either high or low Mg calcite. The filaments are observed only after the death of the algae. The similarities both in structure and habitat between the calcified exposed endolithic algae and Girvanella are striking:

1) Both are calcified centripetally on the interior and radially on the exterior of the sheaths.
2) Filament diameters of the calcified sheaths are in the same size range (5 um to 30 um).
3) Both function as endoliths, as epiliths on grains, and as chasmoliths (live in cavities not of their own making) between grains, and can form masses of calcified filaments on the surfaces of grains which may be termed micrite envelopes.
4) Both can occur as intergranular filament masses which may or may not serve a grain binding function. Originally porous areas between calcified filaments are filled in by micrite or microspar cement shortly after the calcification of the filaments.

Although Ostreobium quekettii is the alga most commonly observed calcified in this manner, some endolithic cyanophytes such as Hyella and Hormatonema also calcify. Calcification of dead filaments may take place either in light, in cavities, or within sediment. Even some of the endolithic chlorophytes are capable of living and growing without light or at extremely low light levels (Halldall, 1968; Shibata and Haxo, 1969; Schroeder, 1972a).

Riding (in press) recently described calcified filaments of Plectonema gloeophilum Borzi from freshwater pools on West Island Aldabra, which are interpreted as living Girvanella.

Riding also makes the distinction between impregnated and encrusted filamentous algal sheaths, both of which he describes as being "calcified". P. gloeophilum apparently has sheaths impregnated, rather than encrusted by carbonates (Riding, in press). The filaments are calcified during the life of the algae, but whether the calcite is a direct metabolic precipitate within the sheath, or is an indirect result of metabolic activity, is not demonstrated. Extension of the conditions within the restricted, stagnant freshwater pools to the shallow open marine environment in which Girvanella lived is a problem, but nevertheless, there are great similarities between the calcified P. gloeophilum and fossil Girvanella. Riding dismisses Ostreobium and other forms as possible modern analogues to Girvanella on the basis of total infilling of calcified Ostreobium sheaths, the apparent lack of "thick" encrustations on Girvanella filaments, and the presence of local swelling on the sheaths of some Ostreobium species. Not all Ostreobium filaments show pronounced swellings, particularly following calcification, some Girvanella filaments were infilled early, and many also were encrusted by micritic carbonate. Not all algal filaments calcified by external encrustation reach very great size, and are apparently limited in some way to about 30 um diameter. The important point is not, however, that Ostreobium in particular, represents modern Girvanella, but rather that Girvanella-like structures could have formed by a cementation process: the infilling and encrustation of sheaths of various dead green and blue-green filamentous algae by precipitated carbonate.

Girvanella resembles the calcified algal filaments described by Schroeder (1972a), and described above, very closely. It may therefore be a "diagenetic taxon" resulting from the early alteration and cementation of a number of different species from possibly widely differing genera, all with similar, though variable, habitats. All come to resemble one another following death and calcification.

CHAPTER 4

ALGAL BORINGS AND FRAMBOIDAL PYRITE IN UPPER ORDOVICIAN BRACHIOPODS

4.1 INTRODUCTION

Hessland (1949) mentioned the occurence of endolithic algae in many types of fossil and recent invertebrates, including orthid brachiopod valves. Many of the algal borings in Hessland's (1949) Lower Ordovician fossils are also coated in limonite (Hessland's limonitic ooids). Specimens of the orthid brachiopods Plaesiomys subquadrata(?) Hall and Hebertella sinuata(?) Hall from the Richmond Group of Ohio are also bored, presumably by endolithic microphytes; the borings are still partly empty and commonly contain various crystal forms of iron sulfide. The pyrite occurs as spheres, octahedra, and framboids. The term framboid, first used by Rust (1935), refers to spheroidal aggregates of micron-sized pyrite crystals, a common feature in modern and ancient sediments. Though by no means a common feature in Ordovician fossil materials, such unmicritized, pyrite-filled, and well-preserved borings provide an opportunity to study ancient endolithic activity and some of the accompanying early diagenetic processes.

4.2 METHOD OF STUDY

The 9 brachiopod specimens were completely removed from the surrounding matrix and carefully cleaned. The convex sides of the ventral valves containing the borings were etched in 2% acetic acid for 15 minutes. A fragment of 1 specimen of Plaesiomys subquadrata(?) Hall, preserved as translucent calcite, was mounted between glass plates and

FIGURE 4-1. Pyrite-infilled algal borings in upper Ordovician brachiopods from Cincinnati, Ohio. a, b) Borings in Hebertella. Scale bars both 13.5 um. c) Partly infilled, partly empty, algal boring in Plaesiomys. Scale bar 5 um. Light microscope.

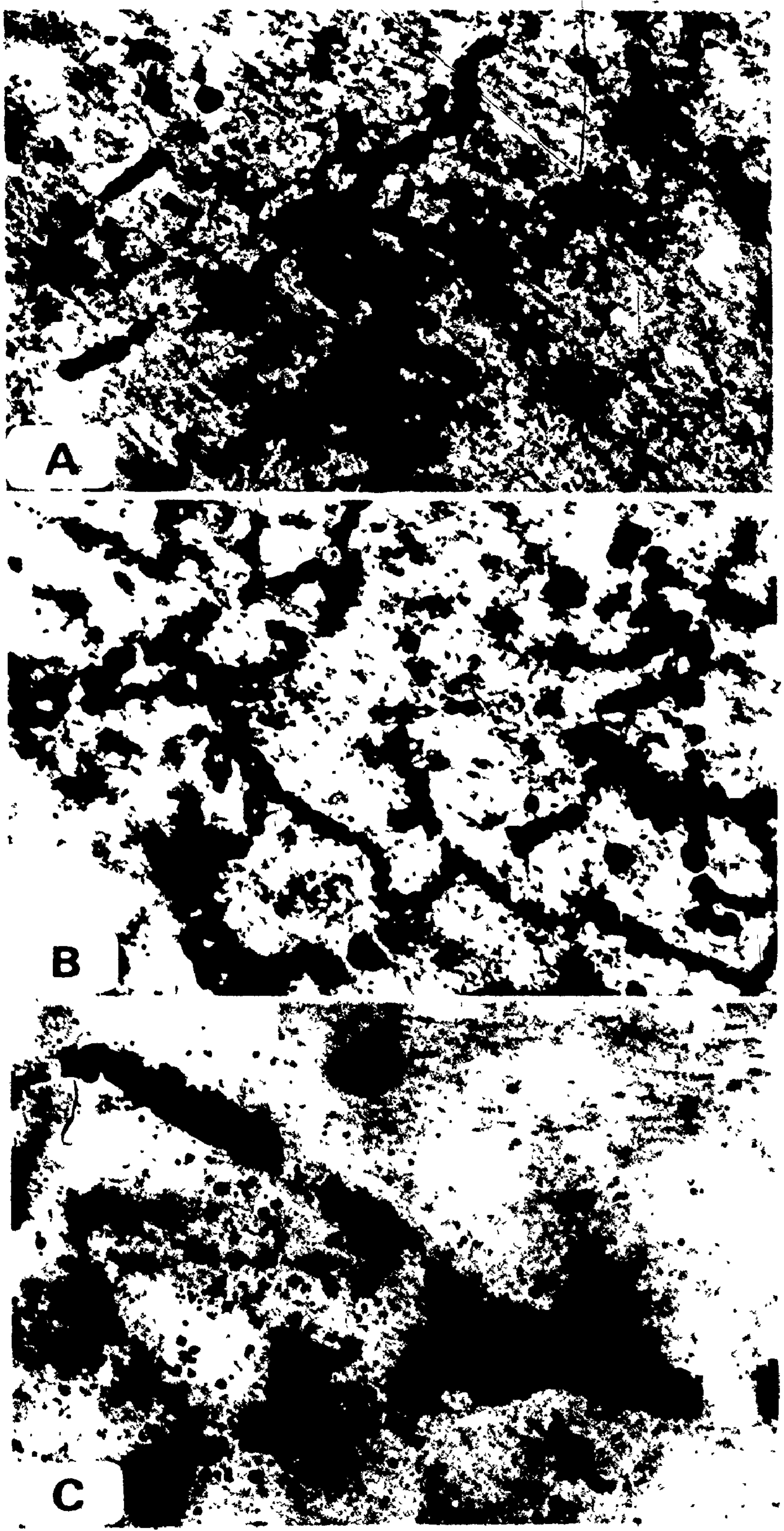

A
B
C

FIGURE 4-2 Sketch of the boring in Fig. 4-1c. Note that in many places the spheres and framboids do not touch the boring wall; the boring is also somewhat irregular.

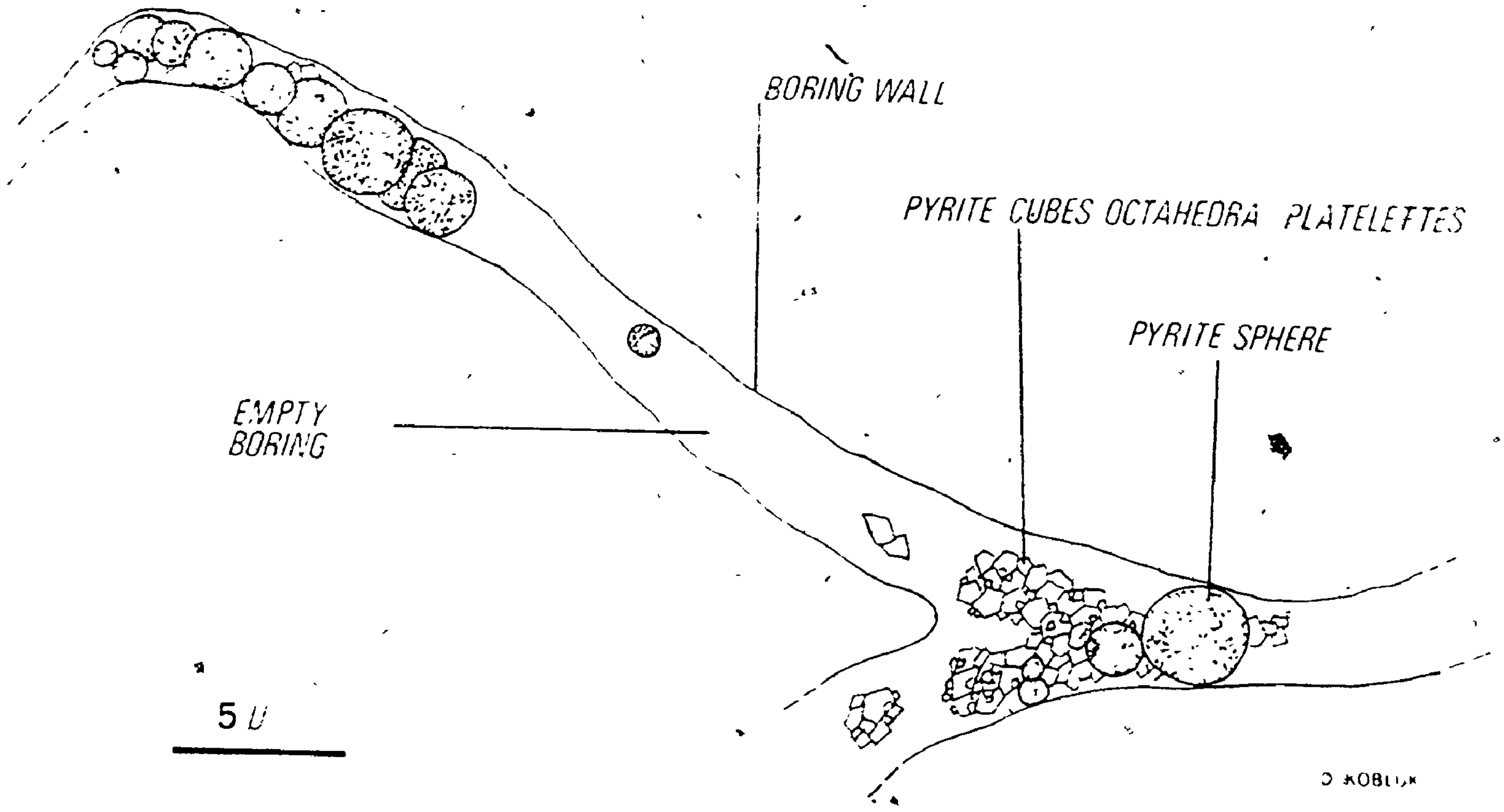
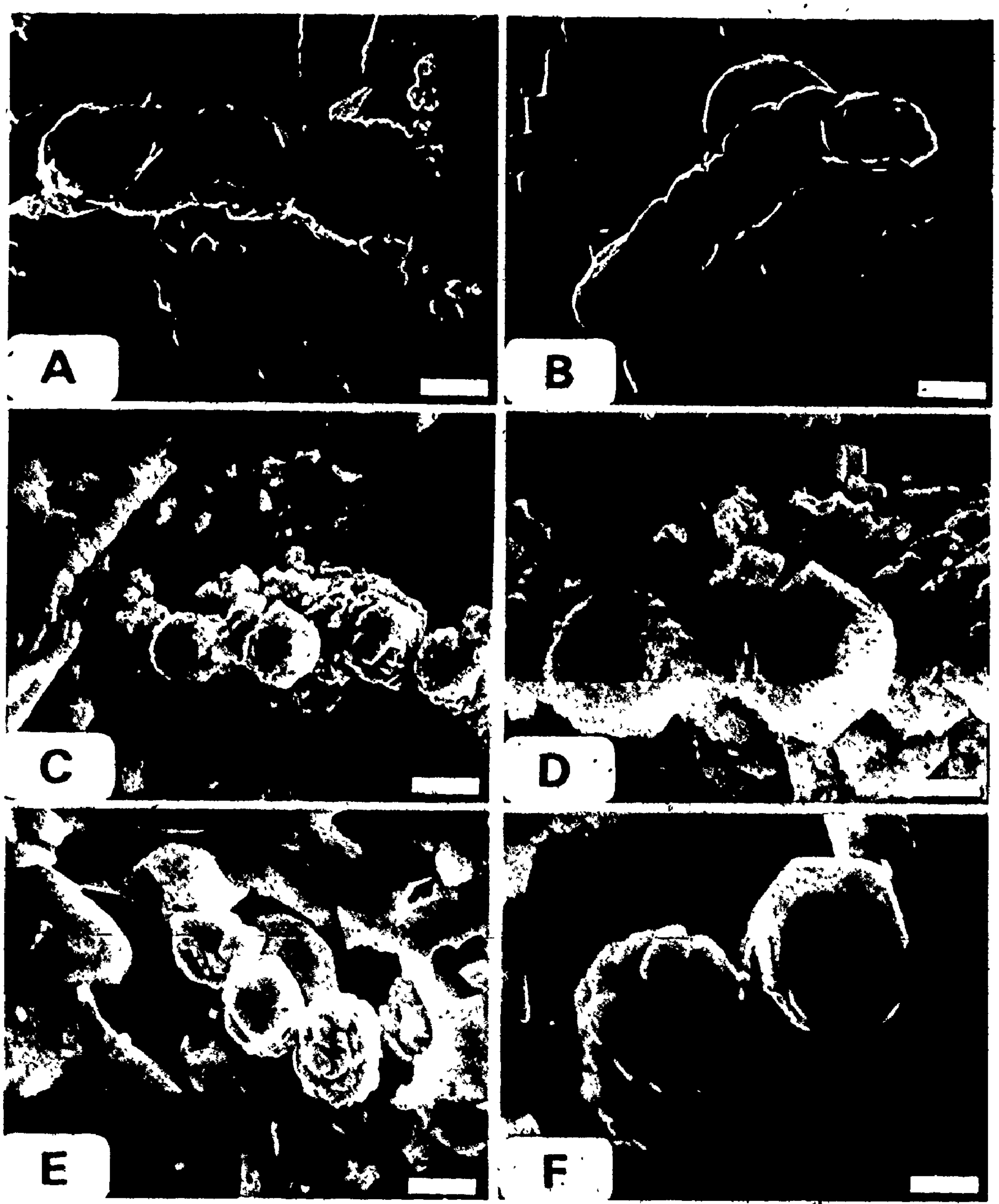

BORING WALL
PYRITE CUBES OCTAHEDRA PLATELETTES
PYRITE SPHERE
EMPTY BORING
5 U
D KOBLUK

FIGURE 4-3 Algal bores filled with pyrite in upper Ordovician brachiopod (<u>Hebertella</u>). Borings have been etched out. a, b) Tightly-packed pyrite crystals occupying the etched boring. Scale bars both 2 um. c, d, e, f) Linked pyrite crystals and framboids filling in algal borings. Scale bars 2 um, 1 um, 2 um, and 1 um, respectively.


A
B
C
D
E
F

studied in transmitted light on a petrographic microscope. The etched specimens were washed in distilled water, dried, and coated with aluminum. Each specimen was studied on a AMR model 1000 scanning electron microscope. Semi-quantitative analyses were carried out on an EDAX unit attached to a Cambridge scanning electron microscope.

4.3 DESCRIPTION

Hebertella sinuata(?) Hall and *Plaesiomys subquadrata*(?) Hall are articulate brachiopods of the superfamily *Orthaceae* Woodward. Paleozoic articulate brachiopod shells were likely low Mg calcite (95%-99%) with a proteinaceous matrix; traces of phosphate, magnesium, and iron were present, but in small and highly variable quantities (Moore, 1957). Analyses by EDAX show that the brachiopod shells are now low Mg calcite, containing calcium and traces of sulfur, iron, silicon and phosphorous; magnesium is absent. The pyrite in the borings is relatively pure.

The microborings are found within the primary and secondary layers of the shell (Rudwich, 1970), in densities ranging from 1 filament per mm^2 to over 100 per mm^2. The borings are generally close to the outer surface of the valve and show no preferred orientation (Fig. 4-1). The occurrence of the borings on, and close to, the exterior of the disarticulated valves of the brachiopod suggests that most of the boring activity took place while the brachiopods were still alive, or while the valves of the dead organisms were still tightly closed before burial.

Examples of false ramification (Bromley, 1968) are rare, but do occur. The branching is dichotomous, and the angles vary between 32°

FIGURE 4-4 Sketch of a cut-away view of a pyrite-filled boring showing pyrite plateletes and spheres, as well as possible framboids within the boring. In this example, the structures are in contact, but are, as is typical, not touching the wall of the boring, except in one or two places.

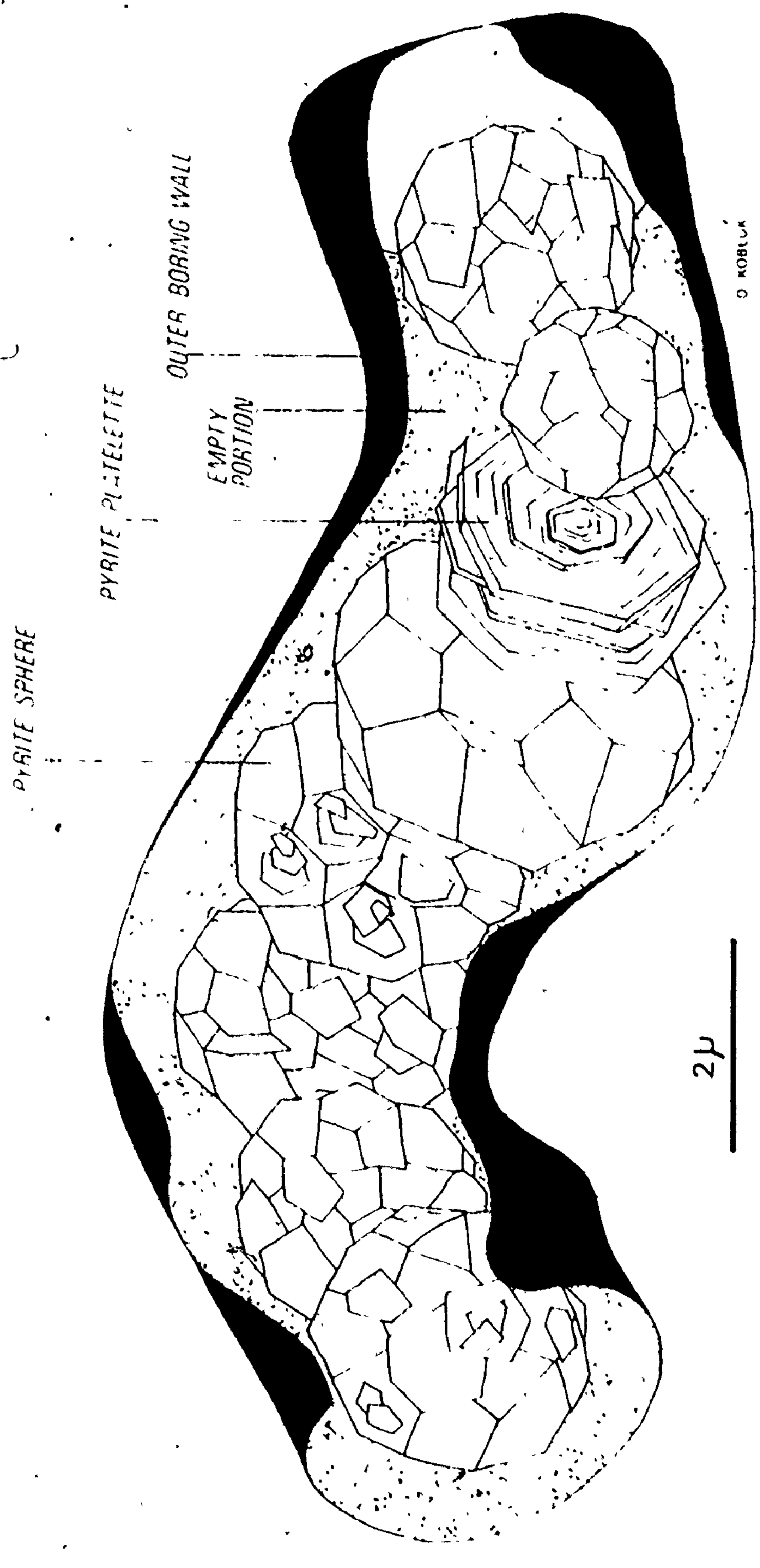
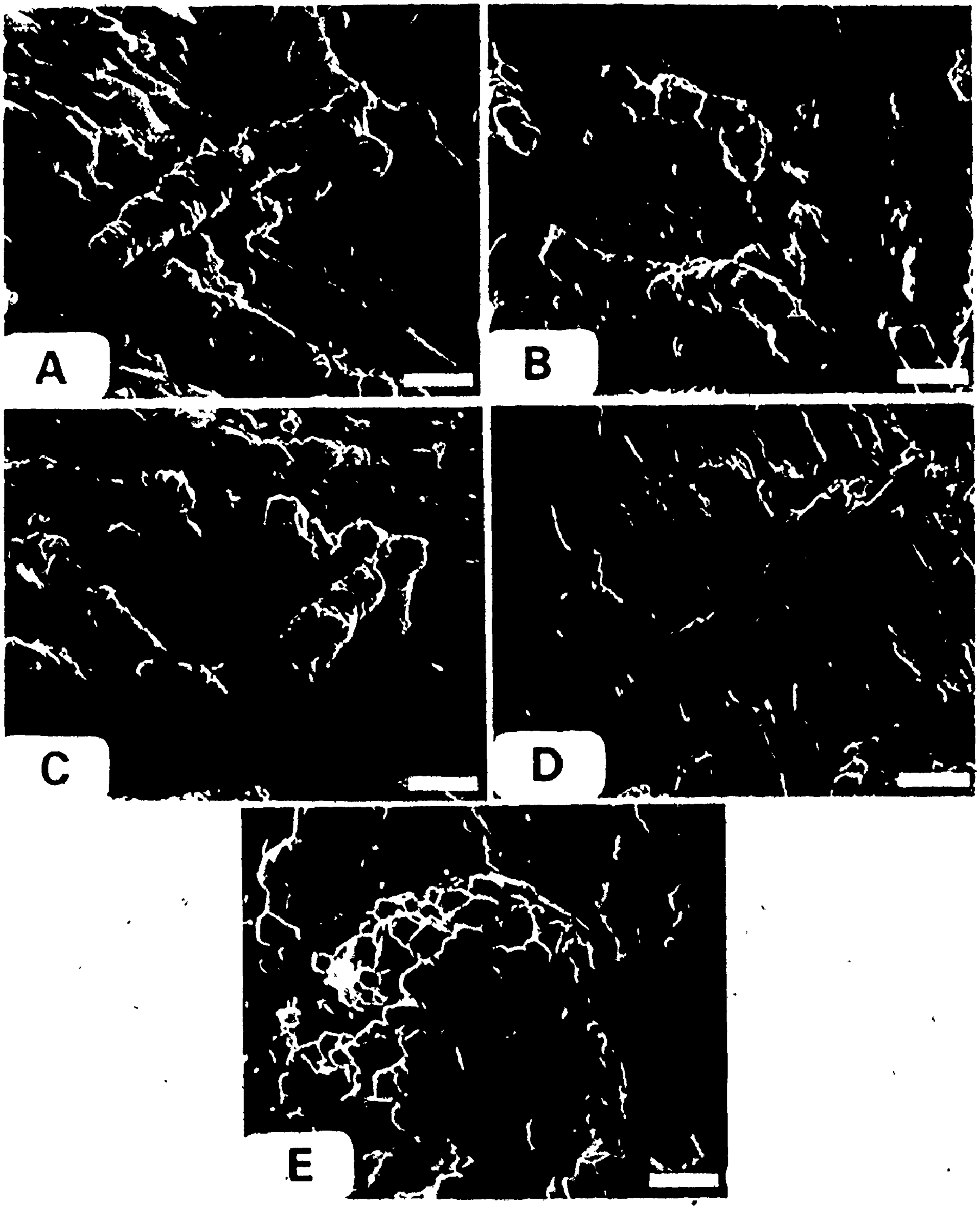
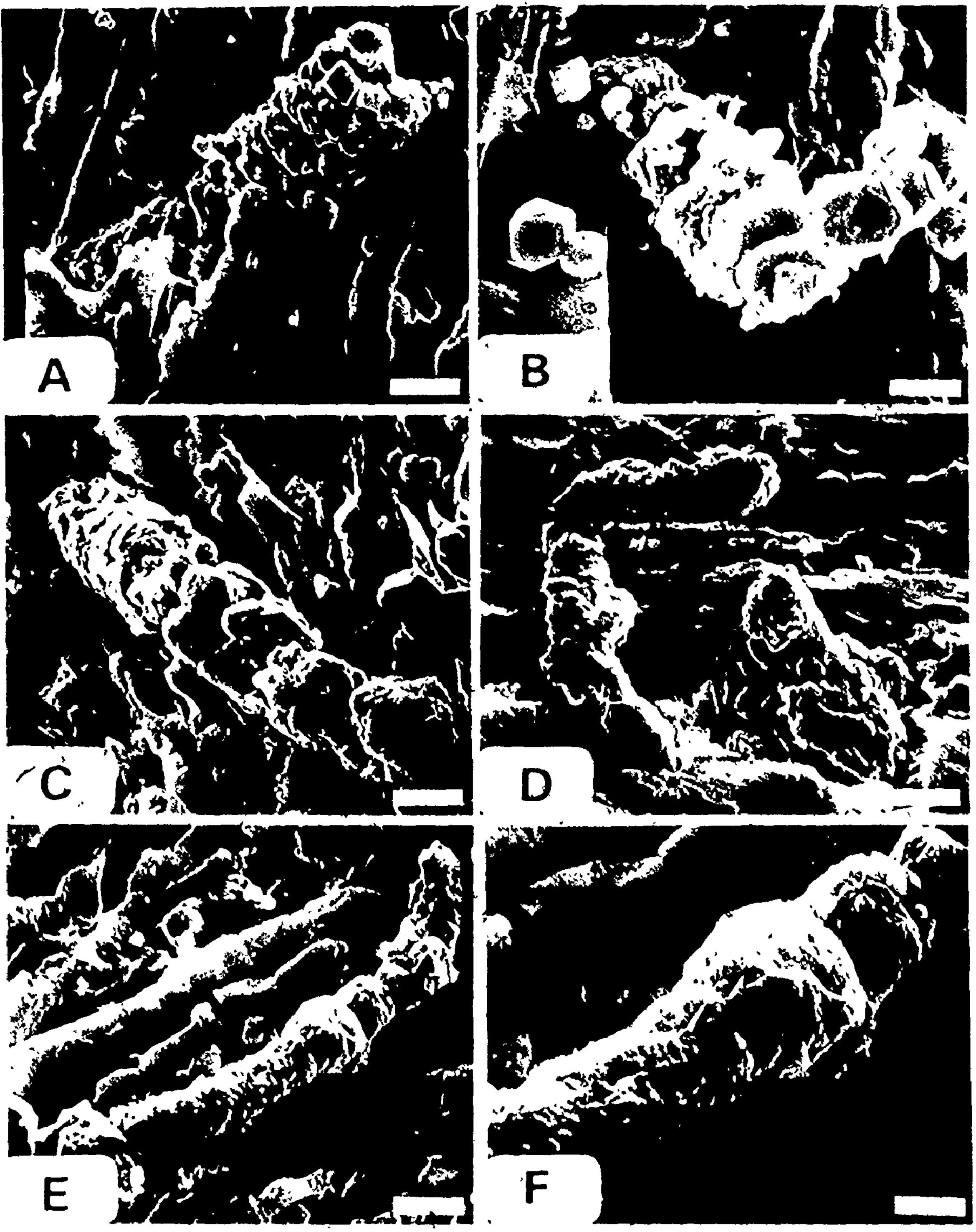

OUTER BORING WALL
EMPTY PORTION
PYRITE PLATELETTE
PYRITE SPHERE
D KOBLUK
2μ

FIGURE 4-5 Pyrite-infilled borings in Plaesiomys from the upper Ordovician near Cincinnati, Ohio. a, b, c, d) Pyrite-infilled branching borings of tightly packed pyritohedra, dodecahedra, octahedra, plateletts, and spheres. Scale bars 5 um, 5 um, 10 um, and 5 um, respectively. e) Pyrite framboid. Scale bar 5 um.


A
B
C
D
E

C?

FIGURE 4-6 Pyrite-infilled algal borings in *Hebertella* from the upper Ordovician. a) Tightly-packed pyrite octahedra, pyritohedra, and plateletts, which in aggregate duplicate the algal filament. Scale bar 5 um. b) Algal boring filled in with plateletts, framboids, and octahedra. Scale bar 2 um. c) Tightly-packed framboids and extremely fine pyrite crystals. Scale bar 5 um. d, e, f) Very tightly-packed pyrite crystals, some of them extremely fine, closely duplicating the original filament morphology. Scale bars 5 um, 5 um, and 2 um, respectively


A
B
C
D
E
F

and 90°, with a mean of 65° (600 measurements). The borings are generally filled or partially filled with pyrite, but some are almost completely empty (Figs. 4-1; 4-2). Infilling by micrite carbonate, and micritization of the bore walls (Bathurst, 1971), did not occur. The borings are ramose, often gently curved, rarely straight (Fig. 4-1); individual borings are variable in diameter (a characteristic of some endolithic algae). The borings vary from about 1.5 um to 10 um in diameter, and attain lengths of up to 600 um.

The pyrite occurs as rare cubes, and commonly as octahedra, trapezohedra, and various iron cross twins of octahedra and pyritohedra. Plate-like clusters of twinned cubes and octahedra are also found. Small framboids (1 um-10 um) are common within the borings and often occur in chains, either touching directly or connected by smaller crystals (Figs. 4-3; 4-4). Aggregates of small (1 um-2 um) framboids are also seen. Larger, isolated framboids (to 30 um) consisting of octahedral pyrite crystals occur outside the borings within the shell (Fig. 4-5e). The pyrite crystals and framboids outside or within the borings rarely touch the bore wall or brachiopod shell material; there is generally a small space (1 um to 3 um) between the pyrite and the wall (Figs. 4-6a, b).

The pyrite reproduces with variable fidelity the gross morphology of the original filaments. Five basic types are found:

1) Pyritized filaments consisting of tightly-packed pyritohedra and spheres, producing rough-surfaced strands; they may or may not show branching. Individual crystals vary from 0.1 um to 1.0 um. The filament diameters may reach 1 um to 5 um, with lengths of 100 um observed.

2) Chains of pyrite framboids, or clusters of framboids arranged in chain-like series. The chains may be several hundred

microns long, and commonly branch. Individual spheres and framboids are 3 um to 10 um in diameter; chains may vary from 2 um to 10 um in diameter.

3) Chains of pyritohedra, rare cubes, octahedra, trapezohedra, and plateletes, reaching up to 600 um in length. The chain diameter is about 5 um; individual crystals vary between 0.5 um and 2 um in size.

4) Smooth, pyritized filaments; no individual crystals can be seen. The crystals are either too tightly packed, or are too small to be seen. The filament diameter is very consistent, at 2 um to 2.5 um; the surface is very regular and smooth. These structures are very rare.

5) Isolated pyrite framboids, from 5 um to 30 um in diameter, with a mean diameter of about 7 um (100 measurements). The framboids are made up of pyritohedra, or more commonly, octahedra. They are generally spherical to slightly ellipsoidal. These are virtually identical to the framboids described by many other authors from different sediments (Berner, 1970; Sweeney and Kaplan, 1973; Rickard, 1970).

4.4 DISCUSSION

The false ramification seen in some filaments, dichotomous branching, irregularity of the borings, and several other features described above suggest algal boring activity (Bromley, 1965), of a type unknown. The possible presence of associated fungi cannot be ruled out, as they are common borers (Kohlmeyer, 1969), and parasitic on some endolithic algae in some substrates (Lukas, 1973); some fungi date from the Ordovician (Tiffney and Barghoorn, 1974).

Preserved endolithic filaments, replaced filaments, and empty unaltered microphytic borings are rare in lower Paleozoic carbonates. Hessland (1949) described preserved and replaced algal filaments from the lower Ordovician; Kobluk and Risk (1974) described preserved endolithic algal or fungal filaments from the Upper Devonian of Western Canada. The borings in the fossil brachiopods described here, however, do not contain preserved filaments; the borings are empty, or the general form of the filament is preserved in pyrite.

Various workers have discussed sedimentary pyrite formation. Roberts et al. (1969) proposed the direct reaction of iron monosulfide (FeS) with elemental sulfur to produce pyrite; in this model the reaction can take place in an aerobic environment. There is, however, no evidence to support the operation of this process in nature.

The pathway which has been best studied and which can account for most sedimentary pyrite formation is that involving hydrogen sulfide (H_2S) and bacterial reduction. Berner (1970) summarized the process (further discussion by Trudinger et al., 1972):

1) Organisms die, and contribute organic matter.
2) Quiet water conditions develop.
3) Fine grained organic materials (eg; clays) contain or absorb iron.
4) Neutral or slightly acidic pH is present.
5) Organic matter is aerobically metabolized, producing a micro-environment depleted in oxygen.
6) Hydrogen sulfide is produced by anaerobic bacterial sulfate reduction.

7) Iron monosulfide is produced by the reaction of iron with water.

8) Hydrogen sulfide is oxidized to produce elemental sulfur.

9) Elemental sulfur oxidizes to sulfate; some sulfur combines with iron monosulfied to form pyrite, which may crystallize as individual crystals or as framboids.

Within the quiet, protected environment of the borings in the brachiopod valves, all the above conditions could easily have been met. Organic material required in the process was readily available when the algae died. The iron was available from many sources, including the brachiopod valves themselves, though this could account for only a small fraction of the total iron; other sources include sea water, clay particles, and the dead algal material. Local physiochemical conditions determined which crystal form of pyrite would develop.

Time is not a problem. Berner (1970) showed that the pyritization process occurs relatively rapidly, within a few years in the presence of hydrogen sulfide and elemental sulfur. Paleoenvironmental conditions in the Richmond were aerobic at the sediment surface. Therefore, while algal boring took place at or near the sediment surface, pyrite precipitation probably began after the valves were buried. This was found to be the case in Recent bivalves studied by Srivastava (1975), in which vacated algal borings were partly or wholly filled by framboidal pyrite; the pyrite was found in shells only after burial at 4 cm-7 cm below the substrate surface.

Some workers argue that not all framboidal pyrite and other sedimentary pyrite is produced through organic processes (Berner, 1969; Farrand, 1970; Sweeney and Kaplan, 1973). In the borings described here, however, the association between filament morphology and occurrence, and pyrite development, is far too strong to suggest that organic materials and processes were not involved to some important degree. It is suggested that the pyrite precipitated either around an organic nucleus, such as a bacterium (Massaad, 1974) or algal cell or other organic membrane (Farrand, 1970). The pyrite crystals and framboids are not considered microfossils themselves in any way, as has been suggested by Love (1957) and Schneiderhöhn (1923). It is not possible to say with any certainty whether the pyrite crystallized around or within an organic structure; the presence of empty space almost completely encircling framboids anc crystals within borings suggests, however, that an organic coating around the crystallizing structures may indeed have been present, and has since disappeared. Both Sweeney and Kaplan (1973) and Farrand (1970) considered such organic coatings or membranes around framboids as both a controlling surface and a protective cover against corrosion. The coating could have been of many forms, such as Farrand's (1970) hydrophobic organic coating or even bacterial or algal cell walls. There are, however, a few examples among the framboids studied of small framboids encircling segments of pyritized algal thalli. Though perhaps coincidental, and by no means common, these suggest that at least some of the pyrite may have developed using segments of algal filaments as nuclei.

The occurrence of long chains of framboids and crystals within bores suggest that crystallization was either directly related to bacterial growth during the breakdown of tha algal filaments themselves, or a combination of both. In some examples, the fidelity with which the pyrite has duplicated the algal filament morphology (Figs. 4-6e, f) argues in favour of direct precipitation within, or on, the filaments themselves;

in other examples, the development of clusters and framboidal aggregates in chains within the borings suggests precipitation within, or about, bacteria, as suggested by Massaad (1974). In the former, it is not suggested that viable algal filaments were precipitating pyrite, but rather that precipitation took place after death and burial of the valves, probably through the intermediate activity of bacteria as proposed by Berner (1970) and others.

CHAPTER 5

SUMMARY AND CONCLUSIONS

Endolithic algal infestation and breakdown of crystals of Iceland spar calcite placed in 5 locations in the subtidal (60 cm) nearshore marine environment along the coast at Discovery Bay Jamaica, was monitored with time. The infestation of crystals placed in sea water tanks at McMaster University was also monitored for comparison and control.

Infestation of the Iceland spar by marine filamentous endolithic (boring) algae proceeded at about 3 times the rate in the crystals studied from Jamaica compared to those from the sea water tanks. This difference is considered to be due mainly to the lower level of illumination in the tanks.

The curve of infestation (measured as percentage of the surface area of the crystals infested by endolithic algae) versus time is very similar to a normal population growth curve (Fig. 2-4). In the nearshore tropical marine environment of Jamaica (installation 1), infestation takes place slowly for the first 15 days (increasing 0.25% per day) and then increases rapidly (increase of 0.93% per day) for the next 80 days, when the rate of infestation begins to level off; 100% surface infestation was achieved 213 days after the crystals were placed in the sea.

Under a light sand cover, (installation 2) initial infestation is retarded and the rate of infestation is reduced, probably as a function of decreased illumination below the sand, and reduced initial algal recruitement. A supratidal pool (installation 3) with minimal sea water exchange, which became clouded and slightly hypersaline, showed very early (less than 1 day) initial infestation. The success of endolithic algae in pools and pockets may be a key factor in nearshore phytokarst and solution pit development. Conditions of restricted circulation and quiet water are also favourable environments for endolithic algal infestation; the algal populations begin infestation very early and grow rapidly. Agitated environments, generally considered unfavourable by other workers for settlement and development of endolithic algal populations, may in certain cases be highly favourable for infestation by endoliths. Highly abrasive or extremely agitated substrates may, however, be unfavourable, preventing initial settlement and resulting in abrasion and removal of endolithic microphytic populations that do develop during quiescent periods.

Endolithic algal infestation of Iceland spar below the sediment surface proceeds at a comparatively extremely slow rate, if at all. The substrate rods buried in the sediment in the "Blue Hole" at Discovery Bay showed no algal infestation of the spar, except at the sediment surface, to a depth of 60 cm for 12 months. Algae therefore, may not be active endoliths more than a few centimeters below the sediment surface. The crystals monitored in installation no. 2 indicate that endolithic algae are active at least 1 cm below the sediment surface; the crystals on the substrate rods show that at greater depths in the sediment, boring algae are inactive. Endolithic fungi are known to be active below the sediment surface, and even deeply buried within rock, but the fungi never penetrated any spar crystals (probably due to the absence of an organic matrix in the crystals).

The absence of any endolithic algal activity below the sediment surface may be a function of the inability of algae to bore in the subsurface environment or of extremely slow algal recruitement rates. It seems unlikely that slow recruitement rates are involved, as certainly some signs of initial infestation should have been noticed during the 12 month period, when, considering the rapid infestation rates at the surface. If the algae cannot bore at any depth greater than a few centimeters below the sediment surface, then heterotrophic activity should be ruled out as significant among the endolithic algae. The dominance of live endolithic fungi in deep water where light levels are reduced, and within bores and the above observations, argue in favour of light dependancy of endolithic algae. The most important conclusions to be drawn from a realization of light dependancy are:

1) Endolithic algae may be a reliable indicator of photic environments.
2) Most, if not all, endolithic algae infestation of grains occurs while the grains are at, or immediately below, the sediment surface. When coupled with variations in rates of infestation due to the light reducing effects of increased water depth, this may provide an index of the relative length of time algal-bored grains remain at the substrate surface.

The crystallography of the substrate exercises strong control over filament orientation during initial infestation; crystallographic control becomes weaker as the filament density increases.

Not all borings contain living filaments. During the earliest stages of infestation (first 15 days), 90%-100% of the borings contain living filaments; as infestation proceeds, the proportion of borings housing live filaments drops to about 5%-10% (95-257 days). At the advancing boring front within the crystal, the proportion of living filaments remains high, but decreases as the front moves deeper and the boring density increases.

Residue micrite, previously considered strictly a feature of temperate $CaCO_3$ undersaturated waters, or subaerial meteoric diagenesis, is found in tropical $CaCO_3$ saturated waters as well. The micritization process takes place beneath a mucous coat, probably due to slightly acid conditions favouring selection leaching of the substrate.

The micrite observed forming as early as 95 days after Iceland spar was placed in the sea in Jamaica, consists of a porous microcrystalline fabric of micrite-size particles, a residue of selective leaching of the original substrate.

Early stages in the formation of micrite tubules, leading to the development of micrite envelopes such as described by Bathurst (1966) were observed in the Iceland spar crystals. Vacated algal borings within the spar commonly show precipitated low Mg calcite on the boring walls by 95 days after placement in the sea. None of the borings are filled completely by micrite even up to 257 days, though an estimated 25% by volume of the boring is filled by 257 days. How long complete infilling would take can only be estimated by projecting the observed rates, giving an estimated 3 years to complete infilling.

Filaments of <u>Ostreobium</u> sp. project out of the Iceland spar crystals into the sea, and become completely calcified (cemented) within 65 to 95 days after placement. Calcification occurs only upon dead filaments by the precipitation of small micrite-size crystals around the exterior and in the interior of the thallus. Crystal precipitation begins inside the thallus and may be partly contemporaneous with, or precede, external calcification.

Calcified filaments broken off from the surface of a grain will contribute to the accumulation of carbonate sediment in the area. Further reduction of the filaments by abrasion or further boring activity, grinding within the guts of deposit feeders, etc., will produce silt and micrite size material. If all the filaments are broken off, then sediment contributions in the range of 1 cm^3 / m^2 / yr may be produced.

The coalescence of the micrite encrustations about exposed filaments in a dense population could produce a micrite envelope of the type commonly found coating bored and micritized grains. The mode of formation of such "constructive" envelopes is not the same as described for the formation of "destructive" micrite envelopes by Bathurst (1966, 1971); the envelope develops outside rather than inside the substrate. Through this process, the generation of at least some micrite envelopes could be very rapid, perhaps occurring within a year or a few years.

Constructive micrite envelopes, produced by the coalescence of masses of calcified exposed algal filaments, appear to be relatively common in marine carbonate sediments throughout the Phanerozoic. The development of constructive micrite envelopes is not an isolated phenomenon, but may and often does, occur in conjunction with other micritization processes such as boring-infilling, residue micritization, and others.

In agitated environments where grains are constantly being moved, it is unlikely that constructive envelopes ~~will~~ develop. However, short periods of quiescence, in the order of weeks or months is sufficient to allow intergranular algal filaments to grow, and some to become calcified. These filaments stabilize the sediment and in some cases, prevent remobilization, thereby allowing further calcification of filaments, micrite envelope formation, and the complete to partial filling of intergranular pores by calcified algal filaments and associated micrite and microspar cement.

The process of filament calcification and sediment stabilization by calcified algae is summarized in Fig. 5-1.

Algal borings in the articulate brachiopods Plaesiomys subquadrata (?) Hall and Hebertella sinuate (?) Hall, from the Richmond formation of Ohio, are empty or partially to wholly filled with pyrite; it occurs as framboids, spheres, platelettes, trapezohedra, octahedra, pyritahedra, rare cubes, and iron cross twins of octahedra and pyritahedra. The pyrite is found as isolated framboids outside the algal borings in the brachiopod shell, or in chains of framboids and single crystals within the borings. The gross morphology of the borings is reproduced with variable fidelity by the pyrite.

The borings provide insight into the early diagenetic history of the Richmond sediments. Though the borings were produced either while the brachiopods were alive or shortly afterwards (probably in the photic zone), pyritization did not take place until immediately after burial; pyritization may have taken only a few years.

Pyrite was precipitated in the borings in a quiet, protected environment; whether the system was open or closed in unknown. The mechanism of pyrite precipitation was probably the same as that proposed by Berner (1970), and involved anaerobic sulfur-reducing bacteria.

Pyrite precipitated around an organic nucleus, such as a bacterium or algal cell, or developed within an organic structure such as an algal cell or organic membrane.

Major Effects Of The Endolithic Algae

The biological effects of endolithic algae are largely unknown. Though it has yet to be demonstrated, many workers hold the view that boring algae may be a nutrient source (either directly or indirectly exploited) for grazers cropping surface algae (and which pull up substrate in the process) and "crunchers" such as urchins and parrot fish (Fig. 5-2). There is also some evidence that epidemic infestation of shelled populations such as barnacles may be responsible for mass mortality in modern and also some ancient populations.

The geological effects of the boring algae are diverse and significant. They are probably very important in the geochemical stability and the alteration of high and low Mg calcite and aragonite through the influence of metabolites. How organic-chemical metabolic processes alter carbonate substrates is unknown as are the major results of such alteration; yet the boring algae probably do significantly affect the substrate. What remains to be worked out is the "what" and "how" of the metabolic effects.

The remaining major geologic effects, summarized in Figure 5-2, may be grouped as destructive or constructive, judged on the basis of the influence on the substrate. Porosity is both enhanced by boring activity, and reduced by bore hole infilling, and cementation of intergranular filaments and constructive envelope formation. Permeability is probably enhanced and reduced in the same manner, although it has yet to be proven.

The influence of boring algae in destructive micrite envelope formation by boring infilling is well known, as are many of the related processes such as internal grain preservation, etc., resulting from the process. Constructive micrite envelopes produced by calcified filaments about the grain exteriour will also form given the right conditions; they may also form together with destructive envelopes, even on the same grain.

Boring algae contribute to the sediment accumulation in an area by weakening and breaking down substrates. The calcified exposed algal filaments, however, when broken off the substrate, will contribute micrite and peloidal sediment in significant amounts. They may be an important source of much of the micrite and peloids found within reef structures themselves.

The end result of much algal boring in carbonate substrates, particularly grains, will be the complete breakdown of the grain to mud or finer material, or wholesale micritization. Fully micritized grains resemble pellets and may in fact be termed only peloids, unless the original skeletal nature is demonstrated -- quite often a difficult if not impossible task.

FIGURE 5-1 Sequence of development of micrite-infilled algal borings, calcified algal filaments, and intergranular calcified filaments in carbonate sediment.

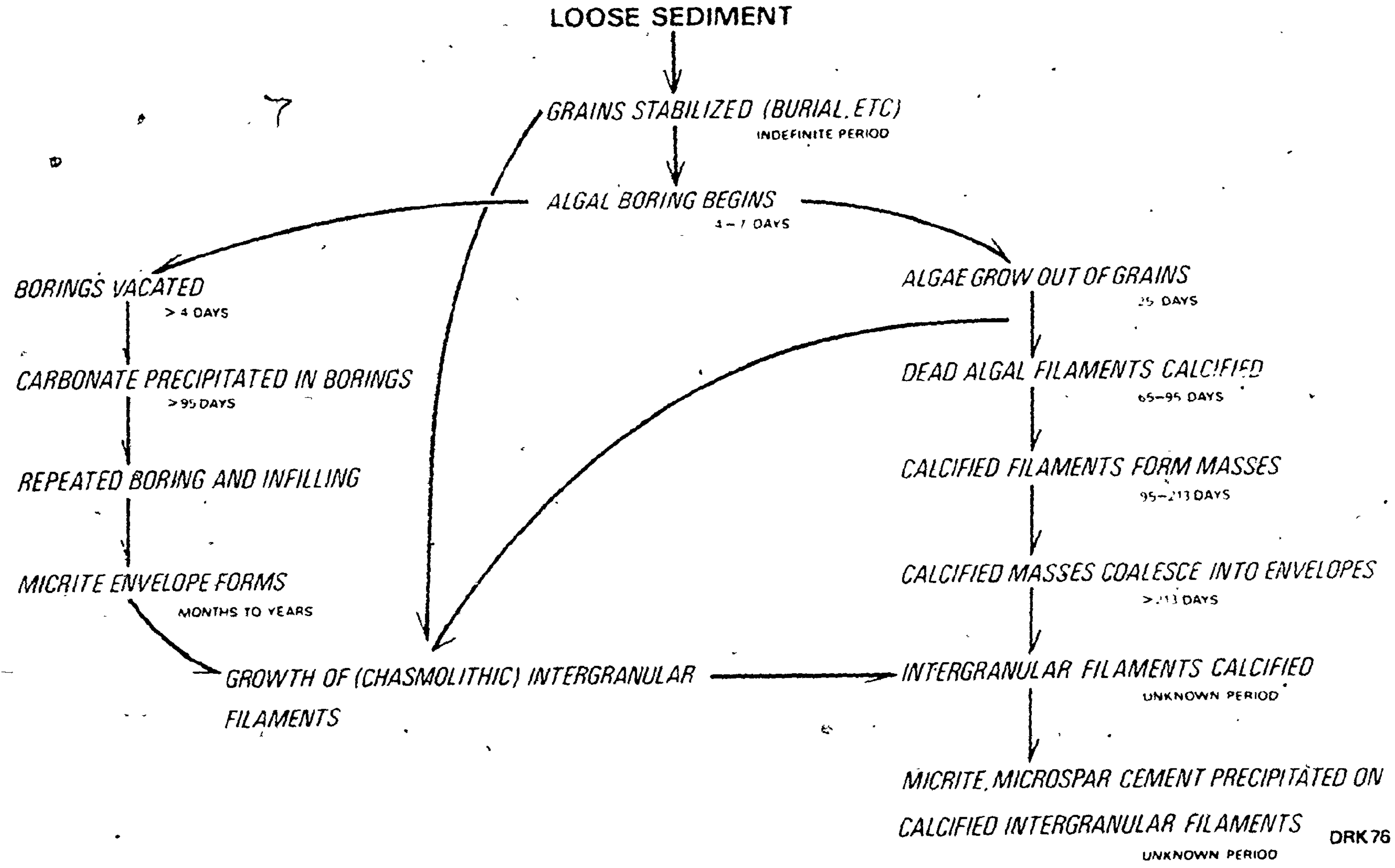

LOOSE SEDIMENT
GRAINS STABILIZED (BURIAL, ETC)
INDEFINITE PERIOD
ALGAL BORING BEGINS
1–7 DAYS
BORINGS VACATED
> 4 DAYS
CARBONATE PRECIPITATED IN BORINGS
>95 DAYS
REPEATED BORING AND INFILLING
MICRITE ENVELOPE FORMS
MONTHS TO YEARS
GROWTH OF (CHASMOLITHIC) INTERGRANULAR FILAMENTS
ALGAE GROW OUT OF GRAINS
25 DAYS
DEAD ALGAL FILAMENTS CALCIFIED
65–95 DAYS
CALCIFIED FILAMENTS FORM MASSES
95–213 DAYS
CALCIFIED MASSES COALESCE INTO ENVELOPES
>213 DAYS
INTERGRANULAR FILAMENTS CALCIFIED
UNKNOWN PERIOD
MICRITE, MICROSPAR CEMENT PRECIPITATED ON CALCIFIED INTERGRANULAR FILAMENTS
UNKNOWN PERIOD
DRK76

FIGURE 5-2 Summary of the major geological and some of the biological effects of the endolithic algae.

GEOLOGICAL EFFECTS OF ENDOLITHIC ALGAE

CONSTRUCTIVE	DESTRUCTIVE
● POROSITY REDUCTION	● POROSITY ENHANCEMENT
● PERMEABILITY REDUCTION	● PERMEABILITY ENHANCEMENT
● GENERATION OF MICRITE ENVELOPE BY EXTERNAL CALCIFICATION	● GENERATION OF MICRITE ENVELOPE BY BORING AND INFILLING
● SEDIMENT PRODUCTION BY CALCIFICATION AND BREAKAGE OF FILAMENTS	● SEDIMENT PRODUCTION BY BORING AND BREAKDOWN OF SUBSTRATES
	● WHOLESALE OR PARTIAL MICRITIZATION

- ALTERATION OF CARBONATE STABILITY FIELD BY METABOLITES

BIOLOGICAL EFFECTS OF ENDOLITHIC ALGAE

- NUTRIENT SOURCE FOR GRAZERS, CRUNCHERS
- MORTALITY IN SHELLED POPULATIONS CAUSED BY EPIDEMIC INFESTATION

REFERENCES

Alexander, C.S., 1961, The marine terraces of Aruba, Bonaire and Curacao, Netherlands Antilles: Ann. Ass. Amer. Geogr., v. 51, p. 102-123.

Alexandersson, E.T., 1972, Micritization of carbonate particles: processes of precipitation and dissolution in modern shallow-marine sediments: Geol. Inst. Univ. Uppsals, Bull. n.s., v. 3, p. 201-236.

Alexandersson, E.T., 1974, Carbonate cementation in coralline algal nodules in the Skagerrak, North Sea: biochemical precipitation in undersaturated waters: Jour. Sedimentary Petrology, v. 44, p. 7-26.

Alexandersson, E.T., 1975, Marks of unknown carbonate-decomposing organelles in cyanophyte borings: Nature, v. 254, p. 212, 237-238.

Balsam, W.L., 1973, Ecological interactions in an early Cambrian archaeocyathid reef commumity: Ph.D. thesis, Brown Univ., 131p.

Barron, E.J., 1975, The role and preservability of algal influence in the formation of fresh water marl: Geol. Soc. Amer. Abstracts with Programs, v. 7, no. 7, p. 990-991.

Bathurst, R.G.C., 1966, Boring algae, micrite envelope, and lithification of molluscan biosparites: Geol. Jour., v. 5, p. 15-32.

Bathurst, R.G.C., 1971, Carbonate sediments and their diagenesis: Developments in Sedimentology 12, Amsterdam, Elsevier Pub. Co., 620p.

Bathurst, R.G.C., 1975, Carbonate sediments and their diagenesis, 2nd ed: Developments in Sedimentology 12, Elsevier, Amsterdam, 658p.

Berner, R.A., 1969, The synthesis of framboidal pyrite: Econ. Geol., v. 64, p. 383-384.

Berner, R.A., 1970, Sedimentary pyrite formation: Am. Jour. Sci., v. 268, p. 1-23.

Bertram, G.C.L., 1937, Some aspects of the breakdown of coral at Ghardaga, Red Sea: Proc. Zool. Soc. London (for 1936), p. 1011-1026.

Boekschoten, G.J., 1966, Shell borings of sessile epibiotic organisms as paleoecological guides (with examples from the Dutch coast): Paleogeog. Paleoclimat. Paleoecol., v. 2, p. 333-379.

Bornemann, J.G., 1886, Die Versteinerungen des Cambrischen Schichten-Systems der Insel Sardinien nebst versleichenden Untersuchungen über analoge Vorkommnisse aus andern Landern: Erst. Abt. Ksl. Leop. -Carol. Deut. Akad. Naturforsch., v. 51, p. 1-147.

Bowerbank, J.S., 1842, On the organic tissues in the bony structure of of the Corallidae: Phil. Trans. Roy. Soc. (London), v. 132, no. 1, p. 215-224.

Bricker, O.P., Ginsburg, R.N., Land, L.S., and Mackenzie, P.T., 1969, Carbonate cements: Bermuda Biol. Stat. for Research Spec. Publ. 3, 325p.

Bromley, R.G.C., 1965, Studies in the lithology and conditions of sedimentation of the Chalk rock and comparable horizons: Ph.D. thesis, Univ. London, 355p.

Bromley, R.G.C., 1968, Burrows and borings in hardgrounds: Medd. Dansk. Geol. Foren., v. 18, p. 247-250.

Bromley, R.G., and Tendal, O.S., 1973, Example of substrate competition and phobotropism between two clionid sponges: Jour. Zoology, v. 169, p. 151-155.

Carpenter, W., 1845, On the microscopic structure of shells: Rept. Brit. Assoc. Adv. Sci. (for 1844), v. 14, p. 1-24.

Carriker, M.R., and Smith, E.H., 1969, Comparative calcicavitology: summary and conclusions: Am. Zool., v. 9, p. 1011-1020.

Chodat, R., 1898, Études de biologie lacustre: Bull. Herb. Boissier, v. 6, p. 431-476.

Clark, T.H., 1972, Montreal area: Quebec Min. Nat. Res. Geol. Rept. 152, 244p.

Cloud, Jr., P.E., 1962, Environment of calcium carbonate deposition west of Andros Island, Bahamas: U.S. Geol. Surv., Prof. Paper, 350, p. 1-138.

De Buisonjé, P.H., 1974, Neogene and Quaternary geology of Aruba, Curaçao and Bonaire: De Boer-Cuperus b.v., Ultrecht, 293p.

Drew, G.H., 1914, On the precipitation of calcium carbonate in the sea by marine bacteria, and on the action of denitrifying bacteria in tropical and temperate seas: Papers Tortugas Lab., Carnegie Inst. Wash. Publ., no. 182, p. 7-45.

Drew, K.M., 1954, Studies in the Bangioidea. III. The life history of Porphyra umbilicalis (L) Kurz. var. lacinata (lightf.) Jour. Ag., Ann. Bot. m.s., v. 18, p. 183-211.

Duerden, J.E., 1902, Boring algae as agents in the disintegration of corals: Amer. Mus. Nat. History Bull., v. 16, p. 322.

Duncan, P.M., 1876, On some thallophytes parasitic within Madreporaria: Roy. Soc. Lond Porc., v. 25, p. 238-257.

Duncan, P.M., 1881, On some remarkable enlargements of the axial canals of sponge spicules and their causes: Jour. Roy. Microscop. Soc., Ser. 2, v. 1, p. 557-572.

Ercegović, A., 1925, Litofitška vegetacija vopnenace i dolomita u Hrvatskoj (La végétation des lithophytes sur les calcaires et des dolomites en Croatie) (in Croation with French summary): Acta Bot. Inst. Bot. Univ. Zagreb, v. 1, p. 64-114.

Eutsler, R.L., 1970, Algal borings, homogenization, and porosity in Recent limestone in the lower Florida Keys (Abstract): Geol. Soc. Amer. Abstracts with Programs, v. 2(3), p. 207-208.

Farrand, M., 1970, Framboidal pyrite precipitated synthetically: Miner. Deposit., v. 5, p. 237-247.

Frémy, P., 1935, Contribution à la physiologie des thallophytes marins perforants et cariant les roche calcaires et les coquilles: Ann. Inst. Oceanog. (Paris), v. 22, p. 107-143.

Frémy, P., Dangeard, L., 1935, Sur la position systématique des Girvanelles: Soc. Linn. Normandie, Bull., v. 8, p. 101-111.

Fogg, G.E., 1962, Extracellular Products. IN R.A. Levin (ed.), Physiology and Biochemistry of the Algae: Academic Press, New York.

Folk, R.L., 1959, Practical petrographic classification of limestones: Bull. Amer. Assoc. Petroleum Geologists, v. 43, p. 1-38.

Folk, R.L., 1965, Some aspects of recrystallization in ancient limestones: IN L.C. Pray and R.C. Murray (eds.); Dolomitization and Limestone diagenesis: A Symposium-Soc. Econ. Paleontologists and Mineralogists, Spec. Publ., 13, p. 14-48.

Foster, J.W., 1949, Chemical Activities of Fungi: Academic Press, New York.

Friedman, I., 1964, Progress in the biological exploration of caves and subterranean waters in Israel: Internat. Jour. Speleology, v. 1, p. 30-33.

Friedman, G.M., 1964, Early diagenesis and lithification in carbonate sediments: Jour. Sedimentary Petrology, v. 34, p. 777-813.

Friedman, G.M., Gebelein, C. and Sanders, J.E., 1971, Micritic envelopes of carbonate grains are not exclusively of photosynthetic algal origin: Sedimentology, v. 16, p. 89-96.

Fuchtbauer, H., 1969, Lithification of carbonate sediments: Sedimentology, v. 12, p. 7-159.

Garrett, P., Smith, D.L., Wilson, A.O., and Patriquin, D., 1971, Physiography, ecology, and sediments of two Bermuda patch reefs: Jour. Geol., v. 79, p. 647-668.

Gebelein, C.D. and Hoffman, P., 1971, Algal origin of dolomite in interlaminated limestone-dolomite sedimentary rocks: IN O.P. Bricker (ed.), Carbonate Cements, The Johns Hopkins University Studies Geology, v. 19, p. 319-326.

Geitler, L., 1930, Cyanophyceae (Blaualgen) Deutschlands, Österreichs und der Schweiz mit Beruchsichtigung der ubrigen Lander Europa soule der angrezendem Mecresgebiete: Rabenhorst's Kryptogamen Flora. Bd. 14, Akademische Verlagsgesellschaft m.b.H., Leipzig.

Ginsburg, R.N., 1956, Environmental relationships of grain size and constituent particles in some south Florida carbonate sediments: Am. Assoc. Petroleum Geologists, Bull., v. 40, p. 2384-2427.

Ginsburg, R.N., Shinn, E.A., and Schroeder, H.H., 1968, Submarine cementation and internal sedimentation within Bermuda reefs (Abstract): Geol. Soc. Amer. Spec. Papers. 115, p. 78-79.

Ginsburg, R.N., and Schroeder, H.H., 1969, Recent synsedimentary cementation in Subtidal Bermuda reefs: IN O.P. Bricker et al, Carbonate Cements, Bermuda Biol. Stat. for Research, Spec. Publ. 3, p. 31-34.

Ginsburg, R.N., Marszalek, D.S., and Schneidermann, N., 1971, Ultrastructure of carbonate cements in a Holocene algal reef of Bermuda: Jour. Sedimentary Petrology, v. 41, p. 472-282.

Glover, E.D. and Pray, L.C., 1971, High magnesium calcite and aragonite cementation within modern subtidal carbonate sediment grains: IN O.P. Bricker (ed.), Carbonate Cements, The Johns Hopkins University, Studies in Geology, v. 19, p. 80-87.

Golubic, S., 1969, Distribution, taxonomy, and boring patterns of marine endolithic algae: Am. Zool., v.9, p. 747-751.

Golubic, S., 1973, The relationship between blue-green algae and carbonate deposits: IN N.G. Carr and B.A. Whitton (eds.). The Biology of the Blue-Green Algae, Univ. California Press, Berkely, p. 434-473.

Golubic, S., Perkins, R., and Lukas, K.J., 1975, Boring microorganisms and microborings in carbonate substrates: IN R.W. Frey (ed.), The Study of Trace Fossils, New York, Springer Verlag, Inc., p. 229-260.

Goreau, T.F., 1959, The ecology of Jamaican reefs. 1. Species composition and zonation: Ecology, v. 40, p. 67-90.

Goreau, T.F. and Goreau, N.I., 1973, The ecology of Jamaican coral reefs, II. Geomorphology, zonation, and sedimentary phases: Bull. Mar. Sci., v. 23, p. 399-464.

Goreau, T.F. and Land, L.G., 1974, Fore-reef morphology and depositional processes, North Jamaica. IN L.F. Laporte (ed.), Reefs in Time and Space, Soc. Econ. Paleontologists and Mineralogists, Spec. Publ., 18, p. 77-89.

Greenfield, L.J., 1963, Metabolism and concentration of calcium and magnesium and precipitation of calcium carbonate by a marine bacterium: Ann. N.Y. Acad. Sci., v. 190, p. 23-45.

Gunatilaka, A., 1976, Thallophyte boring and micritization within skeletal sands from Connemara, western Ireland: Jour. Sedimentary Petrology, v. 46, p. 548-544.

Gygi, R.A., 1975, Sparisoma viride (Blnnaterre), the Stop Light Parrotfish, a major sediment producer on coral reefs of Bermuda?: Eclogae geol. Helv., v. 68, p. 327-359.

Halldal, P., 1968, Photosynthetic capacities and photosynthetic action spectra of endozoic algae of the massive coral Favia: Biol. Bull., v. 34, p. 411-424.

Halsey, S.D., 1970, Distribution and significance of marine boring endolithic algae and fungi in sediments of the North and South Carolina continental margin: M.A. thesis, Duke Univ., Durham, N.C., 85p.

Hessland, I., 1949, Investigation of the Lower Ordovician of the Siljan District, Sweden, II. Lower Ordovician penetrative and enveloping algae from the Siljan District: Geol. Inst. Univ. Uppsala, Bull., v. 33, p. 409-428.

Hinde, G.J., 1887, Review of Bornemann (1887): Geol. Mag., Dec. 3, v. 4, p. 226-229.

James, N.P., 1972, Late Pleistocene reef limestones, northern Barbados, W.I.: Ph.D. thesis, McGill Univ., Montreal.

James, N.P., Ginsburg, R.N., Marszalek, D.S., and Choquette, P.W., 1976, Facies and fabric specifity of early subsea cements in shallow Belize (British Honduras) reefs: Jour. Sedimentary Petrology, v. 46, p. 523-544.

Johnson, J.H., 1961a, Review of Ordovician algae: IN Studies of Ordovician Algae, Colorado Sch. Mines Quart., v. 56(2), pt. 1, p. 1-102.

Johnson, J.H., 1961b, Limestone building algae and algal limestones: Colorado Sch. Mines, 297p.

Johnson, J.H., 1965, Fossil algae from Guatemala: Colorado Sch. Mines, Prof. Contr., v. 1, 152p.

Jordan, C.F., 1973, Carbonate facies and sedimentation of patch reefs off Bermuda: Am. Assoc. Petroleum Geologists Bull., v. 57, p. 42-54.

Kahle, C.F., 1974, Algae, fungi, and transformation of sparry calcite to micrite (Abstract): Am. Assoc. Petroleum Geologists Ann. Mtg., San Antonio, Texas, Apr. 1974.

Kahle, C.F., 1976, Biogenic structures, carbonate cements, sparmicritization and evolution of Miami Limestone (Pleistocene) and calcareous crusts (Recent), Lower Florida Keys: in press, Sedimentology.

Kahle, C.F., Eutsler, R., and Huh, J., 1973, Nature and significance of borings and other structures on and within oolite alochems (Abstract): Am. Assoc. Petroleum Geologists Bull., v. 57, p. 787.

Kapp, U., 1975, Middle Ordovician stromatoporoid mounds in Vermont: Lethaic., v. 8, p. 195-207.

Kendall, C.G. St. C., and Skipwith, P.A.D'E., 1969, Holocene shallow water carbonate and evaporite sediments of Khor al Bazam, Abu Dhabi, southwest Persian Gulf: Am. Assoc. Petroleum Geologists Bull., v. 53, p. 841-869.

Kitano, Y., 1968, Factors controlling the crystal form and the minor element content of carbonates formed in marine biological systems -- the geochemical significance of carbonate fossil: Chem. and Chem. Industry, v. 21, p. 1017-1028.

Kitano, Y., and Hood, D.W., 1965, The influence of organic material on the polymorphic crystallization of calcium carbonate: Geochem. Cosmochim. Atca, v. 29, p. 29-41.

Kitano, Y., Kanamori, N., and Tokuyama, A., 1969, Effects of organic matter on solubilities and crystal form of carbonates: Am. Zool., v. 9, p. 681-688.

Klément, K.W., Toomey, D.F., 1967, Role of the blue-green alga *Girvanella* in skeletal grain destruction and lime mud production in the lower Ordovician of west Texas: Jour. Sedimentary Petrology, v. 37, p. 1045-1051.

Kobluk, D.R., 1975, Stromatoporoid paleoecology of the southeast margin of the Miette Carbonate Complex, Jasper Park, Alberta: Bull. Canadian Petroleum Geol., v. 23/2, p. 224-277.

Kobluk, D.R., Pemberton, A.S., Karolyi, M., and Risk, M.J., 1976, The sub-Devonian disconformity in southern Ontario: Submitted, Bull., Canadian Petroleum Geol.

Kobluk, D.R., and Risk, M.J., 1974, Devonian boring algae of fungi associated with micrite tubules: Canadian Jour. Earth Sci., v. 11, p. 1606-1610.

Kohlmeyer, J., 1969, The role of marine fungi in the penetration of calcareous substrates: Am. Zool., v. 9, p. 741-749.

Kölliker, A., 1859, On the frequent occurrence of vegetable parasites in the hard structures of animals: Roy. Soc. London Proc., v. 10, p. 95-99.

Kölliker, A., 1860, On the frequent occurrence of vegetable parasites in the hard tissues of the lower animals: Quart. Jour. Mic. Soc., v. 8, p. 171-188.

Korringa, P., 1951, Investigations on shell disease in the oyster, *Ostrea* endulis L. Ropp: Proc. Verb. Conseil Permanent Int. L'Explor. Mer., v. 128, p. 50-54.

Kornmann, P., 1959, Die heterogene Gattung Gomontia. I. Der sporangiale Anteil, Codiolum Polyrhizum: Helgol. Wiss. Meeresunters, v. 6, p. 229-238.

Kurogi, M., 1953, Study of the life history of *Porphyra*. I. The germination and development of carospores (in Japanese with English summary): Bull. Tokoku Reg. Fish. Res. Lab., v. 2, p. 67-103.

Land, L.S., 1967, Diagenesis of skeletal carbonates: Jour. Sedimentary Petrology, v. 37, p. 914-930.

Land, L.S., 1973a, Contemporaneous dolomitization of Middle Pleistocene reefs by meteoric water, North Jamaica: Bull. Marine Sci. Gulf Caribb., v. 23, p. 64-92.

Land, L.S., 1973b, Holocene meteoric dolomitization of Pleistocene limestones, north Jamaica: Sedimentology, v. 20, p. 411-424.

Land, L.S., 1973c, The reef wall and deep reef tallus (-250 to -1000 feet), North Jamaica (Abstract): Geol. Soc. Amer., Abstracts with Programs, 1973, p. 706.

Land, L.S., Mackenzie, F.T., and Gould, S.J., 1967, Pleistocene history of Bermuda: Geol. Soc. Amer. Bull., v. 78, p. 993-1006.

Land, L.S., and Epstein, S., 1970, Submarine lithification of Jamaican reefs: Jour. Sedimentary Petrology, v. 40, p. 457-462.

Land, L.S., and Goreau, T.F., 1970, Submarine lithification of Jamaican reefs: Jour. Sedimentary Petrology, v. 40, p. 457-462.

Lang, J.C., Hartman, W.C., and Land, L.S., 1975, Sclerosponges: primary framework constructors on the Jamaican deep fore-reef: Jour. Mar. Res., v. 33, p. 223-231.

LeCampion-Alsumard, T., 1969, Contribution à l'étude des cyanophytes lithophytes des étages supralittoral et médiolittoral (Région de Marseilles): Tethys, v. 1, p. 119-172.

LeCampion-Alsumard, T., 1970, Cyanophycées marines endolithes colonisant des surfaces rocheuses dénudées (Etages supralittoral et médiolitoral de al région de Marseille): Schweizer, Z. Hydrol., v. 32, p. 552-558.

Lewis, J.B., 1960, The coral reefs and coral communities of Barbados, W.I.: Canadian Jour. Zoology, v. 38, p. 1133-1145.

Lipman, C.B., 1924, A critical and experimental study of Drew's bacterial hypothesis on $CaCO_3$ precipitation in the sea: Papers Dept. Marine Sci., Carnegie Inst. Wash. Publ., no. 340, p. 179-191.

Lipman, C.B., 1929, Further studies on marine bacteria with a special reference to the Drew hypothesis on $CaCO_3$ precipitation in the sea: Paper Tortugas Lab., Carnegie Inst. Wash. Publ., 391, p. 231-248.

Loreau, J.P., 1970, Ultrastructure de la phase carbonatés des oolithes marines actuelles: Acad. Sci. Paris Comptes Rendus, v. 271, Ser. D, p. 816-819.

Love, L.G., 1957, Micro-organisms and the presence of syngenetic pyrite: Quart. Jour. Geol. Soc. London, v. 113, p. 429-440.

Lukas, K.J., 1973, Taxonomy and ecology of Recent endolithic microflora of reef corals with a review of the literature on endolithic microphytes: Unpubl. Ph.D. thesis, Univ. Rhode Island, 159p.

Lukas, K.J., 1974, Two species of the chlorophyte genus Ostreobium from the skeletons of Atlantic and Caribbean reef corals: Jour. Phycology, v. 10, p. 331-335.

Margolis, S., and Rex, R.W., 1971, Endolithic algae and micrite envelope formation in Bahamian oolites as revealed by scanning electron microscopy: Geol. Soc. Amer. Bull., v. 82, p. 843-852.

Marszalek, D.S., 1975, Calcisphere ultrastructure and skeletal aragonite from tha alga Acetubularia antilliana: Jour. Sedimentary Petrology, v. 45, p. 266-271.

Massaad, M., 1974, Framboidal pyrite in concretions: Miner. Deposit., v. 9, p. 87-89.

Milliman, J.D., Ross, D.A., and Ku, T.L., 1969, Precipitation and lithification of deep-sea carbonates in the Red Sea: Jour. Sedimentary Petrology, v. 39, p. 724-236.

Moore, D.H., 1973, Patterns of carbonate sedimentation on the reef wall and talus (-180 feet to -1000 feet), North Jamaica (Abstract): Geol. Soc. Amer. Ann. Mtg., 1973, p. 743.

Moore, R.C., 1957, Treatise on Invertebrate Paleontology, Part H, Brachiopods: Univ. of Kansas Press, Lawrence, p. 1-927.

Monty, C.L.V., 1965, Geological and environmental significance of Cyanophyta: Ph.D. thesis, Princeton Univ., 429p.

Monty, C.L.V., 1967, Distribution and structure of Recent algal mats, eastern Andros Island, Bahamas: Ann. Soc. Geol. Belg., v. 90, p. B55-B99.

Moret, L., 1934, Sur les algues cariantes du groupe des Cyanophycées a propos d'observations nouvelles du lac de Marinet: Compt. Rendus Acad. Sci. Paris, v. 198, p. 1449-1451.

Moseley, H.N., 1875, On the structure and relations of the Alcyonarian Heliepora caerula, with some account of the anatomy of a species of Sarcophyton; notes on the structure of species of the genera Millepora, Pocillopora, and Stylaster; and remarks on the affinities of certain Paleozoic corals: Roy. Soc. London Proc., v. 24, p. 59-70.

Mountjoy, E.W., 1965, Stritigraphy of the Devonian Miette reef complex and associated strata eastern Jasper National Park, Alberta: Geol. Surv. Canada Bull. 110.

Multer, H.G., 1975, Field guide to some carbonate rock environments, Florida Keys and western Bahamas: Contr. 40, Dept. Earth Sciences, Fairleigh Dickinson Univ., 175p.

Multer, H.G., and Hoffmeister, J.E., 1968, Subaerial laminated crusts of the Florida Keys: Bull. Geol. Soc. Amer., v. 79, p. 183-192.

Nadson, G.A., 1902, Die perforenden Algen und ihre Bedentieng in der Natur.: Scripta Hort. Bot. Univ. Imperialis, 1900-1902, p. 35-40.

Nadson, G., 1932, Contribution a l'études des algues perforantes: Bull. Acad. Sci. (URSS), 7th Ser. 1932, (7), p. 833-855.

Nicholson, H.A., and Etheridge Jr., R., 1878, A monograph of the Silurian fossils of the Girvan district in Ayrshire with special reference to those contained in the "Gray Collection", I, v. 1, p. 1-135.

Noble, J.P.A., 1966, A Paleoecologic and Paleontologic study of an Upper Devonian reef in the Miette area, Jasper National Park, Alberta, Canada: Ph.D. thesis, Western Reserve Univ.

Oppenheimer, C.H., 1961, Note on the formation of spherical aragonitic bodies in the presence of bacteria from the Bahama Bank: Geochim. Cosmochim. Acta, v. 23, p. 295-296.

Parke, M.W., and Moore, H.B., 1935, The biology of Balanus balanoides: II. Algae of the shell: Jour. Mar. Biol. Assoc. United Kingdom, v. 20, p. 49-56.

Perkins, R.D., and Halsey, S.D., 1971, Geologic significance of microboring fungi and algae in Carolina shelf sediments: Jour. Sedimentary Petrology, v. 41, p. 843-853.

Perkins, R.D., and Tsentas, C.I., 1973, Microbial destruction of carbonate substrates planted on the north eastern St. Croix shelf (Agstract): Geol. Soc. America Abstracts with Programs, v. 5, p. 766.

Pia, J. Von., 1937, Die kalklösenden thallophyten: Arch. Hydrobiol., v. 31, p. 264-328; p. 341-398.

Pitcher, M., 1964, Evolution of Chazyan (Ordovician) reefs of eastern United States and Canada: Am. Assoc. Petroleum Geology Bull., v. 12, p. 632-692.

Pollock, J.B., 1981, Blue-green algae as agents in the deposition of marl in Michigan lakes: Ann. Rep. Michigan Acad. Sci., v. 20, p. 247-260.

Purdy, E.G., 1963, Recent calcium carbonate facies of Great Bahama Bank. 1, Petrography and reaction groups: Jour. Geol., v. 71, p. 334-355.

Purdy, E.G., 1968, Carbonate diagenesis: an environmental survey: Geol. Romana, v. 7, p. 183-228.

Pusey, W.C., 1975, Holocene carbonate sedimentation on northern Belize Shelf: IN Wantland, K.G., and Pusey, W.C. (eds.), Belize Shelf-Carbonate sediments, Clastic Sediments, and Ecology, Amer. Assoc. Petroleum Geologists, Studies in Geology no. 2, p. 131-233.

Rhumbler, L., 1895, Entwurf eines naturlichen Systems der Thalamophen: K. Ges. Wiss. Gottingen. M.P.Kl., Nachr., v. 1, p. 51-98.

Riding, R., 1972, Calcareous algae and some associated microfossils from Ancient Wall reef complex (Upper Devonian), Alberta (Abstract): Am. Assoc. Petroleum Geologists Bull., v. 56, p. 648.

Riding, R., 1975, Girvanella and other algae as depth indicators: Lethaia, v. 8, p. 173-179.

Riding, R., 1976, Calcified Plectonema (blue-green algae), A Recent example of Girvanella from Aldabra Atoll: in press Paleontology,

Richard, D.T., 1970, The origin of framboids: Lithos, v. 3, p. 269-293.

Roberts, W.M.B., A.C. Walker, and A.S. Buchanan, 1969, The chemistry of pyrite formation in aqueous solution and its relations to the depositional environment: Miner. Deposit., v. 4, p. 18-29.

Romanes, M.G., 1916, Note on an algal limestone from Angola: Trans. Roy. Soc. Edinburgh, v. 51, p. 581-584.

Rooney, W.S.Jr., and Perkins, R.D., 1972a, Distribution and geologic significance of micro-boring organisms within sediments of the Arlington Reef Complex, Australia: Geol. Soc. Amer. Bull., v. 83, p. 1139-1150.

Rooney, W.S., Perkins, R.D., 1972b, Microboring organisms as environmental indicators and sediment tracers: Arlington Reef Complex, Australia (Abstract): Am. Assoc. Petroleum Geologists Bull., v. 56, p. 650.

Rose, C.B., 1855, On the discovery of parasitic borings in fossil fish scales: Mic. Soc. London, Trans. N.S., v. 3, p. 7-12.

Rothpletz, A., 1891, Fossile Kalkalgen aus den Famillien der Codiaceen und der Corallineen: Zeitschrift Deutsch. Geol. Gesell., v. 43, p. 295-322.

Rudwick, M.J., 1970, Living and fossil brachiopods: Hutchinson and Co., Ltd., London, 199p.

Rust, G.W., 1935, Colloidal primary copper ores at Cornwall Mines, southeastern Minnesota: Jour. Geol., v. 43, p. 398-426.

Schäfer, W., 1972, Ecology and paleoecology of Marine Environments: Oliver and Boyd, p. 118-119.

Schaub, H.P., 1948, Geological observations on Curacao, N.W.I.: Amer. Assoc. Petroleum Geologists, Bull., v. 32, p. 1275-1291.

Schlonleber, K., 1936, Scytonema julianum. Beitrage zur normalen und Pathologische Cytologie und Cytogenese der Blanalgen: Archiv. Fur Protistenkunde, v. 88, p. 36-38.

Schneiderhöhn, H., 1923, Chalkgraphische Untersuchung des Mansfelder Kupferschiefers: N. Jb. Miner. Geol. Palaont., B. Ed. 47, p. 1-38.

Schroeder, J.H., 1972a, Calcified algal filaments of an endolithic alga in recent Bermuda reefs: N. Jb. Geol. Palaont. Mh., v. 1, p. 16-33.

Schroeder, J.H., 1972b, Fabrics and sequences of submarine carbonate cements in Holocene Bermuda cup reefs: Geol. Rundschau, v. 61, p. 708-730.

Schroeder, J.H., 1974, Carbonate cements in recent reefs of the Bermudas and Bahamas. Keys to the past?: Ann. de la Soc. Geol. Belg., v. 97, p. 153-158.

Schroeder, J.H., and Ginsburg, R.N., 1971, Calcified algal filaments in reefs (Abstract): Am. Assoc. Petroleum Geologists Ann. Mtg., Houston, p. 364.

Scoffin, T.P., 1971, The conditions of growth of the Wenlock reefs of Schropshire (England): Sedimentology, v. 17, p. 173-179.

Setchell, W.A., 1924, American Samoa. III. The vegetation of Rose Atoll: Carnegie Inst. Washington, Paper 341, Dept. Mar. Biol., v. 20, p. 225-261.

Seward, A.C., 1931, Plant Life Through The Ages, a Geological and Botanical Retrospect: Cambridge University Press, 601p.

Shibata, K., and Haxo, T.T., 1969, Light transmission and spectral distribution through epi- and endozoic algal layers in the brain coral, Favia: Biol. Bull., v. 136, p. 416-468.

Shinn, E.A., Lloyd, R.M., and Ginsburg, R.M., 1969, Anatomy of a modern carbonate tidal flat, Andros Island, Bahamas: Jour. Sedimentary Petrology, v. 39, p. 1202-1228.

Smith, C.L., 1940, The Great Bahama Bank. 1. General Hydrographic and chemical factors. 2. Calcium carbonate precipitation: Jour. Marine Res., v. 3, p. 1-31; p. 147-189.

Srivastava, N.K., 1975, Early diagenetic changes in Recent molluscan shells: N. Jb. Geol. Palaont. Abh., 148/3, p. 380-403.

Stockman, K.W., Ginsburg, R.N., and Shinn, E.A., 1967, The production of lime mud by algae in South Florida: Jour. Sedimentary Petrology, v. 37, p. 633-648.

Sweeney, R.F., and J.R., Kaplan, 1973, Pyrite framboid formation: laboratory synthesis and marine sediments: Econ. Geol., v. 68, p. 618-643.

Swinchatt, J.P., 1965, Significance of constituent composition, texture, and skeletal breakdown in some recent carbonate sediments: Jour. Sedimentary Petrology, v. 35, p. 71-90.

Swinchatt, J.P., 1969, Algal boring: a possible depth indicator in carbonate rocks and sediments: Geol. Soc. Amer. Bull., v. 80, p. 1391-1396.

Taylor, J.M.C., and Illing, L.V., 1969, Holocene intertidal carbonate sedimentation, Qatar Persian Gulf: Sedimentology, v. 12, p. 69-107.

Tiffney, B.H., and Barghoorn, 1974, The fossil record of the fungi: occasional papers of the Farlow Herbarium of Cryptogamic Botany, No. 7, Harvard Univ., Cambridge, Mass.

Topsent, E., 1887, Notes on the boring marine thallophytes: Linn. Soc. (Norm.), Mem., Ser. 3, V. 10, p. 296-297.

Trudinger, P.A., I.B. Lambert and G.W. Skyring, 1972, Biogenic sulfide ores: a feasibility study: Econ. Geol., v. 67, p. 1114-1127.

Ulrich, F.R., 1927, Über die Wachtumsform des organogenen abgeschiedenen Kalkspates und ihre Beeinflussung durch das Kristallizations-medium: Zeitschrift fur Krustallographic, v. 66, p. 513-514.

Wedl, G., 1859, Über die Bedentung der in den Schalen von manchen Acephalen und Gasteropoden vorkommenden Canale: Sitzunapber. Kaiserlich, Akad. Wiss., v. 33, p. 451-472.

Wendt, J., 1969, Stratigraphic und palaogeographic des Roten Jurakalks im Somnwendgibirge (Tirol, Austria): Neues, Jb. Geol. Palaont. Abh., v. 132, 219-238.

Wilbur, K.M., and Watabe, N., 1963, Experimental studies in calcification in Molluscs and in the alga Cocolithus huxleyi. Comparative biology of calcified tissue: Ann. N.Y. Acad. Sci., v. 109, pl 82-112.

Wilkinson, M., and Burrows, E.M., 1972, An experimental taxonomic study of the algae comfused under the name Gomontia polyrhiza: Jour. Mar. Biol. Assoc. (U.K.) N.S., v. 52, no. 1, p. 49-57.

Winland, H.D., 1968, The role of high Mg calcite in the preservation of micrite envelopes and textural features of aragonite sediments: Jour. Sedimentary Petrology, v. 38, p. 1320-1325.

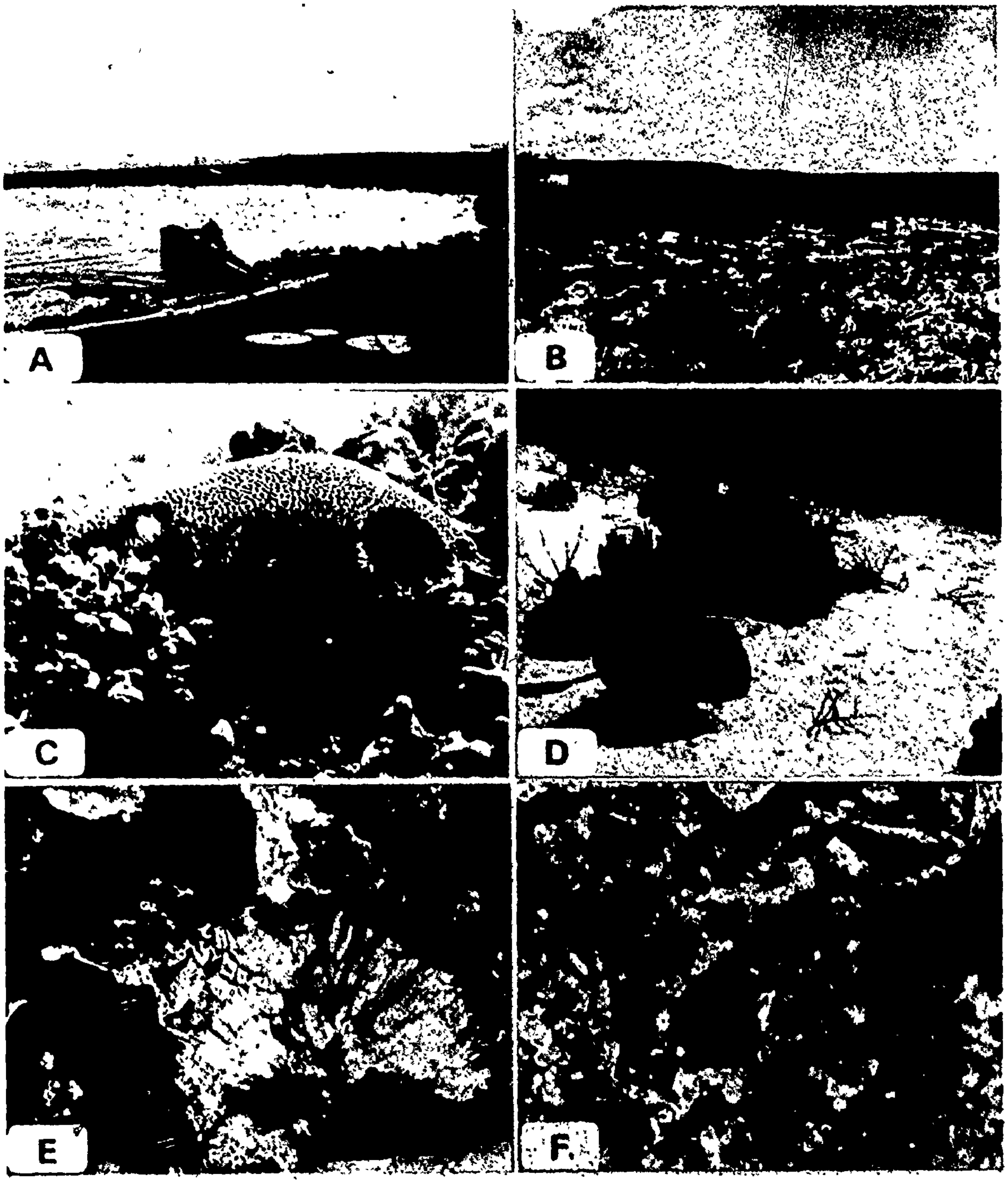
Winland, H.D., and Matthews, R.K., 1974, Origin and significance of grapestone, Bahama Islands: Jour. Sedimentary Petrology, v. 44, p. 921-927.

Woldseth, R., 1973, X-Ray Energy Spectrometry: KEVEX Corporation, Burlingame, California.

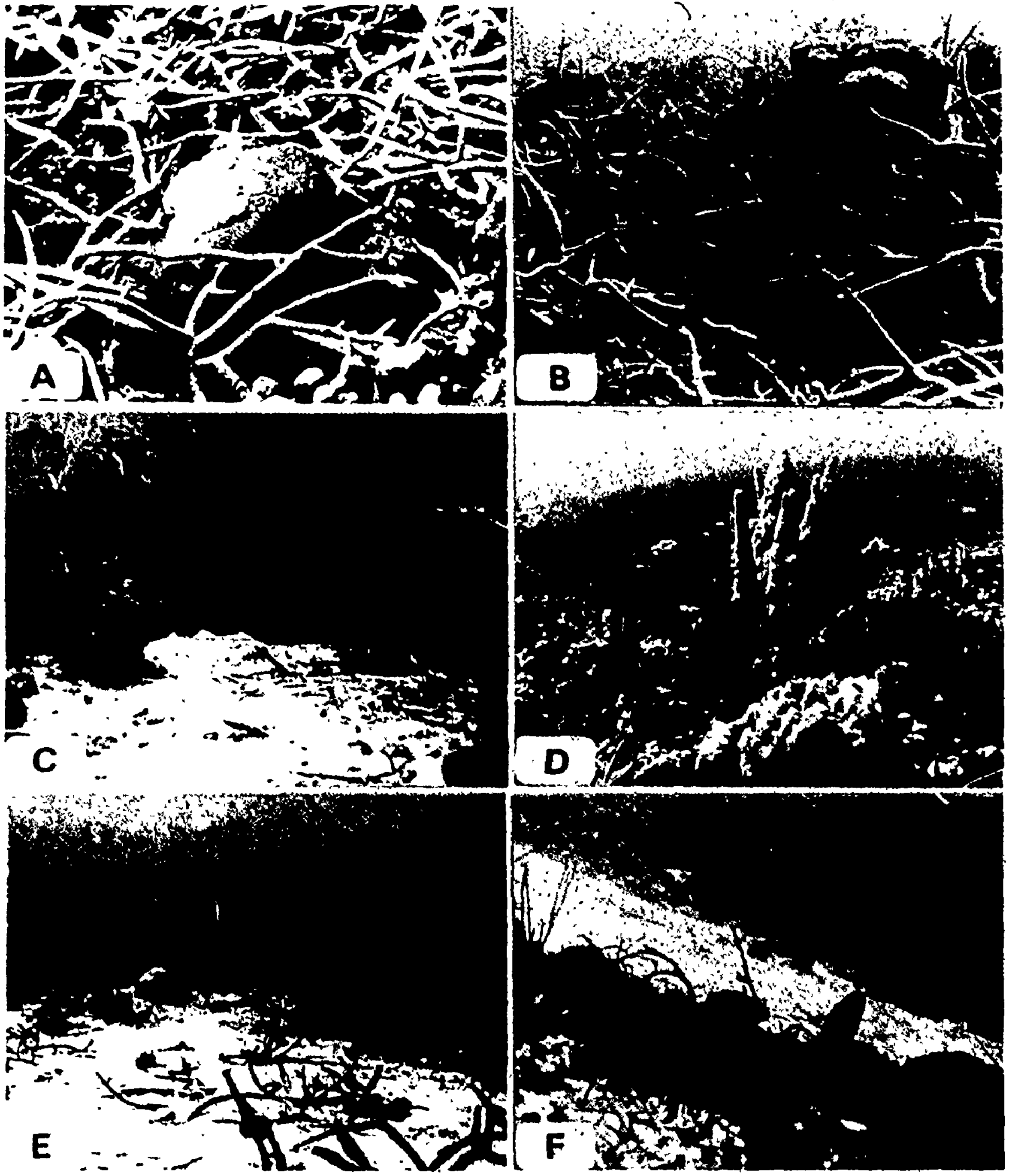
APPENDIX I

STUDY AREAS

APPENDIX FIGURE 1 Jamaica. a) View of south and east shores of Discovery Bay, including Kaiser Bauxite loading facilities. b) First marine limestone terrace at Rio Bueno, 3 km west of Discovery Bay. c) Bioerosion of corals, Discovery Bay forereef. Cavity erosion such as this by parrot fish, urchins, etc. provides an avenue for attack by endolithic algae and fungi; depth 10 m. d) Sand channel, with small bioherms, forereef at Discovery Bay; depth 16 m. e) Coral, same as in c above, but in the Pleistocene reef exposure, first reef terrace, east shore of Rio Buero Bay. f) *Porites furcata*, and *Acropora cervicornis* in place in the first reef terrace (Pleistocene) exposure east Rio Bueno Bay.


A
B
C
D
E
F

APPENDIX FIGURE 2 Jamaica; all are from the forereef, west Discovery Bay. a, b) Detail of cervicornis zone; depth 15 m. c) Sand patch, in the cervicornis zone, at the head of a sand channel; depth 15 m. d) Montastrea zone, with a magnificent specimen of Dendrogyra cylindricus at center; depth 10 m. e) Sand channel between 2 reef buttresses, at buttress front. Note dropoff in the distance; depth 20 m. f) Dropoff at front of buttresses. Note the high-angled slope. Much of the sand here is unstable, and easily moves downslope; depth 25 m.

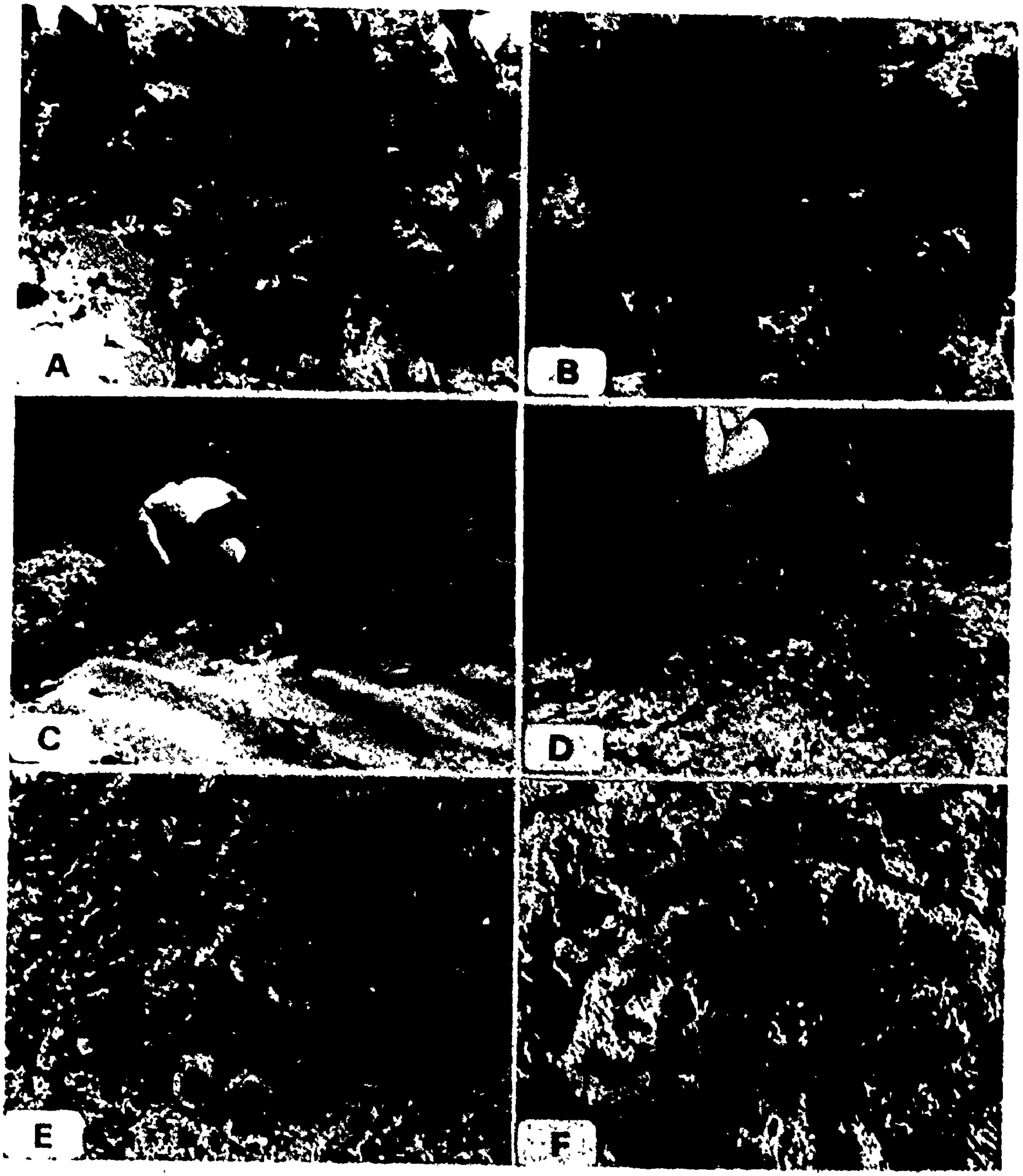

A
B
C
D
E
F

APPENDIX FIGURE 3 <u>Florida Keys</u>. a, b) Pickles reef, off Key Largo. The reef here is dominantly calcareous algae, hemispherical corals and gorgonians; depth 5 m.

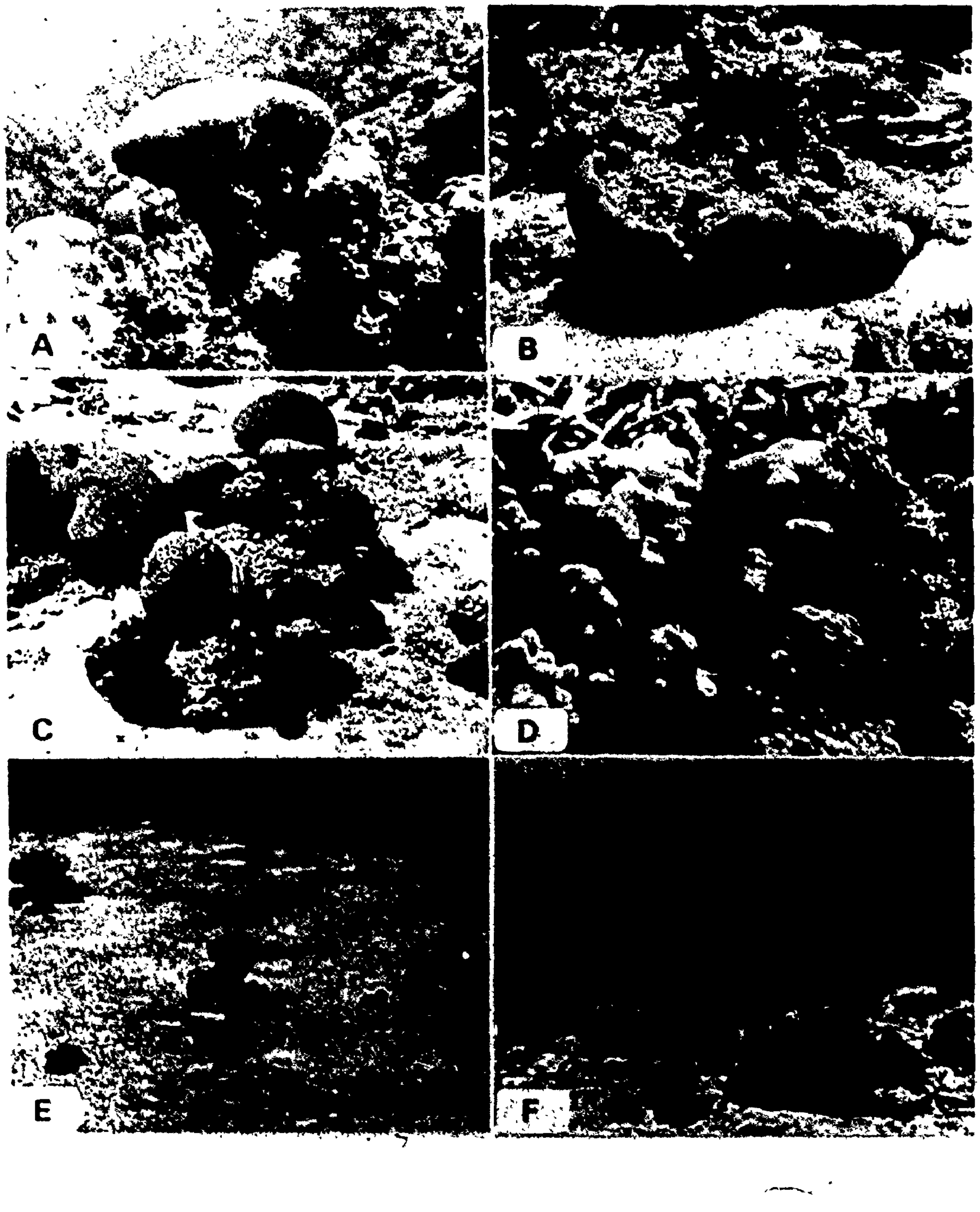
c) Sand channel at Pickles reef; depth 5 m.

d) Patch bare of gorgonians on Pickles reef. Note the large amount of rubble and sand; depth 4 m.

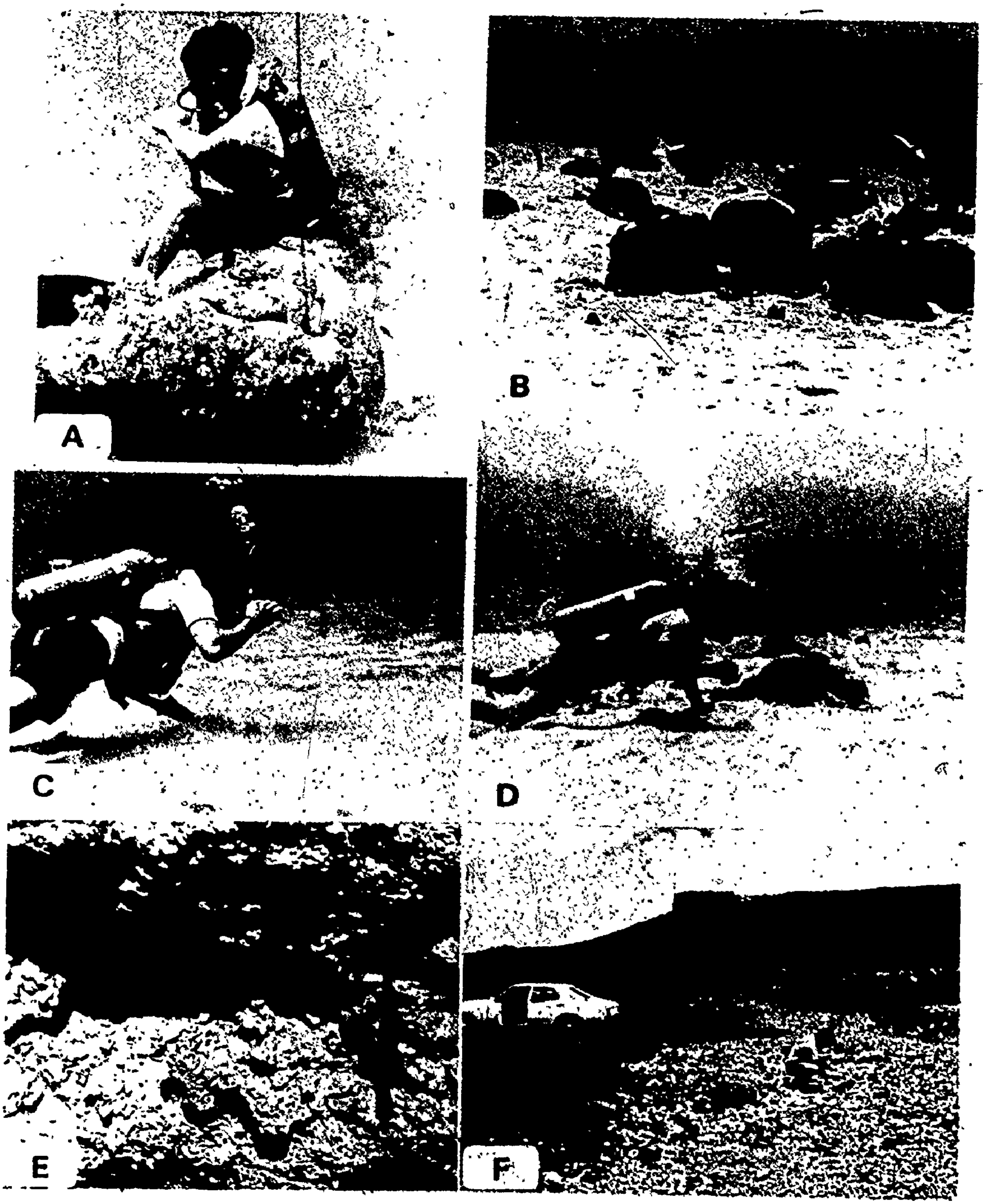
e, f) In place corals in the Key Largo limestone, Key Largo quarry. Note the well-preserved pholad boring in f.


A
B
C
D
E
F

APPENDIX FIGURE 4 <u>Curacao</u>, Dutch West Indies. All are from the reef at Westpunt Baai. a) Forereef, depth 15 m. Heavily bio-eroded coral, showing stalk development. b) Forereef, depth 10 m. Storms, or simple instability caused by continual bioerosion of the stalk may cause some coral heads to fall and overturn. c) Backreef; back reef rubble zone; depth 4 m. d) Forereef; depth 25 m. d) Sand flats land-ward of back reef rubble zone; depth 3.5 m. f) Back reef rubble zone; depth 4.5 m.

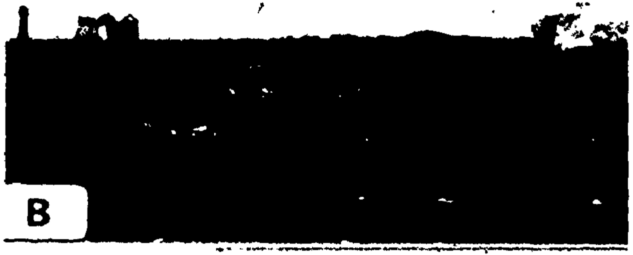

A
B
C
D
E
F

APPENDIX FIGURE 5 Curacao, Dutch West Indies. a) The guru is seated on a large clionid sponge which has completely replaced a hemispherical head of Siderastrea siderea(?); back reef Paradise Bay; depth 4.5 m. b) Transition from back reef rubble zone (background) to sand flats. Paradise Bay; depth 4 m. c) Sand flats, Lagoen; depth 3 m. d) Back reef rubble zone, Paradise Bay; depth 4 m. e) First reef terrace (Pleistocene) exposure at Piscadera Baai. f) First reef terrace at San Pedro; north east coast. The hill in the back is the dacite core of the island, with a remnant of the second (B terrace) marine limestone terrace adhering. Diver and field assistant, B. Pratt.


A
B
C
D
E
F

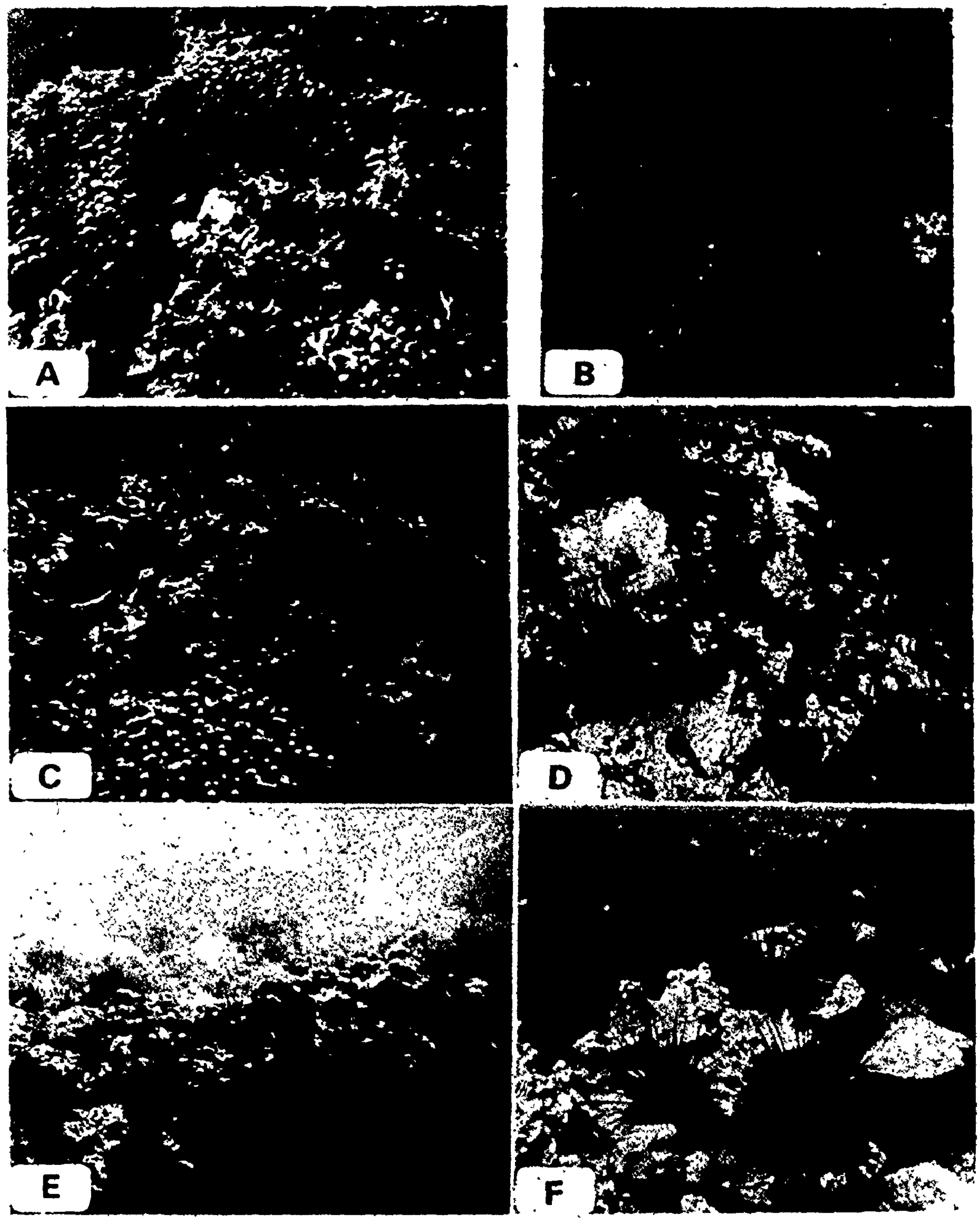
APPENDIX FIGURE 6 <u>Bonaire</u>, Dutch West Indies. a) Intertidal and supratidal beach separating intertidal algal mats (back) from the Lac. The nodules in the foreground are cemented sands and algal stromatolites, most of which contain calcified algal filaments. b, c) Malmok, north coast, showing the Pleistocene marine terrace.

A

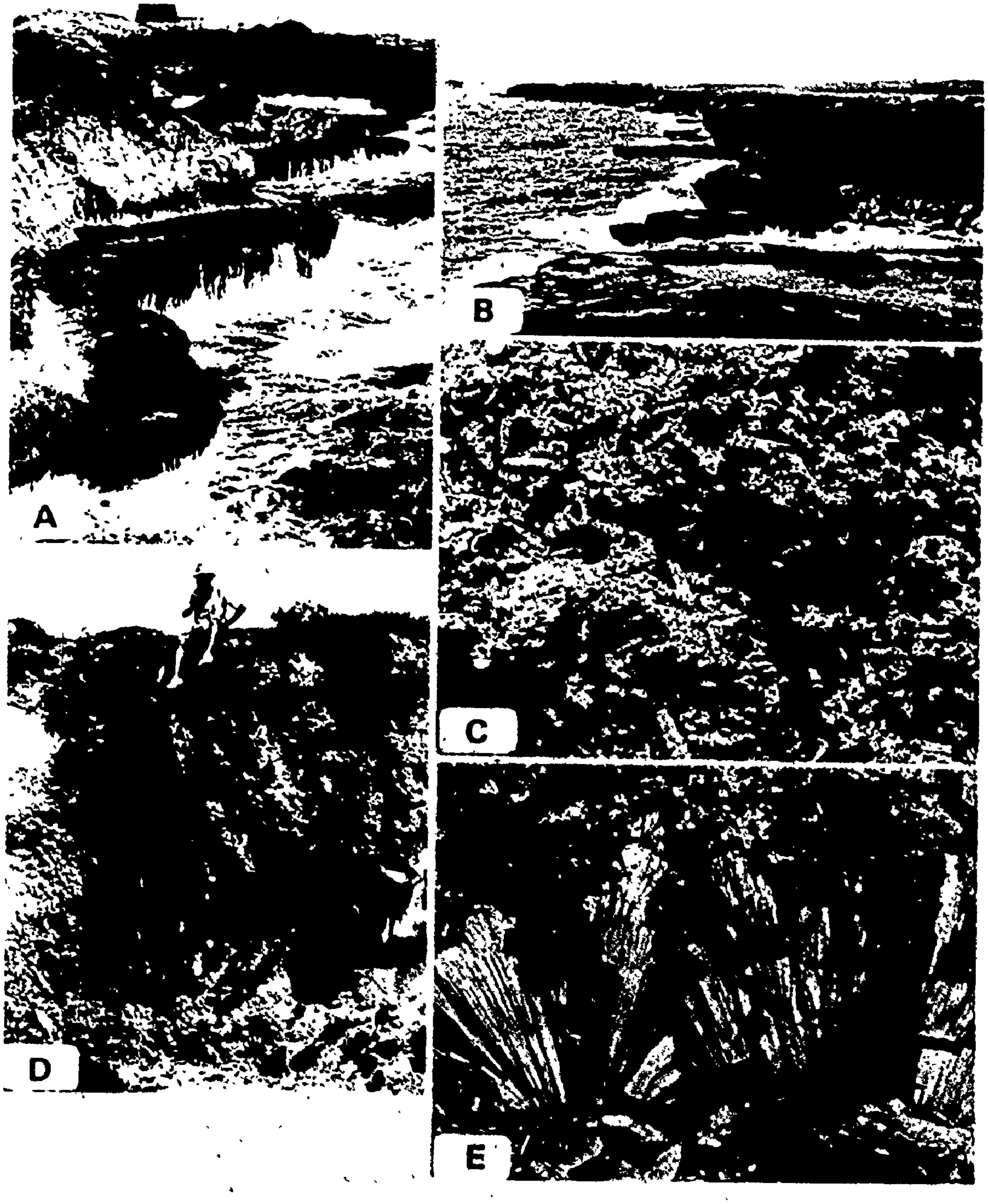

B

C

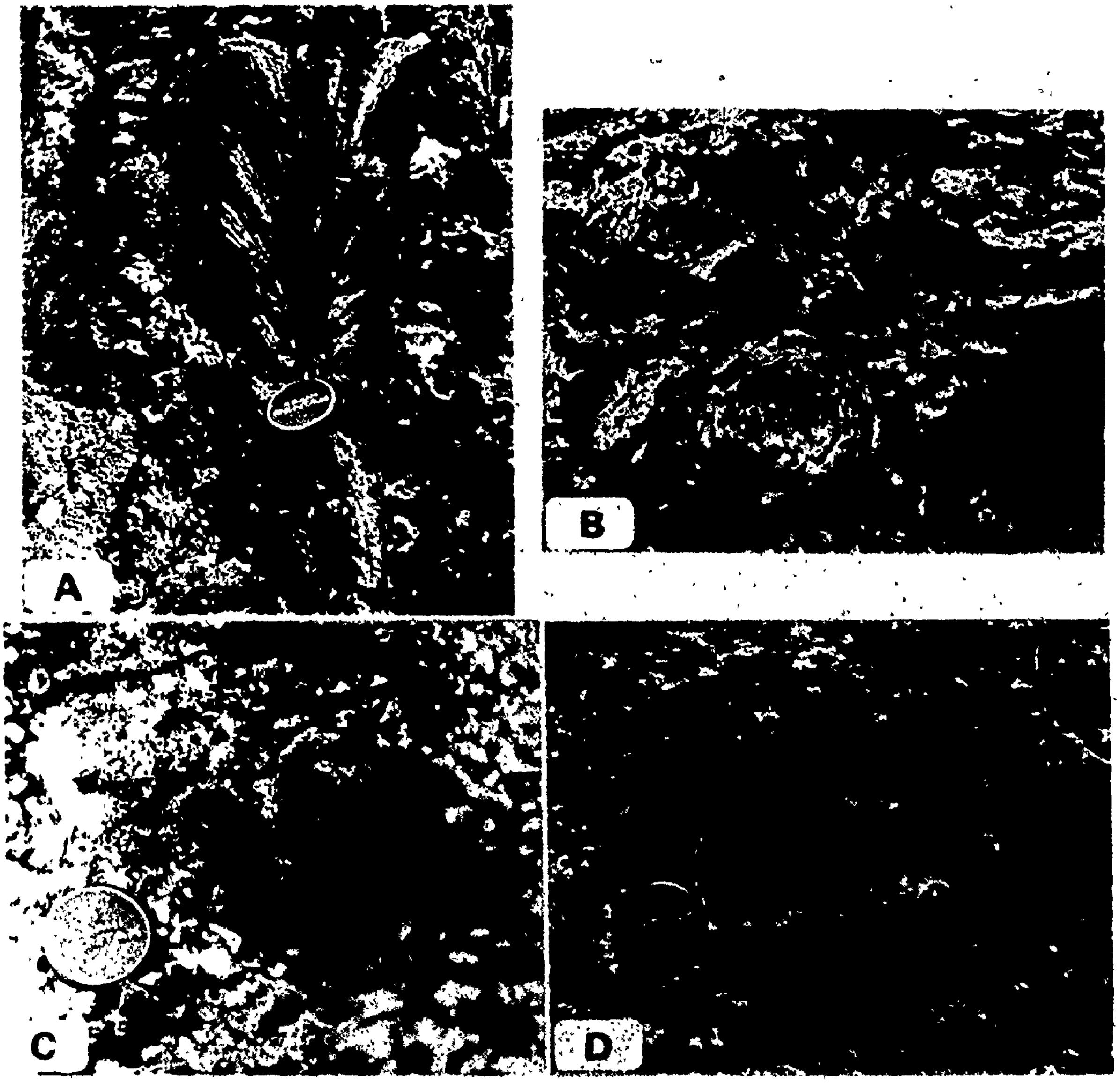
APPENDIX FIGURE 7 <u>Barbados</u>, West Indies. All are from the Bellairs reef, Bellairs, St. James. a, b, c) <u>Porites</u> reefs. These reefs are columnar structures, and are only 100 m offshore. d, e, f) Extensive bioerosion on the reefs is accomplished by <u>Diadema</u> and other urchins and grazing fish. The continued grazing opens up fresh reef surface to infestation by endolithic algae.


A
B
C
D
E
F

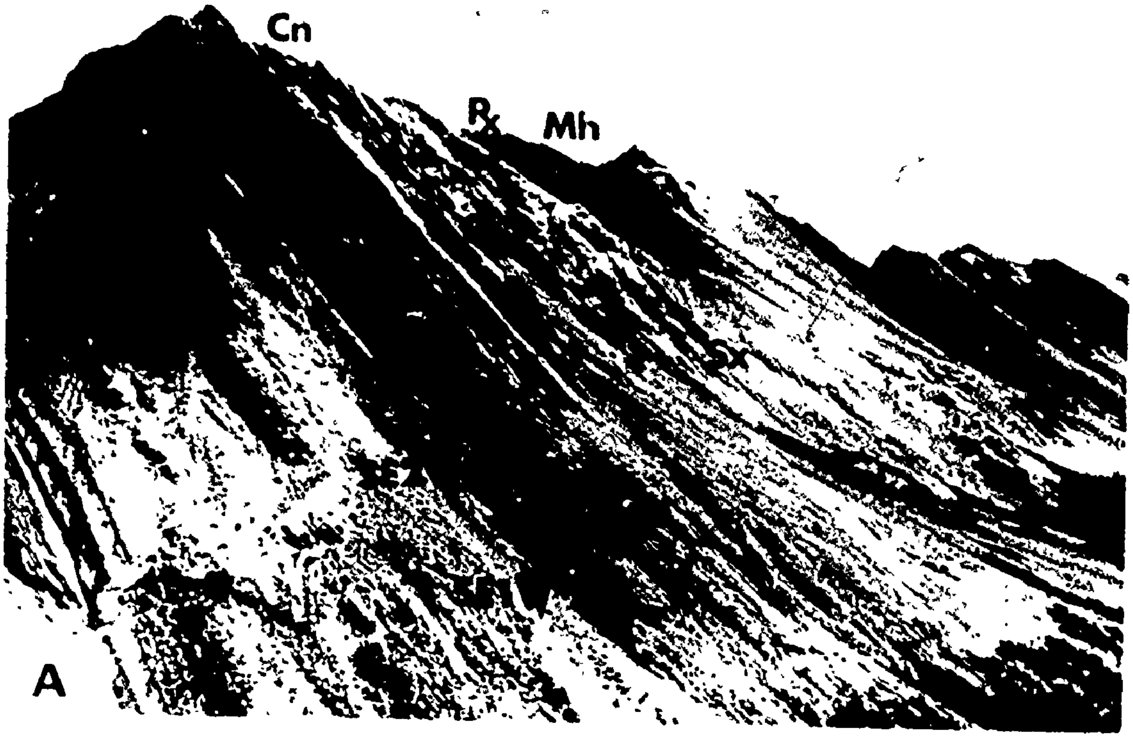
APPENDIX FIGURE 8 Barbados, West Indies. a, b) First reef terrace (83,000 years) at North Point and Animal Flower Caves, north coast. The calcarenites in these rocks have provided particularly fine specimens of calcified algal filaments. c) First reef terrace (83,000) at River Bay. Richard Dodge is sitting on a very well-preserved *in situ* colony of *Montastrea annularis*. d) Sticks of A. *cervicornis* in the first reef terrace at River Bay. e) Extremely well-preserved, *in situ* colonies, of M. *annularis* in the first reef terrace at River Bay.

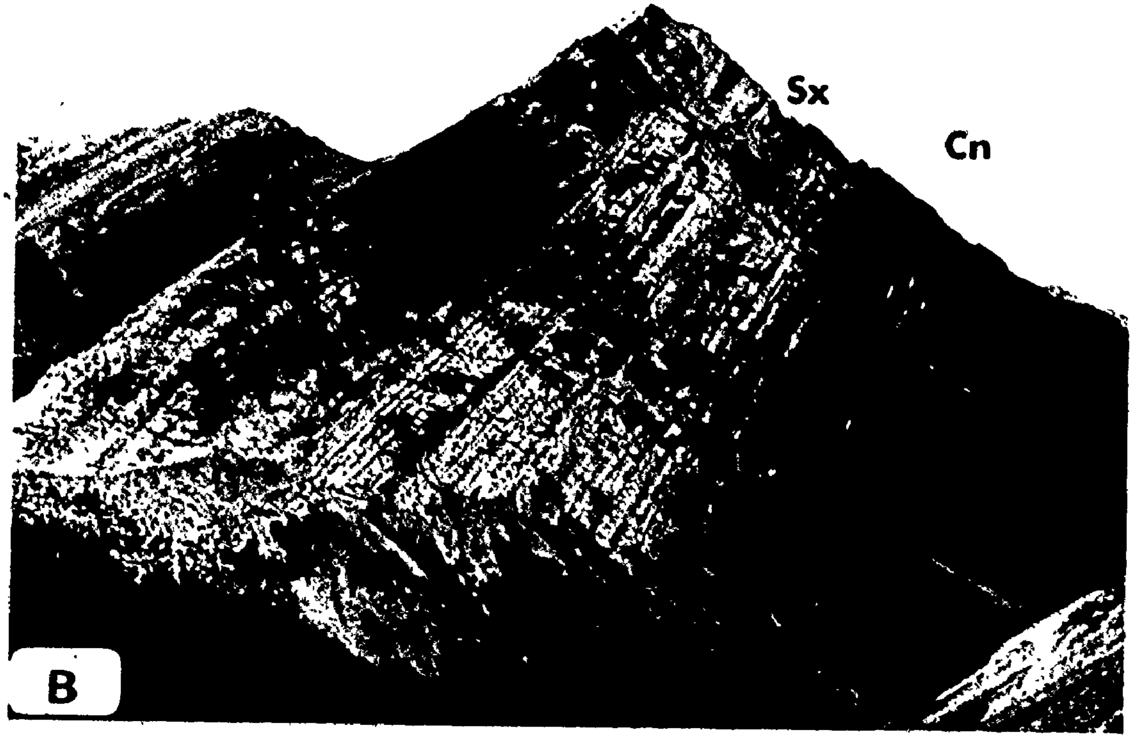

A
B
C
D
E

APPENDIX FIGURE 9 Barbados, West Indies; Pleistocene exposures. a) *Montastrea annularis in situ* in the first reef terrace at River Bay. b) Stalks of *Acropora palmata* (recrystallized), in the 125,000 year old terrace above Holetown. c) Overturned *Siderastrea* in the first reef terrace at Crane. d) Large gastropod in the 125,000 year terrace at Holetown.


A
B
C
D

APPENDIX FIGURE 10 Miette reef complex, Jasper National Park, Alberta. a) Slide Creek southeast, showing the reef margin (at Sx), and the base of the complex (at SE1 and SE2), resting on the Cambrian. Cn: Cairn; Px: Perdrix; Sx: Southesk; Mh: Mount Hawk. Stratigraphic sections used in this study are located at SE1 and SE2. b) Northwest side of Slide Creek, looking into the center of the complex from the area of (a) above. The beds are dominantly lagoon and back reef carbonates. N.W. refers to the section measured on this side of the creek. The beds of the Cairn and Southesk Formations here are represented by Cn and Sx respectively.


Cn
Rx
Mh
Sx
A


Sx
Cn
B

APPENDIX II - SAMPLE DESCRIPTIONS

The samples collected in each of the major study areas are described below by location. Where thin sections were prepared, the thin section number is listed beside the sample number; in some cases several thin sections were prepared from a single sample. Where samples were collected from the modern marine environment, the depth (in meters) is given below the water surface to the sample station.

The first letter(s) of the sample number refers to the study area where the sample was collected:

J	Jamaica
F	Florida
M	Miette, Alberta
BD	Bermuda
Q	Southern Quebec, Ontario, Vermont
B	Barbados
C	Curacao
BN	Bonaire
X	Miscellaneous

Isolated specimens, or specimens used in laboratory experiments at McMaster University, are referred to the miscellaneous group.

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-1	TS-162	2	Dead, degraded P. *porites*; degraded pelecypod valves
J-2	------	3	Calcarenite: plus bored *Ostrea*, bored echinoderm test -
J-3	TS-60	1	Calcarenite: coral, *Halimeda*, calcareous algae rich
J-4	TS-61	1.5	Calcarenite/calcisiltite: coral, *Halimdea* rich
J-5	TS-62	2	Calcarenite: coral rich
J-6	TS-63	2.5	Calcarenite: coral rich
J-7	------	1-4	Calcarenite: pelecypod, *Halimeda* rich; dead corals: A. *cervicornis*
J-8	TS-64	5	Calcarenite: pelecypod rich
J-9	TS-160	5	Calcarenite: pelecypod, *Halimeda* rich
J-10	TS-65	5	Calcarenite: *Halimeda*, pelecypod rich
J-11	TS-66	5	Calcarenite: pelecypod, coral, *Halimeda* rich
J-12	TS-67	5	Calcarenite: calc. algae, coral, pelecypod rich
J-13	TS-68	3.5	Calcisiltite
J-14	TS-69	6.5	Calcarenite: coral, calcareous algae rich
J-15	TS-70	10	Calcilutite
J-16	TS-71	13.5	Calcilutite
J-17	TS-72	13.5	Calcilutite
J-18	TS-73	10	Calcilutite
J-19	TS-74	6.5	Calcilutite
J-20	TS-75	3.5	Calcarenite: coral rich

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-21	TS-76	3.5	Calcarenite
J-22	TS-77	6.5	Calcarenite
J-23	TS-78	10	Calcisiltite
J-24	TS-79	13.5	Calcisiltite
J-25	TS-80	16.5	Calcisiltite
J-26	TS-81	5	<u>Halimeda</u> calcarenite
J-27	TS-82	11.5	Calcarenite
J-28	TS-83	16	Calcarenite
J-29	TS-84	22	Calcarenite
J-30	TS-85	22	Calcisiltite
J-31	TS-86	20	Calcisiltite
J-32	TS-87 to 90	16.5	Calcarenite
J-33	-------	13	Calcarenite
J-34	-------	8	Calcarenite
J-35	TS-91	5.5	<u>Halimeda</u> calcarenite
J-36	TS-163 TS-164	16.5	Calcarenite; coral rich
J-37	TS-92	20	Calcisiltite
J-38	TS-93	16.5	Calcarenite
J-39	TS-94	13.5	Calcarenite
J-40	TS-95	11	<u>Halimeda</u> calcarenite
J-41	TS-96	10	Calcarenite
J-42	TS-97	8	Calcarenite
J-43	TS-98	13.5	<u>Halimeda</u> calcarenite
J-44	TS-99	16.5	Calcarenite

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-45	TS-100	18	Calcarenite
J-46	TS-101	6.5	Calcarenite
J-47	TS-102	10	Calcarenite
J-48	TS-103	11.5	Calcarenite
J-49	TS-104	13.5	Calcarenite
J-50	TS-105	15.5	Calcarenite
J-51	TS-106	20	Calcarenite
J-52	-------	16.5	Calcarenite
J-53	TS-107	13.5	Calcarenite
J-54	-------	10	Calcarenite
J-55	TS-108	6.5	Calcarenite
J-56	TS-109	3.5	Calcarenite
J-57	-------	10.5	Calcarenite
J-58	TS-110	13.5	Calcarenite
J-59	TS-111	17	Calcarenite
J-60	-------	20	Calcarenite
J-61	TS-112	2	Calcarenite: coral, pelecypod, calcareous algae rich
J-62	TS-113	2.5	Calcarenite
J-63	TS-114	2.5	Calcarenite
J-64	TS-115	4.5	Calcarenite
J-65	TS-116	4.5	Calcarenite
J-66	TS-117	4.5	Calcarenite
J-67	TS-118	5	Calcarenite
J-68	TS-119	5	Calcarenite

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-69	TS-120	5.5	Calcarenite
J-70	TS-121	6.5	Calcarenite
J-71	TS-122	3	Calcarenite
J-72	TS-123	3.5	Calcarenite
J-73	TS-124	3.5	Calcarenite
J-74	TS-125	3	Calcarenite
J-75	TS-126	8	Calcarenite
J-76	TS-127	11.5	Calcarenite
J-77	TS-128	15	Calcarenite
J-78	TS-129	18	Calcarenite
J-79	TS-130	22	Calcarenite
J-80	TS-131	8	Calcarenite with fragments of dead coral
J-81	TS-132	10.5	Calcarenite
J-82	TS-133	15	Calcarenite
J-83	TS-134	18	Calcarenite
J-84	TS-135	21	Calcarenite
J-85	-------	25	Dead coral (A. cervicornis), sand channel
J-86	-------	25	Dead coral, sand channel
J-87	-------	20	Dead coral (A. cervicornis), sand channel
J-88	-------	16.5	Dead coral (unidentifiable), sand channel
J-89	-------	13.5	Dead coral (P. porites), sand channel
J-90	-------	10	Dead coral (P. porites), sand channel
J-91	-------	10	Dead coral (A. cervicornis)

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-92	-------	13.5	Dead coral (A. cervicornis)
J-93	TS-136	13.5	Calcarenite and dead coral
J-94	-------	16.5	Dead corals, Diploria, A. cervicornis
J-95	TS-137 to 148	13.5	Sediment core, 55 cm.
J-96	TS-149 to 153	13.5	Sediment core, 50 cm.
J-97	-------	23.5	Dead coral, (unidentifiable)
J-98	TS-154	23.5	Calcarenite, sand channel
J-99	-------	23.5	Sediment core, 50 cm., from sand channel
J-100	TS-155	16.5	Calcarenite
J-101	-------	16.5	Dead coral (A. cervicornis and S. siderea)
J-102	TS-156	13.5	Calcarenite
J-103	-------	13.5	Dead coral (unidentifiable)
J-104	TS-157	20	Calcarenite, sand channel
J-105	-------	20	Dead coral (A. palmata), sand channel
J-106	TS-158	17	Calcarenite, sand channel
J-107	-------	17	Dead coral (M. annularis), sand channel
J-108	TS-159	15	Calcarenite, sand channel
J-109	-------	15	Dead coral (A. cervicornis), sand channel
J-110	-------	10	Dead coral (A. cervicornis), sand channel
J-111	-------	20	Dead coral (unidentifiable), heavily bored

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-112	------	16.5	Dead coral (unidentifiable), heavily bored
J-113	------	13.5	Dead coral (A. palmata)
J-114	------	10	Dead coral (A. palmata)
J-115	------	6.5	Dead coral (A. palmata)
J-116	------	23.5	Dead coral (unidentifiable)
J-117	------	20	Dead pelecypod valves, heavily bored by algae and sponges
J-118	------	16.5	Dead coral (Madracis sp.)
J-119	------	13.5	Dead coral (S. siderea, M. annularis, A. cervicornis)
J-120	------	10	Dead coral (A. agaricea, A. prolifera)
J-121	------	6.5	Dead coral (A. cervicornis, P. porites)
J-122	------	25	Dead coral (Agaricea sp.)
J-123	------	20	Dead coral (A. agaricea), heavily bored
J-124	------	16.5	Dead Pinna
J-125	------	13.5	Dead coral (Eusmilia fastigiata)
J-126	------	10	Dead coral (unidentifiable)
J-127	------	6.5	Dead coral (unidentifiable)
J-128	------	18	Coral, collected live (P. porites)
J-129	------	18	Coral, collected live (A. prolifera)
J-130	------	22	Coral, collected live (A. prolifera)
J-131	------	23.5	Coral, collected live (M. annularis)
J-132	------	13.5	Coral, collected live (A. prolifera)
J-133	------	13.5	Coral, collected live (M. annularis)
J-134	------	11.5	Coral, collected live (P. porites)

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-135	------	5	Coral, collected live (A. palmata, A. cervicornis)
J-136	------	5	Coral, collected live (unidentifiable)
J-137	------	5	Coral, collected live (M. annularis)
J-138	------	5	Coral, collected live (A. grahami, A. palmata)
J-139	------	22.5	Coral, collected live (Agaricea sp.)
J-140	------	20	Coral, collected live (Agaricea sp.)
J-141	------	16.5	Coral, collected live (Agaricea sp.)
J-142	------	13.5	Coral, collected live (Agaricea agaricites)
J-143	------	23.5	Coral, collected live (A. lamarcki)
J-144	------	20	Coral, collected live (P. furcata)
J-145	------	16.5	Coral, collected live (Madracis mirabilis)
J-146	------	13.5	Coral, collected live (Agaricea sp., Madracis sp.)
J-147	------	10	Coral, collected live (P. porites, S. radians)
J-148	------	6.5	Coral, collected live (D. stokesii)
J-149	------	3.5	Coral, collected live (P. furcata)
J-150	------	23.5	Coral, collected live (D. stokesii)
J-151	------	20	Coral, collected live (A. agaricites)
J-152	------	16.5	Coral, collected live (P. porites, A. agaricea)
J-153	------	13.5	Coral, collected live (A. agaricea)
J-154	------	2	Coral, collected live (A. palmata)
J-155	------	2	Coral, collected live (P. astreoides)

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-156	------	2	Coral, collected live (P. furcata)
J-157	------	2	Coral, collected live (P. furcata)
J-158	------	2	Coral, collected live (P. furcata)
J-159	------	2	Coral, collected live (P. furcata)
J-160	------	2	Coral, collected live (P. astreoides)
J-161	------	2	Coral, collected live (P. astreoides)
J-162	------	2	Coral, collected live (P. astreoides)
J-163	------	2	Coral, collected live (P. astreoides)
J-164	------	2	Coral, collected live (P. astreoides)
J-165	------	2	Coral, collected live (P. astreoides)
J-166	------	2	Coral, collected live (P. astreoides)
J-167	------	2	Coral, collected live (P. astreoides)
J-168	------	2	Coral, collected live (P. astreoides)
J-169	------	2	Coral, collected live (P. astreoides)
J-170	------	2	Coral, collected live (P. astreoides)
J-171	------	2	Coral, collected live (P. astreoides)
J-172	------	2	Coral, collected live (P. astreoides)
J-173	------	2	Coral, collected live (A. palmata)
J-174	TS-26 to 33	50	Sclerosponge, (C. nicholsoni) collected live
J-175	------	----	Iceland spar calcite, installation 1, 1 day
J-176	------	----	Iceland spar calcite, installation 1, 3 days
J-177	------	----	Iceland spar calcite, installation 1, 4 days

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-178	-------	----	Iceland spar calcite, installation 1, 5 days
J-179	-------	----	Iceland spar calcite, installation 1, 7 days
J-180	-------	----	Iceland spar calcite, installation 1, 8 days
J-181	-------	----	Iceland spar calcite, installation 1, 9 days
J-182	-------	----	Iceland spar calcite, installation 1, 11 days
J-183	-------	----	Iceland spar calcite, installation 1, 12 days
J-184	-------	----	Iceland spar calcite, installation 1, 13 days
J-185	-------	----	Iceland spar calcite, installation 1, 14 days
J-186	-------	----	Iceland spar calcite, installation 1, 15 days
J-187	-------	----	Iceland spar calcite, installation 1, 17 days
J-188	-------	----	Iceland spar calcite, installation 1, 18 days
J-189	-------	----	Iceland spar calcite, installation 1, 20 days
J-190	-------	----	Iceland spar calcite, installation 1, 21 days
J-191	-------	----	Iceland spar calcite, installation 1, 24 days
J-192	-------	----	Iceland spar calcite, installation 1, 25 days
J-193	-------	----	Iceland spar calcite, installation 1, 26 days
J-194	-------	----	Iceland spar calcite, installation 1, 29 days

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTIONS
J-195	-------	----	Iceland spar calcite, installation 1, 30 days
J-196	-------	----	Iceland spar calcite, installation 1, 32 days
J-197	-------	----	Iceland spar calcite, installation 1, 33 days
J-198	-------	----	Iceland spar calcite, installation 1, 34 days
J-199	-------	----	Iceland spar calcite, installation 1, 36 days
J-200	-------	----	Iceland spar calcite, installation 1, 39 days
J-201	-------	----	Iceland spar calcite, installation 1, 40 days
J-202	-------	----	Iceland spar calcite, installation 1, 42 days
J-203	-------	----	Iceland spar calcite, installation 1, 43 days
J-204	-------	----	Iceland spar calcite, installation 1, 44 days
J-205	-------	----	Iceland spar calcite, installation 1, 46 days
J-206	-------	----	Iceland spar calcite, installation 1, 47 days
J-207	-------	----	Iceland spar calcite, installation 1, 53 days
J-208	-------	----	Iceland spar calcite, installation 1, 54 days
J-209	-------	----	Iceland spar calcite, installation 1, 55 days
J-210	-------	----	Iceland spar calcite, installation 1, 56 days

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-211	-------	----	Iceland spar calcite, installation 1, 57 days
J-212	-------	----	Iceland spar calcite, installation 1, 58 days
J-213	-------	----	Iceland spar calcite, installation 1, 59 days
J-214	-------	----	Iceland spar calcite, installation 1, 60 days
J-215	-------	----	Iceland spar calcite, installation 1, 62 days
J-216	-------	----	Iceland spar calcite, installation 1, 63 days
J-217	-------	----	Iceland spar calcite, installation 1, 65 days
J-218	-------	----	Iceland spar calcite, installation 1, 66 days
J-219	-------	----	Iceland spar calcite, installation 1, 67 days
J-220	-------	----	Iceland spar calcite, installation 1, 68 days
J-221	-------	----	Iceland spar calcite, installation 1, 70 days
J-222	-------	----	Iceland spar calcite, installation 1, 95 days
J-223	-------	----	Iceland spar calcite, installation 1, 129 days
J-224	-------	----	Iceland spar calcite, installation 1, 213 days
J-225	-------	----	Iceland spar calcite, installation 1, 253 days
J-226	-------	----	Iceland spar calcite, installation 1, 255 days

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-227	------	----	Iceland spar calcite, installation 1, 257 days
J-228	------	----	Iceland spar calcite, installation 1, 372 days
J-229	------	----	Iceland spar calcite, installation 1, 373 days
J-230	------	----	Iceland spar calcite, installation 1, 375 days
J-231	------	----	Iceland spar calcite, installation 1, 376 days
J-232	------	----	Iceland spar calcite, installation 1, 379 days
J-233	------	----	Iceland spar calcite, installation 1, 380 days
J-234	------	----	Iceland spar calcite, installation 1, 381 days
J-235	------	----	Iceland spar calcite, installation 2, 121 days
J-236	------	----	Iceland spar calcite, installation 2, 126 days
J-237	------	----	Iceland spar calcite, installation 2, 127 days
J-238	------	----	Iceland spar calcite, installation 2, 129 days
J-239	------	----	Iceland spar calcite, installation 2, 133 days
J-240	------	----	Iceland spar calcite, installation 3, 1 day
J-241	------	----	Iceland spar calcite, installation 3, 2 days
J-242	------	----	Iceland spar calcite, installation 3, 3 days

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-243	------	----	Iceland spar calcite, installation 3, 6 days
J-244	------	----	Iceland spar calcite, installation 3, 7 days
J-245	------	----	Iceland spar calcite, installation 4, 1 day
J-246	------	----	Iceland spar calcite, installation 4, 2 days
J-247	------	----	Iceland spar calcite, installation 4, 3 days
J-248	------	----	Iceland spar calcite, installation 4, 4 days
J-249	------	----	Iceland spar calcite, installation 4, 6 days
J-250	------	----	Iceland spar calcite, installation 5, 2 days
J-251	------	----	Iceland spar calcite, installation 5, 3 days
J-252	------	----	Iceland spar calcite, installation 5, 5 days
J-253	------	----	Iceland spar calcite, installation 5, 6 days
J-254	------	----	Iceland spar calcite, installation 5, 7 days
J-255	------	----	Substrate plate removed Apr 25/75 artificial reef
J-256	------	----	Substrate plate removed May 26/75 artificial reef
J-257	------	----	Substrate plate removed Dec 30/74 artificial reef
J-258	------	----	Substrate plate removed Dec 30/74 artificial reef

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-259	------	----	Substrate plate removed Sept 19/74 artificial reef
J-260	------	----	Substrate plate removed Mar 2/75 artificial reef
J-261	------	----	Substrate plate removed Mar 2/75 artificial reef
J-262	------	----	Substrate plate removed Jan 16/74 artificial reef
J-263	------	----	Substrate plate removed May 26/74 artificial reef
J-264	------	----	Substrate plate removed Nov 9/74 artificial reef
J-265	------	----	Substrate plate removed Jun 28/75 artificial reef
J-266	------	----	Substrate plate removed May 26/75 artificial reef
J-267	------	----	Caliche crust, 1st terrace, Rio Bueno
J-268	------	----	Caliche crust, 1st terrace, Port Maria
J-269	------	----	Collapse breccia, White Lmst. Fm., Lilliput
J-270	------	14	Dead M. <u>annularis</u>, east Discovery Bay forereef
J-271	------	----	A. <u>palmata</u>, 1st terrace, Oracabessca
J-272	------	----	Caliche, 1st terrace, Oracabessca
J-273	------	----	Caliche crust, 1st Pleistocene reef terrace, Rio Bueno, east
J-274	------	14	Dead M. <u>annularis</u>, east Discovery Bay forereef
J-275	------	14	Dead S. <u>siderea</u>, sand channel, east Discovery Bay forereef
J-276	------	14	Dead M. <u>annularis</u>, sand channel, east Discovery Bay forereef

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-277	------	14	Dead M. annularis, sand channel, east Discovery Bay forereef
J-278	------	14	Dead S. siderea, sand channel, east Discovery Bay forereef
J-279	------	14	Dead M. annularis, sand channel, east Discovery Bay forereef
J-280	------	14	Dead S. siderea, sand channel, east Discovery Bay forereef
J-281	------	14	Dead S. siderea, sand channel, east Discovery Bay forereef
J-282	------	14	Dead Dichocoenia? sp., sand channel, east Discovery Bay forereef
J-283	------	15	Coralgal block, sand channel, east Discovery Bay forereef
J-284	------	----	Paleosol, 1st Pleistocene reef terrace, Runnaway Bay
J-285	-----	----	Gastropod calcarenite, 1st Pleistocene reef terrace, west Discovery Bay
J-286	------	14	Dead king conch shell, heavily bored, sand channel, east forereef (Discovery Bay)
J-287	------	----	A. palmata, White Lmst. Fm., Oracabessca
J-288	------	10	Dead king conch, heavily bored, west forereef (Discovery Bay)
J-289	------	15	Spar cemented A. cervicornis, excavated from 2 m below substrate surface in cervicornis zone, 2/3 km west of marine labs, Discovery Bay
J-290	------	20	A. agaricea collected live, off Columbus Park, west Discovery Bay
J-291	------	----	1st reef terrace, east shore Rio Bueno; Agaricea and Siderastrea

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D).

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-292	-------	----	1st reef terrace, east shore Rio Bueno; A. *agaricea*
J-293	-------	----	1st terrace, east shore Rio Bueno; P. *porites*, M. *annularis*, *Manicina* sp.
J-294	-------	----	1st terrace, east shore Rio Bueno; P. *furcata*?
J-295	-------	----	1st terrace, east shore Rio Bueno; *Agaricea* sp., *Manicina* sp.
J-296	-------	----	1st terrace, east shore Rio Bueno; P. *porites*, *Mycetophyllia* sp.
J-297	-------	----	1st terrace, east shore Rio Bueno; A. *agaricea*
J-298	-------	----	1st terrace, east shore Rio Bueno; M. *annularis*
J-299	-------	----	1st terrace, east shore Rio Bueno; P. *furcata*
J-300	-------	----	1st terrace, east shore Rio Bueno; P. *furcata*
J-301	-------	----	Iceland spar crystal on substrate rod, buried in sediment in Blue Hole, Discovery Bay. Rod #1, crystal at surface
J-302	-------	----	Iceland spar crystal on substrate rod, buried in sediment in Blue Hole, Discovery Bay. Rod #1, crystal 15 cm below surface
J-303	-------	----	Iceland spar crystal on substrate rod, buried in sediment in Blue Hole, Discovery Bay. Rod #1, crystal 30 cm below surface
J-304	-------	----	Iceland spar crystal on substrate rod, buried in sediment in Blue Hole, Discovery Bay. Rod #1, crystal 45 cm below surface

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-305	------	----	Iceland spar crystal on substrate rod, buried in sediment in Blue Hole, Discovery Bay. Rod #1, crystal 60 cm below surface
J-306	------	----	Iceland spar crystal on substrate rod, buried in sediment in Blue Hole, Discovery Bay. Rod #2, crystal at surface
J-307	------	----	Iceland spar crystal on substrate rod, buried in sediment in Blue Hole, Discovery Bay. Rod #2, crystal 15 cm below surface
J-308	------	----	Iceland spar crystal on substrate rod, buried in sediment in Blue Hole, Discovery Bay. Rod #2, crystal 30 cm below surface
J-309	------	----	Iceland spar crystal on substrate rod, buried in sediment in Blue Hole, Discovery Bay. Rod #2, crystal 45 cm below surface
J-310	------	----	Iceland spar crystal on substrate rod, buried in sediment in Blue Hole, Discovery Bay. Rod #2, crystal 60 cm below surface
J-311	------	43	Calcarenite, west forereef, below Zingoro reef
J-312	------	53	Halimeda calcarenite, west forereef, below Zingoro reef
J-313	TS-252	----	1st reef terrace, west coast Discovery Bay, taken from supratidal
J-314	TS-253	----	1st reef terrace, west coast Discovery Bay, taken from subtidal
J-315	TS-254	----	1st reef terrace, west coast Discovery Bay, taken from intertidal
J-316	TS-36	3	Bored dead fragment of A. palmata forereef, Discovery Bay

SAMPLE DESCRIPTIONS
DISCOVERY BAY JAMAICA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
J-317	TS-34	----	P. porites, 1st Pleistocene reef terrace at Discovery Bay
J-318	TS-35	10	Bored and encrusted stick of A. cervicornis. Cerviconis zone, west Discovery Bay forereef
J-319	TS-38	10	Unidentifiable coral fragment; heavily bored
J-320	TS-40	10	Bored, dead, A. cervicornis, west Discovery Bay forereef

SAMPLE DESCRIPTIONS
MIETTE, ALBERTA

SAMPLE	THIN SECTION	DESCRIPTION
M-1	TS-178	Stromatoporoid vertical section, uppermost Cairn Fm., Slide Creek N.W.
M-2	TS-179	Fenestral Lmst., Peechee Mbr, Slide Creek Center
M-3	TS-180	Fenestral Lmst., Peechee Mbr, Slide Creek Center
M-4	TS-181	"Red bed", mid. upper Cairn Fm., Slide Creek S.E.
M-5	TS-182	"Red bed", mid. upper Cairn, Slide Creek S.E.
M-6	TS-183	Mid. Cairn Slide Creek S.E.
M-7	TS-184	Cairn Fm. Slide Creek S.E.
M-8	TS-185	Fenestral Lmst., Peechee Mbr., Slide Creek Center
M-9	TS-186	Stromatoporoid vertical section, middle Cairn Fm., Slide Creek S.E.
M-10	TS-187	Stromatoporoid vertical section, upper Cairn Fm., Slide Creek S.E.
M-12	TS-189	Middle Cairn Fm., Slide Creek S.E.
M-13	TS-190	Middle Cairn Fm., Slide Creek S.E.
M-14	TS-191	Middle Peechee Mbr., Slide Creek N.W.
M-15	TS-277	Stromatoporoid, <u>Atelodictyon</u> <u>stelliferum</u>, Cairn Fm.
M-16	TS-290	Pelsparite, lower Cairn Fm., Slide Creek S.E.
M-17	TS-291	Pelsparite, lower Flume Mbr., Slide Creek S.E.
M-18	TS-292	Peechee Mbr., fenestral pelsparite Slide Creek N.W.
M-19	TS-293	Flume Mbr., stromatoporoid T. <u>lecomptei</u>

SAMPLE DESCRIPTIONS
MIETTE, ALBERTA (CONT'D)

SAMPLE	THIN SECTION	DESCRIPTION
M-20	TS-294	Lower Cairn Fm., Slide Creek S.E.
M-21	TS-295	Lower Cairn Fm., Slide Creek S.E.

SAMPLE DESCRIPTIONS
BERMUDA

SAMPLE	THIN SECTION	DESCRIPTION
BD-1	TS-207	Stalactite, coated in aragonite; Crystal Caves
BD-2	TS-208	Stalactite, coated in aragonite; Crystal Caves
BD-3	TS-213	Caliche crust, south coast Bermuda, opposide St. Georges
BD-4	TS-215	Stalactite, heavily bored; Crystal Caves
BD-5	TS-216	Stalactite, heavily bored; Crystal Caves
BD-6	TS-217	Stalactite, heavily bored; Crystal Caves
BD-7	TS-218	Stalactite, heavily bored; Crystal Caves
BD-8	TS-219	Stalactite, heavily bored; Crystal Caves
BD-9	TS-220	Stalactite, coated in aragonite; Crystal Caves
BD-10	TS-221	Stalactite, coated in aragonite; Crystal Caves
BD-11	TS-222	Stalactite, coated in aragonite; Crystal Caves
BD-12	TS-223	Stalactite, coated in aragonite; Crystal Caves

SAMPLE DESCRIPTIONS
SOUTHERN QUEBEC, VERMONT AND ONTARIO

SAMPLE	THIN SECTION	DESCRIPTION
Q-1	TS-201	Chazy Fm. Isle Bizard, P.Q.
Q-2	TS-202	Chazy Fm. Isle Bizard, P.Q.
Q-3	TS-203	Chazy Fm. Isle Bizard, P.Q.
Q-4	TS-204	Chazy Fm. Isle Bizard, P.Q.
Q-5	TS-205	Chazy Fm. Isle Bizard, P.Q.
Q-6	TS-206	Chazy Fm. Isle Bizard, P.Q.
Q-7	TS-210	Rosemount Fm. Pierrefonds, P.Q.
Q-8	TS-211	Rosemount Fm. Pierrefonds, P.Q.
Q-9	TS-212	St. Michel Fm. Pierredonds, P.Q.
Q-10	TS-278	Valcour Fm. Isle LaMotte, Vermont calcarenite
Q-11	TS-279	Valcour Fm. Isle LaMotte, Vermont Goodsell Ridge, *Pachystylostroma goodsellense*
Q-12	TS-280	Valcour Fm. Isle LaMotte, Vermont Goodsell Ridge, P. *vallum*
Q-13	TS-281	Valcour Fm. Isle LaMotte, Vermont Goodsell Ridge, *Pseudostylostroma goodsellense*
Q-14	TS-282	Valcour Fm. Isle LaMotte, Vermont Goodsell Ridge, *Labechia eatoni*
Q-15	TS-283	Valcour Fm. Isle LaMotte, Vermont Goodsell Ridge, *Labechia prima* on calcarenite
Q-16	TS-284	Valcour Fm. Isle Lamotte, Vermont, *Pseudostylodictyon lamottense*
Q-17	TS-285	Valcour Fm. Isle LaMotte, Vermont, *Pachystylostroma pollicellum*
Q-18	TS-286	Valcour Fm. Isle LaMotte, Vermont, *Pachystylostroma pollicellum*
Q-19	TS-287	Valcour Fm. Isle LaMotte, Vermont, *Pachystylostroma pollicellum*

SAMPLE DESCRIPTIONS
SOUTHERN QUEBEC, VERMONT AND ONTARIO (CONT'D)

SAMPLE	THIN SECTION	DESCRIPTION
Q-20	TS-288	Valcour Fm. Isle LaMotte, Vermont, <u>Pachystylostroma goodsellense</u>
Q-21	TS-289	Valcour Fm. Isle LaMotte, Vermont, <u>Pachystylostroma goodsellense</u>

SAMPLE DESCRIPTIONS
BARBADOS

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
B-1	TS-224	----	83,000 terrace, Animal Flower Caves
B-2	TS-225	----	Calcirudite, 83,000 terrace, North Point
B-3	TS-226	----	83,000 terrace, North Point
B-4	TS-227	----	83,000 terrace, North Point (A. *palmata*)
B-5	TS-234	----	83,000 terrace, North Point
B-6	TS-235	----	125,000 terrace, Holetown roadcut
B-7	TS-236 to 238	----	83,000 terrace, Animal Flower Caves
B-8	TS-239	----	83,000 terrace, Animal Flower Caves (A. *palmata*)
B-9	TS-240	----	83,000 terrace, Animal Flower Caves
B-10	TS-241	----	Caliche crust, 83,000 terrace, North Point
B-11	TS-242	----	83,000 terrace, Animal Flower Caves
B-12	TS-243	----	83,000 terrace, Animal Flower Caves
B-13	TS-244	----	Calcarenite, 83,000 terrace, Animal Flower Caves
B-14	TS-245	----	83,000 terrace, Animal Flower Caves
B-15	TS-246	----	83,000 terrace, Animal Flower Caves
B-16	TS-247	----	83,000 terrace, Animal Flower Caves
B-17	TS-248	----	83,000 terrace, Animal Flower Caves (A. *palmata*)
B-18	TS-249	----	83,000 terrace, Animal Flower Caves (A. *palmata*)
B-19	TS-250	----	83,000 terrace, Animal Flower Caves (A. *palmata*)
B-20	TS-251	----	Calcarenite, 83,000 terrace, North Point

SAMPLE DESCRIPTIONS
BARBADOS (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
B-21	TS-255	----	83,000 terrace, Animal Flower Caves
B-22	TS-256	----	83,000 terrace, Animal Flower Caves
B-23	TS-257	----	83,000 terrace, Animal Flower Caves (A. palmata)
B-24	TS-258	----	Caliche, 83,000 terrace, North Point
B-25	TS-268 to 271	----	83,000 terrace, River Bay
B-26	TS-41	----	P. porites, collected live; Bellairs reef
B-27	TS-59	----	Beach sand, swash zone, Morgan Lewis Beach

SAMPLE DESCRIPTIONS
FLORIDA

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
F-1	TS-173	----	Altered zone about soil infill, Key Largo Fm., Key Largo
F-2	TS-172	----	Recrystallized M. *annularis*, Key Largo Fm., Key Largo
F-3	TS-174	----	Mottled Key Largo Lmst., Key Largo
F-4	TS-175	----	Mottled Key Largo Lmst., Key Largo
F-5	TS-176	----	Key Largo Lmst., Key Largo
F-6	------	----	Mottled Key Largo Lmst., Mangrove root facies, Key Largo
F-7	TS-177	----	Mottled Key Largo Lmst., Key Largo
F-8	------	----	Mangrove root facies, Key Largo Fm., Koa Campground
F-9	------	----	Algal boundstone, Key Largo Fm., Quarry at Key Largo
F-10	------	----	Key Largo Fm. algal boundstone, Key Largo at Koa Campground
F-11	------	5	D. *stokesii*, Pickles reef, collected live
F-12	------	5	D. *stokesii*, Pickles reef, collected live
F-13	------	----	Caliche crust, Key Largo Fm., Key Largo
F-14	------	----	Mangrove root facies, Kay Largo Fm., Key Largo
F-15	------	5	D. *stokesii*, Pickles reef, collected live
F-16	------	----	Recrystallized M. *annularis*, Key Largo Fm., Key Largo
F-17	------	----	Cross-bedded Miami Oolite, Big Pine Key
F-18	------	5	D. *stokesii*, Pickles reef, collected live

SAMPLE DESCRIPTION:
FLORIDA (cont'd)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
F-19	------	----	Highly porous pelecypod coquina and oolite, Big Pine Key; Miami Oolite
F-20	------	5	D. *stokesii*, Pickles reef, collected live
F-21	------	5	D. *stokesii*, Pickles reef, collected live
F-22	------	5	D. *stokesii*, Pickles reef, collected live
F-23	------	5	D. *stokesii*, Pickles reef, collected live
F-24	------	5	D. *stokesii*, Pickles reef, collected live
F-25	------	5	D. *stokesii*, Pickles reef, collected live
F-26	------	5	D. *stokesii*, Pickles reef, collected live
F-27	------	5	D. *stokesii*, Pickles reef, collected live
F-28	------	----	Bored and encrusted A. *palmata*, Key Largo Fm., Key Largo
F-29	------	5	D. *stokesii*, Pickles reef, collected live
F-30	------	5	D. *stokesii*, Pickles reef, collected live
F-31	------	5	D. *stokesii*, Pickles reef, collected live
F-32	------	----	Mangrove root facies, Key Largo Fm., Key Largo
F-33	------	----	Caliche crust, Kay Largo Fm., Key Largo
F-34	------	5	D. *stokesii*, Pickles reef, collected live

SAMPLE DESCRIPTIONS
FLORIDA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
F-35	------	----	Mangrove root facies, Koa Campground, Key Largo
F-36	------	----	*Manicina* sp. in algal boundstone, Key Largo Fm., Key Largo
F-37	------	5	D. *stokesii*, Pickles reef, collected live
F-38	------	5	D. *stokesii*, Pickles reef, collected live
F-39	------	5	D. *stokesii*, Pickles reef, collected live
F-40	------	----	Micrite, highly porous (algal?) Key Largo Fm., Key Largo
F-41	------	----	Caliche crust, Key Largo Fm., Key Largo
F-42	------	----	M. *annularis*, Key Largo Fm., Key Largo
F-43	------	2	*Halimeda*, collected live off Lower Matecumbe Key
F-44	------	4	*Udotea*, *Penicillus*, collected live off Lower Matecumbe Key
F-45	------	----	Intertidal gelatinous oncolite, Turkey Key, Florida Bay
F-46	------	4	*Penicillus*, collected live at Pickles reef (back of reef crest)
F-47	------	4	Sponges, assorted soft, Pickles reef
F-48	------	4	Bored and encrusted gastropods Pickles, sand channel
F-49	------	3	Coralgal nodules Pickles reef, sand channel
F-50	------	4	Dead, bored A. *palmata*, Pickles reef, sand channel
F-51	------	5	A. *cervicornis*, collected dead; bored; Pickles reef, sand channel

SAMPLE DESCRIPTIONS
FLORIDA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
F-52	------	5	Coralgal nodule, Pickles reef, sand channel
F-53	------	5	Dead, bored Manicina sp., Pickles reef, sand channel
F-54	------	5	Dead, bored Manicina sp., Pickles reef, sand channel
F-55	------	4	Dead, but bored and intact echinoderm test; Pickles reef
F-56	------	5	Immature Queen Conch, dead, bored, Pickles reef, sand channel
F-57	------	----	Key Largo Fm., Key Windley Quarry
F-58	------	5	Heavily bored and encrusted gastropod, Pickles reef, sand channel
F-59	------	4	Coralgal nodule, Pickles reef, sand channel
F-60	------	3	Gastropods, slightly bored, Pickles reef, sand channel
F-61	------	----	Key Largo Fm., Koa Campground, Key Largo
F-62	------	----	Key Largo Fm., M. annularis, bored; Key Largo
F-63	------	----	Key Largo Fm., Mangrove root facies, Koa Campground
F-64	------	----	M. annularis, Key Largo Fm., Windley Key Quarry
F-65	------	5	Heavily bored and encrusted P. porites, Pickles reef, sand channel
F-66	------	4	Coralgal nodule, Pickles reef, sand channel
F-67	------	5	A. cervicornis, cememted, bored and encrusted, Pickles reef, sand channel
F-68	------	4	Pelecypod valve, heavily bored and encrusted, Pickles reef, sand channel

SAMPLE DESCRIPTION
FLORIDA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
F-69	-------	5	Coralgal nodule, Pickles reef, sand channel
F-70	-------	4	Heavily bored A. cervicornis, Pickles reef
F-71	-------	3	Heavily bored and encrusted Manicina, Pickles reef
F-72	TS-20	4	Heavily bored and encrusted P. porites? Pickles reef, sand channel
F-73	-------	1	Pelecypods, collected live; Turkey Key, Florida Bay
F-74	-------	3	Queen Conch, immature, collected live; Pickles reef
F-75	-------	4	Heavily bored echinoderm test; Pickles reef
F-76	-------	5	Fragment, heavily bored, Queen Conch, Pickles reef, sand channel
F-77	-------	5	Echinoderm test; heavily bored, lightly encrusted, Pickles reef, sand channel
F-78	-------	----	Recrystallized M. annularis, Key Largo Fm., Koa Campground
F-79	-------	----	Key Largo Lmst., Key Largo
F-80	-------	5	King Conch, collected dead, lightly bored, Pickles reef, sand channel
F-81	-------	----	Assorted pelecypods, collected live; Lower Matecumbe Key, intertidal
F-82	-------	5	D. stokesii, Pickles reef, collected live
F-83	-------	----	M. annularis, Key Largo Fm., Big Pine Key
F-84	-------	----	Miami Oolite, Big Pine Key
F-85	-------	----	Pelecypod coquina, Big Pine Key, Miami Oolite

SAMPLE DESCRIPTION
FLORIDA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
F-86	------	----	Caliche crust and paleosol, Big Pine Key, Key Largo Fm.
F-87	TS-259	5	Calcarenite, Pickles reef, sand channel
F-88	TS-260	5	Calcarenite, Pickles reef, sand channel
F-89	TS-261	5	Calcarenite, Pickles reef, sand channel
F-90	TS-262	5	Calcarenite, Pickles reef, sand channel
F-91	TS-263	5	Calcarenite, Pickles reef, sand channel
F-92	TS-264	5	Calcarenite, Pickles reef, sand channel
F-93	TS-265	5	Calcarenite, Pickles reef, sand channel
F-94	TS-200	----	Recrystallized M. annularis, Key Largo Fm., Fisher Island
F-95	TS-17	5	Heavily bored, encrusted coral (D. stokesii?) Pickles reef
F-96	TS-18	4	Heavily bored, unidentifiable coral "lump", sand channel, Pickles reef
F-97	TS-22	5	Calcarenite, sand channel, Pickles reef
F-98	TS-23	5	Calcarenite, sand channel, Pickles reef
F-99	TS-24	5	Calcarenite, sand channel, Pickles reef
F-100	TS-25	5	Calcarenite, sand channel, Pickles reef
F-101	TS-45	----	M. annularis, Key Largo Fm., Key Largo

SAMPLE DESCRIPTION
FLORIDA (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
F-102	TS-46	----	M. *annularis*, Key Largo Fm., Key Largo
F-103	TS-47	----	M. *annularis*, Key Largo Fm., Key Largo
F-104	TS-50	----	M. *annularis*, Key Largo Fm., Key Largo
F-105	TS-52	4	Degraded and encrusted pelecypod valve, Pickles reef
F-106	TS-58	4	Heavily bored gastropod, Pickles reef

SAMPLE DESCRIPTIONS
CURACAO

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
C-1	------	14	Westpunt Baai, forereef, sand pocket, calcarenite
C-2	------	16	Westpunt Baai, forereef, sand channel, calcarenite
C-3	------	20	Westpunt Baai, forereef, sand channel, calcarenite
C-4	------	----	Westpunt Baai, intertidal beach sand
C-5	------	----	Coral, Pliocene, head of Piscadera Baai
C-6	------	----	Calcarenite, Pliocene, Piscadera Baai
C-7	------	----	Mottled caliche, Pliocene, Piscadera Baai
C-8	------	24	Dead, bored *Manicina*, Westpunt Baai, forereef
C-9	------	23	Dead, bored A. *cervicornis* and P. *porites*, Westpunt Baai, forereef
C-10	------	22.5	Dead, bored P. *porites*, and A. *cervicornis*, Westpunt Baai, forereef
C-11	------	23	Dead, bored *Manicina*, Westpunt Baai, forereef
C-12	------	23	*Agaricea* sp., dead, bored; forereef, Westpunt Baai
C-13	------	23	Dead, bored *Agaricea* sp., forereef, Westpunt Baai
C-14	------	----	Oyster, Pliocene, head of Piscadera Baai
C-15	------	----	Bored oyster, Pleistocene, head of Piscadera Baai
C-16	------	----	Oysters, gastropods; Pleistocene, head of Piscadera Baai
C-17	------	----	Oysters, Pleistocene, head of Piscadera Baai

SAMPLE DESCRIPTIONS
CURACAO (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
C-18	------	----	Pelecypods, Pleistocene, head of Piscadera Baai
C-19	------	----	Bored oysters, Pleistocene, head of Piscadera Baai
C-20	------	----	Coral, Pliocene, above Piscadera Baai
C-21	------	----	Assorted pelecypods, Pleistocene, Piscadera Baai
C-22	------	----	Assorted pelecypods, Pleistocene, Piscadera Baai
C-23	------	----	Oysters, Pleistocene, head of Piscadera Baai
C-24	------	----	Paleosol and caliche, Pliocene, above Piscadera Baai
C-25	------	----	Queen Conch with calcarenite, 1st reef terrace, San Pedro
C-26	------	----	Caliche, Pliocene, above Piscadera Baai
C-27	------	----	Caliche, Pliocene, above Piscadera Baai
C-28	------	----	Caliche, Pliocene, above Piscadera Baai
C-29	------	----	Heavily bored coral, Pleistocene, head of Piscadera Baai
C-30	------	----	Recrystallized coral, Pleistocene, head of Piscadera Baai
C-31	------	----	Calcarenite, Pleistocene, head of Piscadera Baai
C-32	------	----	Calcarenite, 1st reef terrace, San Pedro
C-33	------	----	Coral, head of Piscadera Baai, Pleistocene
C-34	------	----	Coral, head of Piscadera Baai, Pleistocene

SAMPLE DESCRIPTIONS
CURACAO (CONT'D)

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
C-35	------	----	S. radians, Pleistocene, head of Piscadera Baai
C-36	------	14.5	Bored and encrusted P. porites, Westpunt Baai, forereef
C-37	------	----	Calcarenite, II reef terrace, San Pedro

SAMPLE DESCRIPTIONS
BONAIRE

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
BN-1	------	3.5	Calcarenite, reef at Lands Radio; forereef
BN-2	------	6.5	Calcarenite, reef at Lands Radio; forereef
BN-3	------	10	Calcarenite, reef at Lands Radio; forereef
BN-4	------	14	Calcarenite, reef at Lands Radio; forereef
BN-5	------	1	Calcarennte, Lac, off Sorobon point
BN-6	-------	----	Beach, Boca Jewfish, intertidal; calcarenite
BN-7	-------	----	Cemented crust; intertidal, Sorobon
BN-8	-------	----	Cemented algal beach nodules, beach at Boca Jewfish; intertidal
BN-9	-------	----	Cemented algal beach nodules, beach at Boca Jewfish; intertidal
BN-10	-------	----	Calcarenite, 1st reef terrace, Malmok
BN-11	-------	----	Crust, N.E. Pekelmeer, intertidal
BN-12	-------	----	Crust, N.E. Pekelmeer, intertidal
BN-13	-------	----	Calcarenite, II reef terrace, Rincon
BN-14	-------	----	Calcarenite, I reef terrace, Malmok
BN-15	-------	----	Algal crust, cemented; Holocene, Sorobon Point, intertidal

SAMPLE DESCRIPTIONS
MISC. SAMPLES

SAMPLE	THIN SECTION	DEPTH (M)	DESCRIPTION
X-1	------	----	Iceland spar, salt water tanks, 35 days
X-2	------	----	Iceland spar, salt water tanks, 60 days
X-3	------	----	Iceland spar, salt water tanks, 74 days
X-4	------	----	Iceland spar, salt water tanks, 84 days
X-5	------	----	Iceland spar, salt water tanks, 105 days
X-6	------	----	Iceland spar, salt water tanks, 126 days
X-7	------	----	Iceland spar, salt water tanks, 255 days
X-8	------	----	Iceland spar, salt water tanks, 441 days
X-9	------	----	Iceland spar, salt water tanks, 563 days
X-10	------	5	Calcarenite, 200 m offshore, Vigie Bay, St. Lucia
X-11	------	6	Beach sand, Vigie Bay, St. Lucia
X-12	------	5	40 m offshore, calcarenite, Vigie Bay, St. Lucia

APPENDIX III

TABLES

TABLE I

ALGAE IN ICELAND SPAR CALCITE
INSTALLATION NO. 1, DISCOVERY BAY, JAMAICA

TOTAL NO. DAYS IN SEAWATER	ALGAL COUNTS	BORINGS % AREA	CALCITE COUNTS	CALCITE % AREA	N TOTAL COUNTS
1	0	0.00	1000	100.00	1000
3	0	0.00	1000	100.00	1000
4	0	0.00	1000	100.00	1000
5	0	0.00	1000	100.00	1000
7	0	0.00	1000	100.00	1000
8	6	0.57	1022	99.43	1028
9	8	0.79	1000	99.21	1008
11	14	1.38	1004	98.62	1018
12	15	1.48	998	98.52	1013
13	18	1.79	984	98.21	1002
14	20	1.96	998	98.04	1018
15	26	2.57	986	97.43	1012
17	75	7.24	966	92.76	1041
18	90	8.83	939	91.17	1019
20	102	9.96	922	90.04	1024
21	120	11.20	951	88.80	1071
24	200	16.67	1000	83.30	1200
25	220	16.00	1155	84.00	1375
26	234	17.33	1116	82.67	1350
29	305	24.59	910	75.41	1240
30	280	21.79	1005	78.21	1265
32	258	22.67	880	77.33	113[illegible]
33	400	31.74	860	66.15	1260
34	312	26.26	788	73.74	1188
36	413	29.94	904	70.06	1379
39	341	33.72	670	66.28	1011
40	350	38.86	645	61.14	995
42	371	36.98	632	63.02	1003
43	450	41.32	639	50.68	1089
44	396	37.50	660	62.50	1056

TABLE 1 CONT'D

TOTAL NO. DAYS	ALGAL	BORINGS	CALCITE		N
IN SEAWATER	COUNTS	% AREA	COUNTS	% AREA	TOTAL COUNTS
46	422	40.66	616	59.34	1038
47	420	41.62	589	58.38	1009
53	501	46.38	579	53.62	1080
54	479	47.80	523	52.20	1002
55	518	49.09	537	50.91	1055
56	546	48.70	575	51.30	1121
57	504	50.24	499	49.76	1003
58	582	51.80	541	48.20	1123
59	591	53.15	521	46.85	1112
60	517	51.28	491	48.72	1008
62	537	53,86	460	46.14	997
63	653	57.48	483	45.52	1136
65	574	56.88	435	43.12	1009
66	650	58.71	457	41.29	1107
67	569	57.01	429	42.99	998
68	598	59.50	407	40.50	1005
70	696	60.73	450	39.27	1146
95	852	76.76	258	23.24	1110
129	772	80.42	188	19.58	960
213	1006	100.00	0	0.00	1006
253	998	100.00	0	0.00	998
255	1002	100.00	0	0.00	1002
257	1116	100.00	0	0.00	1116
372	1000	100.00	0	0.00	1000
373	1002	100.00	0	0.00	1002
375	998	99.80	2	0.20	1000
376	1001	100.00	0	0.00	1001
379	1000	100.00	0	0.00	1000
380	1003	100.00	0	0.00	1003
381	1000	100.00	0	0.00	1000

TABLE 2

ALGAL IN ICELAND SPAR CALCITE
INSTALLATIONS NOS. 2, 3, 4, 5, DISCOVERY BAY, JAMAICA

TOTAL NO. DAYS	ALGAL	BORINGS	CALCITE		N
IN SEAWATER	COUNTS	% AREA	COUNTS	% AREA	TOTAL COUNTS
		INSTALLATION #2			
121	470	47.00	530	53.00	1000
126	510	51.00	490	49.00	1000
127	590	59.00	410	41.00	1000
129	600	60.00	400	40.00	1000
133	558	55.80	442	44.20	1000
		INSTALLATION #3			
1	13	1.30	987	98.70	1000
2	20	2.00	980	98.00	1000
3	15	1.50	985	98.50	1000
6	25	2.50	975	97.50	1000
7	37	3.70	963	96.30	1000
		INSTALLATION #4			
1	0	0.00	1000	100.00	1000
2	15	1.50	985	98.50	1000
3	20	2.00	980	98.00	1000
4	20	2.00	980	98.00	1000
6	36	3.60	964	96.40	1000
		INSTALLATION #5			
2	0	0.00	1000	100.00	1000
3	9	0.90	991	99.10	1000
5	15	1.50	985	98.50	1000
6	10	1.00	990	99.00	1000
7	17	1.70	983	98.30	1000

TABLE 3

ALGAE IN ICELAND SPAR
SALT WATER TANKS, McMASTER UNIVERSITY

TOTAL NO. DAYS IN SEAWATER	ALGAL COUNTS	BORINGS % AREA	CALCITE COUNTS	CALCITE % AREA	N TOTAL COUNTS
35	101	10.07	901	89.03	1002
60	177	17.40	843	82.60	1020
74	254	24.60	777	75.40	1031
84	240	23.40	787	76.60	1027
105	292	28.40	735	71.60	1027
126	318	30.80	716	62.20	1034
255	325	32.10	686	67.90	1011
441	347	34.60	656	65.40	1003
563	373	36.10	659	63.90	1032

TABLE 1.

SUMMARY OF GRAIN SIZE STATISTICS
DISCOVERY BAY SANDS

SAMPLE NO:	"INMAN" MEDIAN	MEAN SIZE	STANDARD DEVIATION	SKEWNESS	KURTOSIS	"TRASK" SORTING CO-EFFICIENT
J-3	2.03	1.84	1.41	-0.77	3.39	0.25
J-4	1.81	1.78	1.27	-0.08	2.20	0.28
J-5	2.20	2.01	1.21	-0.47	2.36	0.30
J-6	1.80	1.55	1.45	-0.40	2.18	0.20
J-8	1.42	1.35	1.29	-0.21	2.09	0.23
J-10	1.18	1.20	1.11	0.05	2.34	0.31
J-11	1.46	1.34	1.36	-0.36	2.28	0.26
J-12	2.00	1.69	1.17	-0.54	2.81	0.36
J-13	2.29	2.07	1.22	-0.58	2.68	0.30
J-14	2.64	2.44	1.06	-1.18	4.26	0.44
J-15	1.70	1.68	1.61	0.01	1.48	0.11
J-16	3.11	2.89	0.78	-0.92	3.57	0.48
J-17	2.90	2.59	1.09	-0.93	3.14	0.38
J-18	2.57	2.42	1.13	-0.69	3.03	0.[illegible]0
J-19	2.64	2.38	1.15	-0.86	3.06	0.36
J-20	1.54	1.57	1.35	-0.08	2.19	0.24
J-21	2.25	2.18	1.01	-0.58	3.00	0.40
J-22	2.29	2.24	0.93	-0.36	2.84	0.41
J-23	2.63	2.39	1.08	-0.70	2.63	0.36
J-24	2.80	2.65	0.92	-0.99	3.47	0.51
J-25	2.90	2.74	0.87	-1.34	6.32	0.47
J-33	2.37	1.55	1.87	-0.57	1.98	0.12
J-34	2.79	2.25	1.47	-0.90	3.04	0.20
J-35	1.43	1.49	1.25	-0.17	2.47	0.28
J-37	1.68	1.50	1.46	-0.32	2.02	0.19
J-43	2.16	1.84	1.34	-0.68	2.48	0.24
J-44	2.56	2.04	1.52	-0.81	2.56	0.21
J-46	2.03	1.76	1.33	-0.82	3.10	0.31
J-47	2.44	2.13	1.23	-0.84	2.87	0.30
J-48	1.11	1.08	1.58	0.00	1.80	0.15

TABLE 4 CONT'D

SAMPLE NO:	"INMAN" MEDIAN	MEAN SIZE	STANDARD DEVIATION	SKEWNESS	KURTOSIS	"TRASK" SORTING CO-EFFICIENT
J-53	2.21	1.94	1.33	-0.76	3.09	0.26
J-58	0.66	0.84	1.24	0.24	2.59	0.33
J-59	0.50	1.27	1.82	0.23	1.42	0.08
J-61	1.58	1.51	1.20	-0.11	2.24	0.28
J-62	2.35	1.97	1.31	-0.62	2.33	0.28
J-63	2.44	2.42	0.65	-0.39	3.20	0.58
J-64	2.41	2.14	1.02	-0.83	3.11	0.45
J-65	0.70	0.90	1.20	0.37	2.39	0.27
J-66	1.48	1.39	0.94	-0.61	3.23	0.49
J-67	1.40	1.41	1.39	-0.26	1.82	0.19
J-69	0.53	0.59	1.03	0.04	3.10	0.44
J-70	2.31	2.31	0.67	-0.62	4.27	0.57
J-71	2.29	2.08	1.02	-0.60	2.97	0.40
J-72	2.23	1.76	1.40	-0.70	2.46	0.26
J-73	2.27	2.12	1.25	-0.86	3.49	0.28
J-74	2.11	1.70	1.26	-0.58	2.50	0.24
J-75	0.19	0.25	0.92	0.58	3.49	0.44
J-76	0.27	0.39	0.86	0.60	4.11	0.54
J-77	0.62	0.76	0.88	0.45	2.43	0.42
J-78	N.A.	1.59	1.77	0.00	1.44	0.08
J-79	0.33	0.42	0.93	0.53	3.28	0.44
J-80	1.26	1.31	1.20	-0.17	3.67	0.41
J-81	1.38	1.27	1.31	-0.57	3.44	0.36
J-82	1.96	1.84	1.32	-0.15	1.98	0.24
J-83	1.96	1.86	1.30	-0.24	2.22	0.28
J-84	1.28	1.35	1.32	0.03	2.02	0.21
J-93	-0.57	-0.30	1.21	1.56	5.44	0.43
J-95 (0-5 cm)	2.69	2.52	1.00	-0.79	3.04	0.43
J-95 (5-10 cm)	N.A.	2.89	0.89	-1.45	5.63	0.48

TABLE 4 CONT'D

SAMPLE NO:	"INMAN" MEDIAN	MEAN SIZE	STANDARD DEVIATION	SKEWNESS	KURTOSIS	"TRASK" SORTING CO-EFFICIENT
J-95 (10-15 cm)	2.80	2.67	0.83	-0.91	3.63	0.49
J-95 (15-20 cm)	2.72	2.60	1.02	-0.81	3.35	0.36
J-95 (20-25 cm)	2.83	2.6-	0.91	-0.84	3.36	0.44
J-95 (25-30 cm)	2.94	2.72	1.01	-1.42	5.06	0.49
J-95 (30-35 cm)	2.73	2.56	1.02	-1.56	6.20	0.50
J-95 (35-40 cm)	2.72	2.60	0.93	-0.70	2.96	0.42
J-95 (40-45 cm)	3.00	2.82	0.84	-1.29	4.80	0.53
J-95 (45-50 cm)	N.A.	2.87	0.89	-1.12	4.06	0.45
J-95 (50-55 cm)	2.52	2.39	0.95	-0.97	4.31	0.46
J-95 (55-60 cm)	2.35	2.26	0.98	-0.44	2.71	0.34
J-98	0.97	1.00	1.06	0.00	2.60	0.37
J-100	0.57	0.64	1.03	0.41	2.63	0.37
J-102	1.17	1.19	0.90	0.12	2.61	0.39
J-104	0.32	0.53	0.98	0.87	3.81	0.45
J-106	-0.73	-0.60	0.66	0.28	2.50	0.48

NOTE: J-95 is a core. The numbers in brackets refer to distance in cm below water-sediment interface.

1. The grain size analyses presented herein are not discussed in the body of the thesis, but are included as peripheral data of some possible use to other investigators.

APPENDIX IV

ENDOLITHIC ALGAE IN A SILURIAN - DEVONIAN SEACOAST [1]

---

[1] This appendix summarizes work which though not central to the thesis, is of value in attempting to understand the overall significance of boring algae in ancient environments, and is included here for peripheral interest.

APPENDIX IV

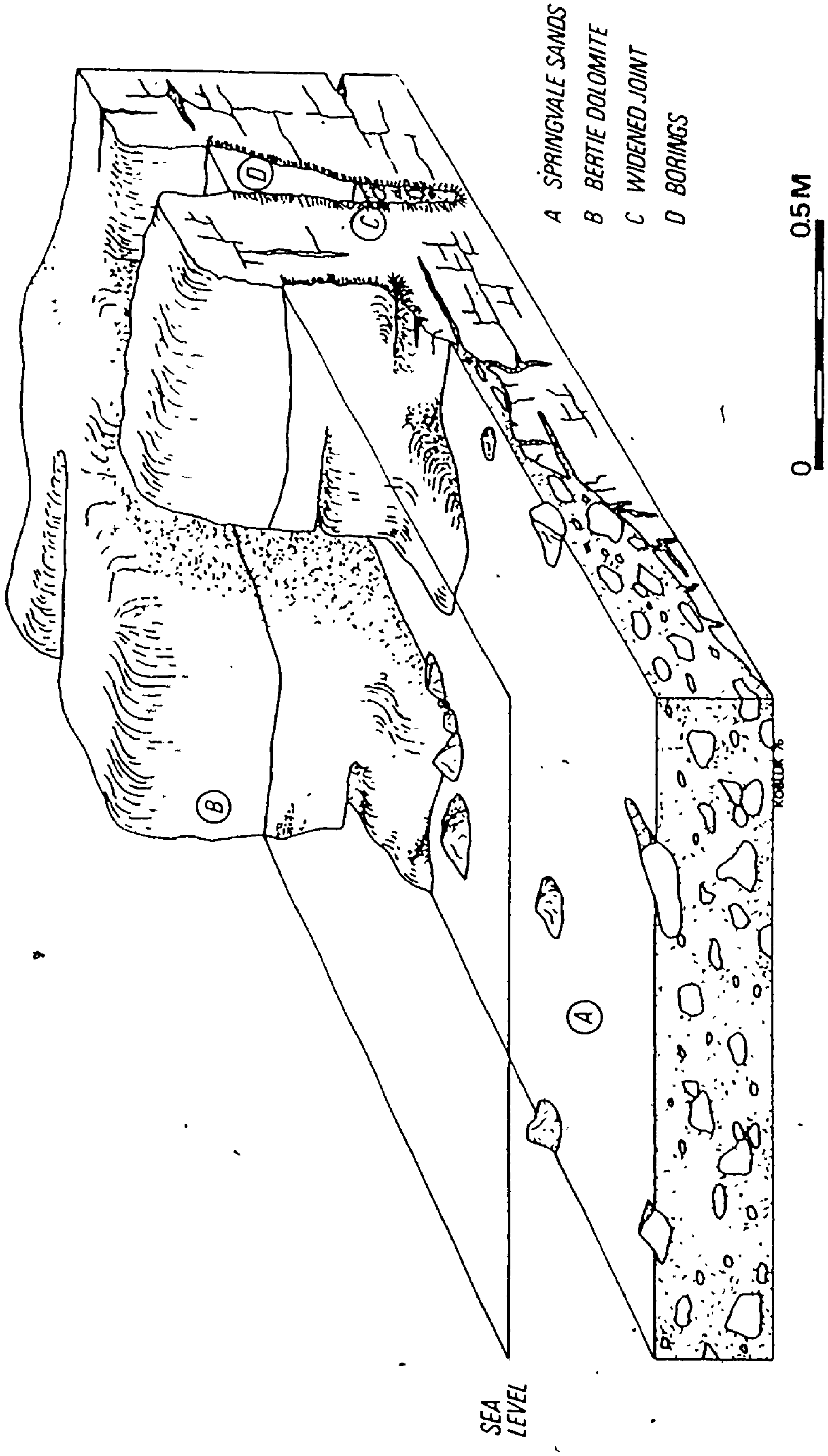
ENDOLITHIC ALGAE IN A SILURIAN - DEVONIAN SEACOAST

Endolithic algae are commonly found boring into limestone outcrop and sea cliff exposures, particularly in tropical latitudes. They are a significant biological-erosive agent (Ginsburg, 1956) and contribute to coastal erosion. Though ubiquitous today, the geologic record of boring algae in ancient seacoast exposures is virtually unknown. There is no reason to doubt that algae did not bore into ancient limestone seacliffs as they do today.

The Silurian-Devonian disconformity in southern Ontario provides a fine example of endolithic algal infestation of ancient seacliff exposures in carbonate sequences. The disconformity, developed on the upper Silurian Bertie Formation, is a paleo-subaerial exposure surface; during the subsequent lower Devonian transgression, the subaerial surface underwent a migrating shoreline phase during which algae bored (in low densities) into the limestone surface (along with other macroborers; Appendix Fig. 11). The disconformity surfaces, associated Karst features, and penetrating biota, are described in detail in Kobluk _et al._ (1976).

The silica-infilled algal borings (10 to 50 um diameter) are found penetrating the disconformity surface (to a depth of up to 250 um), and also penetrating the walls of the macroborings of _Trypanites_ Magdefrau (Appendix Fig. 12). The borings do not show any signs of associated micritization. The reason for the low algal population densities is unknown, but could involve such factors as rapidity of burial of the substrate (leaving only a short period of time in which boring could take place), low rates of algal recruitement, abrasive action of the mobile substrate (preventing settlement, and fostering removal of algae that may have succeeded in penetrating the substrate),etc.

APPENDIX FIGURE 11 The shoreline at the final phase of the lower Devonian marine transgression in southern Ontario. The karstified disconformity exposed in quarries at Hagersville, Humberstone, and Port Colborne, Ontario was bored by the intertidal to shallow subtidal Trypanites (represented in the partially filled solution-widened joint at C). Algal borings are found over the disconformity surface and even penetrating the walls of the macroborings.


A SPRINGVALE SANDS
B BERTIE DOLOMITE
C WIDENED JOINT
D BORINGS
0
0.5M
A
B
C
D
SEA LEVEL
KOBLUK '76

APPENDIX FIGURE 12 Silica-infilled algal boring dissolved from the wall of a Trypanites macroboring in the Silurian disconformity surface at the Law Quarry in Port Colborne.